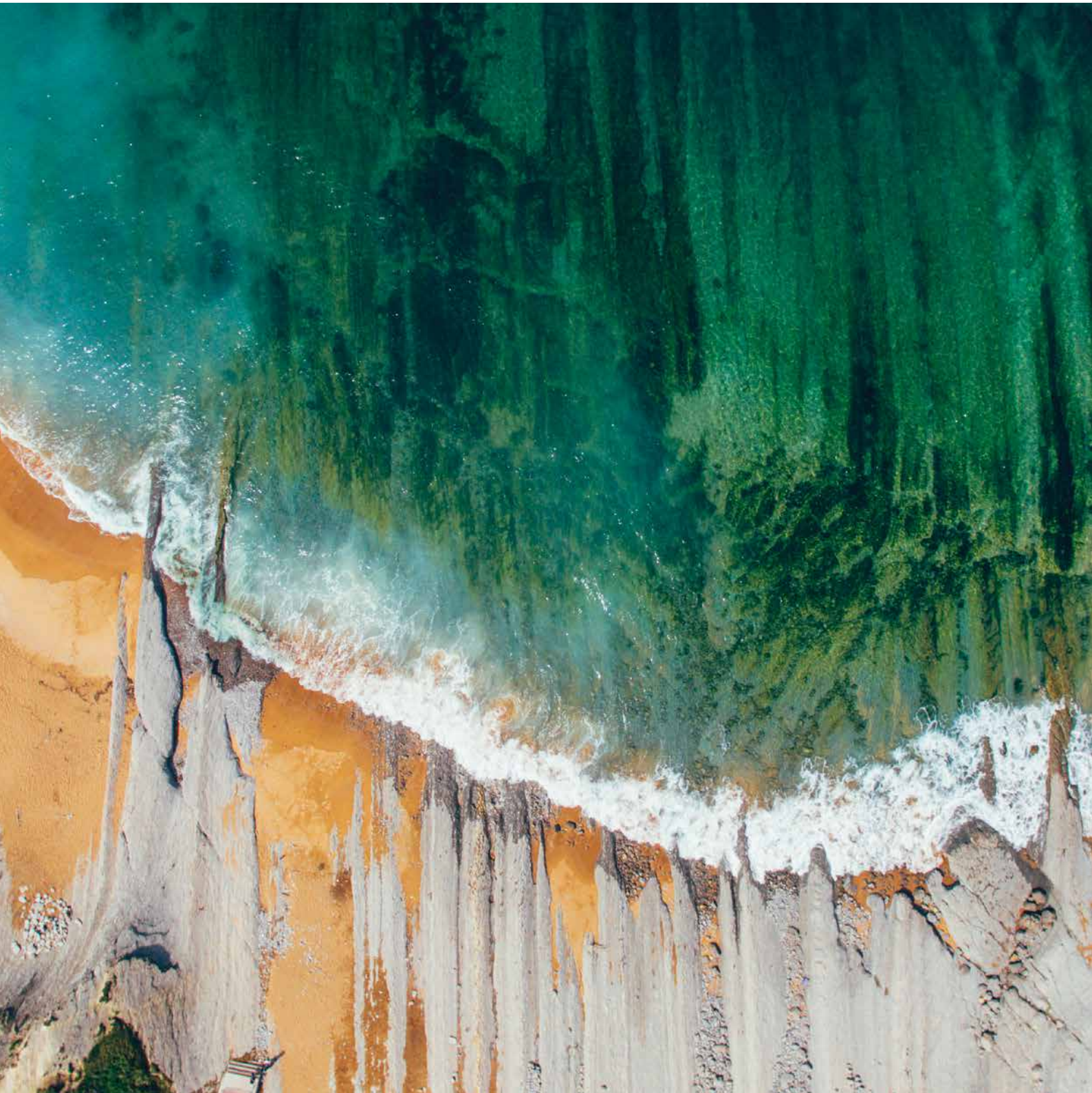


**WORLD
ENERGY
COUNCIL**

World Energy Resources | 2016



ABOUT THE WORLD ENERGY COUNCIL

The World Energy Council is the principal impartial network of energy leaders and practitioners promoting an affordable, stable and environmentally sensitive energy system for the greatest benefit of all.

Formed in 1923, the Council is the UN-accredited global energy body, representing the entire energy spectrum, with over 3,000 member organisations in over 90 countries, drawn from governments, private and state corporations, academia, NGOs and energy stakeholders. We inform global, regional and national energy strategies by hosting high-level events including the World Energy Congress and publishing authoritative studies, and work through our extensive member network to facilitate the world's energy policy dialogue.

Further details at www.worldenergy.org and [@WECouncil](https://twitter.com/WECouncil)

ABOUT THE WORLD ENERGY RESOURCES

The World Energy Resources have been produced by the World Energy Council for over 80 years. The details and analysis provide a unique data set that allows governments, private sector and academia to better understand the reality of the energy sector and the resource developments.

The assessments are compiled with our network of member committees in over 90 countries along with a panel of experts who provide insights from across the globe. With information covering more than 180 countries this is the 24th edition of the World Energy Resources report.

FOREWORD

Sufficient and secure energy is the main enabler for welfare and economic development of a society. As energy-related activities have significant environmental impacts, it is indispensable to provide an energy system which covers the needs of the economies and preserves the environment.

Fundamental structural changes in the energy sector, called energy transitions, occur worldwide. Motivation, objectives and priorities for implementing energy transitions differ, but could mostly be related back to the Energy Trilemma. Securing the energy supply, increasing competitiveness by using least-cost approaches, environmental concerns or a mixture of these aspects are the main drivers.

The diversification of technologies and resources, now applied in the energy sector, creates many opportunities, but the enlarged complexity also leads to increased challenges. With the existing level of volatility, relying on solid facts and data as basis for strategic decision making by the relevant stakeholders, such as governments, international organisations and companies, is becoming even more important than in the past.

In principal, the need for solid foundations is nothing new. In 1923, the founders of the World Energy Council came together to better understand the reality of the energy landscape. One of the most-established flagship programs is the Survey of Energy Resources (SER). The first edition of the SER was published in 1933. Since then this report has been released during the World Energy Congress. World Energy Resources 2016 is the title of the new publication and in fact is the 24th edition, celebrating 83 years of existence.

The reputation and value of the study rests on three main factors: the study presents unbiased data and facts from an independent and impartial organisation, it covers the technological, economic and environmental aspects of conventional and renewable sources, and it provides assessments on global, regional and country levels prepared by an international network of respected experts. The quality of the report has been further enhanced by the collaboration with a number of international organisations and companies in our Knowledge Networks. In particular, IRENA for renewable energy technologies and the German Federal Institute for Geosciences and natural resources on fossil and nuclear fuels data.

The report includes 13 chapters, which cover oil, gas, coal, uranium & nuclear, hydro power, wind, solar, geothermal, marine, bioenergy, waste-to-energy and two cross-cutting topics, energy storage and CC(U)S. Each of the chapters follow a standard structure with sections on definitions and classification, technologies, economics and markets, socio-economics, environmental impacts, outlook and data tables by countries.

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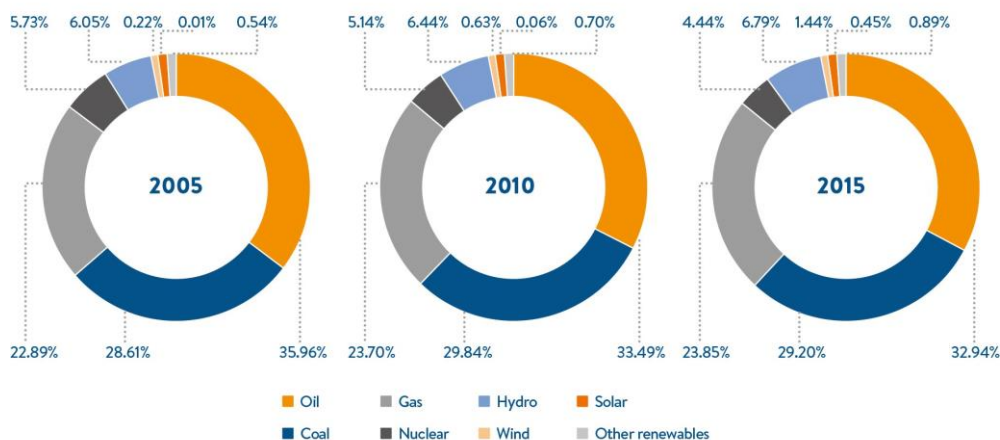
Glossary and Definitions

SUMMARY

The past 15 years have seen unprecedented change in the consumption of energy resources. Unexpected high growth in the renewables market, in terms of investment, new capacity and high growth rates in developing countries have changed the landscape for the energy sector. We have seen the growth of unconventional resources and improvements in technology evolution for all forms of energy resources. This has contributed to falling prices and the increased decoupling of economic growth and GHG emissions. Most countries have achieved a more diversified energy mix with a growth in community ownerships and an evolution of micro grids.

To better understand these unprecedented changes the 2016 World Energy Resources report highlights the key trends and identifies the implications for the energy sector.

FIGURE 1: COMPARATIVE PRIMARY ENERGY CONSUMPTION OVER THE PAST 15 YEARS



Source: BP (2016) Statistical review of world energy 2016 workbook

KEY FINDINGS

Solar

Global installed capacity for solar-powered electricity has seen an exponential growth, reaching around 227 GW_e at the end of 2015, producing 1% of all electricity used globally. The total capacity for solar heating and cooling in operation in 2015 was estimated at 406 GW_{th}.

As solar PV module prices have declined around 80% since 2007 (from ~ US\$4/W in 2007 to ~ US\$1.8/W in 2015), the cost associated with balancing the system represents the next great challenge for the Solar PV industry.

E-storage

E-storage has been characterised by rapid change, driven by reduced costs (especially batteries) and increased industry requirement to manage system volatility.

As of end-2015, the global installed storage capacity was 146 GW (including pumped hydro storage), consisting of 944 projects. There are already around 25 000 residential-scale units in Germany alone.

Bottom-up projections suggest a global storage market of 1.4 GW/y by 2020 (excluding pumped hydro storage), with strong growth in electro-mechanical technologies in particular.

Marine

0.5 GW of commercial marine energy generation capacity is in operation and another 1.7 GW under construction, with 99% of this accounted for by tidal range.

The total theoretical wave energy potential is said to be 32 PWh/y, but is heterogeneous and geographically distributed, technology costs for marine energy are still very high, hindering deployment.

Uranium and Nuclear

Global uranium production increased by 40% between 2004 and 2013, mainly because of increased production by Kazakhstan, the world's leading producer.

As of December 2015, 65 nuclear reactors were under construction with a total capacity of 64 GW. Two-thirds (40) of the units under construction are located in four countries: China, India, Russia and South Korea.

Currently there are more than 45 Small Modular Reactors designs under development and four reactors under construction.

Waste-to-Energy

Despite Waste-to-Energy (WtE) occupying less than 6% of the total waste management market, the global WtE market was valued at approximately US\$25 billion in 2015 and is expected to reach US\$36 billion by 2020, growing at CAGR of around 7.5 % between 2015 and 2020.

Hydropower

Hydropower is the leading renewable source for electricity generation globally, supplying 71% of all renewable electricity at the end of 2015. Undeveloped potential is approximately 10 000 TWh/y worldwide.

The global hydropower capacity increased by more than 30% between 2007 and 2015 accounting to a total of 1 209 GW in 2015, of which 145 GW is pumped storage.

Oil

Oil remained the world's leading fuel, accounting for 32.9% of global energy consumption. Crude oil prices recorded the largest percentage decline since 1986 (73%).

Roughly 63% of oil consumption is from the transport sector. Oil substitution is not yet imminent and is not expected to reach more than 5% for the next five years. Unconventional oil recovery accounts for 30% of the global recoverable oil reserves and oil shale resources contain at least three times as much oil as conventional crude oil reserves, which are projected at around 1.2 trillion barrels.

Natural Gas

Natural gas is the second largest energy source in power generation, representing 22% of generated power globally and the only fossil fuel whose share of primary energy consumption is projected to grow.

Wind

Global wind power generation reached 432 GW in 2015, around 7% of total global power generation capacity (420 GW onshore, 12 GW offshore). A record of 63 GW was added in 2015 and total investment in the global wind sector was US\$109 billion in 2015.

Coal

Coal production decreased with 0.6% in 2014 and with a further 2.8% in 2015, the first decline in global coal production growth since the 1990s. Coal still provides around 40% of the world's electricity. However, climate change mitigation demands, transition to cleaner energy forms and increased competition from other resources are presenting challenges for the sector. Asia presents the biggest market for coal and currently accounts for 66% of global coal consumption.

CCS

CCS is an essential element of any low carbon energy future and industrial future, but policy is the main issue, not technology. The world's first large-scale application of CO₂ capture technology in the power sector commenced operation in October 2014 at the Boundary Dam power station in Saskatchewan, Canada. There are 22 large-scale CCS projects currently in operation or under construction around the world, with the capacity to capture up to 40 million tonnes of CO₂ per year (Mtpa).

Geothermal

Geothermal global output is estimated to be 75 TWh for heat and 75 TWh for power, but is concentrated on geologic plate boundaries.

Bioenergy

Bioenergy (including traditional biomass) is the largest renewable energy source with 14% out of 18% renewables in the energy mix and supplies 10% of global energy supply.

IMPLICATIONS

There is already significant transition in the sector, there are challenges that remain:

Despite some notable progress, the **rate of improvements towards cleaner energy is far slower** than required to meet emissions targets. **Public acceptance remains a challenge**, regardless of the energy source, with an increased 'Not in my back yard' ('NIMBY') attitude to the development of energy sources. Increased commodity and **energy price uncertainty**, that results in higher risk, and larger investments with long lead times are less appealing.

Without **diversification and review of business models**, national and internal oil and gas companies could struggle over the medium to long term. Incentive-assisted renewable energy companies have created a boom in certain countries and regions. However, as incentives are decreased, some companies might **not be viable anymore**.

Rare earth elements, used in especially renewable energies, create **new dependencies in the value chain** and could represent possible future barriers to growth. Change is at its slowest at the moment, but our research identifies that technologies will change a lot quicker and the **regulatory system** is not fully prepared for this change, which may also become a barrier.

Liberalised markets could reach their limit, as the lowest cost generation in the short term can be perceived to provide the highest value. There is a significant need to balance other aspects of the Energy Trilemma such as environmental considerations, including increased resilience and security of supply. This is particularly important for long-term planning in short-term power operations, with the lack and lag of new, expanded, upgraded and **smart infrastructure** offering the potential to hinder new energy developments.

Heat generation and cooling technologies are lagging behind in terms of innovation. Increased use of natural gas combined with decreased use of coal will see energy-associated **carbon dioxide emissions from natural gas** surpass those from coal. Failure to timeously plan for **replacement of decommissioned baseload** might pose a risk to energy reliability in some countries.

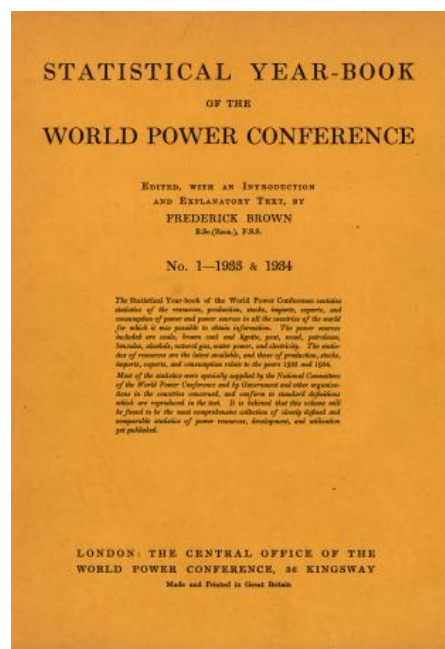
All of this creates a highly dynamic context for the energy sector.

INTRODUCTION

In 2016 we are celebrating 83 years since the first publication World Energy Resources (WER) in 1933. In this edition (24th) we cover 12 energy resources, together with Carbon Capture and Storage (CCS) and energy-storage as two relevant technologies.

This report presents a short summary of the full World Energy Resources report that comprises a comprehensive and unique set of global energy resources data and related information. This information allows energy decision-makers to better understand the reality of the energy sector and the resource developments. With more than 3 million downloads per year, the WER flagship study is a reference tool for governments, industry, investors, IGOs, NGOs, academia and the general public.

The various chapters are compiled with our network of member committees in over 90 countries along with a panel of experts who provide insights from across the globe.



WHAT HAS CHANGED?

Since the previous publication, some emerging energy issues have solidified the level and extend of their impact on the energy environment. This would include the CoP 21 Agreement in Paris; the continued increase in demand in China and India; continued increase in growth in renewable energies and growth in unconventional oil and gas. During this time, we have also experienced new developments such as the low oil and gas price; the role of new technologies and the rise of community ownership and co-operatives in the energy sector.

With long investment and long lead times, the energy industry has traditionally been a long-term industry and change could take a fairly long time, especially on a global scale. Therefore, when the global primary energy consumption numbers over the past 15 years are compared, the changes are quite remarkable. Although the global energy transition towards cleaner energy production is not moving at the speed we would like, it is definitely gaining momentum. Figure 1 shows the increased growth in renewable energy consumption in the context of the other primary energy sources and Figure 2 gives the percentage of renewable energy in electricity production in the various regions. Given that roughly 25% of global greenhouse (GHG) emissions come from the electricity sector, this is a very positive development. The transport sector consumes about 27% of energy demand, but is roughly responsible for 14% of GHG emissions. This compares relatively well to industry, consuming about 28% of energy demand and being responsible for 21% of GHG emissions.

With buildings consuming approximately 34% of energy demand, being responsible for 6% of GHG emissions, and urbanisation increasing in most areas of the world, it is clear that innovative technologies and design in urban areas can be instrumental in achieving long-term sustainability of the global energy system.

FIGURE 2: SHARE OF RENEWABLE ENERGY (INCLUDING HYDRO) IN ELECTRICITY PRODUCTION

Region	Share of renewable energy in electricity production (incl. hydro) (%) in 2005	Share of renewable energy in electricity production (incl. hydro) (%) in 2010	Share of renewable energy in electricity production (incl. hydro) (%) in 2015
Africa	16.9%	17.4%	18.9%
Asia	13.9%	16.1%	20.3%
CIS	18%	16.7%	16.1%
Europe	20.1%	25.7%	34.2%
Latin America	59.3%	57.7%	52.4%
Middle East	4.3%	2.0%	2.2%
North America	24%	25.8%	27.7%
Pacific	17.9%	18.6%	25.0%

Source: Enerdata (2016) Energy Statistical Yearbook

Shale oil and gas technology is unlocking development of more resources at lower costs. In addition to potentially vast shale oil and gas resources, the development of renewables is increasing and becoming cost competitive. Also, energy efficiency is increasing while

energy intensity is decreasing, but this is counteracted by population growth, economic growth and increased access to electricity, in especially developing areas of the world.

The effects of Brexit on the EU and the UK energy policy still remain uncertain and major changes cannot be expected in the near future. Planned investments and financing of energy infrastructure is likely to be delayed in the UK, and if some European utilities or investors decide to leave the UK, it could mean a reallocation of capital into Europe and elsewhere.

For oil and gas producers around the world, 2016 is a year of further cost cutting, restructuring, refinancing when possible, and, in some cases bankruptcy. The transition to cleaner energy means funding for fossil fuel projects are becoming more difficult and therefore it warrants a closer look at possible future impacts of the CoP21 Agreement.

THE ROLE OF THE PARIS AGREEMENT ON SHAPING ENERGY DEVELOPMENTS

Deemed as a historic breakthrough in international climate policy, Article 2 of the Paris Agreement defines the three purposes of the instrument: to make mitigation effective by holding the increase of temperature well below 2°C, pursuing efforts to keep warming at 1.5°C above pre-industrial levels; to make adaptation possible for all parties; and to make finance available to fund low carbon development and build resilience to climate impacts. These three outcomes have an impact on energy developments, primarily through the adoption of commitments labelled as Nationally Determined Contributions (NDCs), which are only “intended” (hence INDCs) until the Agreement enters into force.

The temperature target of Paris requires a profound transformation process and an inherently new understanding of our energy systems. Credible and effective national policies are crucial to translate the pledges made at Paris into domestic policy. New policies will need to be put in place and old ones revisited: carbon emissions will be priced; energy production and consumption technologies will be regulated; funding for research and development will be made available; and low carbon assets will be nurtured by financial markets. Key market disruptions will be experienced by market participants and governments alike, including stranded assets and technology innovation.

Energy prices

It is crucial to have a level playing field where all energy sources can compete on equal terms, but providing, at the same time, the right signals to energy consumers. In this respect subsidies play a significant role and need to be reviewed carefully.

Acknowledging the importance of a strong carbon price signal will be key to promote adequate consumer behaviour and to enable a growth path in low-carbon investments that is consistent with the 2°C scenario. This includes incentives for investments in climate solutions for supply (i.e. renewables) and demand (i.e. enhancing energy efficiency) and ensuring protection of the environment.

Stranded assets

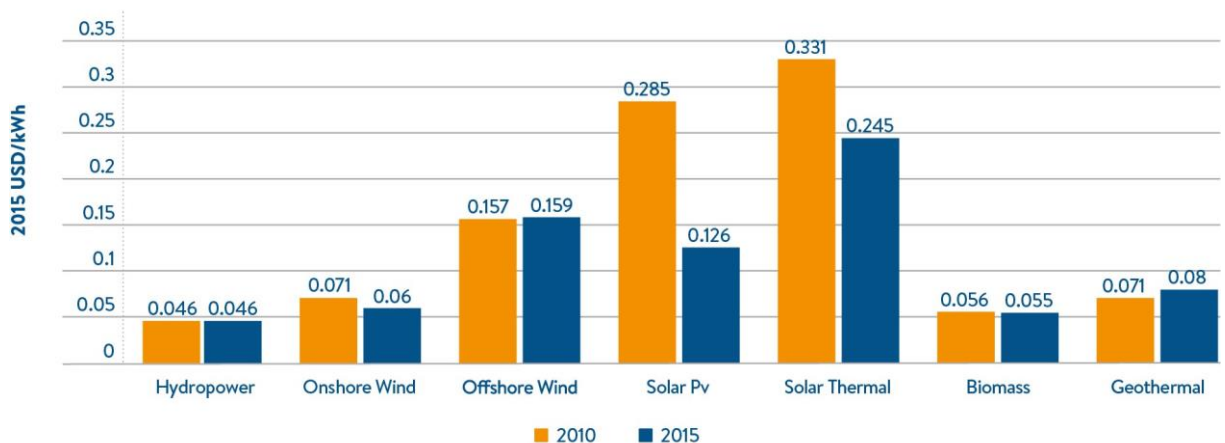
One of the main risks of climate change mitigation strategies is the appearance of stranded assets due to the combination of increased societal pressures, stricter environmental regulation (such as carbon taxes and new standards), and technological development (i.e. cleaner energy, renewable energy or new storage technologies). Such stranded assets can already be observed in Europe with recent gas power plants being mothballed or decommissioned due to overcapacity caused by massive penetration of renewables supported by FITs and other schemes.

According to the journal Nature, the untapped coal, oil and natural gas reserves that would remain unexploited in order to meet the 2°C target could amount to 88%, 35% and 52% of global reserves respectively. The market values of the firms that own fossil fuels assets may undergo major changes because of the reduction both of future revenues and the firms' balance sheets due to the loss of value of those assets affected by climate change mitigation actions.

Technology disruption

More options and innovative solutions that reduce carbon emissions on a large scale are needed to make a real difference in the years ahead. Research and development (R&D) in clean energy technologies is crucial and increased investments are required to move from the laboratory to reality.

FIGURE 3: TRENDS IN GLOBAL RENEWABLE ENERGY LEVELISED COST OF ELECTRICITY (LCOE) IN THE TIME PERIOD FROM 2010 UNTIL 2015



Source: IRENA (2016)

1. COAL

The world currently consumes over 7 700 Mt of coal which is used by a variety of sectors including power generation, iron and steel production, cement manufacturing and as a liquid fuel. Coal currently fuels 40% of the world's electricity and is forecasted to continue to supply a strategic share over the next three decades. The tables below show the top coal producing countries and regions in the world for 2014 and 2015.

TABLE 1: TOP COAL PRODUCING COUNTRIES IN 2014 AND 2015

Country	Production	
	Total production 2014*	Total production 2015**
Australia	503.3	485
China	4000	3747
Germany	186.5	184
India	659.6	677
Indonesia	470.8	392
Kazakhstan	115.6	106
Poland	136.9	136
Russia	357	373
South Africa	253.2	252
USA	906.9	813

TABLE 2: TOP COAL PRODUCING REGIONS IN 2014 AND 2015

Region	Production	
	Total production 2014*	Total production 2015**
Total Africa	265.7	266
Total Asia Pacific	5 651.4	5440
Total CIS	544.8	527
Total EU	8 795.2	528
Total Middle East	2.8	1
Total North America	989.9	888
Total S. & Cent. America	103	98
World	8,176.4	7861

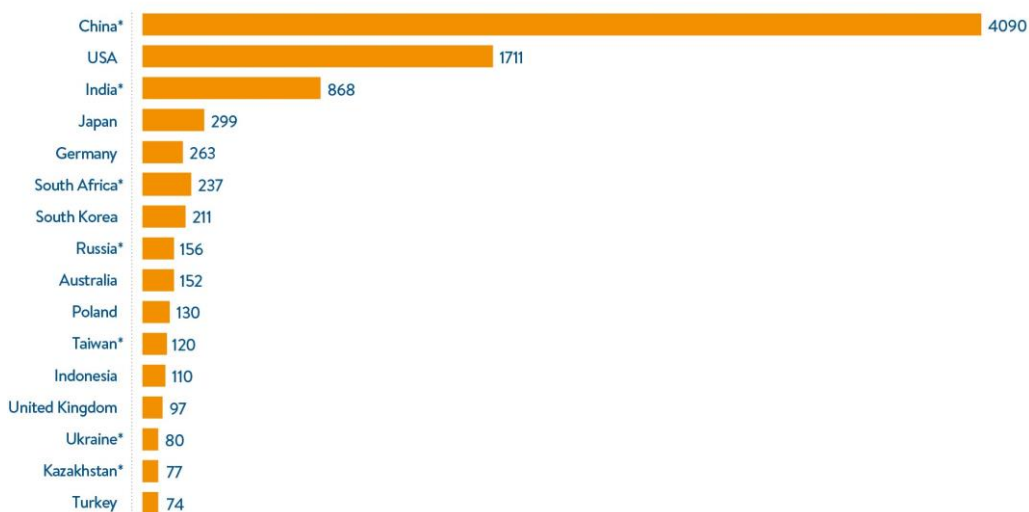
* BGR

** BP (2016) Statistical Review of World Energy

KEY FINDINGS

1. Coal is the second most important energy source, covering 30% of global primary energy consumption. Hard coal and lignite (brown coal) is the leading energy source in power generation with 40% of globally generated power relying on this fuel.
2. Coal is predominantly an indigenous fuel, mined and used in the same country, allowing for security of supply where this is the case. The oversupply and price of natural gas have negatively impacted the coal industry.
3. 75% of the global coal plants utilise subcritical technology. An increase in the efficiency of coal-fired power plants throughout the world from today's average of 33% to 40% could cut global carbon dioxide emissions by 1.7 billion tonnes each year.
4. Apart from the continued increase in the efficiency of power plants, the implementation of carbon capture utilisation and storage (CCUS) is one of the elementary strategies for climate protection.
5. Global coal consumption increased by 64% from 2000 to 2014. That classified coal as the fastest growing fuel in absolute numbers within the indicated period. 2014 and 2015 witnessed the first annual decrease in global thermal coal production of 0.7% and 2.8% respectively, since 1999.
6. China contributes 50% to global coal demand and is shifting to clean coal technologies. India's coal consumption is set to increase, while the US is closing or replacing coal with gas in power plants.

FIGURE 4: 2014 COUNTRY RANKING: COAL-FIRED POWER GENERATION (TWH)



Source: IEA, Electricity Information, Paris 2015 (*for Non-OECD-countries numbers for 2013)

2. OIL

Oil remains the world's leading fuel, accounting for 32.9% of total global energy consumption. Although emerging economies continued to dominate the growth in global energy consumption, growth in these countries (+1.6%) was well below its ten-year average of 3.8%.

Several structural changes are underway in the oil industry, the emergence of non-OPEC supply, the trends in energy efficiency, the diminishing role of high-sulphur oil with the environmental pressures in the marine fuel industry and in the power generation sector, the emergence of unconventional oil (shale oil, heavy oil, tight oil and tar sands), and increased production both from mature and frontier fields. The table below shows global oil demand and projected demand by region from 2014 to 2020.

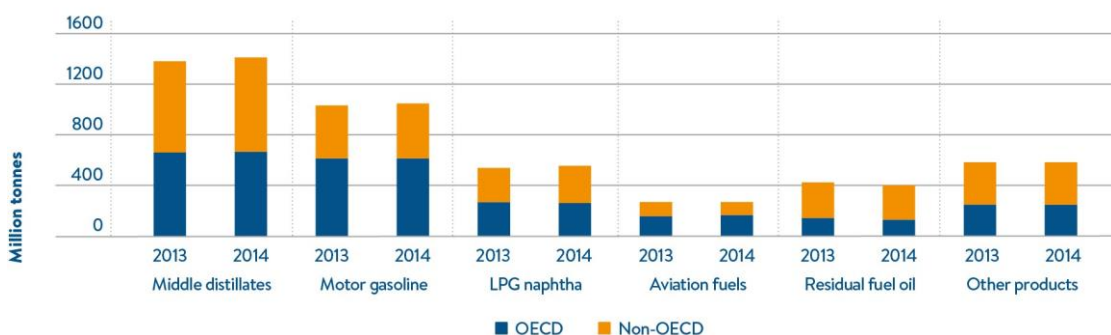
TABLE 3: GLOBAL OIL DEMAND, BY REGION FROM 2014-2020

Region	2014	2015	Change from '14-'15 in %	2016	Change from '15-'16 in %	2017	Change from '16-'17 in %	2018	Change from '17-'18 in %
OECD Americas	24.1	24.2	0.004%	24.3	0.004%	24.4	0.004%	24.5	0.004%
OECD Asia Ocean.	8.1	8.0	-0.012%	7.9	-0.012%	7.9	0%	7.9	0%
OECD Europe	13.4	13.3	-0.007%	13.3	0%	13.2	-0.07%	13.1	-0.07%
FSU	4.8	4.6	-0.041%	4.7	0.021%	4.7	0%	4.8	0.021%
Other Europe	0.7	0.7	0%	0.7	0%	0.7	0%	0.7	0%
China	10.4	10.6	0.019%	10.9	0.028%	11.2	0.027%	11.5	0.026%
Other Asia	12.1	12.5	0.033%	12.9	0.216%	13.3	0.031%	13.7	0.03%
Latin America	6.8	6.9	0.014%	7.0	0.014%	7.1	0.014%	7.2	0.014%
Middle East	8.1	8.3	0.024%	8.5	0.024%	8.8	0.035%	9.0	0.022%
Africa	3.9	4.1	0.051%	4.2	0.024%	4.4	0.047%	4.5	0.22%
World	92.4	93.3	0.009%	94.5	0.012%	95.7	0.012%	96.9	0.012%

KEY FINDINGS

1. Emerging economies now account for 58.1% of global energy consumption and global demand for liquid hydrocarbons will continue to grow. Chinese consumption growth slowed to 1.5%, while India (+5.2%) recorded another robust increase in consumption. OECD consumption increased slightly (+0.1%), compared with an average annual decline of 0.3% over the past decade. In 2015, a rare increase in EU consumption (+1.6%), offset declines in the US (-0.9%) and Japan (-1.2%), where consumption fell to the lowest level since 1991¹.
2. The growth of population and the consumer class in Asia will support oil demand increase and the main increase in consumption will come from transportation sectors.
3. Despite the temporary price drop, the fundamentals of the oil industry remain strong. Price fluctuations seen of late have been neither unexpected nor unprecedented.
4. The main drivers of price changes have been the gradual building up of OPEC spare capacity and the emergence of non-OPEC production, especially US Light Tight Oil (LTO).
7. Substitution of oil in the transport sector is not yet imminent and is not expected to reach more than 5% for the next five years.
8. New and increased use of technologies such as high-pressure, high-temperature (HPHT) drilling; multi-stage fracking; development in flow assurance for mature fields; greater sophistication in well simulation techniques, reservoirs modelling; 3-D seismic technologies, EOR developments are having a positive impact on safety and E&P possibilities.

FIGURE 5: PRODUCT-MARKET CONSUMPTION TRENDS



Source: IEA (2015) Medium Term Oil Report

¹ IEA (2016) Oil Briefing

3. NATURAL GAS

Natural gas is the only fossil fuel whose share of the primary energy mix is expected to grow and has the potential to play an important role in the world's transition to a cleaner, more affordable and secure energy future. It is the number three fuel, reflecting 24% of global primary energy, and it is the second energy source in power generation, representing a 22% share.

Advances in supply side technologies have changed the supply landscape and created new prospects for affordable and secure supplies of natural gas. Natural gas markets are becoming more interconnected as a result of gas-to-gas pricing, short-term trade and consumer bargaining power.

The future of demand is highly uncertain, new policy frameworks and continued cost improvements will be needed to make gas more competitive. Infrastructure build out, government support and the closure of regulatory gaps are needed to unlock the socioeconomic and environmental benefits of natural gas.

TABLE 4: REGIONAL NATURAL GAS DATA BY REGION

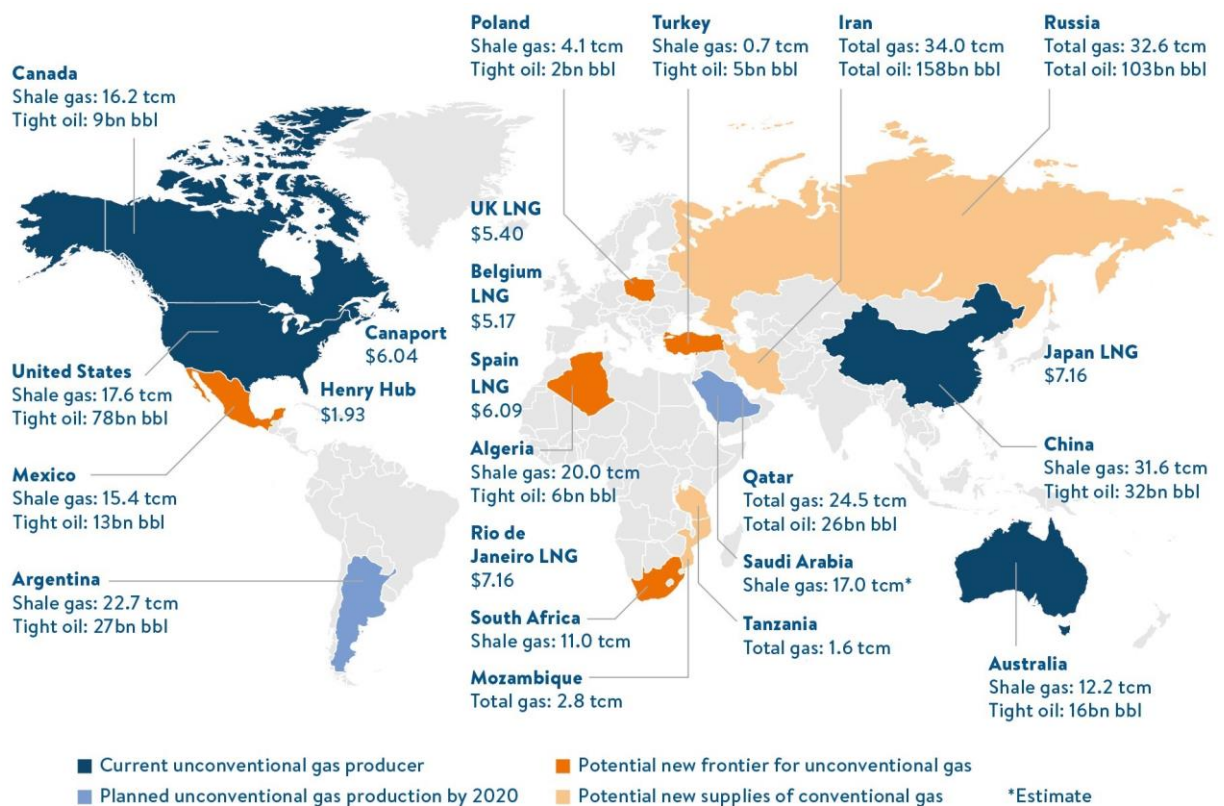
2015 Region	Proved Reserves		Production		R/P Ratio
	Bcm	Bcf	Bcm	Bcf	Years
Africa Total	14064	496666.5	211.8	7479.2	66.4
Asia Pacific Total	15648.1	552607.7	556.7	19658.2	28.1
Europe & Eurasia Total	56778.4	2005109.3	989.8	34955.2	57.4
LAC Total	7591.5	268091.0	178.5	6302.1	42.5
Middle East Total	80040.9	2826617.7	617.9	21821.1	129.5
North America Total	12751.8	450326.0	984.0	34750.4	13.0
Global Total	186874.7	6599418.0	3538.6	124966.2	52.8

Sources: BP Statistical Review of World Energy 2015, OPEC Annual Statistical Bulletin 2015, EIA International Energy Statistics, CIA: The World Factbook, and published national sources

KEY FINDINGS

- Demand projections for natural gas exports to Asia, particularly China and Japan, have been revised down as importing nations push to improve energy security and reduce the impact of volatile commodity markets on domestic energy prices.
- In particular, unconventional gas, shale and CBM, reflected more than 10% of global gas production in 2014 and is entering global markets as LNG, disrupting the global supplier landscape and creating increased competition in regional natural gas markets.
- The shifting dynamics in natural gas pricing in recent years can be attributed to regional supply and demand imbalances. North America prices collapsed in 2009, driven by a domestic oversupply, while from 2011-2013, the Japanese nuclear drove prices higher in Asia.
- Currently, the fall in demand in Asia and growing export capacity in Asia and North America, have created an oversupply globally. As further supplies come to the market, it appears likely that the current market oversupply and low price environment will continue in the short to medium-term.

FIGURE 6: NEW SUPPLY LANDSCAPE (TECHNICALLY RECOVERABLE RESERVES)



Sources: BP Statistical Review of World Energy, EIA, FERC, and Reuters

4. URANIUM AND NUCLEAR

The Fukushima accident in March 2011 resulted in a developmental hiatus and a nuclear retreat in some countries. However, with the benefit of five years of hindsight, the true proportions of that accident are becoming clearer: a barely perceptible direct impact on public health, but high economic and social costs.

The assessments of global uranium resources show that total identified resources have grown by about 70% over the last ten years. As of January 2015 the total identified resources of uranium are considered sufficient for over 100 years' of supply based on current requirements.

The development of nuclear power is today concentrated in a relatively small group of countries. China, Korea, India and Russia account for 40 of the 65 reactors that the IAEA records as under construction in December 2015. The countries that have historically accounted for the majority of nuclear power development are now under-represented in new construction. Currently there are more than 45 Small Modular Reactors designs under development and four reactors under construction.

TABLE 5: URANIUM PRODUCTION AND RESOURCES

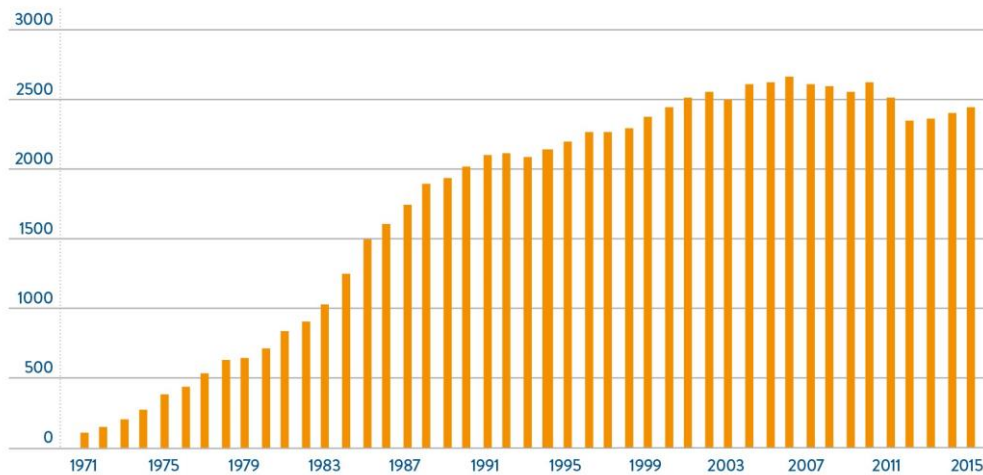
Country	2014 Production tU	Uranium resources (tU)<US\$130/Kg
Australia	5001	1174000
Canada	9134	357500
China	1500	120000
Kazakhstan	23127	285600
Namibia	3255	248200
Niger	4057	325000
Russia	2990	216500
USA	1919	207400
Uzbekistan	2400	59400
Total	56252	3698900

Source: OECD-NEA & IAEA (2014) Uranium 2014: Resources, Production and Demand; World Nuclear Association (2015) Uranium: From Mine to Mill

KEY FINDINGS

1. Global nuclear power capacity reached 390 GW_e at the end of 2015, generating about 11% of the world electricity. As of December 2015, 65 reactors were under construction (6 more than in July 2012) with a total generating capacity of 64 GW.
2. The key drivers and market players defining the future of nuclear power are different from those 20-30 years ago and the emerging non-OECD economies (mainly China and India) are expected to dominate future prospects. The increasing need to moderate the local pollution effects of fossil fuel use, means that nuclear is increasingly seen as a means to add large scale baseload power generation while limiting the amount of GHG emissions.
3. The low share of fuel cost in total generating costs makes nuclear the lowest-cost baseload electricity supply option in many markets. Uranium costs account for only about 5% of total generating costs and thus protect plant operators against resource price volatility. Generation IV reactors promise to remove any future limitation on fuel supply for hundreds of years.
4. Nuclear desalination has been demonstrated to be a viable option to meet the growing demand for potable water around the globe, providing hope to areas in arid and semi-arid zones that face acute water shortages.

FIGURE 7: WORLD NUCLEAR ELECTRICITY PRODUCTION, TWH



Source: International Atomic Energy Agency, Power Reactor Information System

5. HYDROPOWER

There has been a major upsurge in hydropower development globally in recent years. The total installed capacity has grown by 39% from 2005 to 2015, with an average growth rate of nearly 4% per year. The rise has been concentrated in emerging markets where hydropower offers not only clean energy, but also provides water services, energy security and facilitates regional cooperation and economic development.

It is estimated that 99% of the world's electricity storage capacity is in the form of hydropower, including pumped storage². Reservoirs with storage offer a high degree of flexibility, storing potential energy for later use at timescales ranging from seconds, to days, to several months.

Especially pumped storage, provides an array of energy services beyond power, including black start capability, frequency regulation, inertial response, spinning and non-spinning reserve and voltage support, which are increasingly important to the stability of the energy system.

Technological innovation in hydropower include: a) increasing the scale of turbines (1000 MW turbine in development), b) advanced hydropower control technologies that enable renewable hybrids, c) both conventional and pumped storage hydropower increasingly utilised as a flexible resource for balancing variable renewable resources.

TABLE 6: TOP HYDROPOWER CAPACITY AS OF 2015

	Total Capacity end of 2015 (GW)	Added Capacity in 2015 (GW)	Production (TWh)
China	319	19	1 126
USA	102	0.1	250
Brazil	92	2.5	382
Canada	79	0.7	376
India	52	1.9	120
Russia	51	0.2	160

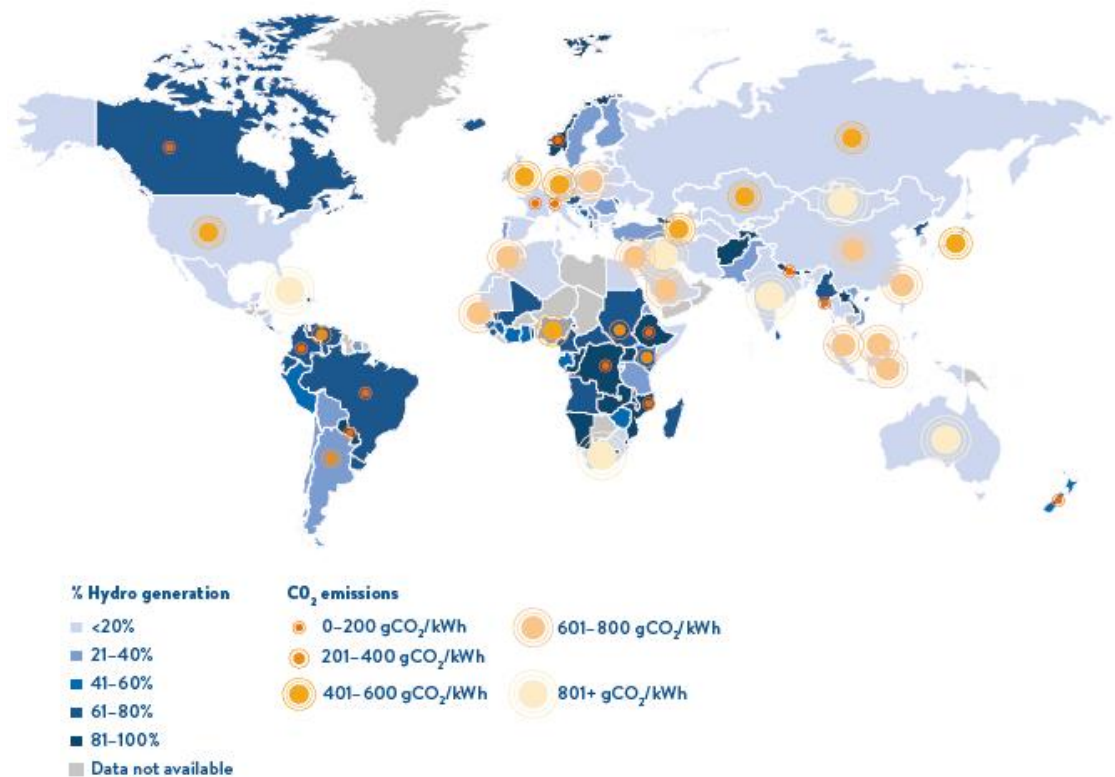
Source: REN21, IHA (2015)

² IEA (2014)

KEY FINDINGS

1. Hydropower is the leading renewable source for electricity generation globally, supplying 71% of all renewable electricity. Reaching 1 064 GW of installed capacity in 2016, it generated 16.4% of the world's electricity from all sources.
2. Significant new development is concentrated in China, Latin America and Africa. Asia has the largest unutilised potential, estimated at 7 195 TWh/y, making it the likely leading market for future development. China accounted for 26% of the global installed capacity in 2015, far ahead of USA (8.4%), Brazil (7.6%) and Canada (6.5%).
3. As hydropower has good synergies with all generation technologies, its role is expected to increase in importance in the electricity systems of the future. This is especially true of pumped hydro used as storage, but also increasingly to balance the volatility caused by increased renewable energy in the system.
4. Consideration of water management benefits offered by hydropower facilities includes flood control, water conservation during droughts or arid seasons.

FIGURE 8: THE CONTRIBUTION OF HYDROPOWER TO A LOW CARBON FUTURE



6. BIOENERGY

The World Energy Council defines bioenergy to include traditional biomass (example forestry and agricultural residues), modern biomass and biofuels. It represents the transformation of organic matter into a source of energy, whether it is collected from natural surroundings or specifically grown for the purpose.

In developed countries, bioenergy is promoted as an alternative or more sustainable source for hydrocarbons, especially for transportation fuels, like bioethanol and biodiesel, the use of wood in combined heat and power generation and residential heating. In developing countries bioenergy may represent opportunities for domestic industrial development and economic growth. In least developed countries traditional biomass is often the dominant domestic fuel, especially in more rural areas without access to electricity or other energy sources. There are multiple challenges and opportunities for bioenergy as a potential driver of sustainable development, given enough economic and technological support.

Lower energy prices do not favour short- to medium-term development of first-generation biofuels and investment in research and development (R&D) for advanced biofuels produced from ligno-cellulosic biomass, waste or non-food feedstock is also set to decline. Decreases in crude oil and biofuel feedstock prices should lead to a decline in ethanol and biodiesel prices. Global ethanol and biodiesel production are both expected to expand to reach respectively, almost 134.5 and 39 billion litres by 2024. Subsequently, both ethanol and biodiesel prices are expected to recover in nominal terms close to their 2014 levels.

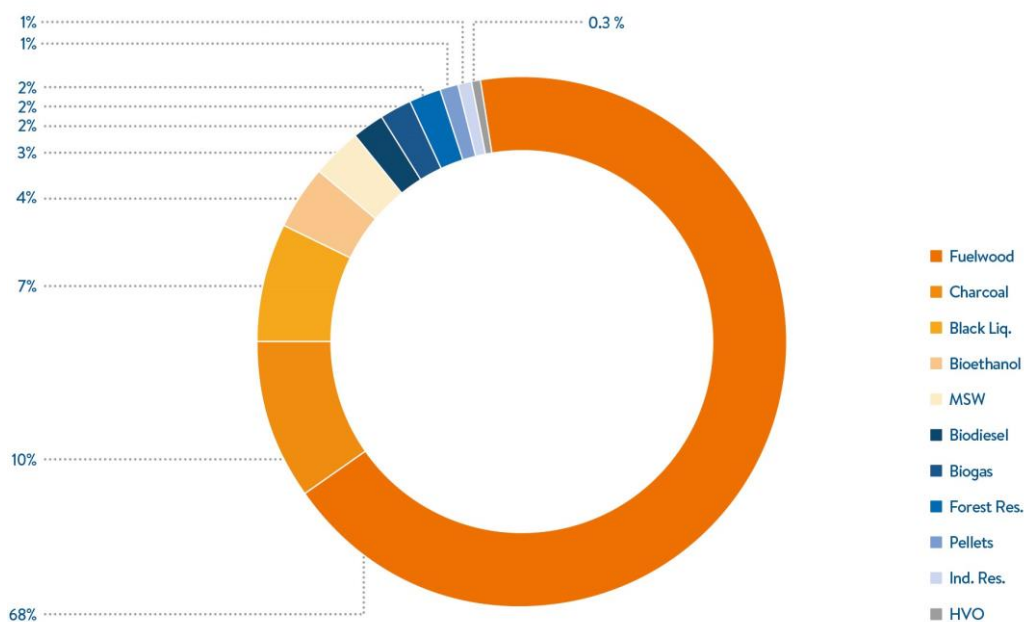
TABLE 7: SHARE OF BIOFUELS PRODUCTION BY REGION

Region	Percentage			
	1993	2003	2013	2014
Asia Pacific		3.3%	9.5%	10.5%
Africa				1.0%
Middle East				
Europe & Eurasia	1.1%	11.1%	17.1%	16.5%
S. & Cent. America	71.4%	49.2%	28.5%	28.7%
North America	27.4%	36.4%	44.8%	44.1%

KEY FINDINGS

1. Bioenergy is the largest renewable energy source with 14% out of 18% renewables in the energy mix and supplying 10% of global energy supply. In contrast to other energy sources, biomass can be converted into solid, liquid and gaseous fuels.
2. It is shifting from a traditional and indigenous energy source to a modern and globally traded commodity. The consumption pattern varies geographically with biofuels in being dominant in the Americas, fuel wood and charcoal in Asia and Africa and combined heat and power generation in Europe.
3. The primary energy supply of forest biomass used worldwide is estimated at about 56 EJ and overall woody biomass provides about 90% of the primary energy annually sourced from all forms of biomass. Wood is also the source of more than 52 million tonnes of charcoal used in cooking in many countries, and for smelting of iron and other metal ores.
4. International trade is driven by pellets (27 million tonnes in 2015) and liquid biofuels. With biofuels being the most viable and sustainable option in replacing oil dependency, future demand will come from the need for renewables in transport, followed by heating and electricity sectors.

FIGURE 9: PRIMARY ENERGY SUPPLY OF BIOMASS RESOURCES GLOBALLY IN 2013



Source: Based on data from World Bioenergy Association (2016)

7. WASTE-TO-ENERGY

The global WtE market was valued at US\$25.32 billion in 2013, a growth of 5.5% on the previous year. WtE technologies based on thermal energy conversion lead the market, and accounted for 88.2% of total market revenue in 2013. The global market is expected to maintain its steady growth to 2023, when it is estimated it would be worth US\$40 billion, growing at a CAGR of over 5.5% from 2016 to 2023.

WtE remains a costly option for waste disposal and energy generation, in comparison with other established power generation sources and for waste management.

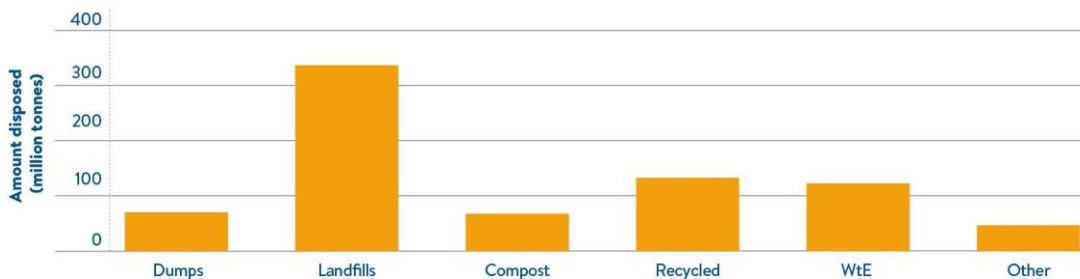
Combustion plants are no longer a significant source of particulate emissions owing to the implementation of governmental regulations on emission control strategies, reducing the dioxin emissions by 99.9%.

FIGURE 10: WASTE GENERATION PER CAPITA (KG/DAY) TO GROSS NATIONAL INCOME (GNI)



Source: Navigant Research, World Bank (2014)

FIGURE 11: AMOUNT OF WASTE DISPOSED IN 2012, BY TECHNIQUE

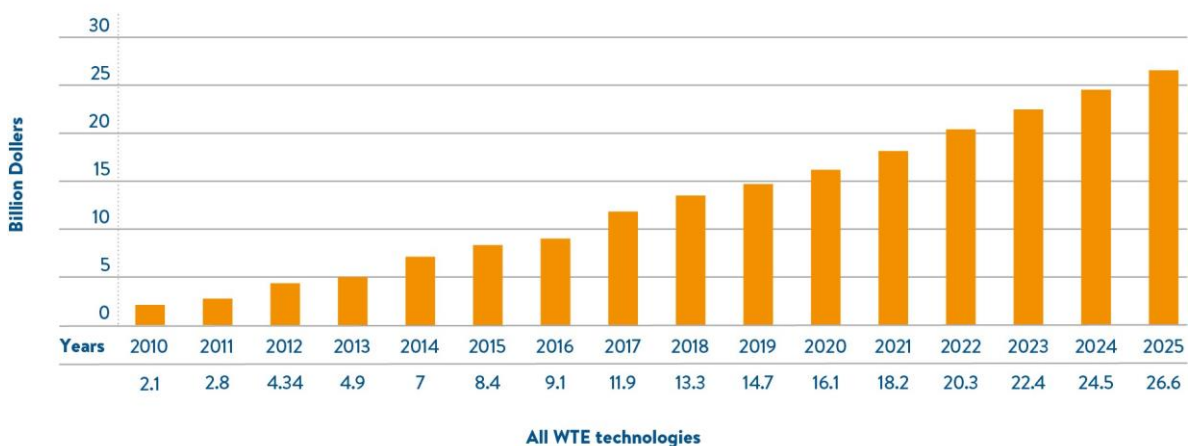


Source: Hoornweg & Bhada-Tata (2012)

KEY FINDINGS

1. Europe is the largest and most sophisticated market for WtE technologies, accounting for 47.6% of total market revenue in 2013. The Asia-Pacific market is dominated by Japan, which uses up to 60% of its solid waste for incineration. However, the fastest market growth has been witnessed in China, which has more than doubled its WtE capacity in the period 2011-2015.
2. Biological WtE technologies will experience faster growth at an average of 9.7% per annum, as new technologies (e.g. anaerobic digestion) become commercially viable and penetrate the market.
3. From a regional perspective, the Asia-Pacific region will register the fastest growth (CAGR of 7.5%), driven by increasing waste generation and government initiatives in China and India and higher technology penetration in Japan.
4. It is estimated that global waste generation will double by 2025 to over 6 million tonnes of waste per day and the rates are not expected to peak before the end of this century. While OECD countries will reach 'peak waste' by 2050, and East Asia and Pacific countries by 2075, waste will continue to grow in Sub-Saharan Africa. By 2100, global waste generation may hit 11 million tonnes per day.

FIGURE 12: GROWTH OF ALL WTE TECHNOLOGIES GLOBALLY WITH A CONSERVATIVE FORECAST UP TO 2025



Source: Ouda & Raza (2014)

8. SOLAR ENERGY

Global installed capacity for solar-powered electricity has seen an exponential growth, reaching around 227 GW_e at the end of 2015. It produced 1% of all electricity used globally.

Major solar installation has been in regions with relatively less solar resources (Europe and China), while potential in high resource regions (Africa and Middle East), remains untapped. Germany has led PV capacity installations over the last decade and continues as a leader, followed by China, Japan, Italy and the United States.

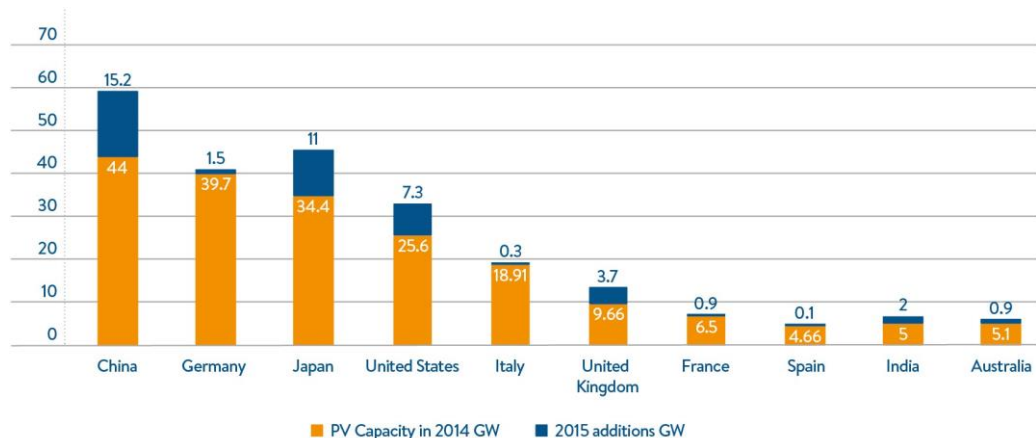
Expansion of solar capacity could be hindered by existing electricity infrastructure, particularly in countries with young solar markets. Solar PV and other renewable technologies are highly dependent on rare earth elements, which, besides general unsustainable mining practices, also carry a high risk of some supply disruption.

TABLE 8: CONSTRAINTS AND RISKS TO MATERIALS CONSUMED BY SOLAR PV

Element	R/P ratio (years)	Production constraint	Level of risk to solar industry
Cadmium	30	Environmental	High
Chromium	>16	Geopolitical & commercial	High
Gallium	N/A	Commercial	High
Germanium	N/A	Commercial	High
Indium	N/A	Commercial	Medium
Tellurium	N/A	Commercial	High

Source: BP Zepf (2014)

FIGURE 13: TOP SOLAR PV CAPACITY IN 2014 AND ADDITIONS IN 2015

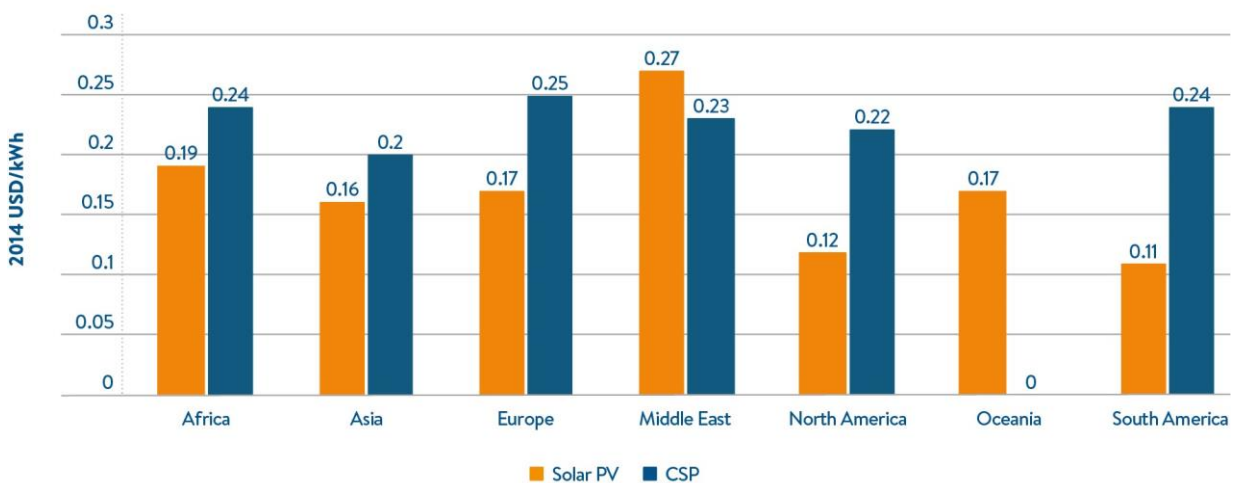


Source: REN21 (2016)

KEY FINDINGS

1. Costs for solar power are falling rapidly and “grid parity” has been achieved in many countries, while new markets for the solar industry are opening in emerging and developing countries. Policy and regulatory incentives, oversupply of installation components, and advancements in technology are driving the reduction in cost.
2. Technology is constantly improving, and new technologies such as Perovskite³ cells are approaching commercialisation. While there has been continuous improvement in the conversion efficiency of PV cells, concentrated photovoltaics (CPV) may hold the key in enabling rapid increases in solar energy efficiency, recently reaching 46% for solar cells.
3. In order to prevent environmental damage from solar PV, there is a need for strict and consistent regulation on processes over the entire life-cycle of infrastructure. Disposal and recycling must be considered as more modules reach the end of their lifespan.

FIGURE 14: AVERAGE LEVELISED COST OF ELECTRICITY FOR SOLAR PV AND CSP IN 2014



Source: IRENA (2016)

³ Perovskite cells include perovskite (crystal) structured compounds that are simple to manufacture and are expected to be relatively inexpensive to produce. They have experienced a steep rate of efficiency improvement in laboratories over the past few years.

9. GEOTHERMAL ENERGY

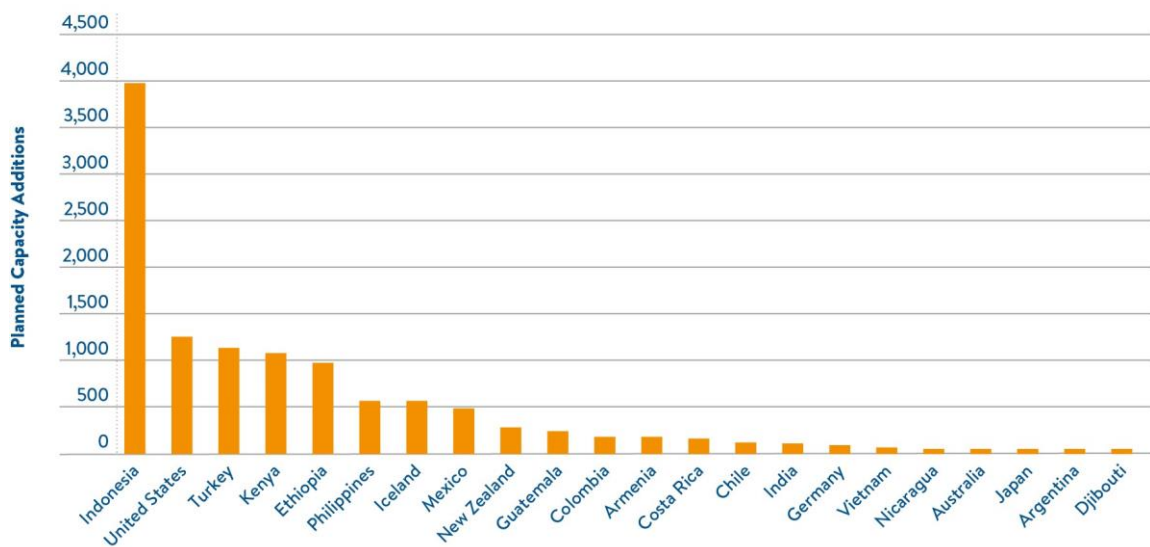
Geothermal energy contributes a small proportion of the world’s primary energy consumption. Electricity generation, geothermal produces less than 1% of the world’s output. There were 315 MW of new geothermal power capacity installed in 2015, raising the total capacity to 13.2 GW.

Turkey accounted for half of the new global capacity additions, followed by the US, Mexico, Kenya, Japan and Germany. In terms of direct use of geothermal heat, the countries with the largest utilisation, accounting for roughly 70% of direct geothermal in 2015, are China, Turkey, Iceland, Japan, Hungary, the US and New Zealand.

The earth’s natural heat reserves are immense. The estimated stored thermal energy down to 3 km within continental crust, is roughly 43×10^6 EJ, which is considerably greater than the world’s total primary energy consumption.

Geographically, 72% of installed generation capacity resides along tectonic plate boundaries or *hot spot* features of the Pacific Rim. A disproportional percentage of installed generation capacity resides on island nations or regions (43%), providing not only a valuable source of power generation, but also both heat and heat storage over a wide spectrum of conditions.

FIGURE 15: CAPACITY UNDER DEVELOPMENT BY COUNTRY (MW)

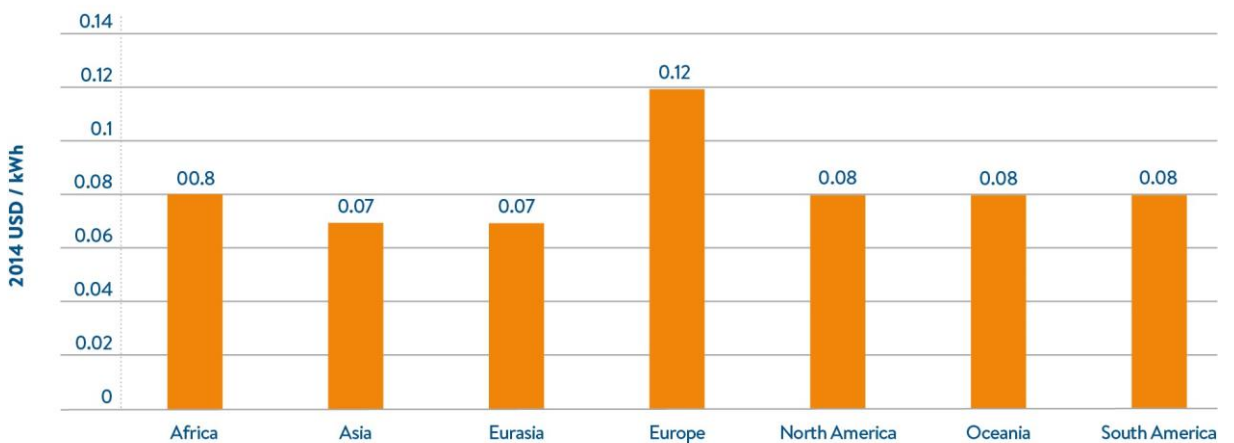


Source: GEA (2016)

KEY FINDINGS

1. In 2015, total power output totalled 75 TWh, the same number being also valid for total heat output from geothermal energy (excluding ground heat pumps). World geothermal heat use (direct & storage) reached 563 PJ in 2014.
2. Global investment in 2015 was US\$2 billion, a 23% setback from 2014. During the period 2010-2014, around US\$20 billion were invested in geothermal energy by 49 countries for both direct use and electric power.
3. Geothermal energy currently finds itself burdened by higher installation costs and longer development periods, relative to solar and wind. As a result, in many countries, geothermal energy projects have been and are reliant on government incentives in order to compete against both natural gas and other renewable generation.
4. The pace of geothermal development has been conditioned by legal frameworks and particularly by conservation legislation. However, the pace of development might accelerate due to climate change concerns and the increasing need to decarbonise the energy sector.

FIGURE 16: AVERAGE LEVELISED COST OF ELECTRICITY FOR GEOTHERMAL IN 2014, BY REGION



Source: IRENA (2016)

10. WIND ENERGY

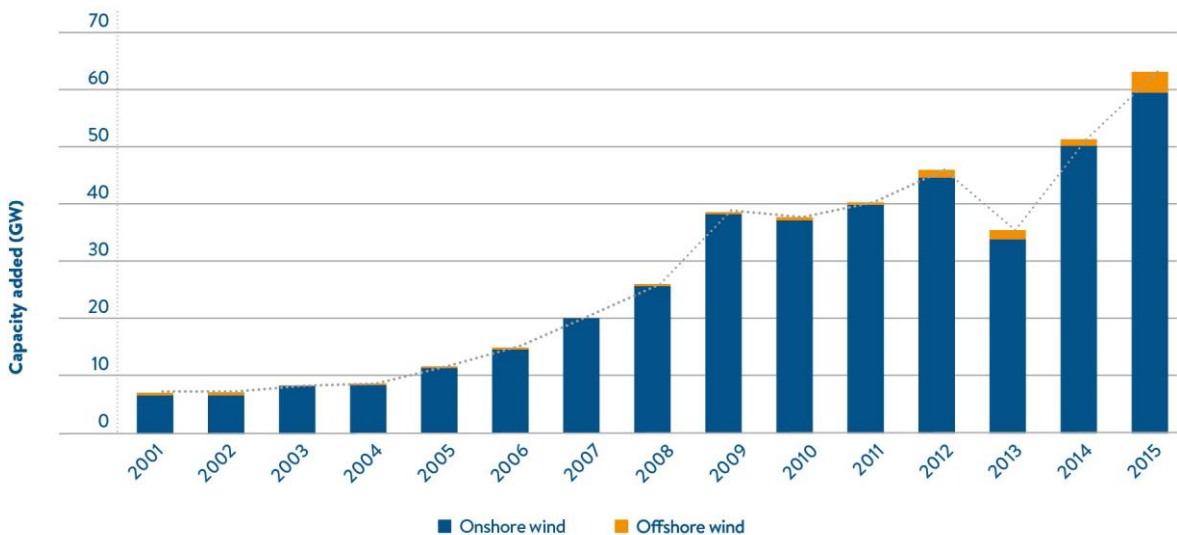
World wind power generation capacity has reached 435 GW at the end of 2015, around 7% of total global power generation capacity. A record of 64 GW was added in 2015. The global growth rate of 17.2% was higher than in 2014 (16.4%).

Global wind power generation amounted to 950 TWh in 2015, nearly 4% of total global power generation. Some countries have reached much higher percentages. Denmark produced 42% of its electricity from wind turbines in 2015, the highest figure yet recorded worldwide. In Germany wind power contributed a new record of 13% of the country's power consumption in 2015.

The next generation of advanced large offshore wind turbines, reduced costs for foundations and more efficient project development practices could reduce the LCOE of offshore wind from US\$19.6 cents per kWh in 2015 to roughly 12 cents per kWh in 2030.

Global installed capacity of offshore wind capacity reached around 12 107 MW end-2015, with 2 739 turbines across 73 offshore wind farms in 15 countries. Currently, more than 92% (10 936 MW) of all offshore wind installations are in European waters. Floating foundations technologies are in development and several full-scale prototype floating wind turbines have been deployed.

FIGURE 17: ANNUAL NET GLOBAL WIND CAPACITY ADDITIONS, 2001-2015

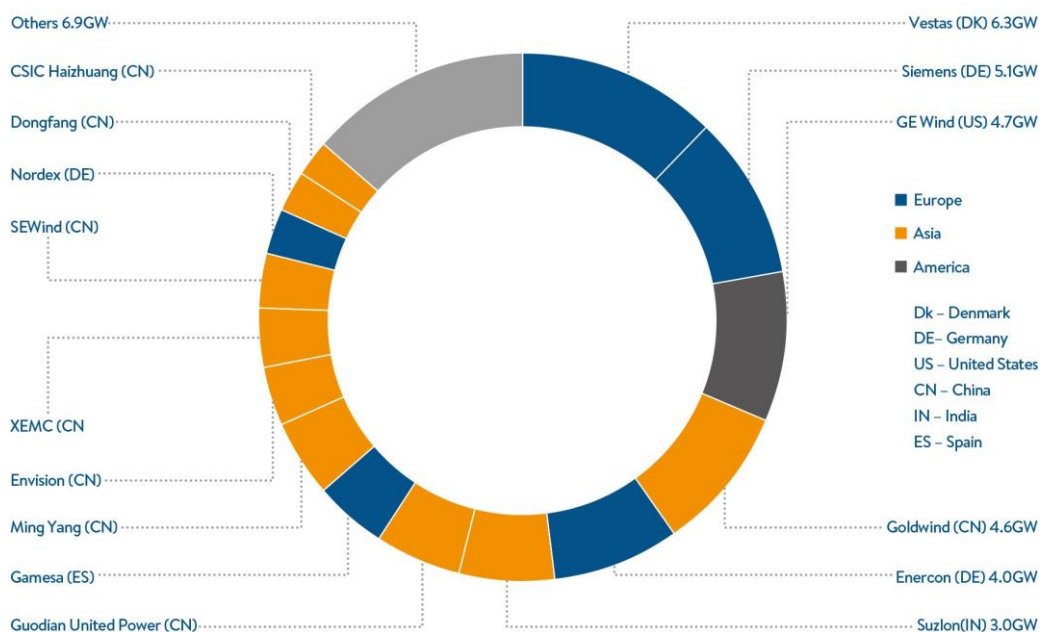


Source: IRENA, GWEC

KEY FINDINGS

1. With current policy plans, global wind capacity could grow from 435 GW in 2015 to 977 GW in 2030 (905 GW onshore and 72 GW offshore wind). The global leaders in wind power as at end-2015 are China, the US, Germany, India and Spain.
2. The total investments in the global wind sector reached a record level of US\$109.6 billion over the course of 2015.
3. For onshore wind, China has the lowest weighted average LCOE with a range between US\$50/MW – US\$72/MW, while the highest weighted average LCOE are found in Africa, Oceania and Middle East with US\$95/MW, US\$97/MW and US\$99/MW.
4. Wind deployment continues to be dominated by onshore wind, supported by continual cost reductions. LCOE for offshore wind has continued to decrease owing to a wide range of innovations. Floating foundations could be game changers in opening up significant new markets with deeper waters.
5. Trends within the supplier industry in recent years show strong consolidation of the major companies and the shift in the global wind market eastwards to China and India.

FIGURE 18: SHARE OF THE GLOBAL TURBINE MANUFACTURER MARKET, WITH RESPECTIVE CAPACITY ADDITIONS, IN 2014



Source: BTM Navigant (2015)

11. MARINE ENERGY

To date only a handful of commercial ocean energy projects have been delivered, reflecting the current immaturity and high costs of these technologies, as well as the challenging market environment in which they operate.

0.5 GW of commercial ocean energy generation capacity is in operation and another 1.7 GW under construction, with 99% of this accounted for by tidal range. Relatively few commercial scale wave, tidal stream or OTEC projects are operational. Three tidal stream commercial projects accounting for 17 MW of capacity are to be commissioned shortly, (two in Scotland and one in France), and a 1 MW commercial wave energy array in Sweden.

Sweden has begun construction of the world's largest commercial wave energy array at Sotenas. It will incorporate 42 devices and deliver 1.05 MW of capacity. They have also recently installed a second project in Ghana consisting of 6 devices, together providing 400 kW of capacity

TABLE 9: REGIONAL THEORETICAL POTENTIAL OF WAVE ENERGY

REGION	Wave Energy TWh/yr
Western and Northern Europe	2 800
Mediterranean Sea and Atlantic Archipelagos (Azores, Cape Verde, Canaries)	1 300
North America and Greenland	4 000
Central America	1 500
South America	4 600
Africa	3 500
Asia	6 200
Australia, New Zealand and Pacific Islands	5 600
TOTAL	29 500

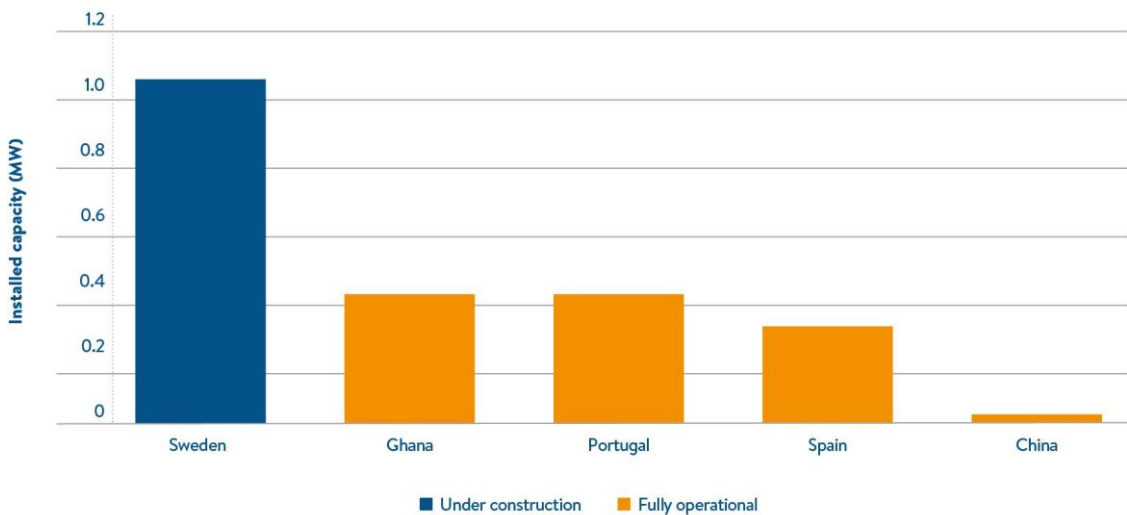
Source: Mørk et al. (2010)

Note: The total resource potential is less than 32 000 TWh/yr quoted previously as the table accounts for only theoretical wave power $P \geq 5$ kW/m and latitude $\leq 66.5^\circ$

KEY FINDINGS

1. 2015 estimates the LCOE of wave energy at approximately US\$500/MWh while tidal sits at approximately US\$440/MWh. The LCOE for small-scale OTEC plants (1-10 MW) ranges somewhere between US\$190/MWh and US\$940/MWh, however if the facility were to be scale up to between 50-400 MW the cost would fall dramatically to a range between US\$70/MWh and U\$320/MWh.
2. The high costs illustrate the immaturity of these technologies and the relatively short gestation period that ocean energy technologies, with the exception of tidal range, have undergone. Despite positive developments, a large number of projects have been suspended as public and private funds have been withdrawn, but many of the cost issues could be addressed through ongoing RD&D efforts.
3. There is 15 GW of ocean energy projects at various stages of the development pipeline with, the majority of these are tidal range (11.5 GW) followed by tidal stream (2.6 GW), wave (0.8 GW) and OTEC (0.04 GW).

FIGURE 19: WAVE ENERGY INSTALLED CAPACITY IN OPERATION OR UNDER CONSTRUCTION



Source: (OES 2016a)

12. CARBON CAPTURE AND STORAGE (CCS)

The world's first large-scale application of CO₂ capture technology in the power sector commenced operation in October 2014 at the Boundary Dam power station in Saskatchewan, Canada. In the US, two additional demonstrations of large-scale CO₂ capture in the power sector, at the Kemper County Energy Facility in Mississippi and the Petra Nova Carbon Capture Project in Texas are planned to come into operation in 2016-2017.

CCS is currently the only available technology that can significantly reduce GHG emissions from certain industrial processes and it is a key technology option to decarbonise the power sector, especially in countries with a high share of fossil fuels in electricity production.

In terms of the scale of CCS deployment, there are 22 large-scale CCS projects currently in operation or under construction around the world, with the capacity to capture up to 40 million tonnes of CO₂ per year (Mtpa). These projects cover a range of industries, including gas processing, power, fertiliser, steel-making, hydrogen-production (refining applications) and chemicals. They are located predominantly in North America, where the majority of CO₂ capture capacity is intended for use in EOR.⁴

TABLE 10: SELECTED KEY ESTIMATES OF EFFECTIVE STORAGE RESOURCES

Nation	Estimated storage resource (Gigatonnes)	
	Deep saline formations	EOR/depleted fields
USA ⁵	2 379 to 21 633	186 to 232
Europe ⁶	96	20
China ⁷	3 000*	2.2
Australia ⁸	33 to 230	17

Note: the example resource estimates above have been calculated based on geological characteristics and do not account for economic or regulatory factors.

*Resources only calculated at theoretical level

⁴ Projects data is sourced from the Global CCS Institute. <http://www.globalccsinstitute.com/>

⁵ US DOE/NETL (2015) Data refers to the USA plus parts of Canada.

⁶ Vangklide-Pedersen (2009)

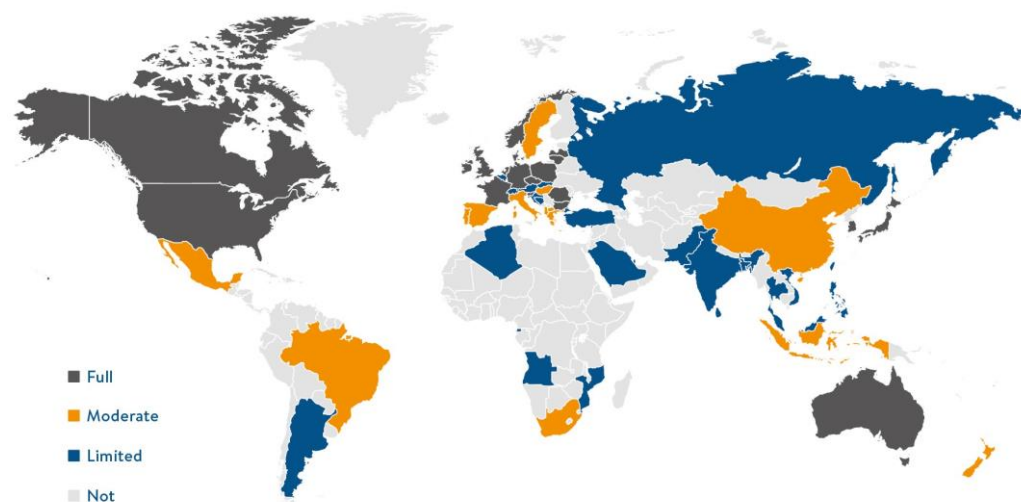
⁷ Dahowski et al. (2009)

⁸ Carbon Storage Taskforce (2009).

KEY FINDINGS

1. Even though the cost of CO₂ transportation is relatively low compared to the cost associated with capturing and storing the CO₂, the scale of investment in CO₂ transportation infrastructure required to support large-scale deployment of CCS will be considerable.
2. Total global CO₂ capture capacity of projects in operation or under construction is around 40 Mtpa. The large-scale projects in operation around the world demonstrate the viability of CCS technology.
3. The Japanese Government is collaborating with technology providers in industry to examine suitable storage sites and the economic feasibility of CCS deployment.
4. The South Korean Government CCS Master Plan includes a large-scale CCS demonstration project operating within certain cost parameters by 2020, and commercial CCS deployment thereafter.
5. In Australia, considerable project activity continues. The Gorgon Carbon Dioxide Injection Project is expected to be operational in 2017. It will be Australia's first large-scale CO₂ injection project and the largest in the world injecting CO₂ into a deep saline formation.
6. The Middle East has two large-scale CCS projects. Main project efforts are centred in Saudi Arabia and Abu Dhabi, although Qatar is also examining CCS opportunities.

FIGURE 20: STATUS OF NATIONAL ASSESSMENTS OF REGIONAL STORAGE RESOURCES



Source: Global CCS Institute (2015) The Global Status of CCS 2015

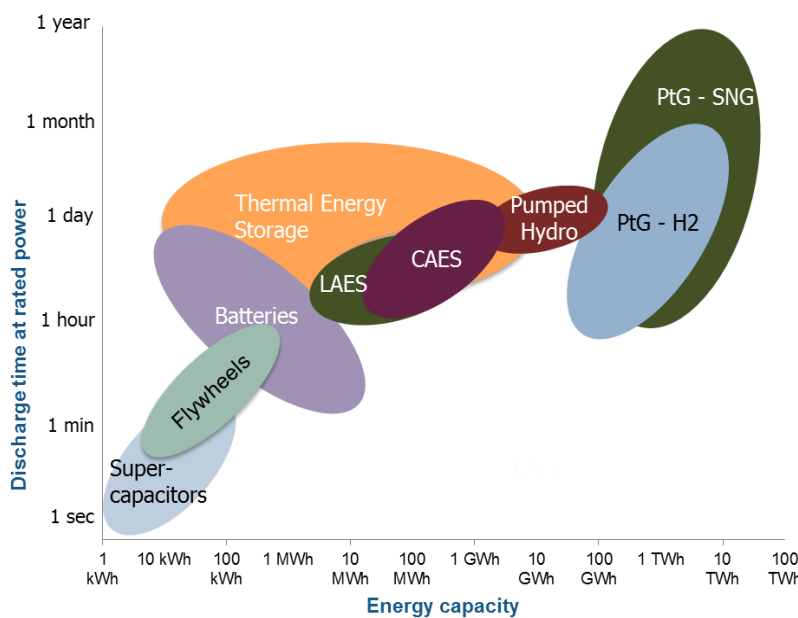
13. E-STORAGE

The concept of energy storage is not new, though development has been mainly restricted to one technology until recently. Pumped hydro storage accounts for well over 95% of global installed energy storage capacity. Compressed air energy storage currently has only two commercial plants (in Germany and the US), in total 400 MW, with a third under development in the UK.

Battery storage capacity is increasing: for example, there are around 25 000 domestic installations in Germany alone in conjunction with solar PV installations, with total capacity of 160 MWh. The total battery capacity in electric vehicles is also growing rapidly. Millions of water heaters have been operated in France for decades; they provide a massive benefit in reducing peak demand, by shifting 5% i.e. 20 TWh from peak periods to low-demand periods. These small-scale energy storage installations are not necessarily well represented in global statistics.

Large batteries are also being developed with installed capacity amounting to almost 750 MW worldwide. Sodium-sulphur became the dominant technology in the 2000s, accounting for nearly 60% of stationary battery projects (441 MW). In recent years, lithium-ion technology has become more popular. Flow batteries, if developed further, could be a game changer in the medium term.

FIGURE 21: MAPPING STORAGE TECHNOLOGIES ACCORDING TO PERFORMANCE CHARACTERISTICS

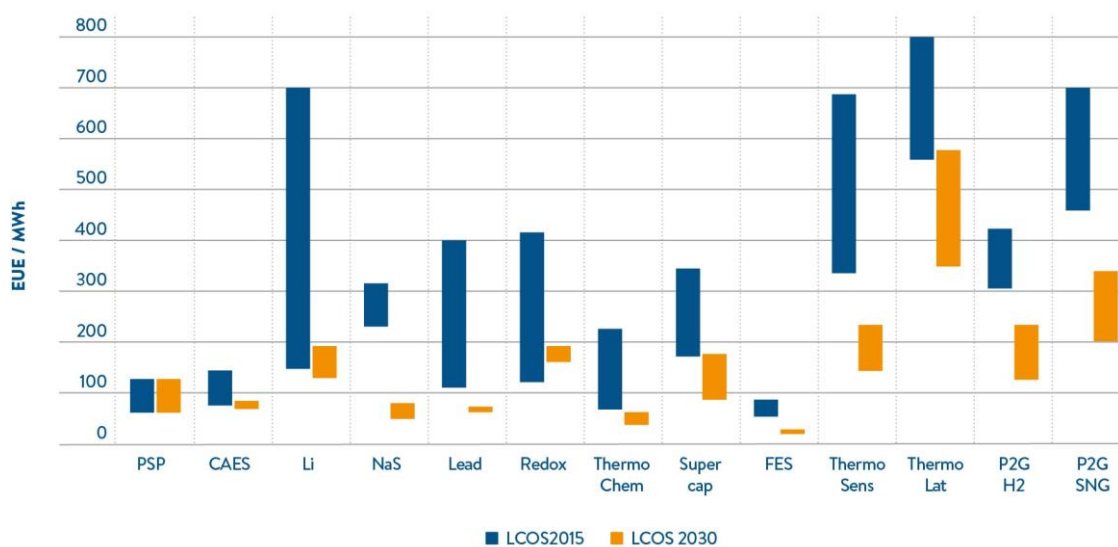


Source: PwC (2015) following Sterner et al. (2014)
 CAES: Compressed Air, LAES: Liquid Air, PtG: Power to Gas.

KEY FINDINGS

1. The main areas of growth in the next five years are likely to be:
 - Small-scale battery storage in conjunction with solar PV. There are already around 25 000 residential-scale units in Germany alone, and this could grow to 150 000 by 2020.
 - Utility-scale electricity storage, for multiple purposes, especially frequency response.
 - Electric vehicles.
 - Commercial, communications and software capabilities to allow multiple small distributed storage, demand response and distributed generation sources to be aggregated, in a 'virtual power plant' or 'swarm'.
 - Pumped storage hydro, especially in south-east Asia, Africa and Latin America.
 - Isolated electricity systems such as islands, to aid integration of renewables in order to save fuel costs.
2. Most commercial interest is in battery storage and the costs of several storage technologies will fall as production volumes increase.
3. The future outlook for energy storage markets is good due to an increasing need, but the regulatory and legal frameworks are failing to keep pace.

FIGURE 22: LEVELISED COST OF STORAGE IN 2015 STUDY PERIOD AND 2030 (€ 2014)



Source: PwC (2015)

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KEY FINDINGS

1. Coal is the second most important energy source, covering 30% of global primary energy consumption.
2. Coal – hard coal and lignite (brown coal) is the leading energy source in power generation with 40% of globally generated power relying on this fuel.
3. Coal is predominantly an indigenous fuel, mined and used in the same country, allowing for security of supply where this is the case.
4. Technology that reduces the emissions from coal-fired power stations is essential to utilizing the abundant coal reserves in an increasingly carbon-constrained environment.
5. 75% of the global coal plants utilise subcritical technology. An increase in the efficiency of coal-fired power plants throughout the world from today's average of 33% to 40% could cut global carbon dioxide emissions by 1.7 billion tonnes each year.
6. Apart from the continued increase in the efficiency of power plants, the implementation of carbon capture utilisation and storage (CCUS) is one of the elementary strategies for climate protection.
7. Carbon Capture and Storage (CCS) is a critical component in a portfolio of low-carbon energy technologies. The quantities of CO₂ to be captured and stored represent tens of giga tonnes, the coming years are critical for demonstrators at industrial scale, aiming at deployment in OECD and non-OECD countries.
8. Global coal consumption increased by 64% from 2000 to 2014. That classified coal as the fastest growing fuel in absolute numbers within the indicated period.
9. 2014 witnessed the first annual decrease in global thermal coal production since 1999.
10. Oversupply & price of natural gas has negatively impacted the coal industry.
11. China contributes 50% to global coal demand. 2014 was the first year within the past decades, in which there was no further increase in the coal demand in China
12. China is shifting to clean coal technologies.
13. India's coal consumption is set to increase.
14. The US is closing or replacing coal with gas in power plants.
15. In Western Europe coal faces much opposition as mitigation of climate change is targeted.

16. Some nations (China, India, Australia, Indonesia, South Africa and Poland) rely heavily on coal to supply base load electricity.

INTRODUCTION

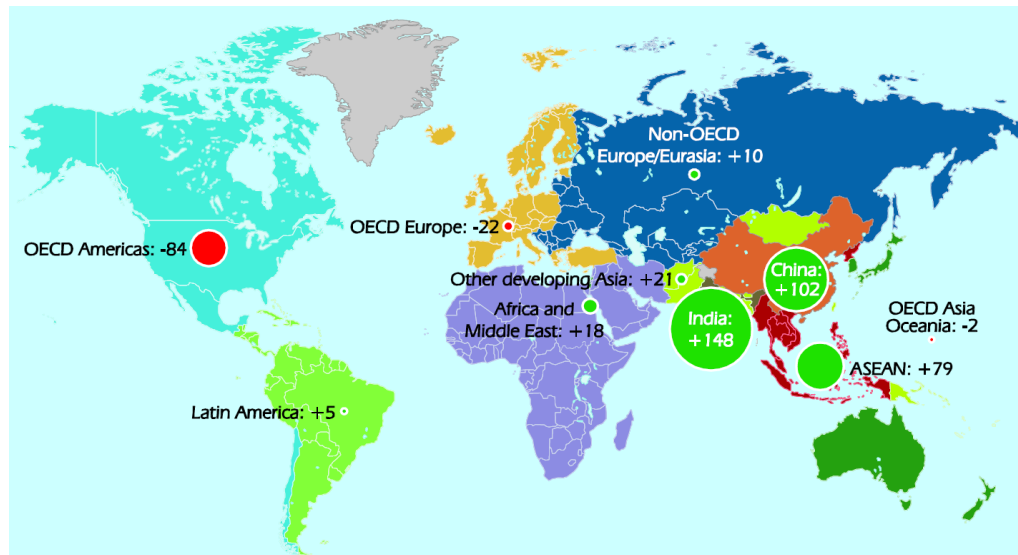
Coal plays an important role in the security of supply in developed countries, and is a key enabler for economic growth and development in developing countries. Coal resource exists in developing countries (including those with significant energy challenges). Therefore, coal has a key role to play in assisting the development of baseload electricity where it is most needed.

Developing countries are increasingly satisfying their growing energy demands with cheap coal in order to sustain economic growth to reduce energy poverty and to achieve the United Nations (U.N.) development goals. Many countries in Asia and Africa are currently making major investments in new coal infrastructures albeit with clean coal technologies¹. The incremental demand for coal is visible because some regions, notably non-OECD Asia, are focused on maintaining the potential for continued economic growth, while simultaneously protecting the environment from excessive accumulation of anthropogenic greenhouse gas (GHG) emissions and other air pollutants (Figure 1).

Coal is known as the most carbon-intensive fossil fuel and the continuing use of coal in global electrification could have implications for climate change mitigation strategies only if low emissions and high efficiency technology will be utilised in high proportions. With modern technological advancements, coal plants could have technologies that allow higher efficiency and low carbon emissions in order to tackle climate change. A further step would be the incorporation of CCUS.

¹ Mercator Research Institute on Global Commons and Climate Change (2015): Renaissance of coal isn't stopping at China

FIGURE 1: FORECAST OF INCREMENTAL GLOBAL COAL DEMAND 2014 - 2020 (MTCE)



Source: IEA (2015)

The step ahead is implementation of CCS. The individual component required technologies are well known and partially mature; for example, transport of CO₂ by pipelines and storage. Addressing the quantities (the order of magnitude is ¼ to 1 Mton CO₂ per TWh), the main challenges is the integration into large-scale demonstration projects, supported by governments if necessary, and accepted by the public and all stakeholders. Co-operation should be encouraging to ensure that the projects cover all the situations in the power industry and in others emitting industries as well. Sharing knowledge will be key for future investments. Given the rapid growth in energy demand in non-OECD countries, OECD and non-OECD countries must work together, and the multilateral institutions should establish the required and relevant support mechanisms.

This chapter seeks to highlight how climate change actions and market dynamics has impacted the coal industry. It discusses how the coal industry is advancing towards clean technologies in order to tackle greenhouse gas emissions and maintaining a role in securing energy supply. This chapter is organised into six sections:

1. Section 2 describes the current technologies available for coal mining, the mode of transportation, coal-fired generation and the investment costs associated with clean technologies.
2. Section 3 looks at different markets and their associated drivers influencing the production and supply of coal.

3. Section 4 focuses on case studies illustrating how the coal industry has impacted communities.
4. Section 5 discusses the extent to which coal-fired electricity generation contributes to water consumption, air and environmental pollution.
5. Section 6 offers the outlook for the coal industry.
6. Section 7 shows data associated with coal reserves and production.

1. TECHNOLOGIES

Comprehensive electrification is essential for sustainable economic development and coal-fired power is seen as a key input to global electricity generation. This accounts for around 40% of total generation². This section briefly explains extraction techniques, transportation and handling, and plant technologies associated with coal-fired power generation.

EXTRACTION TYPES AND MINING TECHNIQUES

Coal, a product of organic sedimentation, occurs in seam-shaped deposits and must be extracted selectively from the surrounding strata. Flat deposits with no faults are of major commercial importance, which account for 50% of the world's deposits. These have few seams that are often of an even thickness and a wide horizontal spread. Flat, hardly disturbed deposits of little depth lend themselves to extraction in opencast operations. These mainly concern lignites, but most hard coal deposits from the Gondwana period on the Southern continents are also of this type.

Sloping to steeply inclined or fault-containing coal deposits have a large number of irregularly shaped seams in layer sequences that are often thousands of metres thick. The seams are encountered at varying depths, with the deposits frequently marked by complicated faults and disturbed conditions, so that extraction is mostly in underground operations. They are generally of high rank; high quality coking coal, non-bituminous coals and anthracites can usually be found in this type of deposit.

Depending on seam depth and formation and on the overlying loose or solid rock, the coal is extracted either in opencast or underground operations. In underground mining, access is by shafts and/or drifts while, in surface operations, the layer above the coal is stripped to permit extraction of the exposed coal. Depending on seam thickness, the composition of the overlying strata and surface use (e.g. inter alia, density of settlement). Opencast mining is an economic proposition down to depths of 500m.

Hard coal extracted in underground operations is mined either from the surface via drifts or shafts, depending on the depth of the deposit. In drift mining, the deposit is developed using slightly inclined drifts equipped with conveyor belts. By contrast, coal deposits at greater depths require shafts, which are also used for proper extraction. The coal is mined either in room-and-pillar or in long-walling operations, with the latter being predominant.

In room-and-pillar mining, continuous miners drive extraction roads into the coal to cross at right angles. Pillars are left standing in-between to support the overlying strata. This method is associated with high extraction losses, since a considerable quantity of coal remains underground. Transportation to the conveyor belts is often by shuttle car. A variant of the

² Office of Chief Economist (2015) Coal in India

room-and-pillar method extraction is by conventional drilling and blasting, with the conveyor belts being fed by wheel loader.

In long-walling, continuous miners are used to drive two parallel roads into the seam at intervals of 200 to 400 m; the roads are then connected at right angles using long-wall equipment. Actual extracted coal falls automatically onto a chain conveyor and is transported further. The long-wall is protected against falling rock by hydraulic shield and frame supports, although the latter are losing importance.

In underground mining, methane gas is released in the long-wall roads; thanks to suitable mine ventilation this gas is so diluted that no firedamp explosions occur. Where the coal is under high pressure from methane gas, gas relaxations are produced by horizontal drilling.

The mining technique used in the extraction of hard coal in open cast operations depends on the number and thickness of the seams and their inclination. In this respect, minimum thicknesses of 0.5 to 1m are considered workable; otherwise, the seams are crushed or loosened by drilling and blasting and removed by dragline/shovel and truck. The seam exposed in dragline operation is likewise drilled and blasted and then loaded by shovel or wheel loader onto heavy trucks for transportation. In this work, small draglines and, to a growing extent, hydraulic excavators are also used. By contrast, the extraction of several inclined seams is by truck and shovel, with the entire group of seams and inter-burden layers being worked in horizontal slices (benches).

The extraction of lignite worldwide is mainly by continuous opencast operation, i.e. bucket wheel excavator (BWE), conveyor belt and spreader. This is also true of the Rhenish lignite mining area to the west of Cologne. The large scale equipment deployed in this German mining area since the end of the 1970s yields a daily output of 240,000 m³ (12,500 m³/h). In the Lusatian mining area near Dresden, the equipment of choice for the removal of over-burden owing to the even formation of the lignite seams is the conveyor bridge. The coal is extracted by bucket wheel excavator and bucket chain dredger. The capacity of the conveyor bridges assuming three upstream bucket chain dredgers is up to 450,000 m³ per day. In the Central German mining area near Leipzig, the same extraction technique has made headway like in the Rhenish area, although with limited use of mobile conveyor methods.

Most other European and non-European large-scale opencast mines also prefer continuous opencast techniques. In Victoria (Australia), for example, the opencast lignite mines employ BWEs, and the Mae Moh (Thailand) mine has been using BWEs for a number of years in the removal of over-burden. By contrast, the opencast lignite mines in Texas (USA) mostly use draglines, shovel and truck combinations. However, some companies have been deploying BWE systems with conveyor belts or cross mine dumpers for years now.

The general trend in extraction technology involves further development of the continuous mining technique that originated in lignite mining for use in harder materials like phosphate or hard coal, including the associated over-burden removal resulting in the non-blasting technique involved with direct extraction and selective mining.

BENEFICIATION, TRANSPORTING AND HANDLING

Owing to relatively high water content (40 to 60%) and a corresponding lower calorific value compared to hard coal, lignite is mostly utilised close to the mines. The focus of lignite use, accounting for nearly 90% worldwide, is on power generation. In Germany, lignite is transported by conveyor belts or train to power plants located near the deposits.

The hard coal quantities mined, a worldwide average of 83% is used in the country of origin itself. Unlike lignite, a functioning international trade exists in hard coal. Since hard coal is seriously contaminated owing to the high degree of mechanisation in mining operation, in that, in raw state its quality often fails to meet customer's requirements, hence it must be subject to a cleaning process. In beneficiation, the raw coal is first crushed and then classified by grain size, i.e. as coarse, fine and ultrafine. In the subsequent sorting of coal and rock particles, the crucial features are specific weight in the case of coarse and fine grain, and surface properties in the case of ultrafine grain. The separating medium in the former case is either water or a heavy liquid (sink/float process), with the separation being in sink/float drum (coarse grain) or washers (jigs), or in water cyclones or in heavy media cyclones (medium grain). The ultrafine grain, by contrast, is cleaned by flotation. The crucial economic factor in beneficiation is product output, i.e. the share of washed coal to raw coal. This is around 80% for steam coal and 65 to 70% for coking coal.

The world trade in hard coal is based not only on an efficient mining industry, but also on capable infrastructure. Its interlocking phases, all the way from mining to consumer use extend via:

- port handling
- marine transportation
- discharge at the port of destination
- inland transportation (road or rail)
- and these are referred to as the coal chain.

Transportation of hard coal to the port of shipment is generally by rail or by truck. The feasible distances for economic transportation are limited by cost consideration, i.e. the export mines are located relatively near the coast. Rail transport is by complete trainloads with trains up to 1.5 km in length and a capacity of over 10,000 tonnes. Where rail links to the coast are non-existent, the coal can also be taken to the port by truck. Another option is shipping by inland waterway, e.g. to the US Gulf ports or, in Indonesia, to the deep-water ports/loading points.

In the port of shipment, the coal is discharged by wagon tippler and moved by belt conveyor to intermediate stockpiles. Recovery is by bucket wheel reclaimer or subsurface extractor onto conveyor belts, which take the coal available with loading capacities of up to 6000 t/h.

The marine transportation of coal is by bulk freighter. Depending on cargo size, distance to the port of discharge and permissible draught in the ports, and three ship sizes are deployed:

- 10,000 to 50,000 dwt (dead weight tonnage) = Handysize
- 50,000 to 80,000 dwt = Panama
- 80,000 to 150,000 dwt = Capesize

Handysize ships are mainly used for small quantities, short distances, coastal shipping and ports of shipment/destination with only little draught. However, most coal transportation is ocean-wide or between oceans, using panama and capesize freighters. The first can pass through the Panama Canal, while the second have to round Cape Horn or the Cape of Good Hope.

In the receiving countries, there are some 200 ports of discharge available, although this does have to be shared with other bulk dry goods. Some of these have dedicated coal terminals e.g. in the ARA ports (Amsterdam/Rotterdam/Antwerp). Coal discharge is usually by grab crane onto belt conveyors, which take the coal to intermediate stockpiles where coal can be collected for inland transportation.

GENERATION TECHNOLOGY

Subcritical boiler technology

These have efficiencies of about 30% and are the most common type of plant globally because they are faster and less costly to build when compared to other technologies. With CO₂ mitigation on a global agenda, the International Energy Agency (IEA) and other international bodies propagate that global deployment and utilisation of subcritical technologies. In addition, the World Bank has made a decision to cease funding for coal fired projects with lower efficiencies in developing countries, unless there is no other viable option³. This may likely increase the rise in utilising more efficient technologies.

Supercritical

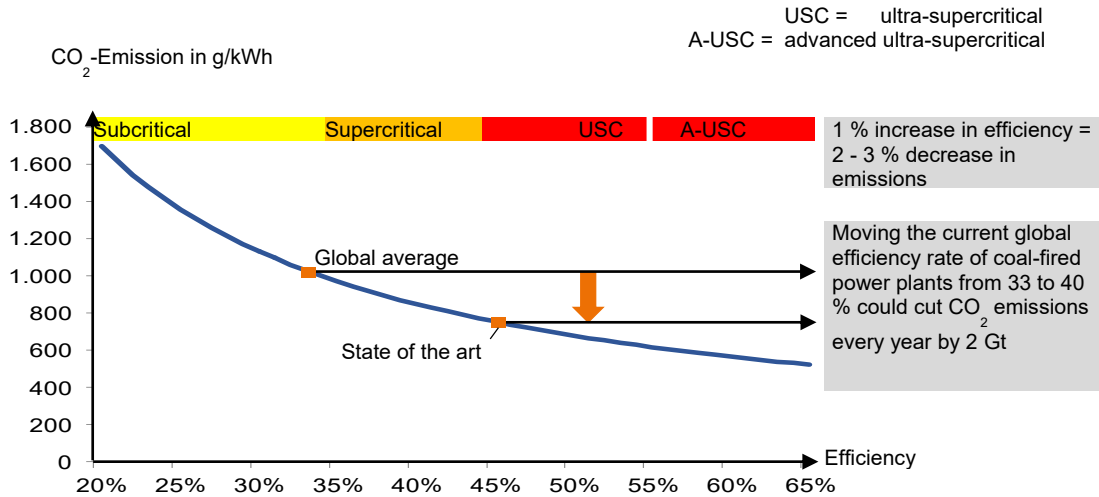
Supercritical plants make up 22% of the global coal-fired power fleet with thermal efficiencies of about 40%⁴ (Figure 2). The high capital costs of supercritical technology are due largely to the alloys used and the welding techniques required for operation at higher steam pressures and temperatures. The higher costs may be partially or wholly offset by fuel savings (depending on the price of fuel). With respect to CO₂ emissions, a supercritical plant emits around 20% less than a subcritical plant⁵.

³ Reuters (2013) World Bank to limit financing coal-fired plants

⁴ <https://www.iea.org/media/workshops/2015/cop21/ieaday/1.3GRAY.pdf>

⁵ Office of Chief Economist (2015) Coal in India

FIGURE 2: REDUCING CO₂ EMISSIONS THROUGH EFFICIENCY IMPROVEMENTS IN COAL-FIRED POWER STATIONS



Source: Coal Industry Advisory Board, Submission to the International Energy Agency for UNFCCC COP 21

Ultra-supercritical (USC) & advanced ultra-supercritical (AUSC)

Like supercritical technology, USC technology uses even higher temperatures and pressure to drive efficiency up to 45%. Currently, around 3% of the global coal fleet uses such technology. The technology also reduces CO₂ emissions by up to a third when compared to subcritical plants with the same amount of coal input. The introduction of USC technology has been driven over recent years in countries such as Denmark, Germany and Japan, in order to achieve improved plant efficiencies and reduce fuel costs⁶. Like supercritical plants, USC technology use high quality, low ash coal and these plants have very high capital cost which is about 40-50% more than a subcritical plant. Current state-of-the-art USC plants operate at up to 620°C, with steam pressures from 25 MPa to 29 MPa.

A further modification of USC is AUSC technology. This uses much higher temperatures and pressure, and as a result, steel which has a high melting point and very high nickel content is used. This makes it more expensive to build than USC plants. In China, United States (US), Europe, Japan and India, demonstration plants are being developed and it is expected that from an AUSC plant emissions would be 20% less than supercritical plants and efficiencies could be close to 50%⁷.

Integrated Gasification Combined Cycle (IGCC)

Gasification can also be used for power generation. IGCC plants use a gasifier to convert coal (or other carbon-based materials) to syngas, which drives a combined cycle turbine to generate electricity. IGCC plants can achieve efficiencies of around 45% and has low emissions because the fuel is cleaned before it is fired in the gas cycle turbine. IGCC

⁶ <http://www.worldcoal.org/setting-benchmark-worlds-most-efficient-coal-fired-power-plants>

⁷ Office of Chief Economist (2015) Coal in India

investment cost is relatively high and it could be twice the cost of supercritical plants. In addition, IGCC technology is still in its nascent stages and the technology has not had much testing as supercritical units.

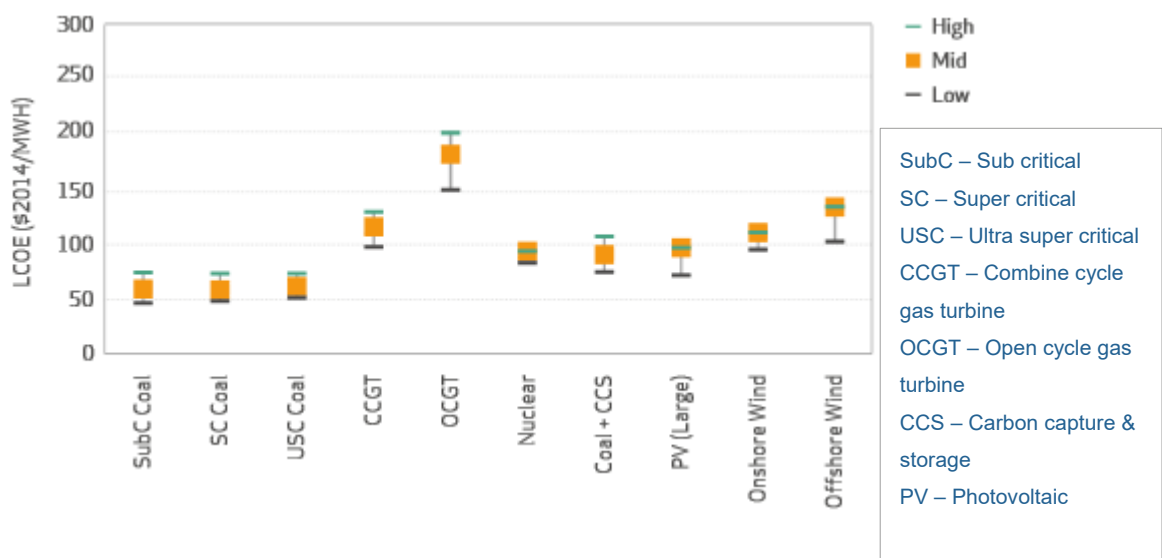
Gasification typically takes place in an aboveground gasification plant. However, the reaction can also take place below ground in coal seams. Underground coal gasification (UCG) uses a similar process to surface gasification. The main difference between both gasification processes is that in UCG the cavity itself becomes the reactor so that the gasification of coal takes place underground instead of at the surface.

The advantages in the use of this technology are the low plant costs (as no surface gasifiers are required) and the absence of coal transport costs. UCG also presents the opportunity to reduce emissions, as there are fewer surface emissions. UCG technology could also have synergies with CCS as the CO₂ could be stored in the coal cavity after gasification.

South African companies Sasol and Eskom both have UCG pilot facilities that have been operating for some time, giving valuable information and data. In Australia, Linc Energy has the Chinchilla site, which first started operating in 2000. Demonstration projects and studies are also currently underway in a number of countries, including the US, Western and Eastern Europe, Japan, Indonesia, Vietnam, India, Australia and China, with work being carried out by both industry and research establishments.

The levelised cost of electricity (LCOE) with regards to India shows that coal is expected to remain the most affordable option through to 2035 (Figure 3). This is driven by low domestic coal prices and limited gas availability.

FIGURE 3: INDIA LEVELISED COST OF ELECTRICITY – 2035



Source: World Coal Associate (2015)

COAL TO LIQUID (CTL)

Converting coal to a liquid fuel is a process referred to as coal liquefaction. This allows coal to be utilised as an alternative to oil. CTL is particularly suited to countries that rely heavily on oil imports and have large domestic reserves of coal. South Africa has been producing coal-derived fuels since 1955 and has the only commercial coal to liquids industry in operation today⁸. Not only are CTL fuels used in cars and other vehicles, but South African energy company Sasol also has approval for CTL fuel to be used in commercial jets. Currently around 30% of the country's gasoline and diesel needs are produced from indigenous coal. The total capacity of the South African CTL operations stands in excess of 160,000 barrels per day. Fuels produced from coal can also be used outside the transportation sector. Coal-derived dimethyl ether (DME) is receiving particular attention today, as it is a product that holds out great promise as a domestic fuel. DME is non-carcinogenic and non-toxic to handle and generates less carbon monoxide and hydrocarbon air pollution than liquefied petroleum gas (LPG).

TECHNOLOGY OUTLOOK

Currently, subcritical coal capacity constitutes a significant share of global installed capacity. By 2025, however, policy interventions and technological progress are likely to drive deployment of high efficiency low emission (HELE) technologies and result in the subcritical fleet declining to around 50% or lower⁹. The rising economies of Asia will lead the efficiency drive, with India and Southeast Asia seeing particular growth. India, for instance, has recently mandated that power plants above 600 MW must employ supercritical or USC technology¹⁰. Elsewhere, the US and Japan also expect to use IGCC technology.

Deployment of CCS technology is key to reducing global CO₂ emissions, not only from coal, but also from all fossil fuels. As previously explored, CCS is an integrated suite of technologies that can capture up to 90% of the CO₂ emissions produced from the use of fossil fuels in electricity generation and industrial processes, preventing the CO₂ from entering the atmosphere. In recent years, positive developments have been made in CCS that suggests increased scope for deployment over the coming decades. For instance, in 2014, SaskPower launched the Boundary Dam Project in southern Saskatchewan, Canada. The project has the potential to reduce GHG emissions by one million tonnes of CO₂ each year. In addition, the Kemper County Energy Facility and Petra Nova Carbon Capture Project are two large-scale CCS projects in the power sector which are targeting operations in 2016 (see CCS chapter for more).

⁸ [https://www.worldcoal.org/sites/default/files/coal_liquid_fuels_report\(03_06_2009\).pdf](https://www.worldcoal.org/sites/default/files/coal_liquid_fuels_report(03_06_2009).pdf)

⁹ World Coal (2015) Cleaning up the coal-fired market

¹⁰ CSE India (2015) An epochal shift in the idea of India – Meeting Aspirations?

2. ECONOMICS & MARKETS

The world currently consumes over 7,800 Mt of coal which is used by a variety of sectors including power generation, iron and steel production, cement manufacturing and as a liquid fuel. The majority of coal is either utilised in power generation that utilises steam coal or lignite, or iron and steel production that uses coking coal.

COAL PRODUCTION IN 2014 – FIRST DECLINE IN DECADES

In 2014, global coal production was approximately 5.7 billion tonnes coal equivalent¹¹. About 77% of the coal production was steam coal to be utilised in other industries and for power generation, 13% was coking coal to be used for coke production in the steel industry and 10% lignite. The total global coal production was 0.7% less than in 2013 and 2.8% less in 2015, making this the first decline in global coal production growth since the 1990s. This was primarily due to the weakening of world economic growth and the flagging electricity demand in some important Asian countries¹².

The largest coal producing countries are not confined to one region. The top five producers are China, the US, India, Indonesia, Australia and South Africa. Much of global coal production is used in the country in which it is produced and only around 18% of hard coal production is destined for the international coal market.

COAL CONSUMPTION

Coal plays a vital role in power generation and this role is set to continue. Coal currently fuels 40% of the world's electricity and is forecast to continue to supply a strategic share over the next three decades.

In 2014, coal demand in China fell for the first time since 1999 by 2.9% to 3.9 billion tonnes¹³, but China remains the world's largest coal consumer with a share of 50%.

In addition, the US coal demand strongly dropped by more than 13% to 835 million tonnes in 2014. The US coal demand peaked at about 1 billion tonnes in 2007. The fall in US coal demand was mainly due to the increasing competition from natural gas. US gas prices visibly fell as a result of the enormous boost in production of unconventional (shale) gas. This led to a large fuel switch from coal to gas. Furthermore, weaker power demand from coal, stronger headwind from political/governmental opposition and increasingly more environmental regulations resulted in a fall in coal demand in the US¹⁴ (Figure 4).

European (EU 28) coal demand fell by nearly 6%, which can partly be explained by continued pressure on coal-fired power generation due to environmental policies. Coal

¹¹ IEA Coal Information (2015) here coal comprises all primary coals like anthracite, coking coal, other bituminous coal, sub-bituminous coal and lignite

¹² German Coal Association (GVSt e.V.), Steinkohle (2015)

¹³ Reuters (2015) Peak coal by 2020 could save China thousands of lives: study

¹⁴ IEA (2015) Medium-term Coal Market Report

demand of the Russian Federation also fell by more than 4% chiefly because of the economic turnaround after the massive oil price decline and due to the Western sanctions (within the scope of Ukraine crisis) and last but not least as a consequence of the mildest winter in the country's weather history¹⁵.

FIGURE 4: FACTORS IMPACTING COAL CONSUMPTION

	Climate policy	Economic growth	Gas competition
China	●	●	●
United States	●	●	●
India	●	●	●
OECD Europe	●	●	●

● Positive factor for coal consumption ● Negative factor ● Neutral

Source: IEA (2015)

Consumption of steam coal is projected to grow by 20% from 2013 to 2040. Lignite, also used in power generation, has been forecasted to grow through to 2020. Demand for coking coal used in iron and steel production has more than doubled since 2000, but according to the IEA's World Energy Outlook 2015, demand will moderate over the coming decade as China enters a new phase of economic development.

The biggest market for coal is Asia, which currently accounts for 66% of global coal consumption, although China is responsible for a significant proportion of this¹⁶. Many countries do not have fossil resources sufficient to cover their energy needs, and therefore need to import energy to help meet their requirements. Japan, Chinese Taipei and Korea, for example, import significant quantities of steam coal for electricity generation and coking coal for steel production.

Coal will continue to play a key role in the world's energy mix, with demand in certain regions set to grow rapidly. Growth in both the steam and coking coal markets will be strongest in developing Asian countries, where demand for electricity and the need for steel in construction, car production, and demands for household appliances will increase as incomes rise.

ENERGY SECURITY

Minimising the risk of disruptions to our energy supplies is ever more important, whether they are caused by accident, political intervention, terrorism or industrial disputes. Coal has an important role to play at a time when we are increasingly concerned with issues relating to energy security.

¹⁵ IEA (2015) Medium-term Coal Market Report

¹⁶ [https://www.worldcoal.org/sites/default/files/coal_resource_overview_of_coal_report\(03_06_2009\).pdf](https://www.worldcoal.org/sites/default/files/coal_resource_overview_of_coal_report(03_06_2009).pdf)

The global coal market is large and diverse, with many different producers and consumers from every continent. Coal supplies do not come from one specific area, which would make consumers independent on the security of supplies and stability of only one region.

Many countries such as China, India, Indonesia, Australia and South Africa rely on domestic supplies of coal for their energy need. Others import coal from a variety of countries: in 2013 the UK, for example, imported coal from Australia, Colombia, Russia, South Africa, and the USA, as well as smaller amounts from a number of other countries and its own domestic supplies:

- Coal therefore has an important role to play in maintaining the security of the global energy mix.
- Coal reserves are very large and will be available for the near future without rising geopolitical or safety issues.
- Coal is readily available from a wide variety of sources in a well-supplied worldwide market.
- Coal can easily be stored at power stations and stocks can be relied upon in an emergency.
- Coal-based power is not dependent on the weather and can be used as a backup for wind and hydropower.
- Coal does not need high-pressure pipelines or dedicated supply routes.
- Coal supply routes do not need to be protected at enormous expense. These features help to facilitate efficient and competitive energy markets and help to stabilise energy prices through inter-fuel competition.

CHINA

China has been the growth engine of world energy and coal demand over the last ten years. The development in China has largely been powered by coal, which accounted for about 72% of primary energy demand growth over the period 2004-2013. In 2013, the share of China's coal consumption was over 50%¹⁷. In 2014 the slowdown in Chinese coal consumption was influenced by the slower growth in the steel and cement sectors. Steel and cement have a share of over 26% of coal demand in China and when compared to that of the US of about 4% and some 14% in the EU¹⁸. Steel and cement production are largely dependent on infrastructure expansion in China, therefore coal consumption is also linked through these sectors to infrastructure developments.

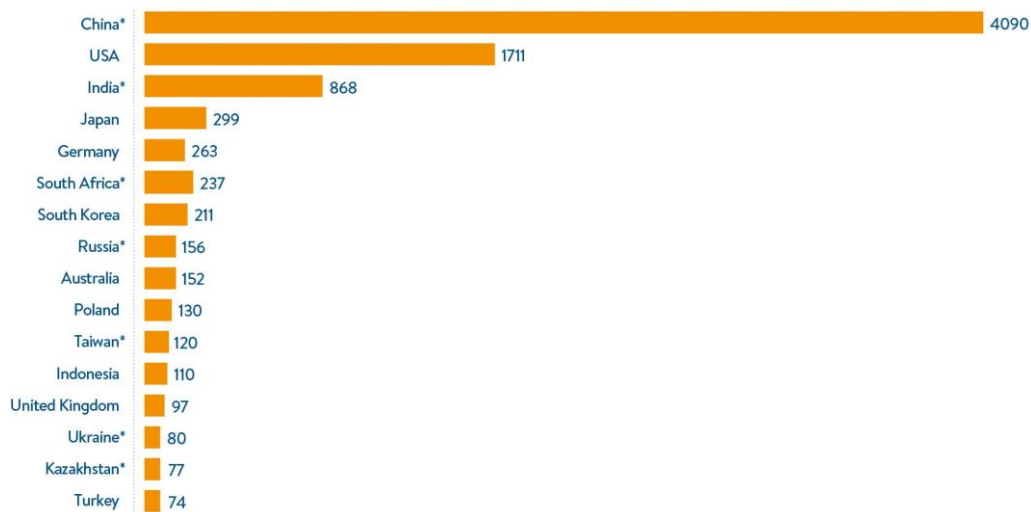
Electricity generation accounts for the majority of coal demand in China (about 60%) and this nation tops the rank in coal-fired power generation (Figure 5). The main driver was

¹⁷ IEA (2015) Medium Term Market Report

¹⁸ Ibid 17

development in the industrial sector, which accounts for the bulk of electricity consumption in China, in contrast to regions such as the EU or North America, where the bulk of electricity consumption is in the service and residential sectors.

FIGURE 5: 2014 COUNTRY RANKING: COAL-FIRED POWER GENERATION (TWH)



Source: IEA (2015) Electricity Information (*for Non-OECD-countries numbers for 2013)

The decreased global supply in 2014 was caused mainly by declining supply in China and Indonesia (Table 1). For both countries, this was a significant change as supply in China and Indonesia grew strongly over the last decade with average growth rates of 7.5% in China and 15.3% in Indonesia.

TABLE 1: COAL SUPPLY OVERVIEW

	Total coal supply (Mt) 2013	Total coal supply (Mt) 2014	Relative growth (%) 2014
China	3749	3650	-2.6%
India	610	668	9.6%
Indonesia	488	471	-3.5%
Australia	459	491	7.0%

United States	904	916	1.4%
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Source: IEA (2015)

INDIA

Out of the total coal production of 565.7 million tonnes in the country, public sector companies accounted for around 93.3% of the production led by Coal India Limited (CIL) and Singareni Collieries Company Limited (SCCL). Similarly, as far as lignite production is concerned, around 90% of the production is done through public sector companies, led by Neyveli Lignite Corporation (NLC). However, the contribution of the private sector is gradually gaining significance mainly facilitated by the Government policy of allocating coal blocks to private players.

Today, CIL is the largest coal producer in India and produces around 81% of the total coal¹⁹ (Table 2).

TABLE 2: PRODUCTION SHARE OF COAL PRODUCING COMPANY IN INDIA

Company	Production (million tonnes)	Share
CIL	462.4	81.7%
SCCL	50.5	8.9%
Other Govt. Companies	15.2	2.7%
Total share of Govt. Companies	528.1	93.3%
Private Companies	37.7	6.6%

Source: Ministry of Coal, India (2013-2014)

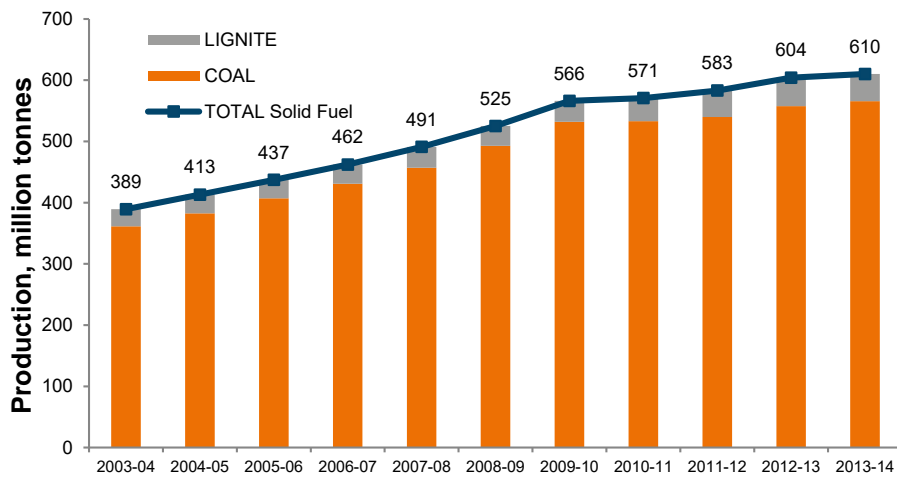
Production and supply

The total solid fuel (coal and lignite) production in India was 610.04 million tonnes (565.8 million tonnes of coal and 44.3 million tonnes of lignite) in 2013 and it was the fifth largest country in the world in terms of coal production. 90% of the total coal produced in the country is thermal coal while the rest consists of coking coal.

¹⁹ Data from Coal Directory of India (2013-14) Ministry of Coal

Domestic coal production has been inadequate to meet the total demand of coal in the country. The production has been slow mainly in the last five years starting from 2009 in comparison to previous years (Figure 6). In addition, this period also experienced increased coal based generation capacity in the country, which demanded large volume imports of coal from other countries to meet the shortfall in domestic coal production, compensation for India's low quality, high ash coal and the total coal demand.

FIGURE 6: COAL PRODUCTION IN INDIA



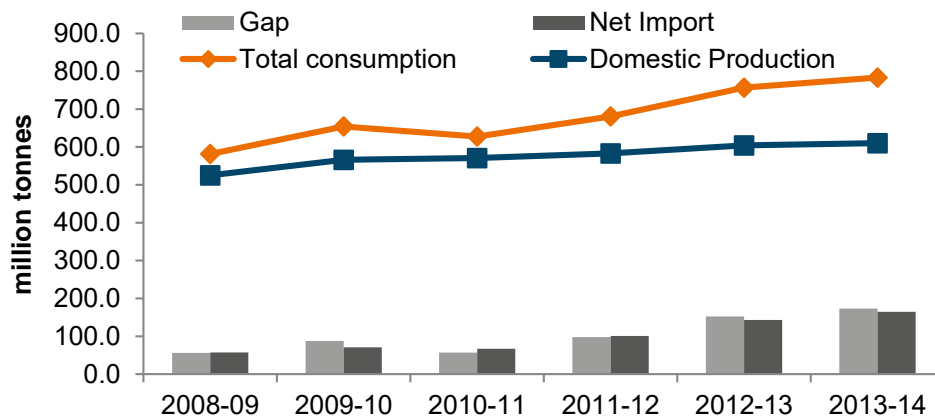
Source: Ministry of Coal, India

While the importance of coal in meeting the primary energy requirement has been increasing incessantly, the production of coal has not kept pace with the demand, particularly in recent years. The gap between domestic coal production and consumption is being met almost entirely through imports. The net import of coal increased by 193% from 2008 to 2013 (Figure 7).

The working group on coal in its report for the 12th five-year plan has estimated that the total demand in the country in the year 2016-2017 will be 980.50 million tonnes and the domestic coal availability has been projected at 715 million tonnes in the 'business as usual' scenario and 795 million tonnes in the 'optimistic scenario'²⁰.

²⁰ Planning Commission of India, 12th Working Group Report on Coal

FIGURE 7: DOMESTIC PRODUCTION AND TOTAL CONSUMPTION IN INDIA



Source: Ministry of Coal, India

As per the Import Policy 1993-1994, coal has been under Open General License (OGL) and therefore consumers are free to import coal based on their requirement. For importation, Indonesia has been a major exporter to India with regards to thermal coal and Australia a major source for coking coal.

The main reason for the increasing dependence of imports is the substantial coal-based power generation capacity added in the recent past. Coal based thermal capacity currently accounts for around 60% of the total generation capacity in the country. In terms of electricity generated in the country, the share of coal-based generation is still high, around 78% of the total generation. The share of thermal coal in the total import of coal has been increasing over the years and has reached 78% in 2013-2014.

The coal based generation capacity has increased by almost 104% in the period from March 2007 to March 2014 whereas the growth in thermal coal production in the country was only 29% in the same period. Because of this gap, the import of thermal coal increased by 40% on average in the same period. It is estimated that coal based power plants meet almost 26% of their total coal requirement through coal importation²¹.

India is endowed with abundant quantity of coal, which serves as the main resource for meeting the primary energy and economic growth needs of the country. However, as the country is on the path to rapid economic growth with added generation capacity, the domestic coal production has not increased in the same proportion, resulting in a huge shortfall between coal demand and domestic coal supply. This has increased reliance on imported coal, which is generally more expensive compared to the domestic coal. Additionally, the imported coal is normally of better quality and this limits the generating plants in utilising domestic coal.

²¹ Data from Central Electricity Authority, www.cea.nic.in

AUSTRALIA

Coal has always been the dominant fuel in the energy mix of Australia where about 75% of the electricity produced is from coal. This is predominantly hard coal, which makes up 47% of Australia's electricity supply. As a result, there are plans to extend mining capacity to a total of 10.8 million tonnes per annum over the next years. For example, in late 2016, the US\$1.9 billion underground coking coal mine project in Grosvenor operated by Anglo American will come online with a capacity of 5 Mtpa²².

Infrastructure investment has aided Australia towards an increase in production and export, but the falling coal prices have caused some coal port projects to be cancelled or postponed, including amongst others the Indgeon Point Terminal in the port of Hay Point. Overall, Australia was able to increase its exports in 2014, with an increase in volume from 29 million tonnes to 387 million tonnes.

The largest importers of Australian coking coal are China, India, Japan, Europe and South Korea. China's import of coking coal was 18% higher and India imported 21% more than in the previous year.

²² IEA (2015) Coal Medium-Term Market Report

TABLE 3: AUSTRALIAN EXPORT DEVELOPMENT IN SELECTED REGIONS (HARD COAL, MT)

	2013	2014
China	27.0	31.9
India	25.1	30.4
Japan	20.6	21.9
Europe	15.1	15.9
South Korea	7.9	8.6
Total	95.7	108.7

Source: VDKI (2015)

SOUTHEAST ASIA

Indonesia

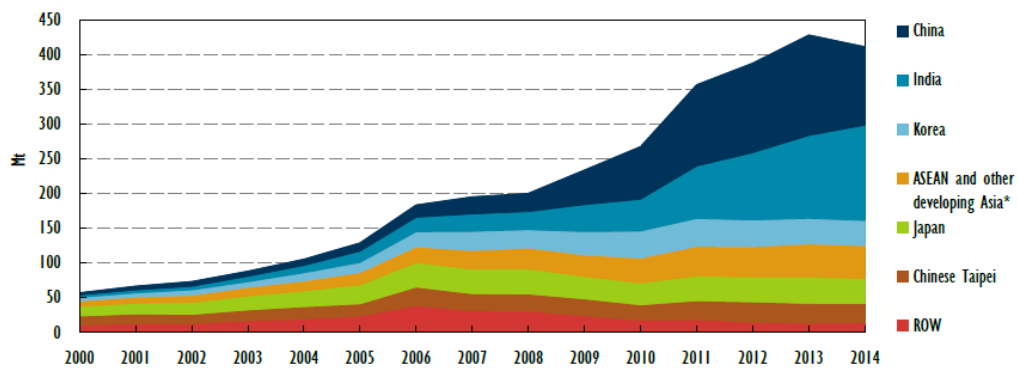
The supply of hard coal in Indonesia declined by 3.6% to 470.8 million tonnes in 2014 as the Indonesian government tried to limit production in order to stabilise prices in the oversupplied international coal market. Most of the coal supply served the export market, with about 8% of the supply utilised for domestic consumption. The decline in supply is because of the export market, more specifically in lower exports to China as well as new regulations in China, such as coal testing requirements to ensure that the imports comply with the new quality standards. The testing is supposed to be conducted exclusively by the Chinese customs and border authorities, and the entire cargo could be refused in the event of non-compliance with the threshold values. Indonesian coal exports in 2014 were also affected by new regulations that came into effect in October, which requires companies to be registered as official exporters in order to reduce exports from illegal mining activities.

In the period 2004-2013 China and India absorbed over 70% of additional coal supplies from Indonesia (Figure 8). Indonesian exports consist almost entirely of steam coal; as Indonesian coal typically has high moisture content, it does not meet the quality requirements for metallurgical/coking coal.

The five largest producers in Indonesia are Adaro, Bumi Resources, Kideco, Banpu and Berau Coal PT²³. These producers account for more than 70% of production in Indonesia.

The increase in domestic coal demand is helping to balance the market oversupply, but the effect is limited, given the size of Indonesian domestic markets compared with the international market or Chinese market.

FIGURE 8: DEVELOPMENT OF INDONESIAN EXPORT DESTINATION



*Excludes Chinese Taipei.

Source: IEA (2015)

The Indonesian government has announced plans to build 35 GW of new power generation capacity, and coal-fired capacity will consist of about 20 GW. This addition would be in place within the next five years in order to speed up electrification and provide a basis for economic growth in the coming decade. The government pushes coal-fired power generation because it increasingly wants to use the abundant domestic coal reserves as cheap fuel in the electricity sector.

VIETNAM

The economic growth in Vietnam's industry has propelled the increase in the consumption of power, which in turn leads to higher consumption of Vietnamese coal for power generation. The construction of new power plants lags behind the growth in the demand for electricity, forcing blackouts that could then lead to investment insecurity.

In 2014, 37 million tonnes of coal were produced and this consisted mainly of anthracite, however, lignite and sub-bituminous coal were also mined. The anthracite coal is most preferred for export while lignite and sub-bituminous are used exclusively for domestic consumption.

Vietnam imported about 3 million tonnes of coal, which was approximately 36% more than in 2013. The domestic production does not seem to be adequate in providing Vietnam's

²³ VDKI (2015) Annual Report

dynamically growing economy with a satisfactory amount of coal supplies²⁴. This could be one of the reasons why the demand for imports of steam coal will steadily rise. Coal-fired power plants would still remain the most important source of power generation in Vietnam, fuelling 48% of the nation's total generation capacity²⁵. The government estimates that coal demand is leaping upward as a result of the additional 24 coal-fired power plants that are planned or under construction which are scheduled to operate before 2016. It is estimated that the demand for coal will move from 43 million tonnes in 2014 to about 70 to 80 million tonnes in 2020²⁶.

THAILAND

There are significant reserves of brown coal estimated at 1.1 billion tonnes, which is produced for local use in power generation. In 2013, 7.3 million tonnes of coal were produced and the import of hard coal continues to rise in quantity, particularly from Indonesia and Australia, to fuel its power stations in coastal areas²⁷.

In 2013, the importation of coal stood at about 17 million tonnes, and this figure is expected to increase significantly in the coming decades due to an expanding coal-fired power generation fleet.

SOUTH AFRICA

South Africa has 70% of all coal found on the African continent and coal-fired generation accounts for about 80% of its electrification. South Africa has well developed infrastructure, unlike countries such as Botswana or Mozambique with undeveloped infrastructures, but with rich coal deposits.

In South Africa, some new mines will be commissioned such as the Boikarabelo mine in the Waterberg region, which is operated by the company Resource Generation and is projected to start in 2016²⁸. Output from the deposits in Limpopo Province is initially supposed to be 6 million tonnes per year; this will be increased to a capacity of 25 million tonnes per year. The state-owned mining company African Exploration and Mining Finance Company (AEMFC) wants to open two new mines that are expected to supply coal to the Eskom power plants from 2017²⁹.

The exports from South Africa increased by 1 million tonnes in 2014 and totalled just slightly less than 77 million tonnes. The structure of exports continues to shift towards India. India imported 30 million tonnes of steam coal, about 10 million tonnes more than in 2013, while China reduced its imports from 13.5 million tonnes to 3.3 million tonnes. In view of India's high need for steam coal in the future, the exports to this country will presumably continue to rise.

²⁴ VDKI (2015) Annual Report

²⁵ <http://www.renewableenergy.org.vn/index.php?mact=News,cntnt01,detail,0&cntnt01articleid=3256&cntnt01origid=53&cntnt01returnid=53>

²⁶ VDKI (2015) Annual Report

²⁷ IEA (2015) Southeast Asia Energy Outlook Report

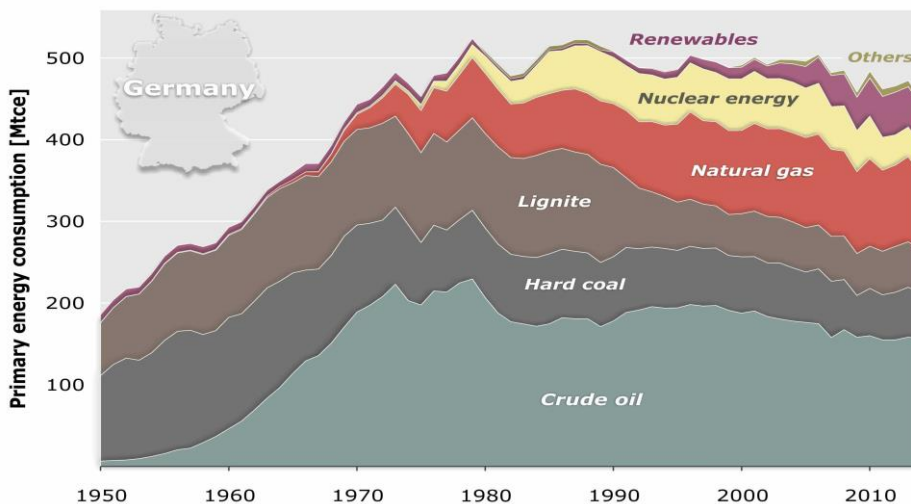
²⁸ IEA (2015) Coal Medium-Term Market Report

²⁹ VDKI (2015) Annual Report

GERMANY

In Germany primary energy consumption peaked at the end of the 1970s. Since then, energy demand has remained at a stable level with a slight downward trend. Today, more than 10 years after the energy transition was initiated, crude oil, natural gas, hard coal and lignite still contribute around 80%, and thus by far the largest share of energy consumption in Germany³⁰ (Figure 9).

FIGURE 9: GERMANY'S PRIMARY ENERGY CONSUMPTION 1950 TO 2014



Source: BGR 2015

Although renewables may dominate in the public's perception, Germany is likely to depend on an energy mix that also includes non-renewables for decades to come in order to achieve a safe transition to a low-carbon energy system. Information on the availability of fossil fuels therefore continues to be of vital importance for safeguarding Germany's energy supply and its role as a centre for industrialisation³¹.

As a highly developed industrialised country and one of the worlds' largest energy consumers, Germany is most expected to import most of its fuel. Based on the value of all imported goods, fuel accounted US\$116.9 billion and thus the largest share of import costs in 2014. Crude oil accounted for the largest share of the cost of fuel, at around 38.1%, followed by natural gas with 25.6% respectively. Hard coal (3.6%) and nuclear fuels (0.5%) accounted for the remaining costs³².

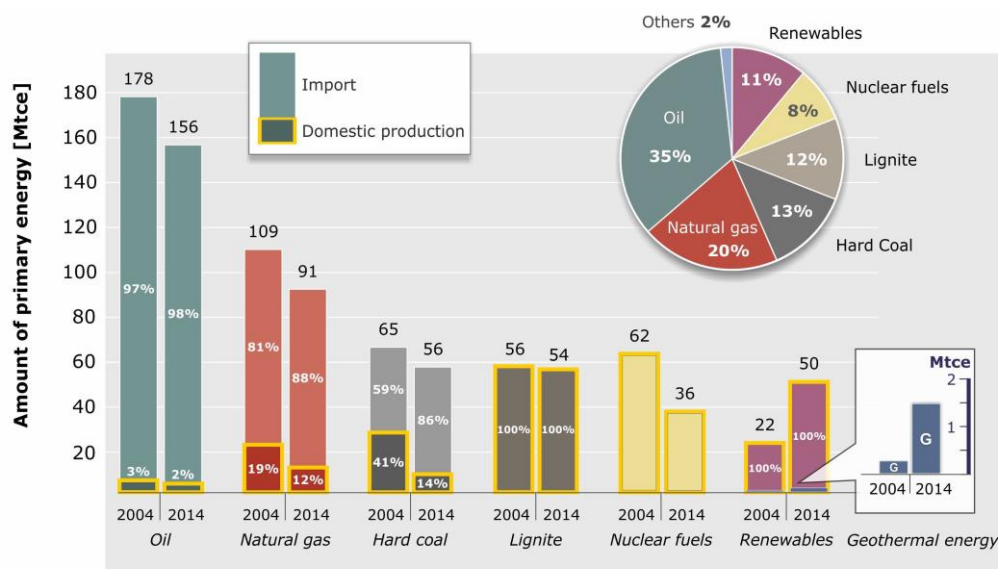
³⁰ BGR (2015): Energy Study 2015. Reserves, resources and availability of energy resources

³¹ AGEBA (Arbeitsgemeinschaft Energiebilanzene. V.) (2015): Energieverbrauch in Deutschland im Jahr 2014. – 42 p.; Berlin and Cologne.

³² BGR (2015): Energy Study 2015. Reserves, resources and availability of energy resources.

Only around 2% of crude oil and about 12% of natural gas was attributed to domestic production in 2014 (Figure 10), because of declining production rates of domestic oil and gas fields due to natural depletion. When subsidies for domestic hard coal mining are stopped in 2018, the share of domestic hard coal (bituminous coal) will disappear altogether.

FIGURE 10: COMPARISON OF THE USE OF PRIMARY SOURCES OF ENERGY AND OF THE RATIO OF DOMESTIC SUPPLY TO IMPORTS FOR GERMANY IN 2004 AND 2014, AND RELATIVE SHARES IN 2014



Source: BGR (2015)

Imports of hard coal rose significantly during the last years. At the same time, the domestic hard coal production decreased (Figure 10) In 2014, imports of hard coal and coke amounted to an all-time high at 46.2 million tonnes. Imports were largely from Russia, the US, Australia, South Africa and Poland. Russia was again the most important supplier in 2014, with about 13.7 million tonnes (24.4%) and followed closely by the US (19.7%). Imports from Poland, the only remaining EU-28 major coal exporter, rose slightly to 4.4 million tonnes, with coke accounting for 1.5 million tonnes³³.

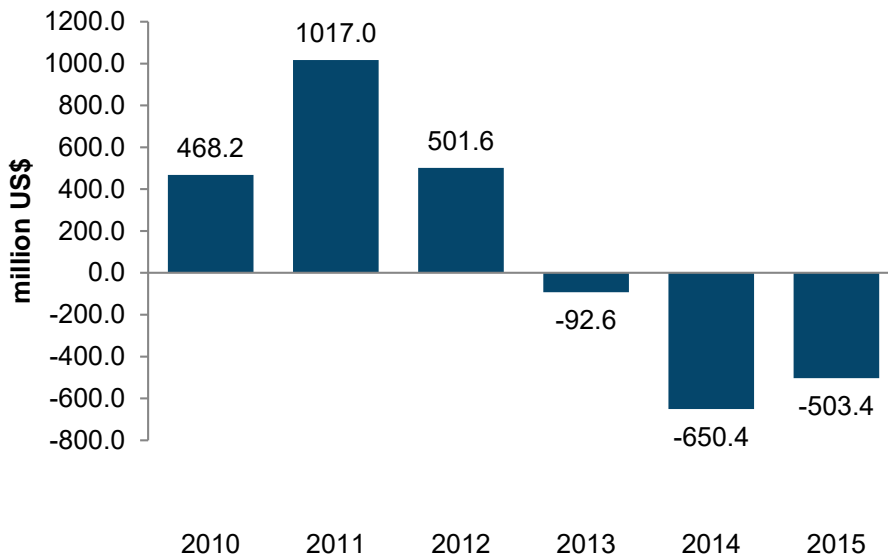
POLAND

The industry is undergoing a restructuring process and its main objectives have been focused on competitive pricing in comparison to the global markets and technical and economic reform of mining companies. The main problem was the high cost of coal production, partially due to the excessive employment and coal mining in exploitation fields with unfavorable geological and mining conditions (thin seams, often disturbed by faults, methane hazard conditions, dust explosions or rock outbursts) or outdated machinery. A

³³ Verein der Kohlenimporteure (VDKI) (2015): Jahresbericht 2015. - 140 p.; Hamburg.

characteristic feature was the high employment in the mining industry resulting in low production efficiency. Extensive restructuring processes supported by funds from the state budget, the World Bank and later by the European Union funds led to the industry's positive financial results in 2003.

FIGURE 11: THE FINANCIAL RESULTS OF HARD COAL MINING IN THE YEARS 2010 TO 2014.

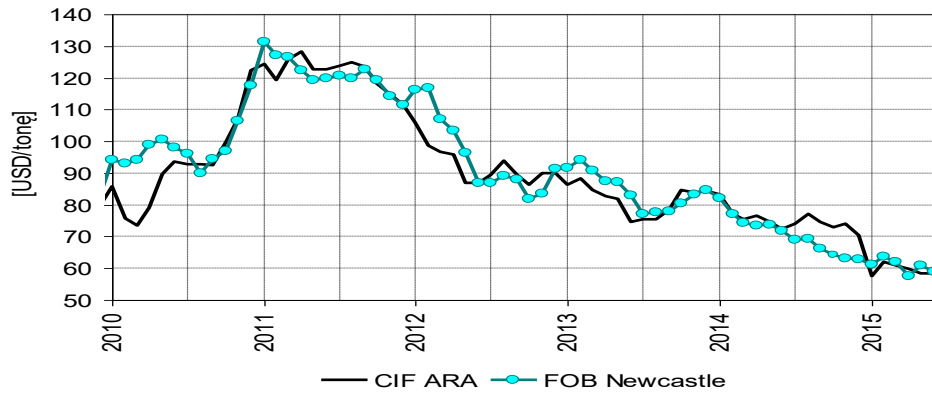


Source: Ministry of Economy, Poland (2015)

In 2011, Polish mining achieved a positive financial result of approximately US\$1.017 billion (Figure 11). Unfortunately, this trend was short lived. In 2014 and in 2015, Polish mining reported heavy losses.

The reasons for such worsening of the financial situation of mining companies was due to several factors, among which the most important was the continued decrease in coal prices since 2011 (Figure 12). This shows two indicators of power coal prices: CIF ARA - representing the price of coal imported to Europe and FOB Newcastle - representing the price of coal exported from Australia.

**FIGURE 12: COMPARISON OF THERMAL COAL SPOT PRICE INDICES:
MONTHLY AVERAGES IN US\$/TONNES**



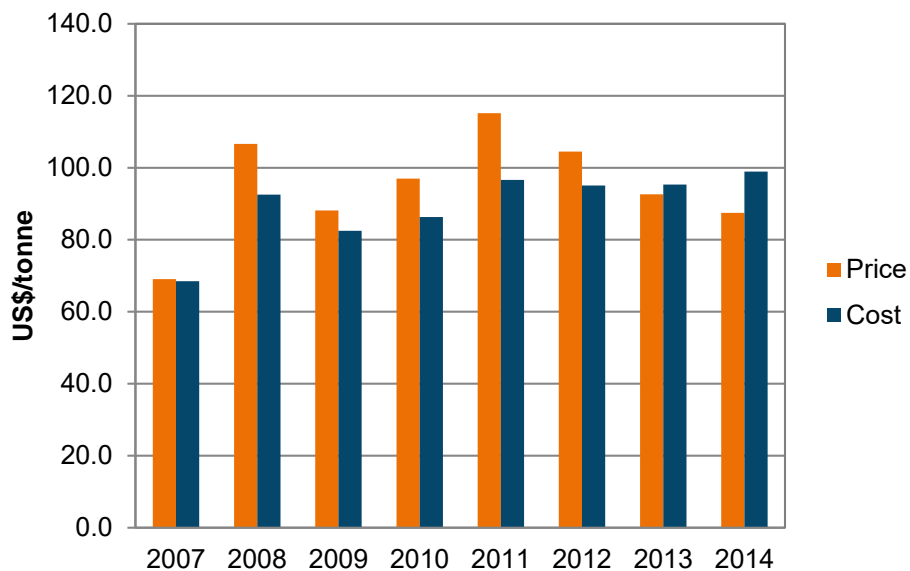
Source: Lorenz U. (2015)³⁴

With the decreasing prices in international markets, the prices received by Polish manufacturers also decreased. In 2013, the average price of coal sold was lower by as much as 14% compared to the previous year which was followed by a further 6% decrease in 2014³⁵ (Figure 13).

³⁴ Lorenz U. (2015), Current situation and forecasts for international steam coal Polityka Energetyczna – Energy Policy Journal 18, 4, 5-18 (in Polish).

³⁵ Ministry of Economy, Poland (2015), Information about the functioning of hard coal mining industry and the evaluation of the realization of the activity strategy of the hard coal mining industry in Poland in the years 2007-2015, Warsaw

FIGURE 13: COMPARISON BETWEEN AVERAGE UNIT COSTS OF COAL EXTRACTION AND COAL PRICES.



Source: Ministry of Economy, Poland (2015)

The yearly rise in the unit of coal extraction resulted from the following:

- deteriorating exploitation conditions in the majority of coal mines
- the need to allocate higher funds for investment to ensure continuity of mining
- no proportional reduction of production capacities under decreasing sales
- the pressure on wage increases from the mining crews and trade unions
- no flexible wage model closely associated with the achieved results
- no solutions for continuous operation which would have contributed to more efficient use of the machinery
- conducting mining activities in unprofitable mines (unfavorable conditions, high costs, and low rank of coal).

As a result, average production costs per tonne of coal in 2014 were higher than the average selling price, which has led to the collapse of the mining industry. Lower coal prices were the reason why Polish coal has ceased to be competitive in international markets.

Mining remains a key supplier of primary fuels for the domestic economy, giving Poland one of the highest rates in Europe's energy security. Energy dependence of Poland on energy imports (for all energy products) was 30.4% in 2012 in comparison to 53.4% for the EU-28 during the same period³⁶. The low dependence is due to the structure of electricity production in the country; in 2013, 83.7% of electricity was produced from solid fuels (49.6% from hard coal and 34.1% from lignite).

The coal market in Poland is currently facing a number of serious challenges arising from the rapidly changing conditions in the sector. Its long-term role depends on many factors, both at the national and international level. In spite of high coal reserves, the future and role of hard coal mining industry will depend on the successful combat of the deep crisis currently experienced in Poland. In view of the high losses and lack of financial liquidity, the mining companies and the government have to undertake a better restructuring process which should be carried out in a planned and systematic manner. It seems that the sector needs some aid and financial support, as demanded by trade unions.

The EU climate policy is a challenge for the Polish national fuel and energy sector. Its intensification can directly affect the position of coal as a fuel for power generation and as a result can affect the entire economy because coal is an enabler for Poland's economic growth.

UNITED STATES

No significant additions to export mining capacity are expected to come on line over the next five years because of the weak domestic coal demand and low international prices.

Coal exports from the US to Asian markets are currently limited by scarce port capacity at the US West Coast. To alleviate the problem, projects like the Gateway Pacific is underway with a planned export capacity of 24-38 Mtpa and Millennium Bulk Logistics project and the Port Westward project both have a projected capacity of 15-30 Mtpa. These projects are currently in the approval process³⁷.

The ongoing limited export capacity and the replacement of coal-fired power plants with power plants fired with natural gas and the plan initiated by the Obama administration to reduce emissions in the energy sector nationwide to 30% below the 2005 level by 2030 could have a major effect on the coal-producing and coal-consuming industry.

Overall, coal will continue as a major part of the US energy mix. It is expected to account for about one quarter of the countries generation capacity in 2030³⁸.

FUTURE OUTLOOK

The total world coal production (lignite and hard coal) declined in 2014 by about 53 million tonnes, which is the first annual decline since 1999³⁹. After more than a decade of strong

³⁶ Eurostat (2014). Energy, transport and environment indicators. Luxembourg.

³⁷ IEA (2015) Medium-term Coal Market Report

³⁸ <http://www.whitecase.com/publications/insight/power-dynamics-forces-shaping-future-coal-united-states>

³⁹ IEA (2015b): Coal Information 2015. – 674 p.; Paris.

growth in global coal production and consumption, the coal sector entered a phase of oversupply and a stagnating global demand. The former high growth rates in coal consumption lead to huge investments in coal exploration, and subsequently to expansions in coal mining capacities worldwide. Due to the continuing oversupply in the global coal market, prices for coal have fallen since 2011 for nearly four consecutive years. In August 2015, thermal coal prices decreased by 50% to about US\$50 per tonne. On the contrary, world coking coal production increased by 2.6% in 2014⁴⁰. This increase has been consistent since 2002, driven by growth in production intended for export by Australia, the world's largest exporter of coking coal and second largest producer (Table 4).

TABLE 4: MAJOR COKING COAL (1) PRODUCERS (MT)

Country	2012	2013	2014p
China	515.7	561.6	567.9
Australia	146.9	159.5	184.8
Russia	72.8	73.8	75
United States	81.3	77.9	75
India	43.5	49.6	51.4
Canada	31.1	34.1	30.6
Kazakhstan	13	13	15.3
Ukraine	20.9	19.7	12.8
Poland	11.7	12.1	12.3
Mongolia	8.8	6.9	10.3
Colombia	4.5	4.2	5.1
Germany	6.3	4.8	4.8
Czech Republic	5.1	4.6	4.6
Mozambique	2.8	3.3	3.8
Indonesia	3.1	3.6	2.7
South Africa	1.6	3.4	2.6

⁴⁰ IEA (2015): Coal information 2015

Other	7.1	5.8	6.0
World	976.1	1,037.6	1,064.8

'(1)' significant proportions of production in some countries may be designated for thermal usage.

Data for Australia and India are provided on a fiscal basis.

Source: IEA (2015) Coal Information

In the last years, more mines with high production costs were closed down, most of them in the United States, Australia and China. At the same time, all coal producers were focusing on cost-saving initiatives and improving their productivity in coal mining. Thus, it seems the global oversupply situation may hardly change in the near future. Furthermore, reductions through mine closures are offset by the commissioning of new production capacities.

In the European coal mining industry, particularly hard coal, there are plans for major restructuring processes. Furthermore, the phasing out of subsidies for hard coal mining in the EU by the end of 2018 based on the EU rules governing state aid for the coal sector as decided on 10 December 2010 by the Competitiveness Council, will have a major impact on hard coal mining in nearly all hard coal producing EU member countries⁴¹. Nonetheless, coal will continue to play an important role, as the rise in global primary energy consumption is expected to continue, particularly in Asian countries⁴².

⁴¹ Council of the European Union (2010) COUNCIL DECISION of 10 December 2010 on State aid to facilitate the closure of uncompetitive coal mines (2010/787/EU). Official Journal of the European Union

⁴² BGR (2014) Energy Study 2014. Reserves, resources and availability of energy resources, Hannover.

3. SOCIO-ECONOMICS

Coal has been a support for the economy in both developed and developing countries, but there are still over 1.2 billion people in the world who live without adequate electricity, which is vital for basic needs⁴³. Electrification is a critical element in the development of societies; the ability to provide reliable electricity has far-reaching effects on economic and social development. Electrification leads to advancements in public health, education, transportation, communications, manufacturing and trade. In some places, access to electricity is a fundamental social right, and yet the demand for electricity continues to outstrip some regions' ability to supply it because of a lack of fuels, transmission, or infrastructure.⁴⁴

In many cases, achieving electrification would simply not be possible without coal-fuelled power plants. Its role in the electricity system is an important one in ending electricity poverty for billions of people and contributing to economic development.

For example, in South Africa, coal accounts for over 70% of the country's primary energy consumption, more than 80% electricity generation and 30% liquid fuels⁴⁵. This has aided the development in infrastructure, industrialisation, and the economy as a whole. Medupi and Kusile, the two new power stations under construction will be South Africa's first supercritical power plants with operating efficiencies of 40% and equipped with flue gas desulphurisation (FGD) installation. The first unit (800 MW) of the 4,800 MW Medupi coal-fired power station was synchronised to the grid in March 2015. The first unit of the 4,800 MW Kusile coal-fired power station is expected to be synchronised during the first half of 2017.

The World Bank estimates that in the last three decades 600 million people have been lifted out of poverty, almost all of whom were in China. Remove China from the mix and poverty levels in the rest of the world have barely improved. The link between access to affordable power from coal, economic growth and prosperity is clear. In China close to 99% of the population is connected to the grid⁴⁶. Advanced boilers and state-of-the-art emission control technology are moving to the forefront in order to tackle China's severe air quality challenge and rapidly growing need for electricity.

Coal also plays a significant role in global steel production. According to recent statistics issued by the World Steel Association, there was an increase in global steel production in 2014 up to 1665 million tonnes, which was a 16.2% increase from 2010 values⁴⁷. Coking

⁴³ IEA (2015) World Energy Outlook Electricity access database

⁴⁴ Coal Industry Advisory Board to the IEA, The Socioeconomic Impacts of Advanced Technology Coal-Fuelled Power Stations, Paris 2015

⁴⁵ Mutemi, A. (2013). MUI Coal mines: A blessing or a curse? Socioeconomic and environmental intricacies. University of Nairobi.

⁴⁶ World Coal Association, <http://www.worldcoal.org/sustainable-societies/improving-access-energy>

⁴⁷ <https://www.worldsteel.org/dms/internetDocumentList/bookshop/2015/World-Steel-in-Figures->

coal is an essential element in blast furnace steel production, making up 70% of total steel production (the remainder is produced from electric arc furnaces using scrap steel).

Steel is an essential material for modern life. Manufacturing steel delivers the goods and services that our societies need – healthcare, telecommunications, improved agricultural practices, better transport networks and access to reliable and affordable energy. Steel is a critical component in the construction of transport infrastructure and high energy efficiency residential housing and commercial buildings.

China is by far the world's largest steel producer followed by Japan, the United States, India and Russia. There has been a significant shift towards China in global steel markets over the past decade. China's share of global production increased from just over 15% in 2000 to more than 49% in 2014⁴⁸.

However, other developing economies in Latin America, Asia, Africa and the Indian sub-continent, where steel will be vital in improving economic and social conditions, are also expected to see significant increases in steel production. In these regions, according to the World Steel Association, more than 60% of steel consumption will be used to create new infrastructure. With world steel production expected to continue to grow, the outlook for the coking coal sector will also be strong.

There are socio-economic benefits and concerns with regards to managing coal resource. Firstly, one can look at the benefit of coal mining in rural and remote areas where transport infrastructural development becomes the norm since roads or rail needs to be present for the transfer of coal. The impact of coal on infrastructure development is more noticeable in developing nations due to the absence of pre-existing infrastructure. The rail line used to transport coal can also be utilised by a variety of industries. The investment in infrastructure caused by the energy industry helps to foster economic development. Also, the local population will benefit since employment is provided and hence, other businesses will begin to prosper owing to the increase in market transactions and needs.

On the other hand, concerns can also be seen in that the natural topography of land close to the mining area is disrupted and disfigured. In addition, air quality significantly deteriorates as coal dust particles linger in the atmosphere; however, this is mainly due to poor emissions control. Another effect of poor management practices is the change that mining brings to ground water, as the water course is diverted in order for extraction process to occur⁴⁹. This often would have an impact on communities that depend on underground water to sustain their source of income or for survival.

2015/document/World%20Steel%20in%20Figures%202015.pdf p.7

⁴⁸ <https://www.worldsteel.org/dms/internetDocumentList/bookshop/2015/World-Steel-in-Figures-2015/document/World%20Steel%20in%20Figures%202015.pdf> p.9

⁴⁹ Mutemi, A. (2013). MUI Coal mines: A blessing or a curse? Socioeconomic and environmental intricacies. University of Nairobi.

Coal resource developments in several regions do have significant socio-economic impacts especially for the cities and communities near the project sites. The following looks at these benefits.

COMMUNITY IMPACTS FROM TAXES

The taxes that come from coal related activities provide significant revenue for the government. In 2011, the direct contribution from the US mining activity provided over US\$20 billion in tax payments to all tier of the government - federal, state and local⁵⁰.

In Germany, about US\$112 million of tax revenue was collected as a result of the construction phase of Neurath Units F&G between 2005 and 2011.

China also had tax revenues of about US\$19 million and US\$65 million annually based on the on-grid prices for Zhoushan Unit 4 and Ninghai Units 5. For this nation, electricity consumption is a significant source of tax revenue via a Value Added Tax (VAT) of 17%⁵¹.

PUBLIC HEALTH AND ENVIRONMENTAL IMPROVEMENT

Cleaner coal technologies can mitigate the present situation by replacing old coal units and through retrofitting older plants, which will result in emissions reduction. Advanced coal power plants have better efficiencies and produce fewer emissions than older generation units. Besides boiler efficiency, new advanced coal units' employ emissions control systems that eliminate more than 95% of nitrogen oxide, sulphur dioxide, and particulate matter. In addition to these air emissions, advanced plants also aid in the reduction of GHG emissions.

LOWER ELECTRICITY PRICES

Economies benefit from lower electricity prices because of reduced energy costs, but this also increases industrial competitiveness. Nations that enjoy reduced cost in energy can manufacture goods at lower prices, thus increasing domestic profits and rise in economic activity.

The efficiencies of modern coal plants have gone beyond 43%, as evidenced by the Neurath F and G lignite plants commissioned in August 2012⁵². Charles River Associate (CRA) estimated that if all German coal was converted overnight to state-of-the-art technology, German power prices would decrease by 6.8% amounting to consumer savings of about US\$2.53 billion annually⁵³. This highlights the negative correlation between advanced coal technology and lower electricity prices.

⁵⁰ CIAB (2014). The socio-economic impacts of advanced technology coal-fuelled power stations.

⁵¹ <https://www.gov.uk/government/publications/exporting-to-china/exporting-to-china>

⁵² <https://www.rwe.com/web/cms/mediablob/en/208030/data/12068/3/rwe-power-ag/fuels/kw-neurath-boa-2-3/Neurath-F-and-G-set-new-benchmarks-Article-by-Dr.-Reinhold-Eisen-RWE-Power-and-Matthias-Fleischmann-Alstom-published-in-Modern-Power-Systems-June-2008.pdf>

⁵³ CIAB (2014). The socio-economic impacts of advanced technology coal-fuelled power stations

CASE STUDIES

This section focuses on the benefits that coal facilities and mines bring to economies and environments.

7. In India, the Sasan Ultra Mega Power Project (UMPP) an advanced 4 GW coal fuelled power plant.
8. Kraftwerk Neurath, a 4.2GW lignite fuel in western Germany. This has two advanced supercritical units of 1,100 MW each.
9. Usibelli Coal Mine (UCM), located in Healy, Alaska, has been producing coal for more than 70 years. UCM's year-round mining activity produced an annual average of 2 million tonnes of coal from 2009 to 2013 for both domestic use and export market.

SASAN UMPP FACILITY, INDIA

- Reliance Sasan Power is expected to provide about US\$42 billion during the operating lifetime of 25 years (Table 5).
- From an environmental perspective, the increased efficiency reduces greenhouse gas emissions. The plant's effect is equal to the removal of 641,000 vehicles from the road annually.
- The increased access to electricity due to Sasan would result in an addition of more than 157,000 new jobs.

TABLE 5: ECONOMIC IMPACTS DUE TO CONSTRUCTION AND OPERATION OF RELIANCE SASAN

	Construction phase: 4 years (US\$ billion)	Operation and Maintenance: 25 year period (US\$ billion)
Direct economic impact	2.4	9.21
Indirect economic impact	3.51	11.29
Induced economic impact	6.24	21.88
Total impact	12.15	42.39

Source: CIAB (2014)

- During Sasan's operating lifetime of 25 years, Sasan would employ about

600 people directly for its operations and a further 19,500 people would benefit through indirect and induced jobs (Table 6).

- At full capacity, the plant generates enough power to supply electricity to 17.5 million people across seven states; enabling 22 million people to get access to safe water supplies.

TABLE 6: SASAN UMPP EMPLOYMENT IMPACTS

	Construction phase: 4 years	Operation and Maintenance: 25 year period	Total
Direct jobs	5000	639	5639
Indirect jobs	3700	3970	7670
Induced jobs	12250	15532	27782
Total jobs created	20950	20141	41091

Source: CIAB (2014)

- 12,000 schools are expected to be powered by Sasan power plant, which will increase enrolment by more than 96,000 students and is expected to provide street lighting to approximately 400,000 households.

KRAFTWERK NEURATH FACILITY, GERMANY

- The development of Neurath, its construction and engineering costs added US\$7.2 billion to the local economy (Table 7)

TABLE 7: ECONOMIC IMPACTS DUE TO CONSTRUCTION AND OPERATION OF NEURATH F AND G

	Construction (million US\$, 2006-2012)	Operation and Maintenance (million US\$ per year)
Direct economic impact	3469	70
Indirect economic impact	2773	34
Induced economic impact	1000	12
Total impact	7242	116

Source: CIAB (2014)

- Since the operation of the Neurath units in 2012, over US\$77 million in wages were paid out. This has also been directly responsible for the employment of 420 employees (including contractors) and other estimated 270 indirect employees (Table 8).

TABLE 8: NEURATH F&G EMPLOYMENT IMPACTS

	Construction (Full time employment, 2006-2012)	Operation and Maintenance (full time employment per year)
Direct jobs	2500	840
Indirect jobs	2800	419
Induced jobs	1700	285
Total jobs created	7000	1544

- Source: CIAB (2014)

In addition, the Rhenish lignite mining industry contributes about 3.7 billion annually to the regional economy, with approximately 42,000 jobs in Germany.

USIBELLI COAL MINE (UCM), ALASKA, US⁵⁴

- Government payments

US\$3 million was paid to the government of Alaska for rent, royalties and taxes.

- Charity support

US\$272,000 was contributed to about 100 non-profit organisations in 16 communities by UCM and The Usibelli Foundation.

UCM also supported more than 20 academic scholarships annually, for example US\$1000 scholarships were presented to students of UCM employees who graduated high school and enrolled for post-secondary education. Five academic scholarships were also granted to graduating seniors at Healy’s Tri-Valley School. In addition, three University of Alaska Fairbank’s staff were honoured with a US\$10,000 prize for outstanding teaching, research and public service.

- UCM and other borough economies

UCM spent about US\$270,000 with 21 Denali Borough vendors.

About 28% of enrolment in Healy’s K-12 Tri-Valley School came from the family of UCM employees. UCM also provided employment for 117 Healy residents (Table 9)

TABLE 9: SEASONAL VARIATION IN THE DENALI BOROUGH WORKFORCE, RESIDENT AND NON-RESIDENT, 2013

	January		July	
	Number of jobs	Percentage (%)	Number of jobs	Percentage
Government	314	40	411	11
Professional services	132	17	167	4

⁵⁴ <http://www.usibelli.com/pdf/McDowell-Report-Statewide-Socioeconomic-Impacts-of-UCM-2015l.pdf>

Usibelli Coal Mine	117	15	117	3
Leisure	102	13	2,673	70
Trade, transportation and utilities	67	8	338	9
Educational and health services	15	2	48	1
Other services	48	6	81	2
Total	794	100	3,834	100

Source: McDowell group (2015) State-wide Socioeconomic Impact of Usibelli Coal Mine

Its operations directly provided 25% of all employment for Healy year-round residents and 31% of all employment for residents working in the private sector. US\$12.9 million was paid to Healy employees by UCM and this represented about 60% of all wages paid to Healy residents.

- Employment and wages

The average wage paid to employees of UCM and its subsidiary mining operator in Healy, Aurora Energy Services (AES) was US\$21.3 million (including benefits of US\$6.6 million) in 2013. UCM/AES also employed local employees, hence creating work, improving the skills and the standard of living for residents of Alaska.

4. ENVIRONMENTAL IMPACTS

Our consumption of energy can have a significant impact on the environment. Minimising the negative impacts of human activities on the natural environment, including energy use is a key global priority. The coal industry works to ensure environmental impacts are minimised.

COAL MINING & THE ENVIRONMENT

Coal mining, in particular surface mining, requires large areas of land to be temporarily disturbed. This raises a number of environmental challenges, including soil erosion, dust, noise and water pollution, and impacts on local biodiversity. Steps are taken in modern mining operations to minimise these impacts. Good planning and environmental management minimises the impact of mining on the environment and helps to preserve biodiversity.

Land disturbance

In best practice, studies of the immediate environment are carried out several years before a coal mine opens in order to define the existing conditions and to identify sensitivities and potential problems. The studies look at the impact of mining on surface and ground water, soils, local land use, and native vegetation and wildlife populations. Computer simulations can be undertaken to model impacts on the local environment. The findings are then reviewed as part of the process leading to the award of a mining permit by the relevant government authorities.

Mine subsidence

A consideration that can be associated with underground coal mining is subsidence, whereby the ground level lowers as a result of coal having been mined beneath. Any land use activity that could place public or private property or valuable landscapes at risk is clearly a concern, as shown in the Witbank-Middelburg case study where poor management practices were undertaken. A thorough understanding of subsidence patterns in a particular region allows the effects of underground mining on the surface to be quantified. This ensures the safe, maximum recovery of a coal resource, while providing protection to other land uses.

WITBANK-MIDDELBURG AREA, SOUTH AFRICA

Close to the Middelburg Steam Mine is Ligazi, a settlement area in which the land trembles and sinks. Residents found the 126 sinkholes and the trembling worrying. The holes appeared suddenly in homes and sometimes it was quite laborious for

residents to keep filling the holes. Objects sometimes fell into the earth and residents saw these sinkholes as a hazard to the children or night travellers. This was clearly as a result of poor management practices.

Source: Victor Munnik (2010) The social and environmental consequences of coal mining in South Africa.

Dust & noise pollution

During mining operations, the impact of air and noise pollution on workers and local communities can be minimised by modern mine planning techniques and specialised equipment. Dust at mining operations can be caused by trucks being driven on unsealed roads, coal crushing operations, drilling operations and wind blowing over areas disturbed by mining. Dust levels can be controlled by spraying water on roads, stockpiles and conveyors. However, this should be guided by strong water management practices in order to increase water efficiency and reduce the strain on water scarcity in certain regions. Other steps can also be taken, including fitting drills with dust collection systems and purchasing additional land surrounding the mine to act as a buffer zone between the mine and its neighbours. Trees planted in these buffer zones can also minimise the visual impact of mining operations on local communities.

Noise can be controlled through the careful selection of equipment and insulation and sound enclosures around machinery. In best practice, each site has noise and vibration monitoring equipment installed, so that noise levels can be measured to ensure the mine is within specified limits.

Rehabilitation

Coal mining is only a temporary use of land, so it is vital that rehabilitation of land takes place once mining operations have ceased. In best practice, a detailed rehabilitation or reclamation plan is designed and approved for each coal mine, covering the period from the start of operations until well after mining has finished. Land reclamation is an integral part of modern mining operations around the world and the cost of rehabilitating the land once mining has ceased is factored into the mine's operating costs.

Reclaimed land can have many uses, including agriculture, forestry, wildlife habitation and recreation.

Using methane from coal mines

Methane (CH₄) is a gas formed as part of the process of coal formation. It is released from the coal seam and the surrounding disturbed strata during mining operations.

Methane is highly explosive and has to be drained during mining operations to keep working conditions safe. At active underground mines, large-scale ventilation systems move massive quantities of air through the mine, keeping the mine safe but also releasing methane into the atmosphere at very low concentrations. Some active and abandoned

mines produce methane from degasification systems, also known as gas drainage systems, which use wells to recover methane.

As well as improving safety at coal mines, the use of coal mine methane improves the environmental performance of a coal mining operation and can have a commercial benefit. Coal mine methane has a variety of uses, including onsite or off-site electricity production (Gaohe coal mine case study), use in industrial processes and fuel for co-firing boilers.

GAOHE COAL MINE

Lu'an Group uses 99% of methane gas from the Gaohe coal mine in north China's Shanxi Province to operate a generator with a capacity of 30 MW. This new technology converts methane concentrations lower than 10%, which constitutes about 80% of the gas released during mining. Gas having a concentration level of more than 10% is transformed to methyl alcohol and utilised as fuel for internal combustion engines. Low concentration coal mine methane (CMM) has contributed majorly to China's environmental pollution. It is estimated that coal mines produces more than 10 billion m³/year of gas, leading to a massive GHG emissions. This is likely to help reduce 1.4 million tonnes of GHGs and produce 200 million kWh/year of electricity. This facility installed at Gaohe coal mine has attracted a number of interests from coal mining firms, as the industry develops emissions reduction initiatives in order to control carbon emissions.

Source: World Coal Association

COAL USE & THE ENVIRONMENT

Global consumption of energy raises a number of environmental considerations. For coal, the release of pollutants, such as oxides of sulphur and nitrogen (SO_x and NO_x), particulate matter and trace elements, such as mercury, have been a challenge. However, technologies have been developed and deployed to minimise these emissions.

The release of CO₂ into the atmosphere from human activities has been linked to global warming. The combustion of fossil fuels is a major source of anthropogenic emissions worldwide. While the use of oil in the transportation sector is the major source of energy-related CO₂ emissions, coal is also a significant source. As a result, the industry has been researching and developing technological options to meet this new environmental challenge.

Technological response

Clean coal technologies (CCTs) are a range of technological options which improve the environmental performance of coal. These technologies reduce emissions, reduce waste, and increase the amount of energy gained from each tonne of coal (Emissions reduction case study). Different technologies suit different types of coal and tackle different

environmental problems. The choice of technologies can also depend on a country's level of economic development.

EMISSIONS REDUCTION INITIATIVES

Alstom saved 207 million tonnes of CO₂ from being emitted yearly for nine years (2002 – 2011). This was achieved by constructing new highly efficient plants and retrofitting new technology to existing plants. In Germany, the Rheinhafen Dampfkraftwerk 8 (RDK 8) coal-fired power station in Karlsruhe is one of the first new generation units adopting the ultra-supercritical technology. The 912 MW plant achieves 46% efficiency and even more when its district heating capabilities are taken into consideration (58% efficiency). RDK 8 emits 740gCO₂/kWh since its commissioning in 2012. A 1980s generation coal-fired power station emits 1200gCO₂/kWh which is about 40% improvement.

Source: World Coal Association

Steps have been taken to significantly reduce SO_x and NO_x emissions from coal-fired power stations. Certain approaches also have the additional benefit of reducing other emissions, such as mercury. The activated carbon injection (ACI) technology has demonstrated mercury removal rates of 70% to 90%. However, there is a huge difference in capital cost when considering different control technologies (ACI systems costs US\$5- US\$15/kW while fabric filters and carbon injection costs US\$120 – US\$150/kW).⁵⁵

Sulphur is present in coal as an impurity and reacts with air when coal is burned to form SO_x. In contrast, NO_x is formed when any fossil fuel is burned. In many circumstances, the use of low sulphur coal is the most economical way to control sulphur dioxide. An alternative approach has been the development of flue gas desulphurisation (FGD) systems for use in coal fired power stations (unpolluted air case study).

UNPOLLUTED AIR

In South Africa, Kusile and Medupi power plants utilise supercritical technology with the incorporation of Alstom's wet flue gas desulphurisation system which removes 90% of the SO_x generated in the boilers. In sub-Saharan Africa, these are the most environmentally friendly plants and also the world's largest air-cooled coal power plants having six 800 MW turbines each. The use of air cooling is significant in water stressed areas which increases the local environmental sustainability.

⁵⁵ Natural Defence Council (2011): Evaluating mercury control technologies for coal power plants.

Source: World Coal Association

Oxides of nitrogen can contribute to the development of smog as well as acid rain. NO_x emissions from coal combustion can be reduced by the use of 'low NO_x' burners, improving burner design and applying technologies that treat NO_x in the exhaust gas stream. Selective catalytic reduction (SCR) and selective non-catalytic reduction (SNCR) technologies can reduce NO_x emissions by around 80-90% by treating the NO_x post-combustion.

Fluidised bed combustion (FBC) is a high efficiency, advanced technological approach to reducing both NO_x and SO_x emissions. FBC is able to achieve reductions of 90% or more.

REDUCING CARBON DIOXIDE EMISSIONS

A major environmental challenge facing the world today is the risk of global warming. The IEA advocates a two-step process to reducing emissions from coal: firstly, by improving power plant thermal efficiency while providing meaningful reductions in CO₂ emissions and secondly, by advancing CCS technologies to commercial scale.

Energy efficiency

Improving efficiency levels increases the amount of energy that can be extracted from a single unit of coal. Increases in the efficiency of electricity generation are essential in tackling climate change. A single percentage point improvement in the efficiency of a conventional pulverised coal combustion plant results in a 2-3% reduction in CO₂ emissions. Highly efficient modern supercritical and ultra-supercritical coal plants emit almost 40% less CO₂ than subcritical plants.

Efficiency improvements include the most cost effective and shortest lead time actions for reducing emissions from coal-fired electricity. This is particularly the case in developing countries and economies in transition where existing plant efficiencies are generally lower and coal use in electricity generation is increasing.

The average global efficiency of coal-fired plants is currently 28% compared to 45% for the most efficient plants. A programme of repowering existing coal-fired plants to improve their efficiency, coupled with the newer and more efficient plants being built, will generate significant CO₂ reductions of around 1.8 Gt annually. Although the deployment of new, highly efficient plants is subject to local constraints, such as ambient environmental conditions and coal quality, deploying the most efficient plant possible is critical to enable these plants to be retrofitted with carbon capture technology in the future.

Improving the efficiency of the oldest and most inefficient coal-fired plants would reduce CO₂ emissions from coal use by almost 25%, representing a 6% reduction in global CO₂ emissions. By way of comparison, under the Kyoto Protocol, parties have committed to reduce their emissions by "at least 5%". These emission reductions can be achieved by the replacement of plants that are < 300 MW capacity and older than 25 years, with larger and

markedly more efficient plants and, where technically and economically appropriate, the replacement or repowering of larger inefficient plants with high-efficiency plants of >40%. The role of increased efficiency as a means to CO₂ mitigation is often overlooked in discussions about climate and energy. As the IEA notes “If the average efficiency of all coal-fired power plants were to be five percentage points higher than in the New Policies Scenario in 2035, such an accelerated move away from the least efficient combustion technologies would lower CO₂ emissions from the power sector by 8% and reduce local air pollution”. It is also important to note that the cost of avoided emissions from more efficient coal-based generation can be very low, requiring relatively small additional investments. This is especially the case when compared to the cost of avoided emissions through deployment of renewables and nuclear.

WATER USAGE

A good start for efficient water consumption is by improving the washing rate of thermal coal⁵⁶. This reduces net water consumption and removes ash which results in less waste and improves thermal efficiencies. It is estimated that if all thermal coal was washed and 10% of ash removed, overall water consumption would fall by 6-16%. However, in China the washing rate is below 40%⁵⁷ and this rate may be similar or lower in India where its coal is mainly low-grade, with a high ash content of around 40%. In China, steps are in place in order to conserve water in some regions, such as the requirement for new coal-fired power plants to have closed-cycle and air-cooling loops in the face of water scarcity. However, this cooling technology can reduce production efficiency by 3-10%, thus the need for more coal per unit of energy produced⁵⁸.

THERMOSYPHON DRY COOLING

Electric Power Research Institute (EPRI) is moving fast with the scale-up of thermosyphon cooling (TSC) by integrating this air-cooling technology with an experimental cooling tower at the Water Research Centre at Georgia Power’s Plant Bowen. This is a dry cooling technology that transfers heat from hot condenser and returns water to a refrigerant and then to the ambient air without water evaporation. In 2015 a commercial demonstration of a 15 MW TSC dry cooling operation will commence. In retrofit applications with TSC, the annual water usage could reduce to about 75% with less energy penalty than present air-cooled technologies.

Source: EPRI (2014) Technology Innovation Prospectus

Water shortages are also experienced in developed worlds, such as the US where 52% of US coal-fired power plant utilises once-through cooling technology⁵⁹. Due to extreme water

⁵⁶ Carbon Tracker (2014) The Great Coal Gap: China’s energy policies and the financial implications for thermal coal, *ibid.*

⁵⁷ *ibid.* 56

⁵⁸ <http://www.theguardian.com/sustainable-business/china-conflict-coal-fired-plants-water#>

⁵⁹ EIA (2014) Many newer plants have cooling systems that reuse water.

shortages in western US many states could follow the footsteps of California. The once-through technology was not favoured in this state because 2010 witnessed the California State Water Resources Control Board approve a measure to ban this technology. This will force 19 plants to retrofit their cooling systems between 2010 and 2024, thus encouraging better water-efficient technologies⁶⁰. A solution could be to incorporate dry cooling which could drastically reduce the amount of water use (Thermosyphon Dry Cooling case study).

At the power generation end of the coal-energy cycle, new technologies are also reducing coal's water footprint. As with other forms of thermal power generation, water in coal-fired plants is used in different ways depending on the type of cooling technology employed. Many technologies do not actually consume significant amounts of water but it is important to make sure that the extraction and return process minimises impacts on water temperature and wildlife.

Eskom, South Africa's largest electricity provider is a leader in dry cooling technology. This is crucial because South Africa is a water-stressed country. Eskom is currently constructing two new dry-cooled plants at Medupi and Kusile that are incorporating lessons learned from their older plants that already consume approximately 19 times less water than an equivalent wet-cooled power plant.

WASTE GENERATION

The combustion of coal generates waste consisting primarily of non-combustible mineral matter along with a small amount of unreacted carbon. The production of this waste can be minimised by coal cleaning prior to combustion. Waste can be further minimised through the use of high efficiency coal combustion technologies.

There is increasing awareness of the opportunities to reprocess power station waste into valuable materials for use primarily in the construction and civil engineering industry. In the year 2009-2011, slightly above half (53%) of the coal combustible products (CCPs) were utilised while the rest were transferred to storage or disposal sites (Table 10).

⁶⁰ California's Clean Energy Future (2011) Once Through Cooling Phase-Out

TABLE 10: ANNUAL CCPs PRODUCTION, UTILISATION RATE BY COUNTRIES 2010

Country/Region	CCPs Production (Mt)	CCPs Utilisation (Mt)	Utilisation rate %
Australia	13.1	6.0	45.8%
Canada	6.8	2.3	33.8%
China*	395.0	265	67.1%
Europe (EU15)	52.6	47.8	90.9%
India*	105.0	14.5	13.8%
Japan	11.1	10.7	96.4%
Middle East & Africa	32.2	3.4	10.6%
USA	118.0	49.7	42.1%
Other Asia*	16.7	11.1	66.5%
Russia	26.6	5.0	18.8%
Total/s	777.1	415.5	53.5%

Source: Heidrich, C. et al. (2013)⁶¹ (* non-members of World Wide Coal Combustion Products Networks)

The fly ash, FGD gypsum, bottom ash and boiler slag generated from coal combustion are utilised in a variety of ways. A common global application is the substitution of Portland cement in concrete with fly ash, which improves performance of concrete because of its decrease in permeability and high durability⁶². In developed countries, FGD gypsum utilisation has progressed quite well and these are also adopted by the construction industries⁶³.

⁶¹ Heidrich, C., Feuerborn, H., Weir, A. (2013) Coal Combustion Products: a global perspective.

⁶² World Coal Association (2015)

⁶³ Jiabin Fu (2010) Challenges to increased use of coal combustion products in China.

5. OUTLOOK

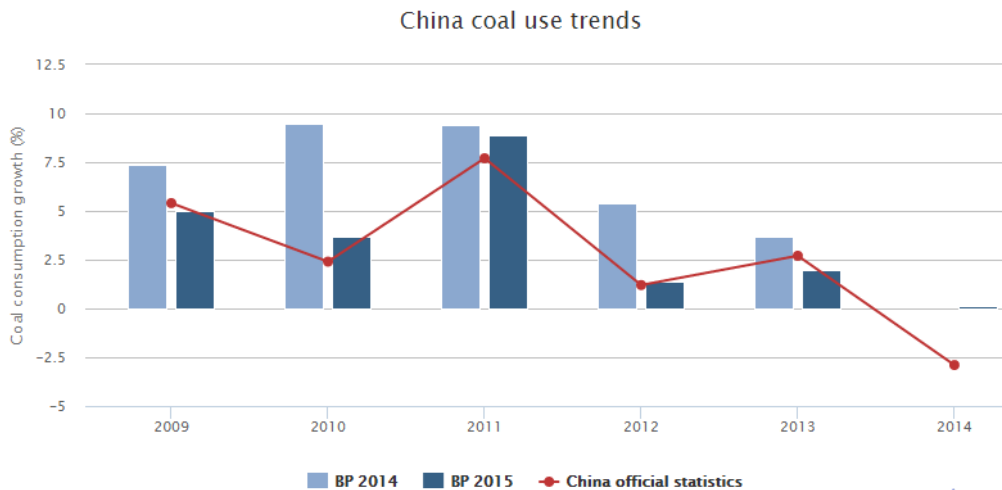
Thermal coal has been available for over nine decades, but this resource has been suffering from a supply surplus for years. It is no surprise that the price of thermal coal has reduced by half since 2011.

Countries need to meet their electricity needs and this will be possible with low-cost electricity, which in turn points to the role coal has played and what it would play in the future. Coal is abundant, accessible, secure, reliable and affordable, and has a substantial existing infrastructure. However, despite these attributes the leverage for coal seems uncertain in light of growing CO₂ emission levels and increasing competitiveness of non-coal power sources in China, the US and the EU.

CHINA

China, the key market driver experienced an unexpected decline of 2.7% in 2014 (Figure 14).

FIGURE 14: CHINA COAL USE TRENDS



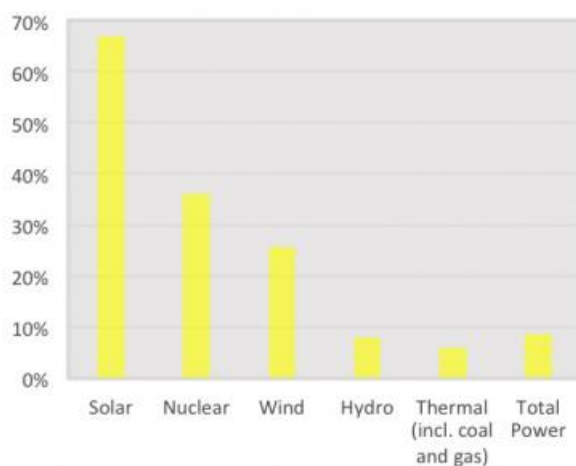
Source: China National Bureau of Statistic, BP Statistical Review (2015)

Essentially, not only is the decline due to a fall in demand but also on tougher regulations that do not favour low quality coal imports from some producers like Indonesia and Australia. The reduction in coal importation would favour China as larger volumes of coal

exportation are expected due to the domestic coal oversupply and the export tax reduction from 10% to 3% which was effective since January 2015⁶⁴.

China continues to tackle its severe air pollution and it is likely that the share of primary energy consumption from renewables such as solar and wind will continue to increase up to 15% in 2020⁶⁵. It is important to note that coal will not be completely phased out because it would be needed as base load to secure supply. However, China will target to reduce its consumption from coal to below 62% by 2020⁶⁶. In 2014, coal had less than 10% of growth capacity, this means there is growth, but in modest level (Figure 15).

FIGURE 15: 2014 GROWTH OF POWER GENERATION CAPACITY IN CHINA



Source: National Bureau of Statistics of China

China added 39 GW of coal-fired capacity in 2014 which was 8.3% increase from the previous year⁶⁷. Only about 60% of the new plants are built using ultra supercritical technology which produces efficiency as high as 44%, meaning CO₂ emissions can be cut by more than a third compared to plants with efficiency between 27% - 36%⁶⁸. It is likely to see this trend progressing in the future as under the IEAs New Policies Scenario, China is seen to cumulatively have 383 GW of coal based power generation between 2014-2015, as the usage of coal as an enabler for economic growth persists (Figure 16).

⁶⁴ China coal Resource, <http://en.sxcoal.com/111509/NewsShow.html>

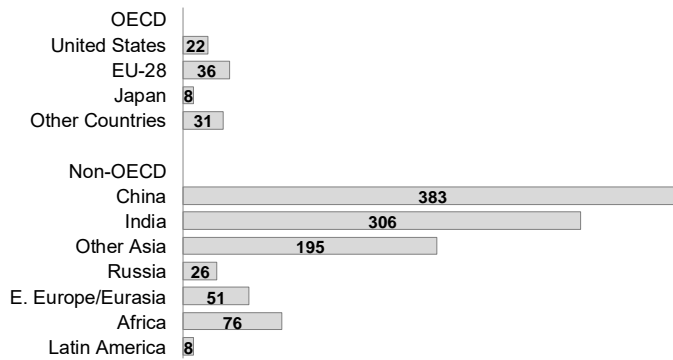
⁶⁵ Climate News Network (2015) China's investment in renewables soars by a third.

⁶⁶ South China Morning Posts (2015) China aims to reduce coal reliance in next five-year plan.

⁶⁷ Institute for Energy Research

⁶⁸ Office of Chief Economist (2015) Coal in India

FIGURE 16: CUMULATIVE COAL BASED POWER PLANT ADDITION BY



COUNTRIES/REGIONS 2015-2040 IN GW

Source: IEA World Energy Outlook (2015)

INDIA

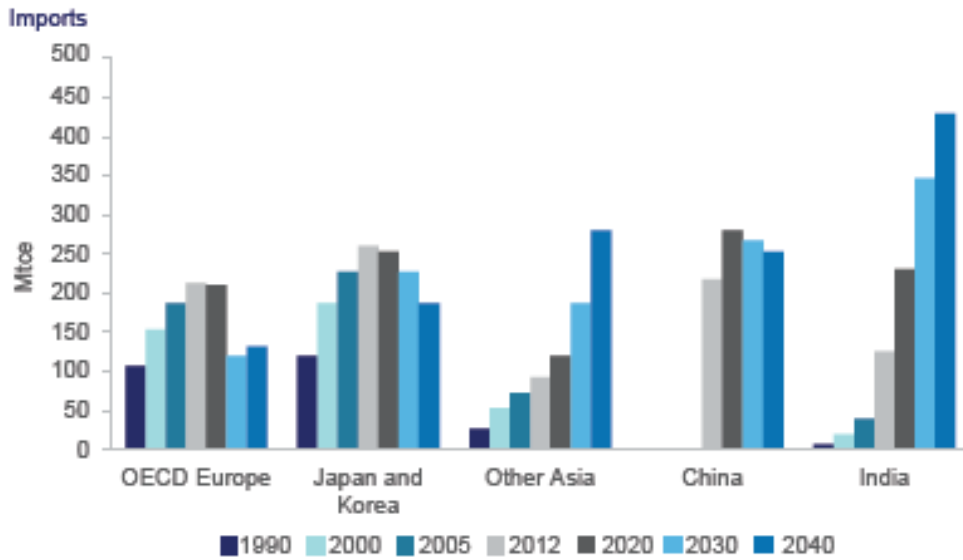
Since China’s cut on coal importation, it seems India is set to overtake them as the biggest importer of thermal coal. IEA new policies scenario which takes into account announced policies that are yet to be enacted illustrated that by 2025 or sooner, Indian thermal coal imports would surpass China’s⁶⁹ (Figure 17).

India’s dependence on imported coal will continue to increase (Figure 14) because the quality of domestic product is considered inferior, with a high ash content of over 30%. Furthermore, given the slow rise in domestic production in the past few years, the Government estimates that imports could almost be a third of its total coal or up to 350 million tonnes by 2016-2017⁷⁰. The rising prediction of imports associates coal to remain the primary energy supply for the nation.

⁶⁹ Office of Chief Economist (2015) Coal in India

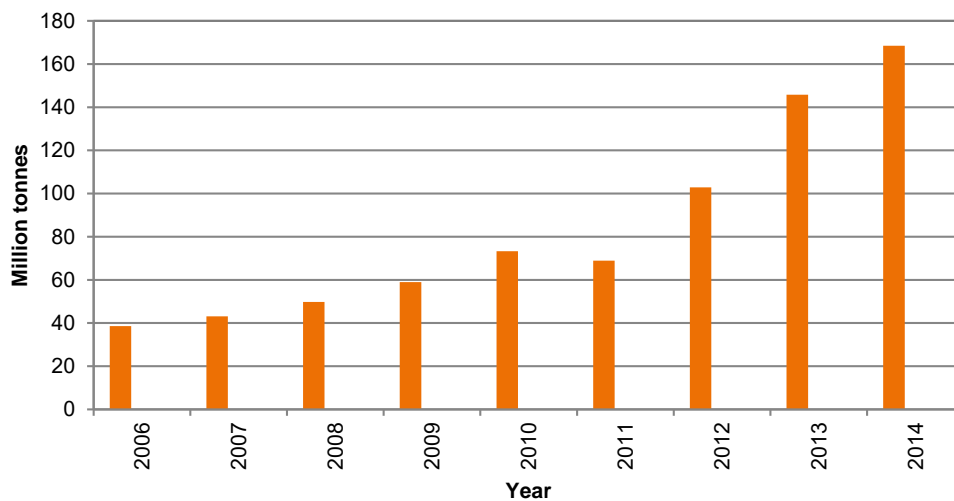
⁷⁰ Coal India Limited (2015) About Us

FIGURE 17: WORLD COAL IMPORTS, NEW POLICIES SCENARIO



Source: Office of the Chief Economist, Australian Government (2015) Coal in India Report

FIGURE 18: INDIA'S GROWING COAL IMPORTS



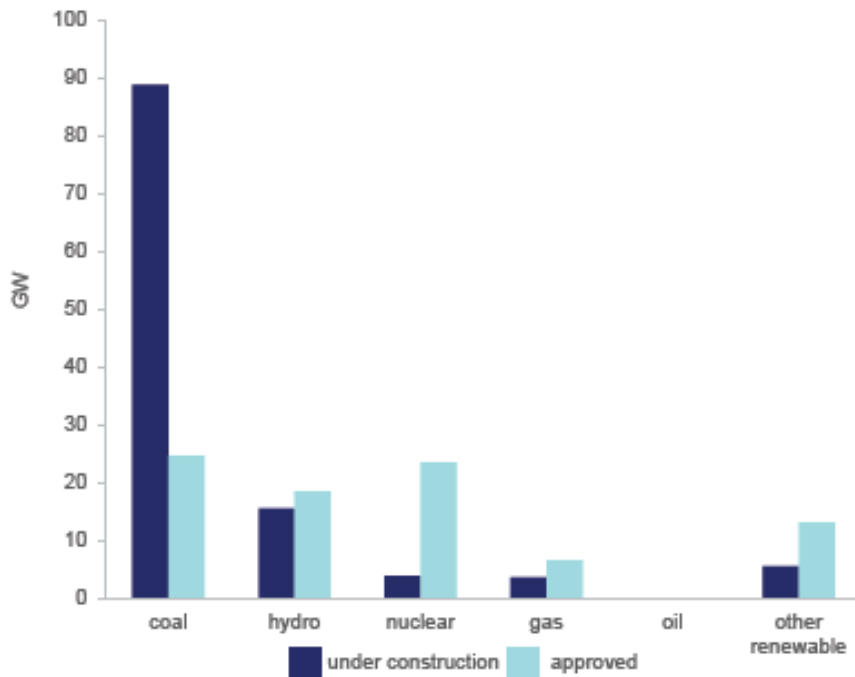
Source: Central Statistical Office, India

India like most nations is diversifying its generation sector, however coal is projected to remain in dominance and also coal-fired power is projected to more than double with an

increasing rate of 3.3% per year, from 840 TWh to about 2,100 TWh before 2025⁷¹. Currently there are plans for coal in this nation's generation capacity as a majority of new plants under construction are mainly coal-fired (Figure 19).

Over the past decade about 90% of India's coal-fired capacity was based on subcritical technology. With global talks on CO₂ emission mitigations, the proportion of subcritical coal-fired technology commissioned in the next five years will decrease. In the next five years it is expected that supercritical technology will be 36% of total coal-fired plants⁷².

FIGURE 19: INDIA'S ELECTRICITY GENERATION CAPACITY UNDER DEVELOPMENT > 50MW



Source: Coal in India 2015 Report, Office of the Chief Economist, Australian Government

Overall, electricity generation from coal is expected to grow with increasing focus on improved coal-fired power plant efficiency because the cost competitiveness of coal is driven primarily by low coal prices and limited availability of alternative fuels.

SOUTHEAST ASIA

In the New Policies Scenarios, the total primary energy demand in Southeast Asia remains heavily reliant on fossil fuels with their share of 74% in 2013 expanding to 78% in 2040.

⁷¹ Coal India Limited (2015) About Us

⁷² Enerdata (2015)

In Southeast Asia the demand for coal is expected to more than triple from 2013 to 2040 growing at an average of 4.6% per year (Table 11). The need to provide electricity to 120 million people in the region that still lack access all contributes to coal's expanding role in the fuel mix, especially in Indonesia, Malaysia, Philippines, Thailand and Vietnam.

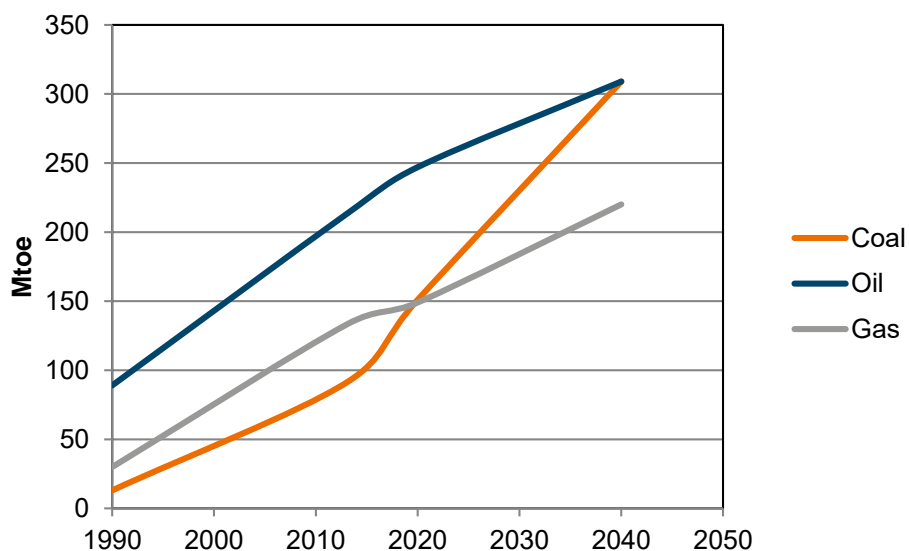
TABLE 11: PRIMARY ENERGY DEMAND IN SOUTHEAST ASIA (MTOE)

Fuel	Shares					
	1990	2013	2020	2040	2013	2040
Fossil fuels	131	437	547	838	74%	78%
Coal	13	91	151	309	15%	29%
Oil	89	213	247	309	36%	29%
Gas	30	133	149	220	22%	21%

Source: IEA (2015)

Southeast Asia is one of the regions in the world where coal's share of the energy mix is projected to increase. The coal share is to rise in 2020 overtaking natural gas (Figure 20). This trend is underpinned by the price advantage and relative availability of coal versus gas in the region.

FIGURE 20: PRIMARY ENERGY DEMAND BY FOSSIL FUEL IN SOUTHEAST ASIA, 1990-2040



Source: IEA (2015)

By 2040, Southeast Asia's total electricity generation will almost triple from 789 TWh in 2013 to 2200 TWh in 2040. Coal use increases its share in power generation from 32% to 50%, while the share of natural gas declines from 44% to 26% (Table 12). Southeast Asia's electricity depends largely on fossil fuels, especially coal where countries such as Indonesia, Malaysia and Thailand intend to expand their use of coal.

TABLE 12: ELECTRICITY GENERATION BY FOSSIL FUELS IN SOUTHEAST ASIA (TWH)

					Shares	
	1990	2013	2020	2040	2013	2040
Fossil fuels	120	648	925	1699	82%	77%
Coal	28	255	482	1097	32%	50%
Oil	66	45	36	24	6%	1%
Gas	26	349	406	578	44%	26%

Source: IEA (2015)

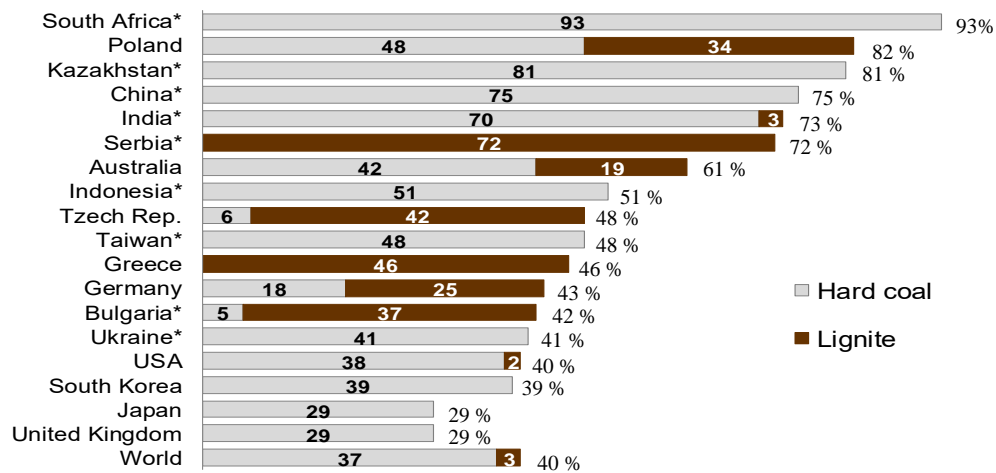
SOUTH AFRICA

More than 85% of South Africa's electricity is generated from coal and about 90% of the supply is provided by Eskom, the nation's electricity public utility⁷³ (Figure 21). In early 2015 the company was forced to implement three stages of load shedding which reduced supply by up to 4 GW because of years of under investment in new generation capacity and insufficient maintenance⁷⁴.

⁷³ Burton, J.& Winkler, H. (2014) South Africa's planned coal infrastructure expansion: Drivers, dynamics and impacts on greenhouse gas emissions

⁷⁴ Wood Mackenzie (2015)., South Africa's power supply crisis

FIGURE 21: COAL SHARE IN POWER GENERATION IN 2014



Source: IEA, Electricity Information, Paris 2015 (* for Non-OECD-countries numbers for 2013)

There could be a challenge for South Africa’s electrification as the available coal reserve is expected to be in mass shortage in the 2020s⁷⁵. With this in light, the government and major players in the supply chain industry have implemented a plan called “coal roadmap”. It is expected that provision will be made to supply higher grade coal to the older Central Basin power stations from the Waterberg and also rail infrastructure are likely to be available in the early 2020s to facilitate transport of coal to overcome shortfalls in local utility supply⁷⁶.

As the nation is struggling to meet its demand as it upgrades aging plants and builds new generating capacity, including coal-fired power plants such as Medupi Power Station which will produce 4.8 GW when completed in 2019⁷⁷, it is likely that electricity importation from neighbouring Mozambique could increase by as much as 40%⁷⁸. The building of non-coal-fired new generation capacity is already a challenge, for example the first new nuclear power stations which are projected to be operational in 2023 are facing severe financial constraints. However, this will aid in rebalancing the mix of power generation⁷⁹.

EUROPE

The pace of closure in the coal sector is accelerating because of ample supplies of gas and environmental policies to cut GHG emissions, but this does not mean coal-fired power generation will completely disappear.

In Germany, its energy policy points to a 2.7 GW capacity reserve for lignite plants which will pay plant operators to put their power stations on standby and subsequently shut them

⁷⁵ Christian, S. (2015) Eskom South Africa: A case of planning failure

⁷⁶ Ibid 75

⁷⁷ Business Day live (2015) Medupi finally produces first power

⁷⁸ Bloomberg (2015) Eskom Sees Power Supply from Mozambique up by up to 40%

⁷⁹ World Nuclear Association (2015) Nuclear Power in South Africa

down after 2020⁸⁰. In the UK's electricity mix, in 2014, it provided 35.4% of UK's electricity generation, but the capacity of UK's coal-fired stations could fall by 66% by 2021 and disappear altogether by 2030 with gas, nuclear and renewable power expected to pick up what's left⁸¹.

As with other hydrocarbons, Russia has a rich supply of coal reserves. According to BP's Statistical Review of Energy 2015, Russia had 157,010 million tonnes of coal reserves or 17% share of global reserves. In 2014, Russia produced 334,058 tonnes of coal, with 74,995 tonnes coking coal. Major coking coal export destinations include: China, Ukraine, Japan and Korea. Major steam coal export destinations include: UK, Japan, Korea, China and Germany. The 'Coal Industry' was identified in the 'Energy Strategy of Russia for the Period up to 2030' as a priority area for scientific and technological progress. A key element of this programme will be driving efficiencies in coal-fired power generation. Average efficiency of coal-fired power plants is planned to reach 41% by 2030, with the most advanced coal-fired stations having electricity production net efficiency between 45% and 47%.

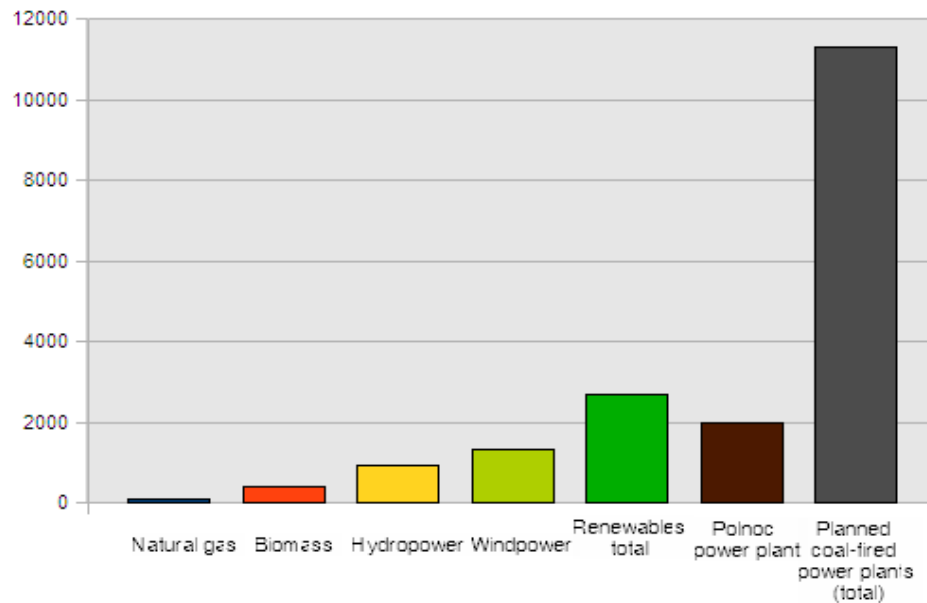
Countries with growing economies and abundant coal reserves, such as Poland, plan to increase their installed capacity with coal. However, this task is challenging as there is a cross road, the huge investments into energy generation are needed as well as phasing out 7GW of its current coal-fired generation capacity by the end of 2015⁸², despite the reality that 85% of electricity is from coal.

Amid climate change talks, Poland will still remain clear on fossil fuels being its main energy source, with this, the nation plans to construct a capacity of 11,300 MW of coal power by 2020 (Figure 22)

⁸⁰ Financial Times (2015) Germany –decision means the coal industry lives on

⁸¹ Financial Times (2015) British coal-fired power plant bows to the inevitable,

⁸² Bank watch (2015) Coal-fired plant in Poland

FIGURE 22: MW OF GENERATION CAPACITY IN POLAND BY 2020

Source: Bank watch (2015)

“Black gold” or “Polish gold” as supporters call this energy source is believed to be significant in avoiding dependence on Russia’s natural gas⁸³. It is projected that coal will remain Poland’s primary fuel for electricity generation because it is an affordable option for a nation that cannot afford a quick transition to cleaner alternatives. As the EU puts in tougher rules, it is expected that coal’s share from Poland’s electricity generation will slowly decline. Polish mining companies will have to adjust its production level to the economically profitable demand, but coal is expected to remain the primary electricity generation source. Despite the current economic slowdown, coal companies and other investors, both national and international are interested in making investments in new Polish coal mines⁸⁴.

UNITED STATES

In the US, the coal industry is declining as a result of the Environmental Protection Agency (EPA) policies and low natural gas prices⁸⁵. The EPA will require existing power plants to cut carbon emissions by 30% by 2030. Since 2010, utilities have formally announced retirement of substantial amounts of coal-fired generating units (Figure 23) and it is expected to see more coal-fired stations closed or substituted with natural gas by 2020, with the majority of generating capacity retiring by end of 2016⁸⁶.

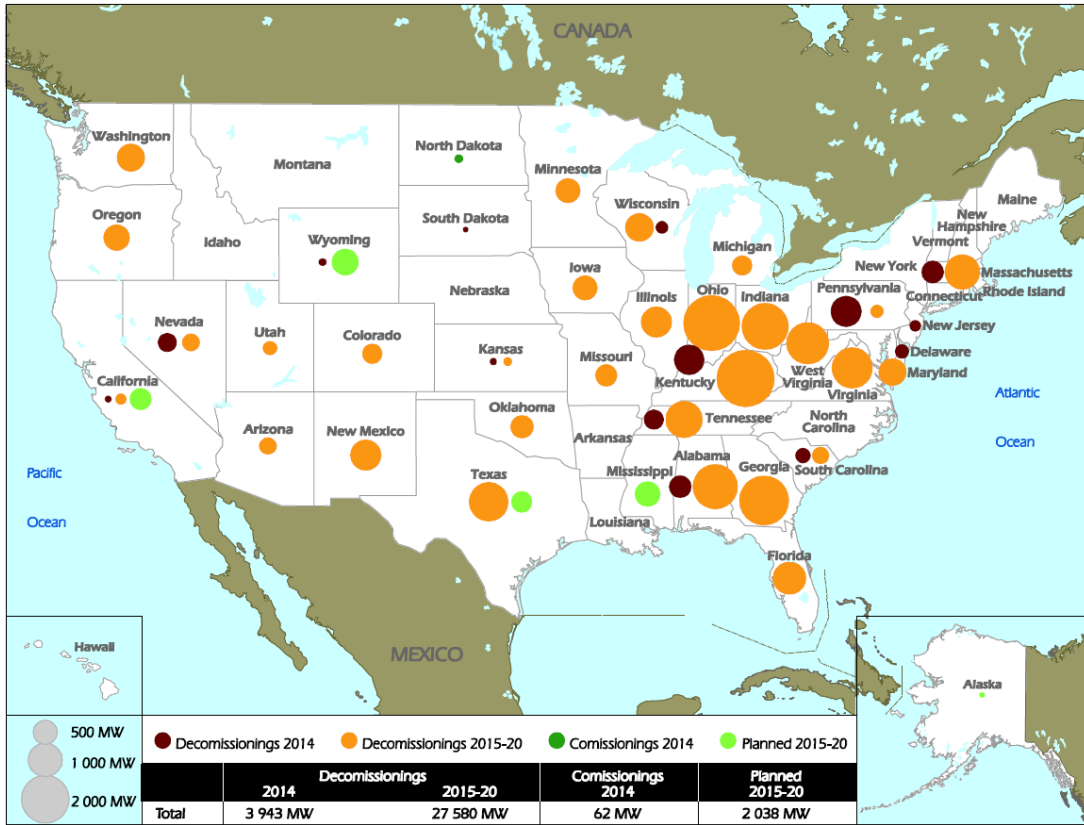
⁸³ New York Times (2015) Coal in Poland lowering life spans

⁸⁴ EURACOAL (2015)

⁸⁵ Coal Unit Shutdowns, American Coalition for Clean Coal Electricity (ACCCE)

⁸⁶ Coal Unit Shutdowns, American Coalition for Clean Coal Electricity (ACCCE)

FIGURE 23: COAL-FIRED POWER PLANT PROJECTS AND DECOMMISSIONINGS IN THE UNITED STATES



Source: IEA (2015)

A good example is PacifiCorp, the Berkshire Hathaway controlled utility laid out plans to retire nearly 3,000 MW of capacity by 2029 and to add more renewable energy resource⁸⁷.

Overall, there is demand for coal but the growth in demand will slow over the long-term. However, coal will continue as a major part of the US energy mix. It is expected to account for about one quarter of the countries generation capacity in 2030⁸⁸

⁸⁷ Utility dive 2015

⁸⁸ <http://www.whitecase.com/publications/insight/power-dynamics-forces-shaping-future-coal-united-states>

6. GLOBAL TABLE

2014/2015 COAL RESERVES, RESOURCES AND REMAINING POTENTIAL

Source: BP Statistical Review of World Energy 2016, BGR Energy, WEC, and IEA

Hard coal - energy content of $\geq 16,500$ kJ/kg comprises sub-bituminous coal, bituminous coal and anthracite.

Lignite - possess lower energy content ($< 16,500$ kJ/kg) and higher water content

Million Tonnes Region	RESERVES 2014*			RESERVES 2015**	RESOURCES 2014*		REMAINING POTENTIAL 2014*	
	Hard coal	Lignite	Total	Total	Hard coal	Lignite	Hard coal	Lignite
Afghanistan	66		66		n.s.		66	
Albania		522	522			205		727
Algeria	59		59		164		223	
Argentina	500		500		300	7300	800	7300
Armenia	163		163		154		317	
Australia	62095	44164	106259	76400	1536666	399267	1598761	443431
Austria						333		333
Bangladesh	293		293		2967	3	3260	3
Belarus						1500		1500
Belgium					4100		4100	
Bhutan	n.s.				n.s.		n.s.	
Bolivia	1		1		n.s.		1	
Bosnia & Herzegovina		2264	2264			3010		5274
Botswana	40		40		21200		21240	
Brazil	1547	5049	6596	6630	4665	12587	6212	17636
Bulgaria	192	2174	2366	2366	3920	2400	4112	4574
Canada	4346	2236	6582	6582	183260	118270	187606	120506
Central African Rep.		3	3			n.s.		3
Chile	1181	n.s.			4135	7	5316	7
China	124059	7555	131614	114500	5338613	325097	5462672	332652
Colombia	4881		4881	6746	9928		14809	
Congo DR	88		88		900		988	
Costa Rica					17		17	
Croatia		n.s.				300		300
Czech Republic	1107	2604	3711	1052	15419	7163	16526	9767
Dominican Rep.						84		84
Ecuador		24	24			n.s.		24
Egypt	16		16		166		182	
Ethiopia		n.s.				n.s.		n.s.
France		n.s.			160	114	160	114
Georgia	201		201		700		901	

WORLD ENERGY COUNCIL | COAL

Germany	21	36300	36321	40548	82961	40500	82982	76800
Region	Hard coal	Lignite	Total	Total	Hard coal	Lignite	Hard coal	Lignite
Greece		2876	2876	3020		3554		6430
Greenland	183		183		200		383	
Haiti						40		40
Hungary	276	2633	2909	1660	5075	2704	5351	5337
India	85562	4714	90276	60600	174981	37932	260544	42645
Indonesia	17394	8274	25668	28017	92431	32365	109825	40639
Iran	1203		1203		40000		41203	
Ireland	14		14		26		40	
Italy	10	7	17		600	22	610	29
Japan	340	10	350	347	13543	1026	13883	1036
Kazakhstan	25605	n.s.		33600	123090	n.s.	148695	n.s.
Korea DPR	600	n.s.			10000	n.s.	10600	n.s.
Korea Rep.	326		326		1360		1686	
Kosovo		1564	1564			9262		10826
Kyrgyzstan	971	n.s.			27528	n.s.	28499	n.s.
Laos	4	499	503		58	22	62	521
Macedonia		332	332			300		632
Madagascar					150	37	150	37
Malawi	2		2		800		802	
Malaysia	141	39	180		1068	412	1209	451
Mali						3		3
Mexico	1160	51	1211	1211	3000	n.s.	4160	51
Mongolia	1170	1350	2520	2520	39854	119426	41024	120776
Montenegro	142	n.s.			195	n.s.	337	n.s.
Morocco	14		14		82	40	96	40
Mozambique	1792		1792		21844		23636	
Myanmar	3	3	6		248	2	252	5
Namibia					350		350	
Nepal	1		1		7		8	
Netherlands	497		497		2750		3247	
New Caledonia	2		2		n.s.		2	
New Zealand	825	6750	7575	571	2350	4600	3175	11350
Niger		6	6		90	n.s.	90	6
Nigeria	287	57	344		1857	320	2144	377
Norway	2		2		90		93	
Pakistan	207	2857	3064	2070	5789	176739	5996	179596
Peru	102		102		1465	100	1567	100
Philippines	211	105	316		1012	912	1223	1017
Poland	16203	5429	21632	5465	162709	222458	178913	227886
Portugal	3	33	36		n.s.	33	3	66
Romania	11	280	291	291	2435	9640	2446	9920
Russia	69634	90730	160364	157010	2658281	1288894	2727915	1379623
Serbia	402	7112	7514	13411	453	13074	855	20186

WORLD ENERGY COUNCIL | WORLD ENERGY RESOURCES 2016

Sierra Leone						2		2
Slovakia		135	135		19	938	19	1073

Million Tonnes Region	RESERVES 2014*			RESERVES 2015**	RESOURCES 2014*		REMAINING POTENTIAL 2014*	
	Hard coal	Lignite	Total	Total	Hard coal	Lignite	Hard coal	Lignite
South Africa	9893		9893	30156	203667		213560	
Spain	868	319	1187	530	3363	n.s.	4231	319
Swaziland	144		144		4500		4644	
Sweden	1		1		4		5	
Taiwan	1		1		101		102	
Tajikistan	375		375		3700		4075	
Tanzania	269		269		1141		1410	
Thailand		1063	1063	1239		826		1889
Turkey	380	12466	12846	8702	802	362	1182	12828
Turkmenistan					800		800	
Uganda					800		800	
Ukraine	32039	2336	34375	33873	49006	5381	81045	7717
United Kingdom	70		70	228	186700	1000	186770	1000
USA	222641	30483	253124	237295	6457688	1367877	6680329	1398360
Uzbekistan	1375	n.s.		1900	9477	n.s.	10852	n.s.
Venezuela	731		731	479	5981		6712	
Viet Nam	3116	244	3360	150	3519	199876	6635	200120
Zambia	45		45		900		945	
Zimbabwe	502		502	502	25000		25502	
Total Africa	13151	66	13217		283611	402	296762	468
Total Asia Pacific	296416	77627	374043	288328	7224567	1298505	7520985	1376131
Total CIS	130363	93066	223429	227833	2872736	1295775	3003099	1388840
Total Europe	20255	77365	97620		471820	317713	492077	395077
Total Middle East	1203		1203	1122	40000		41203	
Total North America	228330	32770	261100	245088	6644148	1486147	6872478	1518917
Total S. & Cent. America	8943	5073	14016	14641	26491	20118	35434	25191
World	698660	285964	984624	891531	17713376	4418658	18412036	4704622
Slovenia	56	315	371		39	341	95	656

*BGR

** BP Statistical Review of World Energy 2016

2014 COAL PRODUCTION

Source: BP Statistical Review of World Energy 2016, BGR Energy, R/P (reserve to production ratio)

Million Tonnes Region	PRODUCTION			
	Hard coal 2014*	Lignite 2014*	Total production 2014*	Total production 2015**
Afghanistan	0.7	-	0.7	
Albania	-	< 0.05	-	
Algeria	-	-	-	
Argentina	0.1	-	0.1	
Armenia	-	-	-	
Australia	441.3	62	503.3	485
Austria	-	-	-	
Bangladesh	0.9	-	0.9	
Belarus	-	-	-	
Belgium	-	-	-	
Bhutan	0.1	-	0.1	
Bolivia	-	-	-	
Bosnia & Herzegovina	-	6.3	6.3	
Botswana	0.8	-	0.8	
Brazil	4.5	3.4	7.9	8
Bulgaria	-	31.3	31.3	36
Canada	60.5	8.5	69	61
Central African Rep.	-	-	-	
Chile	4	0.2	4.2	
China	4	145	4	3747
Colombia	88.6	-	88.6	86
Congo, DR	0.1	-	0.1	
Costa Rica	-	-	-	
Croatia	-	-	-	
Czech Republic	8.3	38.3	46.6	46
Dominican Rep.	-	-	-	
Ecuador	-	-	-	
Egypt	0.3	-	0.3	
Ethiopia	-	< 0.05	-	
France	0.3	-	0.3	
Georgia	0.4	-	0.4	
Germany	8.3	178.2	186.5	184
Greece	-	48	48	48
Greenland	-	-	-	
Haiti	-	-	-	
Hungary	-	9.6	9.6	9
India	612.4	47.2	659.6	677
Indonesia	410.8	60	470.8	392

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Iran	2.8	-	2.8	
Million Tonnes PRODUCTION				
Region	Hard coal 2014*	Lignite 2014*	Total production 2014*	Total production 2015**
Ireland	-	-	-	
Italy	0.1	-	0.1	
Japan	1.3	-	1.3	1
Kazakhstan	109.0	6.6	115.6	106
Korea, DPR	33	7	40	
Korea, Rep.	1.7	-	1.7	
Kosovo	-	7.2	7.2	
Kyrgyzstan	0.3	1.3	1.6	
Laos	0.2	0.5	0.7	
Macedonia	-	6.5	6.5	
Madagascar	-	-	-	
Malawi	0.1	-	0.1	
Malaysia	2.5	-	2.5	
Mali	-	-	-	
Mexico	14	-	14	14
Mongolia	18.1	6.3	24.4	24
Montenegro	-	1.6	1.6	
Morocco	-	-	-	
Mozambique	6.1	-	6.1	
Myanmar	0.5	< 0.05	0.5	
Namibia	-	-	-	
Nepal	< 0.05	-	-	
Netherlands	-	-	-	
New Caledonia	-	-	-	
New Zealand	3.7	0.3	4	3
Niger	0.3	-	0.3	
Nigeria	< 0.05	-	-	
Norway	1.7	-	1.7	
Pakistan	1.9	1.2	3.1	3
Peru	0.2	-	0.2	
Philippines	8.1	-	8.1	
Poland	73.0	63.9	136.9	136
Portugal	-	-	-	
Romania	-	23.6	23.6	25
Russia	287	70	357	373
Serbia	0.2	29.9	30.1	38
Sierra Leone	-	-	-	
Slovakia	-	2.2	2.2	
Slovenia	-	3	3	
South Korea				2
South Africa	253.2	-	253.2	252
Spain	3.9	1.24	3.9	3

WORLD ENERGY COUNCIL | COAL

Swaziland	0.2	-	0.2	
Region	PRODUCTION			Total production 2015**
	Hard coal 2014*	Lignite 2014*	Total production 2014*	
Sweden	-	-		
Taiwan	-	-	-	
Tajikistan	0.6	-	0.6	
Tanzania	0.2	-	0.2	
Thailand		18	18	15
Turkey	1.8	60	61.8	
Turkmenistan	-	-	-	
Uganda	-	-	-	
Ukraine	65	0.2	65.2	38
United Kingdom	11.6	-	11.6	9
USA	835.1	71.8	906.9	813
Uzbekistan	< 0.05	4.4	4.4	4
Venezuela	2	-	2	1
VietNam	41.7	-	41.7	42
Zambia	0.4	-	0.4	
Zimbabwe	4	-	4	4
Total Africa	265.7	-	265.7	266
Total Asia Pacific	5,303.9	347.5	5,651.4	5440
Total CIS	462.3	82.5	544.8	527
Total E.U.	7,262.2	2	8,795.2	528
Total Middle East	2.8	-	2.8	1
Total North America	909.6	80.3	989.9	888
Total S. & Cent. America	99.4	3.6	103	98
World	7,153.0	1,023.4	8,176.4	7861

*BGR

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- AGEB (2015), Arbeitsgemeinschaft Energiebilanzene. V, Energieverbrauch in Deutschland im Jahr 2014. – 42 p.; Berlin and Cologne www.ag-energiebilanzen.de/index.php?article_id=29&fileName=ageb_jahresbericht2014.pdf
- Energieverbrauch in Deutschland im Jahr (2014), 42 p; Berlin and Cologne.
- Bank watch (2015), Coal-fired plant in Poland, <http://bankwatch.org/our-work/projects/coal-fired-power-plants-poland>
- BGR (2014), Energy Study, Reserves, resources and availability of energy resources, Hannover www.bgr.bund.de/EN/Themen/Energie/Downloads/energiestudie_2014_en.pdf;jsessionid=34994D9251AE00977EBFF6FFF1240FC6.1_cid321?__blob=publicationFile&v=3
- BGR (2015), Energy Study, Reserves, resources and availability of energy resources, Hannover www.bgr.bund.de/DE/Themen/Energie/Downloads/Energiestudie_2015.pdf?__blob=publicationFile&v=2
- Bloomberg (2015), *Eskom Sees Power Supply from Mozambique up by up to 40%*, www.bloomberg.com/news/articles/2015-07-28/eskom-sees-power-supply-from-mozambique-increasing-by-up-to-40-
- Burton J, & Winkler H, (2014), South Africa's planned coal infrastructure expansion: Drivers, dynamics and impacts on greenhouse gas emissions, www.erc.uct.ac.za/Research/publications/14-Burton-Winkler-Coal_expansion.pdf
- Business Day live (2015), *Medupi finally produces first power*, www.bdlive.co.za/business/energy/2015/03/03/medupi-finally-produces-first-power
- California's Clean Energy Future (2011), Once Through Cooling Phase-Out
- Carbon Tracker (2014), The Great Coal Gap: China's energy policies and the financial implications for thermal coal,
- China coal Resource, <http://en.sxcoal.com/111509/NewsShow.html>
- Christian S, (2015), Eskom South Africa: A case of planning failure, www.slideshare.net/smakoso/simonchristian-eskom-south-africa
- CIAB (2014), The socio-economic impacts of advanced technology coal-fuelled power stations
- Climate News Network (2015), China's investment in renewables soars by a third, <http://climatenewsnetwork.net/chinas-investment-in-renewables-soars-by-a-third/>
- Coal India Limited (2015), www.coalindia.in/en-us/company/aboutus.aspx
- Coal Industry Advisory Board to the IEA (2015), The Socioeconomic Impacts of Advanced Technology Coal-Fuelled Power Stations, Paris
- Coal Unit Shutdowns (2015), American Coalition for Clean Coal Electricity (ACCCE), www.americaspower.org/sites/default/files/Coal-Unit-Retirements-JUNE-18-2015.pdf
- Council of the European Union (2010), COUNCIL DECISION of 10 December 2010 on State aid to facilitate the closure of uncompetitive coal mines (2010/787/EU). Official Journal of the European Union

- CSE India (2015), An epochal shift in the idea of India – Meeting Aspirations?, www.cseindia.org/userfiles/The%20Indian%20Power%20Sector.pdf
- Data from Central Electricity Authority, www.cea.nic.in
- Data from Coal Directory of India (2013-14), Ministry of Coal
- EIA (2014), Many newer plants have cooling systems that reuse water.
- Enerdata (2015), www.enerdata.net/enerdatauk/press-and-publication/energy-news-001/india-plans-invest-us105bn-thermal-power-plant-replacement_34118.html
- EURACOAL (2015), <http://euracoal.eu/info/country-profiles/poland/>
- Eurostat (2014), Energy, transport and environment indicators. Luxemburg.
- Financial Times (2015), British coal-fired power plant bows to the inevitable, www.ft.com/cms/s/0/f3d1b352-fef4-11e4-84b2-00144feabdc0.html#axzz3m0U1uZcl
- Financial Times (2015), Germany –decision means the coal industry lives on, [<http://blogs.ft.com/nick-butler/2015/07/06/germany-the-coal-industry-lives-on/>]
- German Coal Assosiation (GVSt e.V.) (2015), Steinkohle
- Heidrich C, Feuerborn H, & Weir A, (2013), Coal Combustion Products: a global perspective, www.mcilvaineconomy.com/Decision_Tree/subscriber/Tree/DescriptionTextLinks/International%20flyash%20perspective.pdf
- <http://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32010D0787&from=EN>
- IEA (2015), Medium Term Market Report
- IEA (2015), Medium-term Coal Market Report
- IEA (2015), Southeast Asia Energy Outlook Report
- IEA (2015), World Energy Outlook Electricity access database
- IEA (2015), Coal information 2015
- IEA Coal Information (2015), here coal comprises all primary coals like anthracite, coking coal, other bituminous coal, sub-bituminous coal and lignite
- Institute for Energy Research, <http://instituteforenergyresearch.org/analysis/as-u-s-shutters-coal-plants-china-and-japan-are-building-them/>
- Jiabin Fu (2010), Challenges to increased use of coal combustion products in China, www.diva-portal.org/smash/get/diva2:324274/FULLTEXT01.pdf
- Lorenz U, (2015), Current situation and forecasts for international steam coal
- Mercator Research Institute on Global Commons and Climate Change (2015), Renaissance of coal isn't stopping at China, www.mcc-berlin.net/en/media/press-information/press-release-detail/article/renaissance-of-coal-isnt-stopping-at-china.html
- Ministry of Economy (2015), Information about the functioning of hard coal mining industry and the evaluation of the realization of the activity strategy of the hard coal mining industry in Poland in the

- years 2007-2015, Warsaw,
www.mg.gov.pl/files/upload/8155/Informacja%20na%20RM%20za%202014%20r.pdf
- Mutem, A. (2013), MUI, Coal mines: A blessing or a curse? Socioeconomic and environmental intricacies. University of Nairobi
- Natural Defence Council (2011), Evaluating mercury control technologies for coal power plants
- New York Times (2015), *Coal in Poland lowering life spans*,
www.nytimes.com/2015/06/08/business/energy-environment/coal-in-poland-lowering-life-spans.html?_r=0
- Office of Chief Economist (2015), Coal in India, www.industry.gov.au/Office-of-the-Chief-Economist/Publications/Documents/Coal-in-India.pdf
- Planning Commission of India, Working Group Report on Coal 12th
- Polityka Energetyczna – Energy Policy Journal, 18, 4, 5-18 (in Polish),
www.minpan.krakow.pl/pliki/czasopisma/polityka%20energetyczna/PE20155/01-19-lorenz.pdf
- Reuters (2013), World Bank to limit financing coal-fired plants, www.reuters.com/article/2013/07/16/us-worldbank-climate-coal-idUSBRE96F19U20130716j
- Reuters (2015), Peak coal by 2020 could save China thousands of lives: study
- South China Morning Posts (2015), China aims to reduce coal reliance in next five-year plan,
www.scmp.com/business/commodities/article/1694984/china-aims-reduce-coal-reliance-next-five-year-plan
- Utility Dive (2015), www.utilitydive.com/news/pacificorp-embraces-efficiency-plans-to-reduce-coal-burn-in-irp/400790/
- VDKI (2015), Annual Report, Verein der Kohlenimporteure (VDKi) (2015), Jahresbericht 2015. - 140 p.; Hamburg. www.kohlenimporteure.de/aktuelles/jahresbericht-2015.html
- Wood Mackenzie (2015), South Africa's power supply crisis, www.woodmac.com/public/views/south-africa-power
- World Coal (2015), Cleaning up the coal-fired market, www.worldcoal.com/special-reports/13072015/Cleaning-up-the-coal-power-market-2551/
- World Coal Association (2015), www.worldcoal.org/coal/uses-of-coal/coal-combustion-products/
- World Coal Association, www.worldcoal.org/sustainable-societies/improving-access-energy
- World Nuclear Association (2015), Nuclear Power in South Africa
www.world-nuclear.org/info/Country-Profiles/Countries-O-S/South-Africa/
- www.ag-energiebilanzen.de/index.php?article_id=29&fileName=ageb_jahresbericht2014.pdf
- www.gov.uk/government/publications/exporting-to-china/exporting-to-china
- www.iea.org/media/workshops/2015/cop21/ieaday/1.3GRAY.pdf
- www.renewableenergy.org.vn/index.php?mact=News,cntnt01,detail,0&cntnt01articleid=3256&cntnt01origid=53&cntnt01returnid=53

www.theguardian.com/sustainable-business/china-conflict-coal-fired-plants-water#

www.usibelli.com/pdf/McDowell-Report-Statewide-Socioeconomic-Impacts-of-UCM-2015l.pdf

www.whitecase.com/publications/insight/power-dynamics-forces-shaping-future-coal-united-states

www.worldcoal.org/setting-benchmark-worlds-most-efficient-coal-fired-power-plants

www.rwe.com/web/cms/mediablob/en/208030/data/12068/3/rwe-power-ag/fuels/kw-neurath-boa-2-3/Neurath-F-and-G-set-new-benchmarks-Article-by-Dr.-Reinhold-Elsen-RWE-Power-and-Matthias-Fleischmann-Alstom-published-in-Modern-Power-Systems-June-2008.pdf

[www.worldcoal.org/sites/default/files/coal_liquid_fuels_report\(03_06_2009\).pdf](http://www.worldcoal.org/sites/default/files/coal_liquid_fuels_report(03_06_2009).pdf)

[www.worldcoal.org/sites/default/files/coal_resource_overview_of_coal_report\(03_06_2009\).pdf](http://www.worldcoal.org/sites/default/files/coal_resource_overview_of_coal_report(03_06_2009).pdf)

www.worldsteel.org/dms/internetDocumentList/bookshop/2015/World-Steel-in-Figures-2015/document/World%20Steel%20in%20Figures%202015.pdf p.7

www.worldsteel.org/dms/internetDocumentList/bookshop/2015/World-Steel-in-Figures-2015/document/World%20Steel%20in%20Figures%202015.pdf p.9

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**World Energy
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KEY FINDINGS

1. Oil remains the world's leading fuel, accounting for 32.9% of total global energy consumption.
2. Emerging economies now account for 58.1% of global energy consumption and global demand for liquid hydrocarbons will continue to grow.
3. The growth of population and the consumer class in Asia will support oil demand increase. The main increase in consumption will come from transportation sectors in developing countries.
4. Despite the temporary price drop, the fundamentals of the oil industry remain strong. Price fluctuations seen of late have been neither unexpected nor unprecedented.
5. Neither sudden geopolitical developments, nor OPEC decisions, nor any supply side discontinuity has driven the recent price collapse, as the market is already rebalancing.
6. The main driver of price changes has been the gradual building up OF OPEC spare capacity and the emergence of non-OPEC production, especially US Light Tight Oil (LTO).
7. Substitution of oil in the transport sector is not yet imminent and is not expected to reach more than 5% for the next five years.
8. New and increased use of technologies such as High-pressure, high-temperature (HPHT) drilling; multi-stage fracking; development in Flow Assurance for mature fields; greater sophistication in well simulation techniques, reservoirs modelling; 3-D seismic technologies, EOR developments and many more are having a positive impact on safety and E&P possibilities.

INTRODUCTION

Oil remains the world's leading fuel, accounting for 32.9% of total global energy consumption. Although emerging economies continue to dominate the growth in global energy consumption, growth in these countries (+1.6%) was well below its ten-year average of 3.8%. Emerging economies now account for 58.1% of global energy consumption. Chinese consumption growth slowed to just 1.5%, while India (+5.2%) recorded another robust increase in consumption. OECD consumption increased slightly (+0.1%), compared with an average annual decline of 0.3% over the past decade. In 2015, a rare increase in EU consumption (+1.6%), offset declines in the US (-0.9%) and Japan (-1.2%), where consumption fell to the lowest level since 1991¹.

It is an obvious statement that oil is one of the most important globally traded commodities in the world. This global nature and the central role that oil and oil products play in modern life globally underscore the role the political economy of the oil industry plays in international affairs.

Several structural changes are underway in the oil industry, the emergence of non-OPEC supply, the trends in energy efficiency, the diminishing role of high-sulphur oil with the environmental pressures in the marine fuel industry and in the power generation sector and indeed the emergence of unconventional oil (shale oil, heavy oil, tight oil and tar sands) and increased production both from mature and frontier fields.

It is worthwhile to capture the key global developments within and without the energy industry that might have a bearing on the forward looking views, time period up to 2020, expressed in this paper.

The last 12 months can be characterised as a period of a much expected, but sharper than previously envisaged fall in oil price with the prices of other fuels moving in tandem in many parts of the world. Countries including India and Indonesia, took advantage of the oil price decline to move ahead with their phase-out of fossil-fuel subsidies. Amid the turmoil in parts of the Middle East, a clear pathway opened up that could lead to the return of Iran, one of the world's largest hydrocarbon resource-holders, to oil markets. China's role in driving global trends is changing as it enters a much less energy-intensive phase in its development, having just ratified the Paris Accord, as we write this paper. Renewables contributed almost half of the world's new power generation capacity in 2014. The coverage of mandatory energy efficiency regulation worldwide expanded to more than a quarter of global consumption. There was also a tantalising hint in the 2014 data of a decoupling in the relationship between CO₂ emissions and economic activity, until now a very predictable link.

According to the latest available numbers in August 2016, in 2015, world oil production reached 4,461 Mt (94.2 mb/d), an increase of 3.0% from 2014 (130 Mt,2.5 mb/d), representing steady

¹ IEA (2016) Oil Briefing

growth in the OECD (+4.2%, 47 Mt, 1.1 mb/d) and OPEC (+3.7%, 64 Mt, 1.3 mb/d) and an average lower growth in other producing countries (+1.3%, 19 Mt, 0.4 mb/d). In 2014, OPEC production declined (-1.0%), while the OECD and the rest of the world showed substantial growths (+8.4% and +1.6%, respectively)².

This chapter seeks to highlight the substantial role that oil continues to play in the energy system and provides a perspective on how the oil industry is undergoing structural changes to establish its position in the low carbon world.

Total world production includes crude oil, NGLs, other hydrocarbons and 106 Mt (2.2 mb/d) of liquid biofuels in an industry system of around 100mb/d. (In reality the range has been between 90-105mb/d in the last few years and is expected to continue.)

As can be seen from the table below, from the IEA forecasts made in 2015 for the period up to 2020, this is the regional breakdown of global oil demand -we will cover demand-supply economics in detail later on in this chapter but it is important to introduce the 100mb/d metric to understand the underlying global forces at work on oil and the force that oil demand exerts on international geopolitics. The actual 2015 world production figure of 94.2 is higher than the figure 93.3 for 2015 in the table below, reflecting a stronger oil industry than was believed to be just a year ago – this in a period of intense climate change activism and around the time the international accord for climate change was achieved in Paris, in December 2015.

TABLE 1: GLOBAL OIL DEMAND, BY REGION FROM 2014-2018 (MB/D)

Region	2014	2015	Change from '14-'15 in %	2016	Change from '15-'16 in %	2017	Change from '16-'17 in %	2018	Change from '17-'18 in %
OECD Americas	24.1	24.2	0.004%	24.3	0.004%	24.4	0.004%	24.5	0.004%
OECD Asia Ocean.	8.1	8.0	- 0.012%	7.9	- 0.012%	7.9	0%	7.9	0%
OECD Europe	13.4	13.3	- 0.007%	13.3	0%	13.2	-0.07%	13.1	- 0.07%
FSU	4.8	4.6	- 0.041%	4.7	0.021%	4.7	0%	4.8	0.021%
Other Europe	0.7	0.7	0%	0.7	0%	0.7	0%	0.7	0%

² IEA, 2016

China	10.4	10.6	0.019%	10.9	0.028%	11.2	0.027%	11.5	0.026%
Other Asia	12.1	12.5	0.033%	12.9	0.216%	13.3	0.031%	13.7	0.03%
Latin America	6.8	6.9	0.014%	7.0	0.014%	7.1	0.014%	7.2	0.014%
Middle East	8.1	8.3	0.024%	8.5	0.024%	8.8	0.035%	9.0	0.022%
Africa	3.9	4.1	0.051%	4.2	0.024%	4.4	0.047%	4.5	0.22%
World	92.4	93.3	0.009%	94.5	0.012%	95.7	0.012%	96.9	0.012%

Source: IEA

Some key events of 2015 gives us an insight into the emerging pressures on the oil industry and how these pressures, which cannot change course as quickly as other parts of the energy sector due to its size and complexity, may impact on the rest of the energy system.

The last 12 months saw clear signs towards decarbonisation and growth of alternative technologies, assisted by: the drop in the oil price, the signing of the Climate Accord at COP21 in Paris, the growth in renewable energy capacity, the acceleration in energy efficiency trends and the decarbonisation of the power generation industry. These however, were offset by the emergence of India to centre stage and the market consuming countries reducing excess supply (which explains the difference in actual production figures vis-a-vis the forecasts) as well as the emergence of Iran on the supply side as it seeks accommodation in the changing oil supply landscape.

This price decrease also brought with it job lay-offs, cuts in capital expenditures, bankruptcy, mergers and farm-ins, among others, by oil and service companies. Countries that heavily rely on oil revenues like Venezuela, one of the world's largest producers and exporters of crude oil whose energy sales account for 95% of all government revenue, underwent a macroeconomic crisis. It was forced to bring down the production of conventional crude by more than 300,000 b/d to around 2.6 mb/d in 2015 and to cut down on imports. Consequently, Venezuela experienced adverse shortage of basic commodities, hyperinflation of more than 200%, fiscal deficit and depleted foreign reserves.

Russia, whose oil contributes to 70% of export income, was forced to cut down its 2016 budget spending in order to remain within its 3% acceptable deficit limit. Nigeria, which also relies on oil revenue to finance its budget, has also been grappling with a devalued naira, delays in infrastructural projects and job cuts. Saudi Arabia recently announced a budget cut for 2016, a

fall in basic commodities subsidy and decreased commitment to its foreign allies (Egypt, Lebanon and Palestine) as a result of a deficit equivalent to 15% of its GDP³.

Increased future uncertainties have led to revisions of price forecasts by several oil companies and research firms. The World Bank's price forecasts for 2016 for Brent and WTI crude stand at US\$40/bbl and US\$38/bbl respectively and US\$50/bbl and US\$47/bbl for Brent and WTI crude for 2017. Crude surplus is set to gradually decrease as a result of increased world demand reaching a deficit of 0.13 million barrels in the third quarter of 2017.

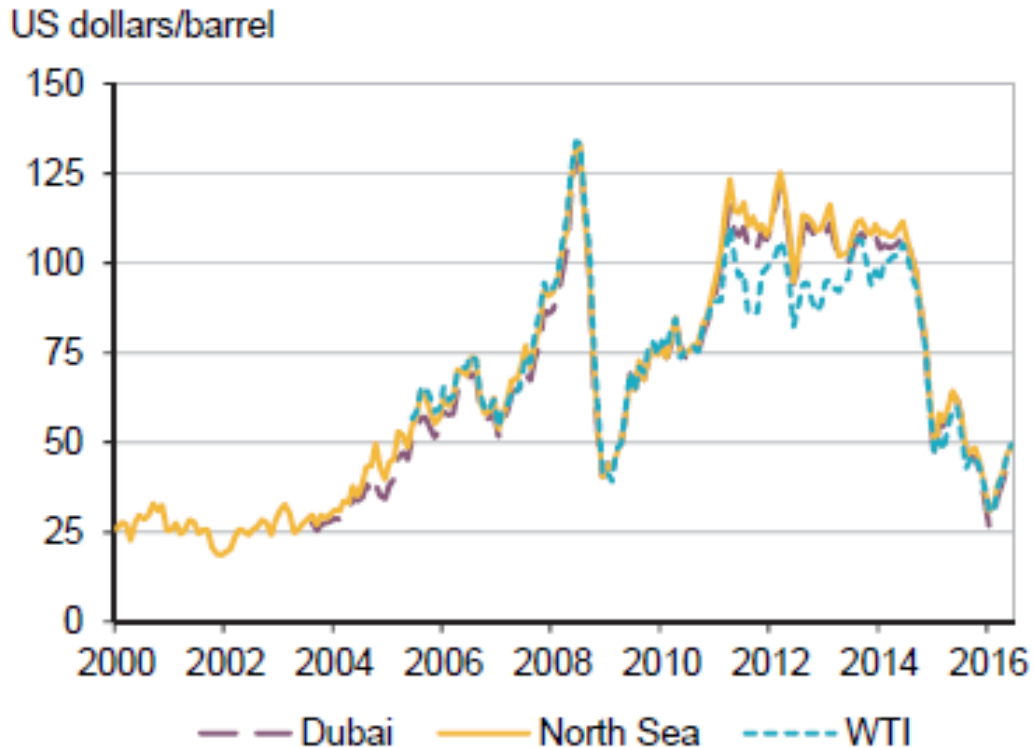
Developments in unconventional oil (shale, heavy oil, light tight oil/LTO and tar sands), deep offshore exploration and increased number of mature fields, coupled with the need to optimise on the operational efficiency in order to minimise costs, has necessitated the advancement in technology within the oil industry. Such technologies include greater use of digital technology in oil fields, nanotechnology, real-time drilling optimisation, integrated reservoir modelling, in-well fibre optics and diagnostics are trends to watch.

Pressure increased to act in response to climate change and the oil industry seized this game changing development. e.g. the heads of BG Group, BP, Eni, Pemex, Reliance Industries, Repsol, Saudi Aramco, Shell, Statoil, and Total (members of the Oil and Gas Climate Initiative – OGCI) pledged their support in achieving COP21 objectives a month before the Paris meeting. All IOCs appear to have started to factor in the risks relating to climate change in their annual statements and regulatory filings.

Despite the temporary price drop, the fundamentals of the oil industry remain strong, its response to clean energy investment growth in China, Africa, the US, Latin America and India, is seen to be robust and positive. Substitution of oil in the transport sector is not yet imminent and broader economic and demographic trends confirm that oil will continue to play a crucial role in the energy system⁴.

³ Guardian (2015)

⁴ IEA (2016)

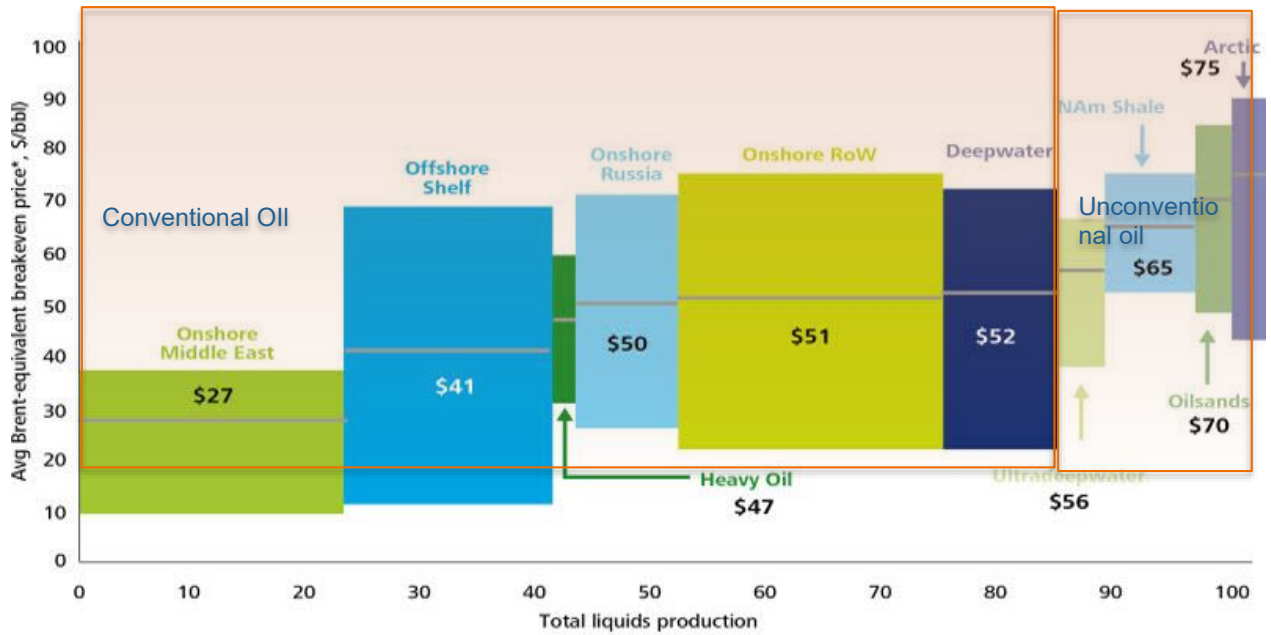
FIGURE 1: IS \$50-60 THE NEW NORMAL IN GLOBAL OIL FOR 2016-2020?

Source: IEA

DEFINITIONS AND CLASSIFICATIONS

Crude oil consists of hydrocarbons which have formed from sediments rich in organic matter (for example algae and plankton). 'Conventional' oil and gas reservoirs are created when hydrocarbons migrate from the source rock into permeable reservoirs, where they become trapped by an overlying layer of impermeable rock. Wells are then drilled into these 'traps' to drain the hydrocarbon (oil and gas) resource. Many of the hydrocarbons however, are not expelled and remain behind in the source rock. Oil and gas extracted directly from tight source rocks are generally termed 'unconventional'. Horizontal wells and hydraulic fracturing are required to develop these resources. There is no major chemical difference between unconventional and conventional oil and gas. There are, however, differences in the reservoirs where the hydrocarbons are found and the techniques required to extract them.

FIGURE 2: DIFFERENTIATION BETWEEN CONVENTIONAL AND UNCONVENTIONAL OIL⁵



Source: Bashir, Deloitte

An important inference that can be drawn from the figure above is the challenges of exploration for the heavier oils especially the Unconventionals and the Oil Sands resources in a US\$50/b oil price environment. These are open questions today and we believe that the next 24-36 months may see another likely price rally, possibly up to US\$75/b. A number of uncertainties still remain for such a rally to occur. These are addressed in the outlook section towards the end of this chapter.

⁵Bashir, n.d. Cruse awakening

OIL QUALITY: API GRAVITY AND SULPHUR CONTENT

The American Petroleum Institute and the National Bureau of Standards developed a scale of the density of petroleum products. The gravity scale is calibrated in terms of degrees API, which equals: $(141.5/\text{specific gravity at 60 degrees F}) - 131.5$

The higher the API gravity, the lighter the compound. If the API gravity is greater than 10, the oil is lighter and floats on water; if less than 10, it is heavier and sinks. Light crudes generally exceed 38 degrees API and heavy crudes are commonly below 22 degrees. Intermediate crudes fall between 22 and 38 degrees. Oils are extra-heavy below 10; the API gravity of bitumen approaches zero.

Sour crude oil defined as a crude oil containing larger amounts of the impurity Sulfur, an extremely corrosive element that is difficult to process, and deadly when released (hydrogen sulfide gas). When the total sulfur level is over 0.5% the oil is called sour; lower sulfur oils are sweet.

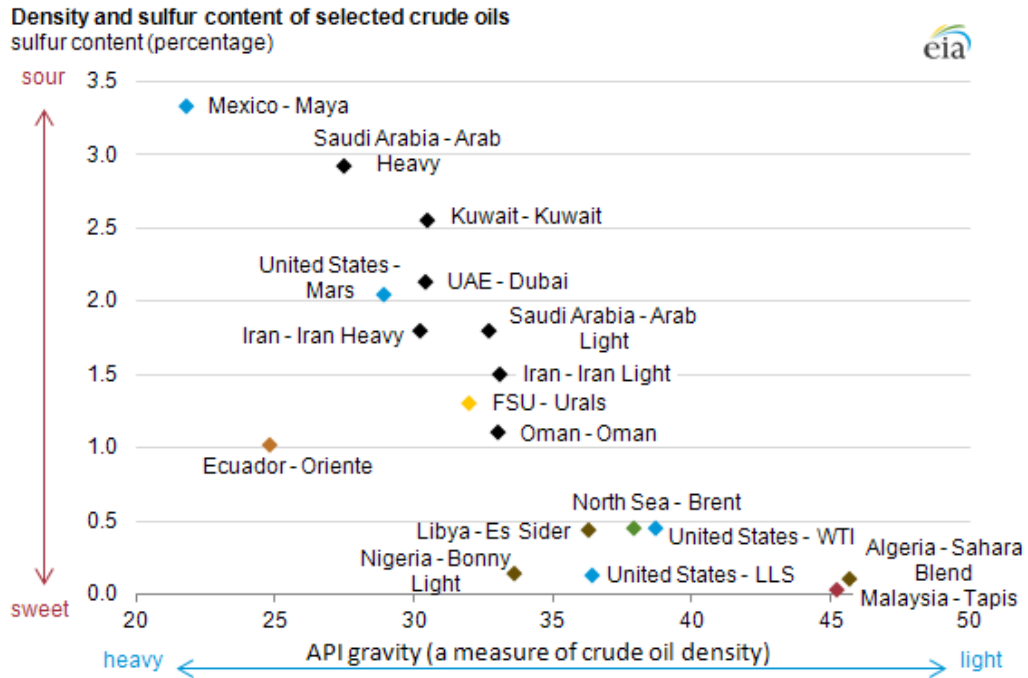
The crude barrel composition is changing and ranges from heavy/sour to light/sweet, by region:

Location	Low Quality Range	High Quality Range
Africa	Angola (Kuito) 19°, 0.68%	Nigeria (Agbami Light), 47°, 0.04%
Asia	China (Peng Lai) 22°, 0.29%	Indonesia (Senipah Condensate) 54°, 0.03%
Australia	Enfield 22°, 0.13%	Bayu Udan 56°, 0.07%
Europe	UK (Alba) 19°, 1.24%	Norway (Snohvit Condensate) 61°, 0.02%
Middle East	Saudi Arabia (SA heavy) 27°, 2.87%	Abu Dhabi (Murban) 39°, 0.8%
North America	Canada (Albian) 19°, 2.1%	US (Williams Sugarland Blend) 41°, 0.20%
Latin America	Venezuela (Bascan) 10°, 5.7%	Columbia (Cupiaga) 43°, 0.14%
Central Asia	Russia (Espo) 35°, 0.62%	Kumkol (Kazakhstan) 45°, 0.81%

Benchmark crudes: Brent 38°, 0.37%; WTI (West Texas Intermediate) 40°, 0.24%; Dubai 31°, 2.0%

Source: Gordon (2012)

FIGURE 3: DENSITY AND SULFUR CONTENT OF SELECTED CRUDE OILS
SULFUR CONTENT (PERCENTAGE)



Source: EIA (2012)

Crude oils that are light (higher degrees of API gravity, or lower density) and sweet (low sulphur content) are usually priced higher than heavy, sour crude oils. This is partly because gasoline and diesel fuel, which typically sell at a significant premium to residual fuel oil and other "bottom of the barrel" products, can usually be more easily and cheaply produced using light, sweet crude oil. The light sweet grades are desirable because they can be processed with far less sophisticated and energy-intensive processes/refineries. The figure shows select crude types from around the world with their corresponding sulphur content and density characteristics⁶.

What is important to infer from the chart above is that as newer resources from "heavier plays" are produced, the refining requirements and its costs are likely to change. This is a substantial technological challenge in the mid-stream and downstream refining industry. In a US\$50/b oil price environment these challenges will exacerbate.

⁶EIA (2012)

TABLE 2: PRODUCT CLASSIFICATIONS, PROPERTIES AND APPLICATIONS

Petroleum fraction / Physical state	Product	Number of C atoms	Boiling temp (C*)	Uses
Petroleum gas / Gas	Methane	1	-161,6	Heating, cooking, electricity
	Ethane	2	-88,6	Plastics, petrochemicals
	Propane	3	-42,1	LPG, transport, domestic use
	Butane	4	-11,7	
Light ends / Liquid	Naptha	5-11	70-200	Petrochemicals, solvents, gasoline
	Gasoline	7-10	100-150	Transport
Middle distillates / Liquid	Kerosene	11-18	200-300	Jet fuel, heating, cooking
	Gas oil	11-18	200-300	Diesel, heating
Heavy ends / Liquid	Lubricating oil	18-25	300-400	Motor oil, transmission oil, lubricants
	Residual fuel oil	20-27	350-450	Shipping fuel, electricity
Heavy ends / Solid	Greases & Wax	25-30	400-500	Lubricants
	Bitumen	35+	500+	Roads, roofing
	Coke	50+	600+	Steel production

BRIEF COMMENT ON OIL SHALE AND SHALE OIL

The terms **oil shale** (for the rock) and **shale oil** (for the retorted product) and also known as Light tight oil (LTO), have been well understood for more than one hundred years now. These two terms have been consistently applied to the fine-grained, organic-rich rock that only yields its petroleum product on heating either at the surface or at depth.

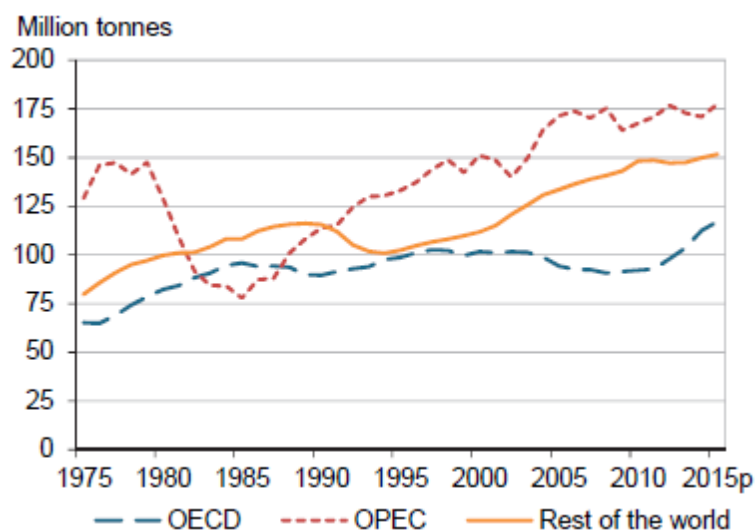
The most commonly used classification of oil shale divides it into three groups based on how it was formed: marine, lacustrine and terrestrial oil shale. Most known oil shales are deposited at the bottom of bodies of water and therefore, belong to the first two groups. In addition to the kukersite found in Estonia, tasmanite and marinite are also marine type oil shales. Oil shale can also be divided into three groups according to its composition: carbonate rich shale where minerals such as calcite and dolomite are dominant; marleous shale, which contains both carbonate and clay minerals; and clayey shales, which mainly consist of terrigenous clay materials. Estonian kukersite is one of the carbonate rich shales, whereas the Green River oil shale from the United States is marleous. The oil shale in deposits in Brazil, Fushun oil shale in China and Stuart oil shale in Australia are of clayey shale.

The history of using oil shale goes back to ancient times, when oil shale was used for various applications. The use of oil shale as a source of liquid fuels took off in the 20th century when processing plants were built in Europe, North and South America and also in Asia.

GLOBAL AND REGIONAL CURRENT RESOURCE POTENTIAL

The figure below shows the key trends in Crude Oil production over the last 40 years, as published in the latest IEA report on Oil Briefing. The key observations are that while the OPEC and the OECD countries demonstrate secular trends in production growth volumes, it has been the non-OPEC production in the rest of the world that has demonstrated the biggest rise, a near doubling of its production volumes. The recent trends observed in the growth of unconventional oil suggests that this trend will continue, possibly accelerate.

FIGURE 4: KEY TRENDS IN CRUDE OIL PRODUCTION OVER THE LAST 40 YEARS



Source: IEA, Oil Briefing

At a country level, the growth in 2015 can be mainly attributed to large increases in production in the United States (+7.8%, 45 Mt, 1,027 kb/d), Saudi Arabia (+5.8%, 31 Mt, 636 kb/d), Iraq (+13.8%, 21 Mt, 431 kb/d) and Brazil (+7.7%, 11 Mt, 227 kb/d).

The largest five top liquids producers increased their share of total world production (to almost 49%), and the United States remained the world's top producer (620 Mt). The second top producer was Saudi Arabia (572 Mt), followed by the Russian Federation (533 Mt), Canada (226 Mt) and the People's Republic of China (220 Mt).

In the OECD, production growth slowed down for the first time since 2011, but was still above growth rates seen between 1978 and 2011. Production grew by around 4% between 2014 and 2015, against 8% between 2013 and 2014. Still, the incremental OECD production in 2015 represented more than the entire production of the United Kingdom.

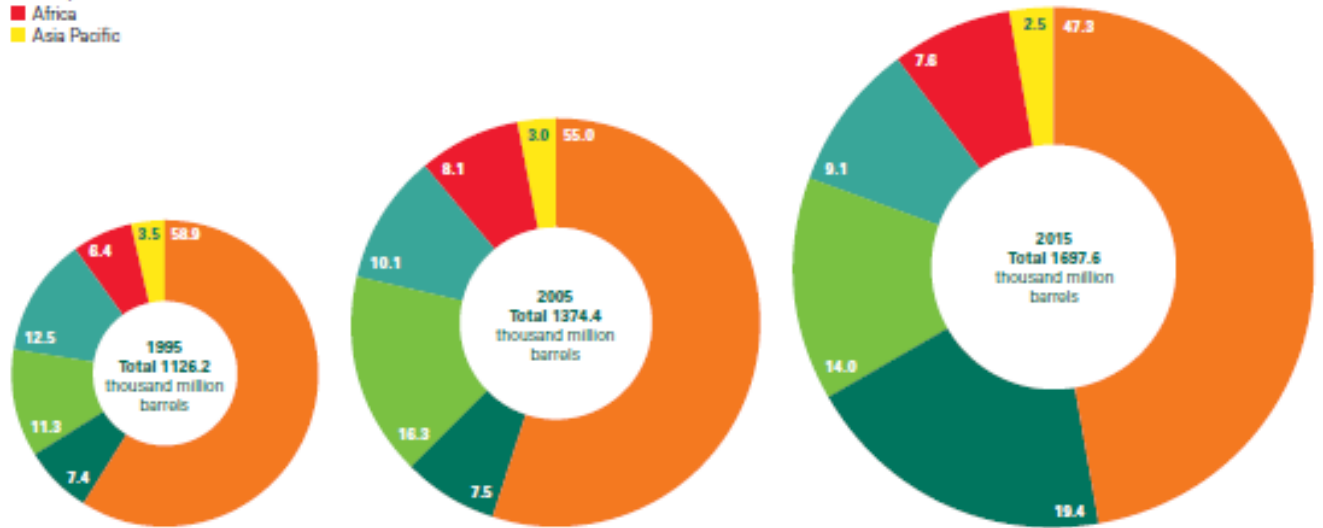
What really matters in understanding the future resource trends is however, not production but the reserves of petroleum, their regional distribution and importantly the reserves-to-production ratio (R/P ratio).

The two figures given below indicate how the distribution of proven reserves has evolved over the last 20 years.

FIGURE 5: DISTRIBUTION OF PROVED RESERVES IN 1995, 2005 AND 2015

Distribution of proved reserves in 1995, 2005 and 2015
Percentage

- Middle East
- S. & Cent. America
- North America
- Europe & Eurasia
- Africa
- Asia Pacific



Source: BP (2016) Energy Statistics June

The proven reserves have grown over the last 20 years from 1126.2 billion barrels to 1697.6 billion barrels with regional distribution largely being maintained consistently over time, with one important exception – South and Central America has captured a greater share of the proven reserves over time as the Middle East – the traditional source of crude oil supply for the best part of the last century lost share from 55% to 47% in the last 10 years. This is a significant and a developing trend which needs to be watched, especially given the rising tide of terrorism in the Middle East – though the re-emergence of Iran could potentially off set this, it remains to be seen how the situation in the Middle East evolves over time and how much of a space Iran can create for itself in an OPEC which too, is in a state of flux – again, largely attributable to the social upheaval in the region and the rising tide of terrorism.

What this trend does not however capture, is the nature of the reserves being proven, how remote they are and what it would take to bring it to the market. An additional aspect is the often ignored or poorly understood role of technology and its advances that make production from already operational/mature fields possible. Hence a trend depicting the R/P ratios is a better indicator for future production profiles.

In general terms, reserves refer to discovered quantities of hydrocarbons which are economically extractable at prevailing prices and current technologies. The term proved

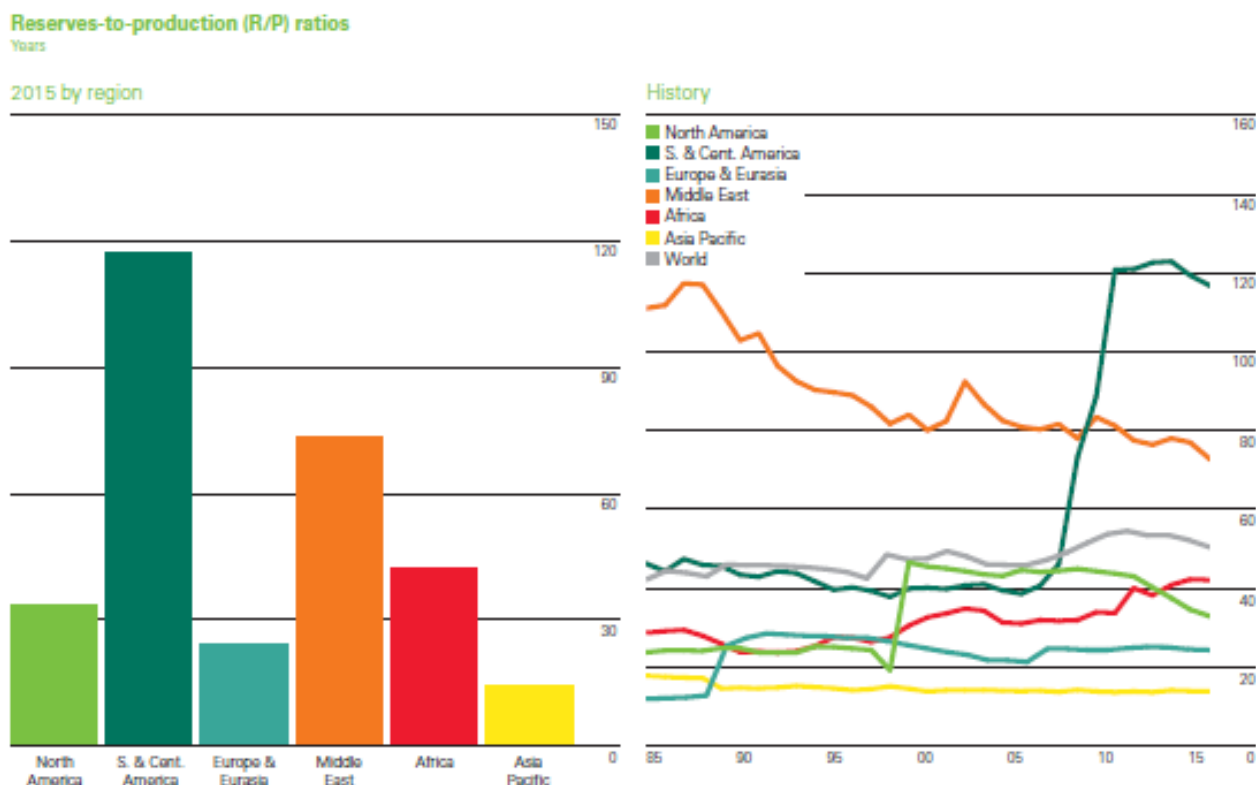
reserves is more specific and refers to that portion of reserves which can be estimated to be recoverable with a very high degree of confidence.

In addition, some companies in the US are being forced to make revisions as some reserves today do not meet the rather strict US Securities and Exchange Commission's (SEC)⁷ definition of 'proved developed reserves'. However, despite revisions owing to unfavorable economic conditions and to strict reporting procedures one should keep in mind that larger quantities of oil are still present in the subsurface.

The slide below shows the R/P ratios for crude oil across regions for 2015 and the graph on the right gives an indication of the R/P trend line over the last 20 years.

The dramatic rise in the R/P ratio of Central and South America and the gradual decline of the Middle East is evident, but what is less obvious in absolute terms is the steady rise and future potential that Africa demonstrates.

FIGURE 6: RESERVES-TO-PRODUCTION (R/P) RATIOS



Source: BP (2016) Energy Statistics June

From the Council’s perspective, the important questions are not only restricted to the growth prospects of the various regions, but given the global nature of oil as a liquid traded commodity, how will the regional energy balances evolve? How, if at all, will the trade flows evolve? What impact these may have on investment flows into the energy sector? There is of course the issue of the inter-fuel competition that is emerging globally to oil, especially as low emission/clean burning natural gas/LNG begins to replace oil and the resulting implications for energy security within the wider spectrum of security challenges the world we live in, now confronts. These are covered in the remainder of the chapters. This section would not be complete without a brief comment on unconventional oil resources and a commentary on the Oil Industry organisation.

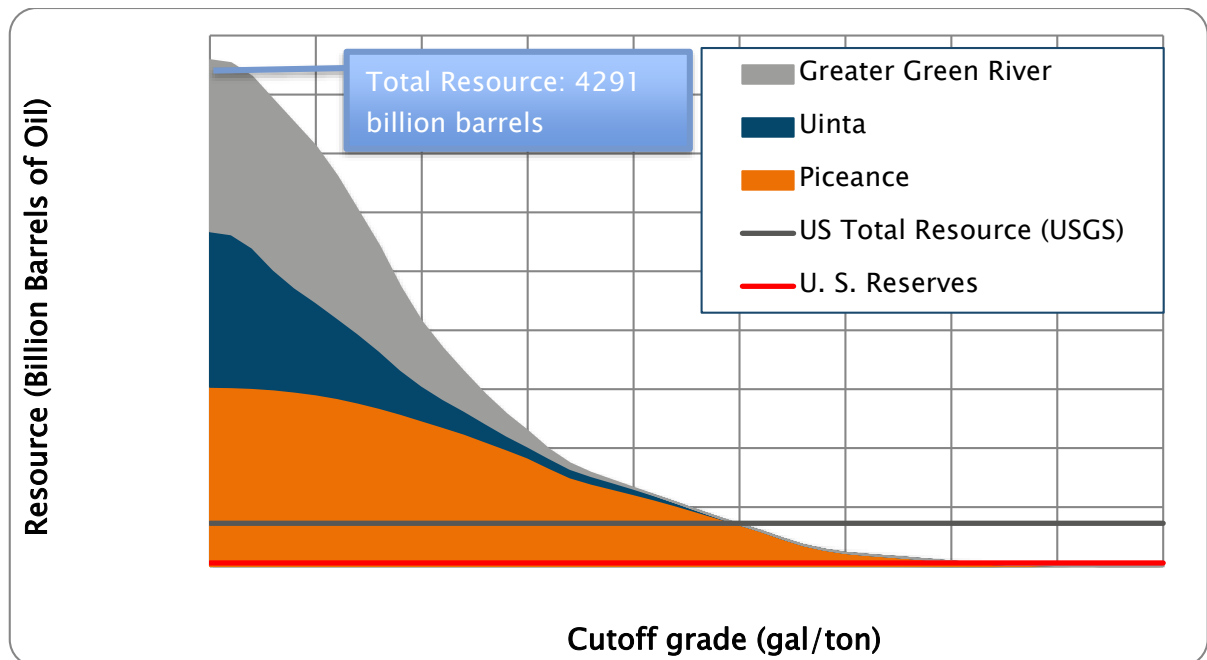
The world’s oil shale resources are estimated to contain around 6,050 billion barrels of shale oil, which makes them four times the size of the world’s conventional crude oil resources. There are over 600 known deposits in 33 countries on all continents.

The largest oil shale resources are located in the USA, and it is estimated that more than 80% of the world’s reserves are to be found in the USA. The richest area is the Green River deposit in the states of Utah, Colorado and Wyoming. There are currently several companies in the USA that plan to start using oil shale in the near future.

It has been noted that the estimates for oil shale resources are rather conservative, as several deposits have still not been adequately explored. Consequently, many countries are re-examining their resource potential. For example, China just discovered one billion bbl resource in Heilongjiang Province. The largest recent estimates put US oil shale resources at 6 trillion bbl, China is second at 330 billion bbl, Russia third at 270 billion bbl, Israel fourth at 250 billion bbl, and Jordan and DR Congo tied for fifth at 100 billion bbl. Estonia, which is on the way to become the largest producer of shale oil next year, is currently 11th with only 16 billion bbl.

The size of the oil shale resources is highly dependent on which grade cut-off is used.

FIGURE 7: OIL SHALE RESOURCES



Source: Birdwell et al. (2013)

ORGANISATION OF THE OIL INDUSTRY

The traded market for oil

Total world production of crude oil is around 95 million barrels per day. The crude oil feeds a network of refineries at key locations situated close to consuming centers or next to pipelines or shipping facilities. The crude oil is processed at the refineries and transformed into finished oil products.

Some companies are fully integrated, refining their own crude oil production and then feeding their retail networks with the oil products produced. For the most part, production and refining

are not fully integrated and refiners engage in trade to secure supplies for their facilities or to dispose of surpluses.

This oil is primarily secured via term contracts as refiners are typically wary to rely too heavily on spot supplies as these may be unreliable and exhibit high price volatility. End users (airlines, manufacturers, etc.) operate similarly. An airline, for instance, usually secures supplies at airports from term suppliers rather than entering the spot market to fuel its fleets. Hence, the bulk of the crude oil and oil products are sold through term contracts, where a volume is agreed with a specified tolerance over a defined period. The tolerance is built in to provide flexibility to either buyer or seller to load more or less than the contracted amount.

Estimates vary but typically, industry sources concur that 90-95% of all crude oil and oil products are sold under term contracts. The mechanisms for pricing crude and products vary by market sector and geographical region.

The balance of 5-10%, is sold on the spot market. A spot deal is usually defined as a one-off deal between willing counterparties for a physical commodity. Because the deals are on a one-off basis, the spot market is representative of the marginal barrel in terms of supply and demand. Typically, spot sales are surpluses or amounts that a producer has not committed to sell on a term basis or amounts that do not “fit” scheduled sales. Buyers may also have under- or overestimated their consumption and may have oil surpluses to sell or shortages to cover.

A variety of derivatives instruments are available that allow people to lock in or hedge a price for oil deliveries in the future. These include forwards, futures, options and swaps. These may typically overlap.

IOCs-versus-NOCs:

In the mid-1990s a new wave of globalisation hit the oil market, bringing considerable change. Three changes were key:

1. The emergence of the US as a global power following the collapse of the Soviet Union;
2. The end of the Gulf War; and
3. Emerging markets growth

Previously-controlled economies liberalised; nationally-operated oil companies privatised; and barriers to entry into new oil rich markets fell. The IOCs and independents benefited considerably because they could explore and produce in markets which had vast oil reserves, helping them build their resource base and replace legacy assets.

Rising global growth, especially in developing Asia, increased the demand for oil resources. Asia-Pacific consumption doubled, from just under 14 mb/d in 1990 to over 28 mb/d in 2011.

Middle East production rose over 40% from 1990 to 2011 to meet growing demand. The drop in production from the Middle East in the mid-1980s was largely a result of production cuts by Saudi Arabia. Eastern European and Eurasian production fell in the early 1990s, and subsequently recovered strongly, approaching the previous peak. Western European production meanwhile declined significantly.

Rising globalisation, and the consequent flow of goods, people and capital, enabled producing nations to operate independently, and compete with the IOCs as never before. Equipment and technology could be exchanged in the open market, allowing NOCs to develop their oil resources on their own, rather than rely on IOC assets. As a result, producing nations gained more economic and political power.

In need of new reserves, the IOCs consolidated to build resources to fund complex exploration projects. This gave rise to a new industry structure, the 'Super Majors' –Chevron, British Petroleum, ConocoPhillips, Royal Dutch Shell, Total and ExxonMobil.

According to Daniel Yergin, author of 'The Prize', the consolidations of the majors marked a significant reshaping of the structure of the oil industry: "What had unfolded between 1998 and 2002 was the largest and most significant remaking of the structure of the international oil industry since 1911. All the merged companies still had to go through the tumult and stress of integration, which could take years. They all came out not only bigger but also with greater efficiencies, more thoroughly globalised, and with the capacity to take on more projects – projects that were larger and more complex."

Today, NOCs dominate global oil and gas reserves. In 2005, it was estimated that NOCs controlled around 77% of the global oil and gas reserves. Independents controlled an additional 8% of global oil and gas reserves.

Four of the original Seven Sisters (ExxonMobil, Chevron, BP and Royal Dutch Shell) produce less than 10%-odd of the world's oil and gas, and hold just 3% of reserves. The world's largest NOCs, the so-called 'New Seven Sisters' include:

- Petrobras (Brazil)
- Petronas (Malaysia)
- Saudi Aramco (Saudi Arabia, largest oil company in the world)
- NIOC (Iran)
- Gazprom (Russia)
- CNPC (China) and
- PDVSA (Venezuela).

This new landscape contrasts starkly with the market in 1949, when the Seven Sisters controlled 88% of the entire global oil trade. The size and influence of the NOCs continues to grow through re-nationalisation, and aggressive exploration and acquisition efforts. In recent years, for example, oil assets have been re-nationalised in Russia (nationalisation of Yukos in 2003); Venezuela (ExxonMobil and ConocoPhillips were forced to leave Venezuela in June

2007, leaving billions of dollars' worth of investments behind); and Argentina (Argentina nationalised 51% of YPF, an oil and gas group, in April 2012).

NOCs are increasingly competing with IOCs in exploration for new reserves, and collaborating with other nationals to gain a competitive edge over the IOCs. Producing nations have, however, also asked IOCs and independents to enter into joint ventures to help them develop their reserves. Although preferring to operate independently, many NOCs realise that in order to grow and become more efficient, they need help from IOCs and Independents because these private sector firms have the requisite technologies and skills that NOCs often lack, or cannot fund. Requests for private sector assistance can be found in Latin America. In Brazil, for example, state-owned Petrobras took steps toward privatisation when it sold part of the company in a public share offering in 2010, raising US\$70 billion. Then newly-elected president of Mexico, Enrique Peña Nieto, had made strong statements in 2013 indicating his intention to improve Mexico's NOC Pemex by engaging in joint ventures with private companies.

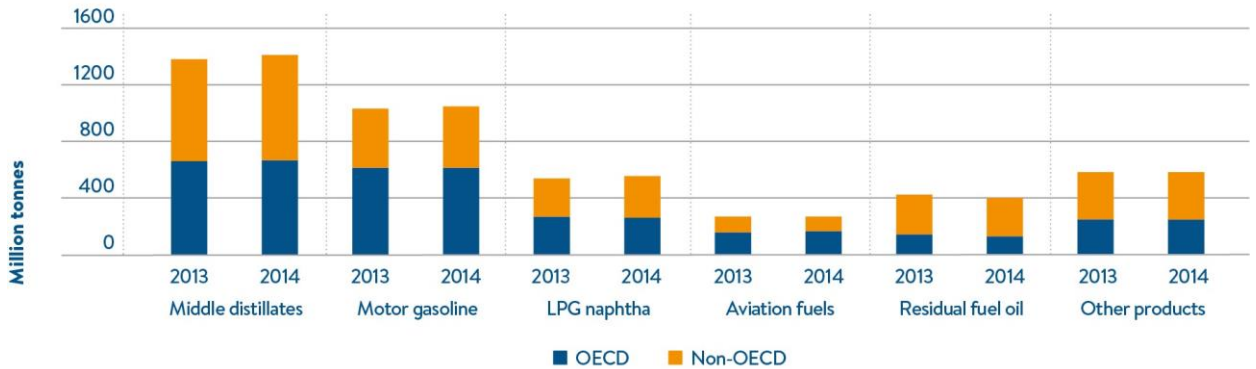
NOCs also often lack down-stream distribution networks. This makes it advantageous for them to work with the IOCs, independents and independent trading companies which possess down-stream assets and distribution networks. In Africa, for example, Angola's national oil company Sonangol has partnered with mid- and down-stream independent Puma Energy to assist it with the refining, and distribution of Angola's vast oil resources.

Exploration for new reserves has been a high priority for all players in the industry, and while high prices have encouraged this, the new oil price environment triggered by the recent collapse in oil prices may well see a new set of business models emerge, as well as the emerging role of trading giants as market makers for the NOCs.

Oil Consumption Trends

Within the oil consuming sectors globally, oil is the dominant fuel for transportation and this trend is expected to continue. Electrification of transport or the use of biofuels in transportation is not expected to make any significant impact in the use of oil for transportation until about 2035. At current estimates for example, EVs are expected to achieve penetration of no more than 5% in individual vehicle fleet segment.

FIGURE 8: PRODUCT-MARKET CONSUMPTION TRENDS



Source: IEA (2015) Medium Term Oil Report

Furthermore, a number of global market segments such as non-OECD aviation fuels, as seen from the figure above, are poised for growth where oil products do not have any viable competitive options and are expected to dominate.

Overall, the oil industry is facing tremendous upheaval whilst its dominant (33% share) of energy usage remains stable. The industry structure is undergoing immense change, consumer tastes, regulations and climate activism is posing challenges to its value proposition and forces of technology, globalisation, geopolitics and international trade and finance are all at work in a fundamental reshaping of this industry.

1. TECHNOLOGIES

KEY MESSAGES FOR TECHNOLOGIES

- Deep water E&P poses the most significant challenges to the Oil and Gas Industry.
- Development in Flow Assurance for mature fields and new field development is a rapidly transforming technology space.
- Greater sophistication in well simulation techniques, reservoirs modelling and 3-D seismic technologies is playing a key role in de-risking E&P activities, this space is changing rapidly.
- Enhanced Oil Recovery (EOR) developments on the back of developments in Carbon Capture and Storage (CCS) technologies portend a near/medium term attractive technology.
- Materials Engineering for High Pressure and High Temperature applications is expected to enable effective exploitation of deepwater opportunities.
- The US experiments in hydraulic fracturing and horizontal drilling have unlocked a huge unconventional potential. This will spread globally marking a huge step forward in the use of sustainable chemicals and water usage management practices.
- IT and Automation is bringing costs down across the oil and gas value chain

TECHNOLOGY OVERVIEW

As the demand for energy grows in the next few decades, the oil industry needs to exploit new ways of securing more resources. Unfortunately, these resources are progressively being found in hostile and complex environments. The access to relatively low cost oil is also largely limited to state owned companies. The challenge becomes harder in a setting where oil prices are worryingly low and the global push for low carbon emission systems is becoming significant. The convergence of a myriad of innovative technologies is however allowing the industry to overcome these challenges. They range from improved exploration data (the so called 'Big Data') to robotic technologies that allow workers to remotely control oil wells using their smartphones. In 2015, Saudi Aramco were granted a record 123 patents by the United States Patent and Trademark Office, marking significant progress in their strive to become a pioneer in technological innovations.

Drilling Technologies

A large proportion of the technology currently under development in the industry is focused on the drilling process. However, automation is emerging as the next big thing in the industry and has already been put into use in certain regions of the world.

According to a recent analysis by Frost & Sullivan, a number of countries in Southeast Asia together with Australia and New Zealand are leading the trend toward automation and software solutions. They estimated that the market for automation technologies in these geographical regions is expected to reach US\$447.8 million in 2018, up from US\$282.1 million in 2011.

This is mainly due to low-cost manufacturing facilities in developing markets that have enabled them to create a global supply chain network. Companies such as Saudi Aramco are leading the pack in the innovation of automated systems that solve real-world problems. They have recently developed an award winning robotic crawler capable of visual and ultrasonic inspection. It is an intelligent system that can detect steel thinning due to corrosion in pipes, tanks, vessels and other hard-to-reach steel structural assets

Automation is also being applied in other parts of the world such as the Norwegian North Sea where, in 2014, a Statoil platform received a US\$33-million upgrade to its automated systems (the Visund project) aimed at improving efficiency and safety. The new systems will boost oil recovery and extend the life of the field while also reducing operating costs and minimising safety and environmental risks.

At the beginning of 2015, Suncor Energy Inc. purchased 175 driver-less trucks from a Japanese autonomous vehicle manufacturer for its production activities in Canada's oil sands. The pace at which automation is being implemented in the industry is quickening, but for full-scale implementation to become a reality, there is need to first improve data acquisition and transmission. A host of companies are working on how to address this problem. Xact, which uses applied acoustics to deliver real-time downhole drilling and completion data, is one of the companies making big strides in this front. They are able to achieve this without the constraint of depth, fluid flow or formation type.

In terms of drilling innovations, the idea of using lasers to drill is close to becoming a reality. Researchers at Colorado School of Mines, led by Prof Ramona Graves, are actively working towards commercialising high-powered lasers for drilling purposes. Laser technology has significantly improved over the last three decades from 10 kW lasers to MW lasers, capable of drilling an oil well. The advantage of laser drilling is that it has potential to penetrate rocks many times faster than conventional drilling system; therefore, reducing operational cost of a rig.

Technological innovations are also improving operational safety and efficiency in the industry. DynaStage perforating system, developed by DynaEnergetics, utilises the latest generation of integrated, intrinsically safe switch detonator technology and an improved mechanical design which eliminates potential human error. The system reduces the number of electrical connections by approximately 40% and thus improves reliability and time required to set-up the device.

Technology Challenges of Deepwater E&P

Deepwater (and Ultra-Deepwater, 5,000 feet of water depth and beyond) is recognised as one of the last remaining areas of the world where oil and natural gas resources remain to be discovered and produced. The architecture of the systems employed to cost-effectively develop these resources in an environmentally safe manner, reflect some of industry's most advanced engineering accomplishments. There is a recognised need for research funds to catalyse further advances that can help attractive deepwater areas such as the Gulf of Mexico discoveries to progress to production quickly and safely, and that can help maximise oil and gas recovery from fields that are currently at the edge of industry capabilities.

Many of these technology efforts focus on subsea production systems, as well as research to help quantify the environmental risks of deepwater development. The three main areas of focus for Deepwater Technology are offshore architecture, safety and environmental, and a wide range of technologies that can only be classified as "other" deepwater technology.

Offshore Architecture

Offshore architecture encompasses the hardware, systems, and equipment used to drill for, produce, and transport oil and natural gas from offshore locations. This includes surface facilities, subsea equipment, and pipelines, as well as the tools and systems used to operate and maintain them. There is a need for National Energy Research institutions, such as the NETL in the US which is already quite active in this area, to fund research to improve the cost effectiveness of these systems, enhance their operational safety, and extend their capabilities to allow more resources to be developed with less of an environmental footprint.

Safety and Environmental

Ensuring that oil and natural gas production in deep water does not harm marine ecosystems is a top priority. The technologies in this space, therefore concentrate on research to quantify and develop new technologies that can reduce the environmental risks of ultra-deepwater oil and gas development. These efforts include research to improve the competency of casing cement jobs, more accurately predict hurricane intensity, more effectively assess corrosion in subsea equipment, and design improved subsea system monitors.

There is a greater emphasis, following some high profile recent accidents, to focus on low probability high impact events. These technologies play an important role in the "social license to operate" for the oil and gas industries.

Other Deepwater Technology

Maximising recovery from deepwater reservoirs requires that we fully understand the behavior of hydrocarbon mixtures as they move from extremely deep rock formations, through complicated subsea piping systems, to surface facilities. The extreme variations in temperature and pressure along this path can present unique challenges to equipment designers. The focus of these technologies is around methods to improve the industry's understanding of ultra-deepwater production processes to help ensure that these systems operate safely and effectively.

Flow Assurance and Understanding Subsurface Parameters

In its Autumn 2015 newsletter E&P News published by the National Energy Technology Laboratory (NETL) the publication notes: "The last three decades have seen significant advances across the oil and gas exploration, drilling and production sectors. From deep and ultra-deep water enabling technologies to advanced fracturing technologies and capabilities, these advances, many funded by NETL, have allowed the country to once again become a key producer of oil and gas. Perhaps nowhere, however, has as much progress been made as in our understanding of subsurface parameters. Advanced seismic, downward looking VSP, cross-well tomography and electromagnetic imaging have allowed the industry to look at formations and reservoirs in a way, and with a resolution, never before possible. This, in turn, has spawned a new research emphasis on understanding the basics of subsurface mechanics."

Investments are required in high technology areas to increase subsurface understanding, from fluid flow in permeable environments to fracture generation mechanics to chemical interactions in various formation types.

This understanding of subsurface includes sophisticated technologies such as 3D Seismics, Well Performance Simulation, sophisticated tools and software including data handling technologies that can enable a better understanding of the risks of exploration and production in these frontier high risk areas.

Enhanced Oil Recovery Technologies (incl. CO₂ EOR)

Crude oil development and production in oil reservoirs can include up to three distinct phases: primary, secondary, and tertiary (or enhanced) recovery. During primary recovery, the natural pressure of the reservoir or gravity drive oil into the wellbore, combined with artificial lift techniques (such as pumps) which bring the oil to the surface. But only about 10% of a reservoir's original oil in place is typically produced during primary recovery. Secondary recovery techniques extend a field's productive life generally by injecting water or gas to displace oil and drive it to a production wellbore, resulting in the recovery of 20 to 40% of the original oil in place.

However, with much of the easy-to-produce oil already recovered from maturing oil fields all over the world, producers have attempted several tertiary, or enhanced oil recovery (EOR), techniques that offer prospects for ultimately producing 30 to 60%, or more, of the reservoir's original oil in place. Three major categories of EOR have been found to be commercially successful to varying degrees:

- **Thermal recovery**, which involves the introduction of heat such as the injection of steam to lower the viscosity, or thin, the heavy viscous oil, and improve its ability to flow through the reservoir. Thermal techniques account for over 40% of US EOR production, primarily in California.
- **Gas injection**, which uses gases such as natural gas, nitrogen, or carbon dioxide (CO₂) that expand in a reservoir to push additional oil to a production wellbore, or other

gases that dissolve in the oil to lower its viscosity and improve its flow rate. Gas injection accounts for nearly 60% of EOR production in the United States.

- **Chemical injection**, which can involve the use of long-chained molecules called polymers to increase the effectiveness of water floods, or the use of detergent-like surfactants to help lower the surface tension that often prevents oil droplets from moving through a reservoir. Chemical techniques account for about 1% of US EOR production.

Each of these techniques has been hampered by its relatively high cost and, in some cases, by the unpredictability of its effectiveness.

In the U.S alone there are about 114 active commercial CO₂ injection projects that together inject over 2 billion cubic feet of CO₂ and produce over 280,000 BOPD⁸.

EOR through CO₂ Injection

The EOR technique that is attracting the newest market interest is CO₂-EOR. First tried in 1972 in Scurry County, Texas, CO₂ injection has been used successfully throughout the Permian Basin of West Texas and eastern New Mexico, and is now being pursued to a limited extent in Kansas, Mississippi, Wyoming, Oklahoma, Colorado, Utah, Montana, Alaska, and Pennsylvania.

Until recently, most of the CO₂ used for EOR has come from naturally-occurring reservoirs. But new technologies are being developed to produce CO₂ from industrial applications such as natural gas processing, fertiliser, ethanol, and hydrogen plants in locations where naturally occurring reservoirs are not available. One demonstration at the Dakota Gasification Company's plant in Beulah, North Dakota is producing CO₂ and delivering it by a 204-mile pipeline to the Weyburn oil field in Saskatchewan, Canada. Encana, the field's operator, is injecting the CO₂ to extend the field's productive life, hoping to add another 25 years and as much as 130 million barrels of oil that might otherwise have been abandoned.

Next Generation CO₂ Enhanced Oil Recovery

In the US, DOE's R&D program is moving into new areas, researching novel techniques that could significantly improve the economic performance and expand the applicability of CO₂ injection to a broader group of reservoirs; expanding the technique out of the Permian Basin of West Texas and Eastern New Mexico into basins much closer to the major sources of man-made CO₂. Next generation CO₂-EOR has the potential to produce over 60 billion barrels of oil, using new techniques including injection of much larger volumes of CO₂, innovative flood design to deliver CO₂ to un-swept areas of a reservoir, and improved mobility control of the injected CO₂.

⁸ Oil and Gas Journal (2010, April 19)

Collaboration is Key

In early 2015, Lloyds Register revealed results of its comprehensive survey of the role of technologies in oil and gas, called “The Technology Radar” survey. It takes the pulse of technical innovation in the sector and looks ahead to the future investment drivers. It revealed the investment drives to be:

- Safety improvements (45%)
- Improving operational efficiency (44%)
- Reducing costs (43%)
- Accessing new reserves (29%)
- Increasing asset lifespan (27%)

Lead participants in the survey include commentary from UK Onshore Operations Group, Woodside Energy, Enertech, Maersk Drilling, TouGas Oilfield Solutions, Horton Wison Deepwater, Royal Dutch Shell, GE Oil & Gas, and also Douglas-Westwood, National Energy Technology Laboratory (US), and the Institute for the Analysis of Global Security.

The Technology Radar survey, one of the largest polls on the issue of technology and innovation in the oil and gas industry, takes into account respondent’s opinions and their business strategies in the near term (before 2020); the medium term (the years before and after 2020); and the longer term (from 2025 and beyond), and is based on five research questions:

1. Which technologies are likely to have the biggest impact in the next decade?
2. How are technical developments addressing the challenges faced by the sector?
3. What are the drivers and barriers to innovation?
4. What patterns of innovation adoption can be identified?
5. Which types of organisations are leading the way?

The key findings of the survey include:

1. Innovation is drawing on a range of technologies, rather than any single breakthrough.
2. A variety of technologies looks set to have a high impact in the coming years relating to extending the life of existing assets – EOR.
3. Near-term impact - automation - remote and subsea operation is identified as firms seek to cope with challenging environments.

4. High-pressure, high-temperature (HPHT) drilling and multi-stage fracking are also expected to have a major impact, which are expected to be fully deployed from 2020.
5. 73% of those surveyed believe that the rate of innovation in the sector is increasing.
6. 68% intend to increase their R&D budgets in the next two years.
7. 58% agree that future breakthroughs involve 'bits and bytes', rather than physical hardware.
8. In the last 2 years, 46% of breakthroughs have been driven by IOCs and 31% by Exploration & Production Companies.
9. In the next 2 years, two-thirds surveyed expect NOCs to increase spend on R&D significantly, supporting their drive for greater international growth – and increasingly operating like IOCs.
10. Continued risk aversion in the sector, especially in the deployment of new technologies, is however, a major brake on innovation. Only one quarter of oil and gas companies consider themselves to be early adopters.
11. Given the link between innovation and competitive advantage, in the last 2 years, in-house research has been the most widespread approach to developing innovation (cited by 59%). Joint ventures with external partners are set to become more common.

Technology continues to be the central axis around which risk perceptions in the oil and gas industry will evolve. A better understanding of technology, combined with judicious deployment of scarce R&D and innovation research funds and collaboration within and without the oil industry will be central to safe, responsible and efficient production of resources.

The remainder of this chapter on technology is focused on Unconventional and in particular Oil Shales, an area of the unconventional space which we believe needs wider and better appreciation.

UNCONVENTIONAL OIL

Shale plays suffer from higher decline rates and deteriorating well quality as 'sweet spots', or high productivity areas are getting sparse. This implies the drilling of more and more wells in order to keep production constant. At some stage this is no longer achievable. Continued drilling requires significant amounts of capital which can only be supported by high levels of debt or higher prices. There are many different numbers cited for the break-even cost of light tight oil reflecting the fact that there is no single break-even price for any play⁹. The break-even cost varies from well to well and from company to company. There are oil wells in the Bakken that probably break even when the price of West Texas Intermediate (WTI) is US\$30/bbl. That is because the break-even price is largely a function of the cost to drill and complete the well and the amount of oil that can ultimately be recovered from a well. But the amount of oil produced from a well can vary a great deal over the course of just a few miles, so there is a wide range of break-even estimates even for a single shale oil play¹⁰. However, historically cost curves have shifted and break-even costs have fallen as companies have traversed the learning curve. In the early days of the shale boom, break even costs of US\$100/bbl were common. Oil prices remained at that level for a long enough period of time enabling operators to gain a lot of experience in optimising hydraulic fracturing in horizontal wells. As a result, the portion of the break-even costs that are a function of the well cost and the amount of oil ultimately recovered steadily declined.

Several shale oil extraction technologies have been developed within the past 100 years. Some are obsolete by now and only a handful are in commercial use. The shale oil can be extracted by surface and in situ retorting and depending upon the methods of mining and processing used. As much as one-third or more of this resource might be recoverable.

The amount of oil shale that can be economically recovered from a given deposit depends upon many factors, including mine depth, surface land uses and transport of the oil to the market. There are several technologies which make it possible to produce shale oil within the given economic boundaries and at current market conditions.

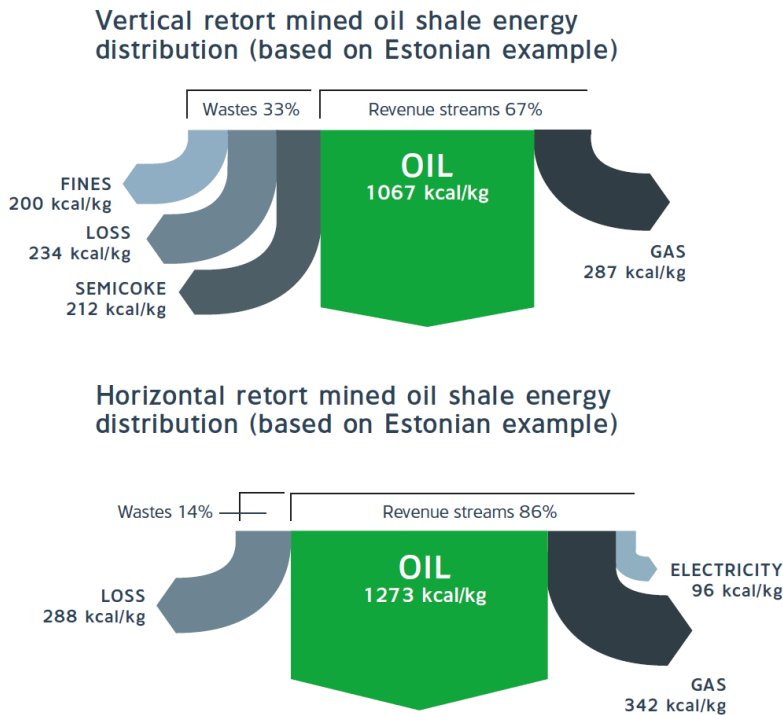
⁹ Rapier (2016)

¹⁰ Ibid

Above ground extraction

Above ground extraction is the oldest technique of getting the oil shale out of the ground and can be further divided into categories depending on the way heat is applied.

FIGURE 9: OVERVIEW OF VERTICAL AND HORIZONTAL RETORTING



Source: Academic Journals

Vertical retorts

Vertical retorts or gaseous heat carrier retorts are used in Estonia, Brazil and China. Vertical retorts use lump size oil shale.

The Fushun process

Fushun type retorts are operated in China and have unit capacity of 4 tonnes an hour. The first commercial scale plant was built in 1930. The process uses a vertical retort, with outside steel plating lined with inner fire bricks. Raw oil shale (10-75 mm particle size) is fed in at the top of the retort where it is dried and heated by ascending hot gases. The descending oil shale is heated to around 500°C. Oil shale is decomposed in the process into shale coke and oil vapors and gases. The shale coke is partially burned in the lower part of the retort to heat up gases necessary for pyrolysis. Retorts are operated in sets of 10 and have heat-carrier preparation units and rotating hydro seals designed for the whole set.

The Petrosix Process.

The largest production unit running on this process is PetroSix operated by Petrobras, and it has capacity of 260 tonnes an hour. The Brazilian energy company Petrobras started developing the Petrosix technology to extract oil from the Irati oil shales in the 1950s. The above-ground retorting technology uses externally heated hot gas for the oil shale pyrolysis. Mined shale is crushed to particles between 12 and 75 mm, and these are transported to a vertical shaft kiln where the shale is heated to about 500°C by hot gases. The kerogen decomposes to yield oil and gas. Spent shale is discharged from the bottom and oil vapors and gases are discharged through the top.

The Kiviter Process

The Kiviter retorts have been used in Estonia since the 1920s and are still operated by ViruKeemiaGrupp and KiviõliKeemiatööstus in Estonia. The vertical Kiviter retort heats coarse oil shale with recycled gases, steam and air. To supply heat, gases and spent residue are combusted within the retort. Drying of oil shale takes place in the upper section of the retort. Pyrolysis is completed in the middle section of the retort using hot gases from the gas and spent shale combustion in the bottom part of the retort. The spent shale is discharged from the bottom and sent for disposal.

Hot Solids Mixing

This method involves mixing preheated solids with fresh shale. The heat needed to heat up the solids is generated outside the retort vessel, because there is no combustion inside the retort. The resulting gas has a very high calorific value. Hot solids mixing technology are utilising the full oil shale resource. Fine grained oil shale is used in hot solids mixing technology.

The Alberta Taciuk Process (APT)

The ATP process was developed in the 1970s. It is based on rotary-kiln technology. The drying and pyrolysis of the oil shale and the combustion, recycling and cooling of the spent shale all occur in a single rotating multi-chamber horizontal retort. It uses fine particles as a feed source.

The Galoter Process

The first Galoter-type pilot retort and industrial retort were built in Estonia in 1953 and 1980, respectively. In this process, crushed oil shale (particle size less than 25 mm in diameter) is fed into a dryer. Dry oil shale is transported to a mixing chamber, where it is mixed with ash produced by combustion of spent shale in a separate furnace. The resulting hot ash and oil shale mixture decomposes at 500°C to oil vapors, retort gas spent shale. In Estonia, there are currently six plants in operation that are based on the Galoter Process – Enefit140, Enefit280, Petroter I, II and III, and TSK-500. New generation retort based on hot solids mixing principle was developed by Enefit in Estonia and is called Enefit280. This process produces in addition to shale oil and retort gas, electricity from waste heat. The Enefit280 plant has shown the lowest environmental impact compared to other industrial retorting

plants in commercial operation. The new technology has also improved quality of produced shale oil and retort gas.

EcoShale Process

EcoShale is an in-capsule process. This means that oil shale is mined and then buried again in a capsule to be heated up. Oil shale is surface-mined and the capsule is lined with an impermeable barrier. Once the oil shale is encapsulated, hot gas will be injected until the shale ore reaches approximately 370°C, at which point vapors rich in hydrocarbons are released from the rock. A liquids collection pan at the bottom and slotted vapor collection pipes at the top of each capsule, capture the oil products and feed them into a separation and processing facility. Construction of a first full size facility is expected to start in 2017.

In-situ retorting (underground extraction)

This process involves heating the oil shale underground to extract the oil and gases. The heating leads to the thermal decomposition of kerogen. The oil vapours and gases are then forced to flow to the production well. In-situ extraction methods differ in the different heating methods used.

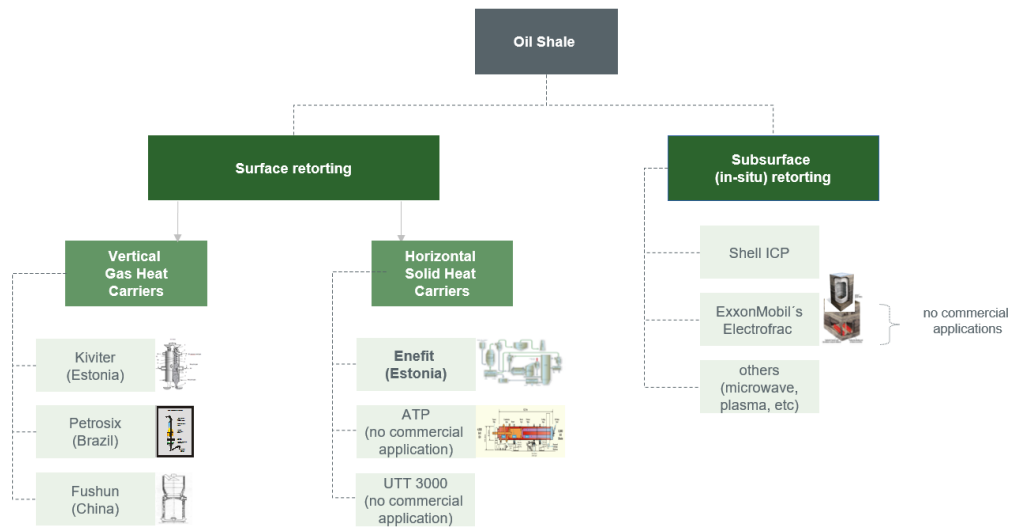
True in-situ are methods by which the oil and all the other components of oil shale are produced underground and pumped above ground.

All in-situ technologies are in a development stage. One of the most advanced projects is in Jordan, where JOSCO, a wholly owned Shell subsidiary, has drilled 340 wells on its 1,000 km² lease hold. JOSCO activated a small-scale in-situ pilot in September 2015. Oil was pumped to the surface after a few months, and heating will continue until summer 2016.

Although Shell has been a leader in this field, ExxonMobil, AMSO (a partnership of Total and Genie Oil), IEI (Israel Energy Initiatives, a Genie subsidiary) and others are also researching different technologies.

The drawback of in-situ heating is that takes longer (on the scale of years), requires more energy, and might need a manmade barrier (usually by freezing the ground) to prevent oil from flowing to unwanted places. The benefits are that as pyrolysis occurs at lower temperatures it leads to a lighter oil with a larger gas fraction. Therefore, the amount of secondary processing is lower compared to surface retorting.

FIGURE 10: OIL SHALE RETORTING PROCESSES

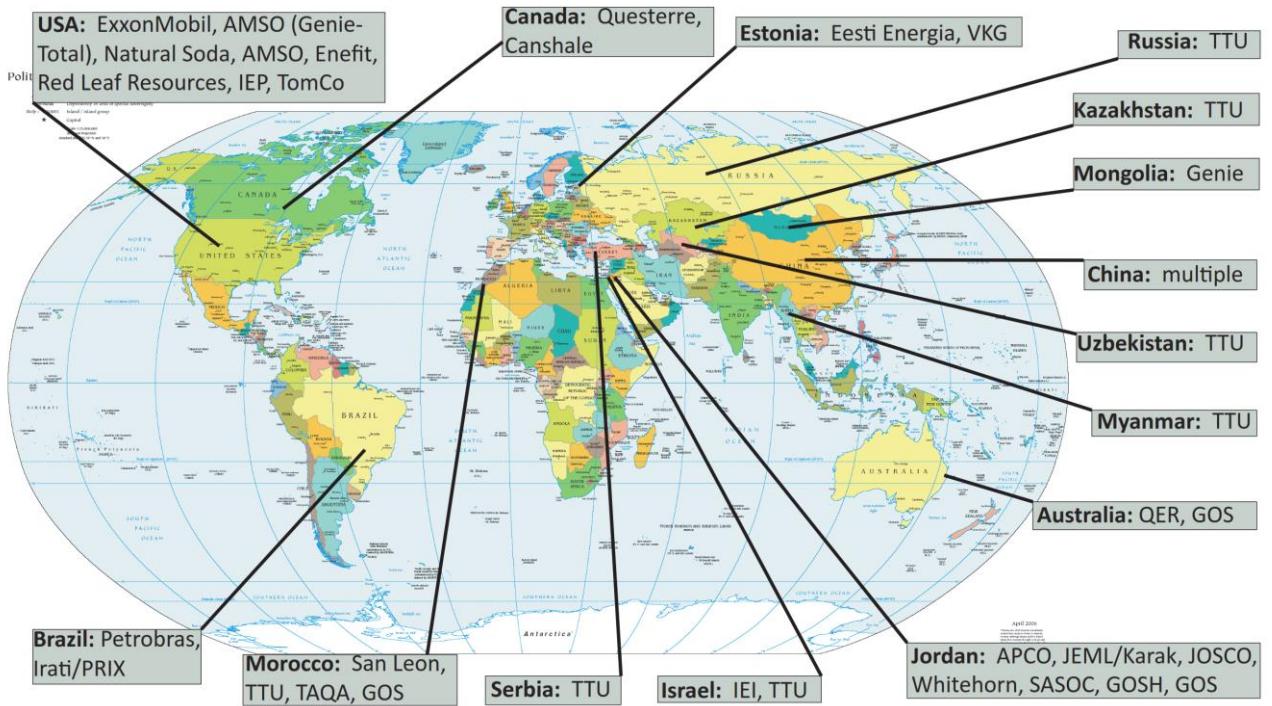


Source: Academic Journals

CURRENT AND PROJECTED SHALE OIL PRODUCTION

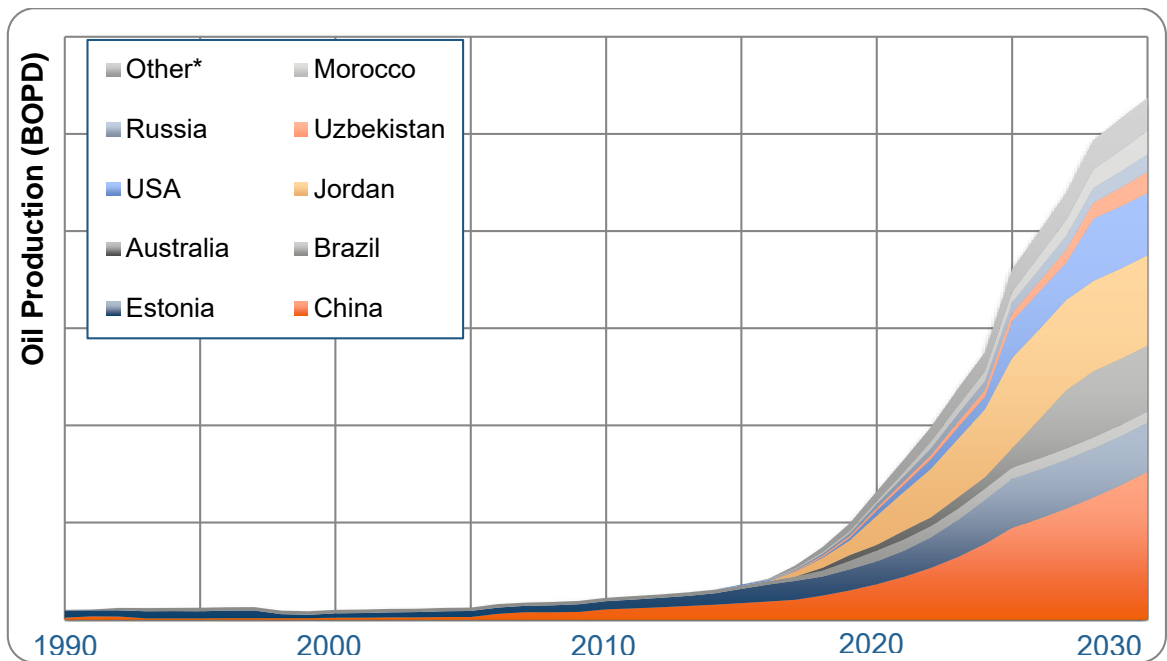
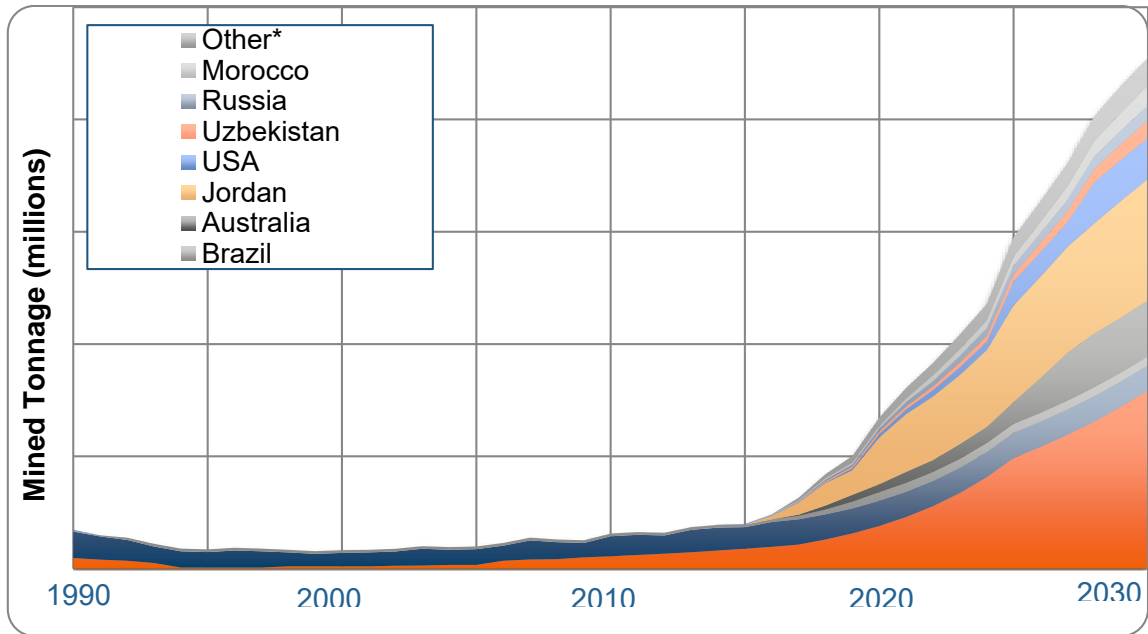
Total global production of shale oil for 2015 is estimated to be about 45,000 BOPD, all from China, Estonia, and Brazil. Chinese production is estimated to be about 17,000 BOPD, Estonia production about 25,000 BOPD, and Brazilian production about 4,000 BOPD. Current projections show that oil shale will not be a significant part of global production (>500,000 BOPD) for at least another decade. However, projects are in line over the next several years that could increase production significantly over current levels.

FIGURE 11: GLOBAL OIL SHALE PROJECTS



Source: Boak (2014)

FIGURE 12: CURRENT AND PROJECTED QUANTITIES OF MINED OIL SHALE AND SHALE OIL PRODUCED BY PYROLYSIS



Source: Boak (2014)

CASE STUDY FOR NANOTECHNOLOGY IN THE OIL INDUSTRY WITH A KEY FOCUS ON NANOCOATINGS

Nanotechnology is fast becoming a subject of immense interests in the oil industry. This is mainly attributed to the fact that the industry faces a range of materials-related challenges in their operations. As readily accessible reserves become depleted, exploration and production activities faces increasing technical challenges. Remaining reserves are found in deeper, more remote locations which expose drilling and production equipment to very hostile conditions. The result is a steady increase in development costs and a perpetual need to push materials and technology to their operating limits. Corrosion is another major materials-related challenge faced by the industry. According to NACE International, the total annual cost of corrosion in the oil and gas sector is estimated to be US\$1.372 billion. Surface pipeline and facility costs take the huge junk of this with US\$589 million in costs followed by downhole tubing with US\$463 million and another US\$320 million in capital expenditures related to corrosion. Nanotechnology and especially nanocoatings has the potential to provide strong and durable materials able to withstand these conditions.

Nanocoating is where a material is coated with a nanoscaled substance so as to achieve desirable performance of a system or process – in most cases to make them light and stronger. Depending on a particular property (mostly anti-corrosion, hardness, thermal insulation and anti-fouling) of the material that is intended to be improved, this technology can be achieved through various methods which includes nanocomposite coatings, superhard nanocrystalline coatings, transitional metal nitride coating, vapour deposition, electroplating and plasma thermal spraying. Nanotechnology is widely perceived as an expensive and exclusive venture. In truth, some of the methods, especially in nanocoating such as electro-deposition, are relatively cheap to implement and could substantially extend the performance envelope of oil field components.

Using TiO₂ nano-particle reinforced nickel nanocomposite coating as an example, the processes, effectiveness and cost involved in this new technology are demonstrated. Yilmaz et al. 2015 published a paper in the Journal of Materials Engineering and Performance detailing how the nickel composite coatings are obtained through direct and pulse current electrochemical co-deposition of TiO₂ nano-particles (mean diameter 21 nm). The base material, which in most cases is mild steel plates, are electroplated with nickel and reinforced with TiO₂ nanoparticles. The process must be ions-free at all the stages. Electro-deposition is then carried out using a 50°C standard Watts bath electrolyte containing suitable surfactants to lower the interfacial or surface tension. Potentiodynamic polarisation and electrochemical impedance spectroscopy methods are used to assess corrosion performance of the applied nanocoatings. Finally, characterisation of the surface morphology, composition, structure and cross-sectional profile of the nanocoated material is carried out on a scanning

electron microscopy (SEM).

Results of the experiment showed that pulse-plated TiO₂ particle-reinforced Ni composite electrodeposits exhibit excellent corrosion resistance and presented higher micro hardness. In general, the wear rate of the Ni-TiO₂ nanocoating has approximately 48% improvement when compared to the conventional Ni coating. The corrosion rate of Ni-TiO₂ reinforced nanocoating is also considerably smaller (by about 25%) than that of Ni coating. Moreover, the composite shows interesting photoelectrochemical and photocatalytic behaviour accompanied by improved mechanical properties. In terms of costs, the process utilises low cost solvents and surfactants which are readily available. It is also a fast process that can be easily scaled up to industrial levels.

2. ECONOMICS & MARKETS

KEY MESSAGE FOR ECONOMICS AND MARKETS

- Price correction seen of late has been neither unexpected nor unprecedented.
- Neither sudden geopolitical developments, nor OPEC decisions, nor any supply side discontinuity has driven the recent price collapse, as the market is already rebalancing.
- The main driver of price changes has been the gradual building up of OPEC spare capacity and the emergence of non-OPEC production, especially US Light Tight Oil (LTO).
- On the demand side, the reducing oil intensity of Chinese demand has been a contributing factor.
- The market has re-balanced very quickly to the new price levels, countries like India and Indonesia have absorbed the surplus.
- As the IEA points out, the production for 2015 has been greater than predicted and is a good indicator of market tightening by 2020.
- US LTO developments are the one to watch, as US LTO is likely to now emerge as the “stabilising force” in global oil price volatility.
- A slight pause up to 2020 in US LTO is possible but post-2020, US LTO may continue to grow.
- Terrorist activity in the Middle East perpetrated by Islamic State in Iraq and Levant (ISIL) has had little to no impact on production levels, particularly in Iraq. This is an important indicator.

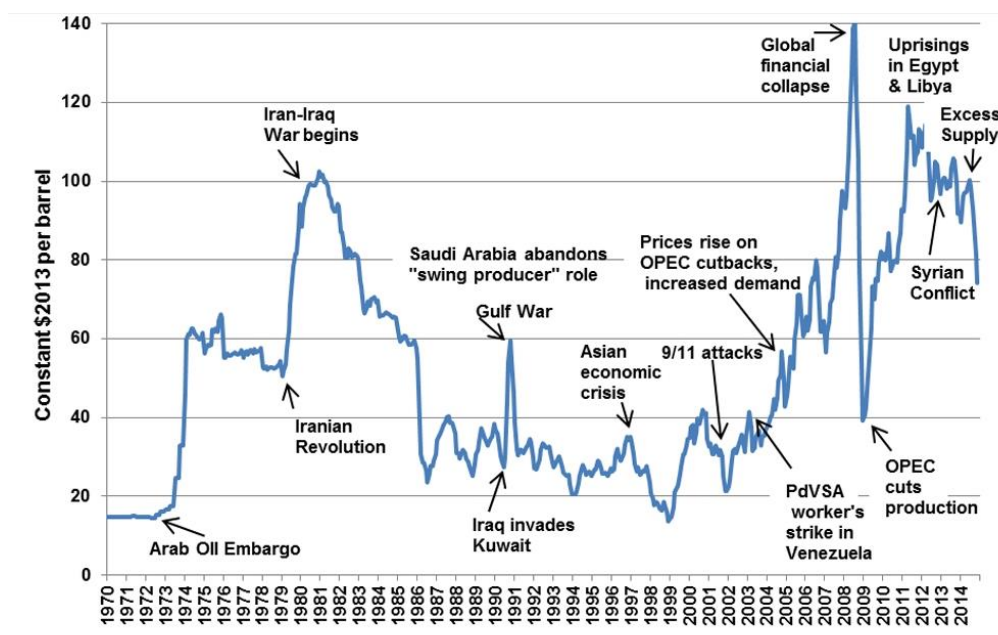
The IEA in its Medium Term Oil Market Report, begins by saying “As surprising as it might have seemed, the price collapse that has shaken the oil market since June 2014 was neither wholly unexpected nor unprecedented. Not unexpected, because earlier editions of this Report had pointed at a looming surge in implied OPEC spare capacity, an expression of the supply/ demand imbalance that would emerge if the producer group, faced with rising North American supply, held production.”

The report further explains “not unprecedented” as “more or less equally sharp corrections have rocked the market roughly every 10 years since the price shocks of the 1970s: in 1986, in 1998, and again in 2008. Looking at the medium-term consequences of this latest price plunge, the real question is not so much how price and supply growth expectations have

been reset; nor whether a rebalancing of the market will occur – for that is inevitable. The issue is how that necessary rebalancing, and the price recovery that will accompany it, might depart from those that followed similar price drops in the past, and where they will leave the market after they run their course.”

The evidence seems clear, and the consensus analyst view up to 2020 is a price band of US\$55-70/b. The 2016 price trends so far, shown in slide in the introduction chapter (Figure 13), too seem to support this view.

FIGURE 13: OIL PRICE SUSCEPTIBILITY TO GLOBAL EVENTS OVER TIME



Source: BP (2015) Energy Statistics

Oil is of crucial importance to the world economy, according to Aguilera and Radetzki¹¹ the value of oil production corresponded to 4.8% of the global GDP in 2013, and oil exports generated 12% of global trade. In the period of 1970-1972 oil exports were greater in value than the next nine biggest commodities taken together.

Other reasons for the importance of oil according to Aguilera and Radetzki include its indispensability, large fluctuations in the real price of oil and the uncertainty about the future developments of oil price. Price of oil rose almost tenfold between 1970s and 2013, while at

¹¹ Roberto F. Aguilera and Marian Radetzki (2016) *The Price of Oil*, Cambridge University Press, Cambridge, UK

the same time the price of iron ore rose just 133%, copper 67%, nickel 50%, and the price for aluminium even decreased 16%.¹²

MAJOR TRENDS IN THE OIL INDUSTRY GLOBALLY

In order to assess the ability of the oil industry to successfully continue to attract new capital, it is important to understand the key forces that are shaping the changing structure of the oil industry.

Competition in the oil industry today is as intense as ever. In response, the key players are operating quite distinct strategies. Very broadly, the IOCs are decentralising, and trading houses are looking increasingly like a new asset portfolio aggregator to mirror a nimble/capital efficient oil 'major'. The insight-foresight advantage that trading firms enjoy, the advantage of not having to deal with legacy asset portfolios and their ability to leverage technology (as we have discussed in the chapter on technology) today, suggest that capital efficiency and nimble portfolio management are two major determinants that will help attract new capital to the oil sector.

- The dominant NOCs are progressively building up their reserves, and developing their up-stream capabilities.
- Many independents operate all along the value chain and remain competitive by specialising, and by being nimble and flexible than the big multinationals.
- The IOCs are decentralising, and focusing on 'core up-stream activities'. Down-stream assets in saturated Western markets are being sold, and exploration and production activity funding is being increased.
- Trading houses are growing in size and scope, building their asset base globally, and becoming more vertically integrated by investing in upstream assets. To fund acquisitions, ownership structures are being transformed.
- Determinants of success for both IOCs and trading houses will depend, in particular, on access to finance, their ability to remain flexible, and their readiness to continue adapting to the changing market conditions.

Morgan Downey¹³ explains in "Oil 101" that there have been four periods of oil price control throughout the history of oil production:

- Standard Oil 1870-1911;
- Texas Railroad Commission 1931-1971;
- OPEC 1971-2005 and
- Free markets accompanied by a lot of speculation after 2005.

¹² Aguilera and Radetzki (2016) 11

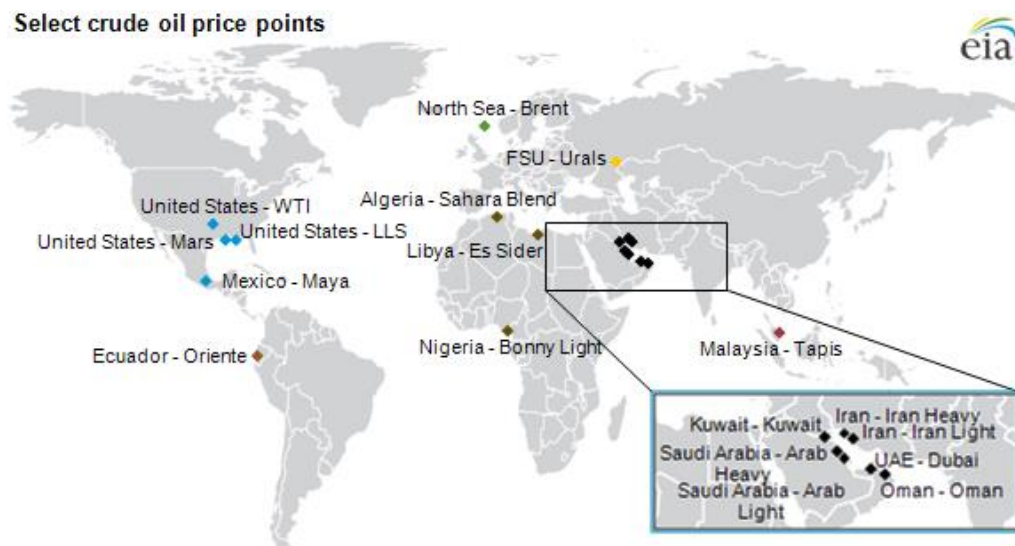
¹³ Morgan Downey (2009) Oil 101, Wooden Table Press LLC

In the first period the oil price was set by Standard Oil, a company that controlled almost 90% of the US oil market. This continued until standard oil was split into several different companies in 1911.

What followed was a period of relatively free markets until oversupply of oil brought prices so low, that it was thought best to limit the production of oil. The responsibility was given to Texas Railroad Commission and as a result US started to dictate the price of oil on a global level.

Downey continues to describe the actual pricing mechanisms used and he concludes that until 1973 the international crude oil price was determined by the posted prices set by oil majors; in the period between 1973-1984 the same mechanism of posted prices was used by OPEC - this mechanism is now unravelling rapidly as oil is freely traded, liquidity is high and several pricing points have emerged, as shown below.

FIGURE 14: SELECTED CRUDE OIL PRICE POINTS



Source: EIA (2012)

Figure 15 below illustrates the unpredictability of the oil price.

FIGURE 15: HISTORICAL BRENT CRUDE OIL PRICES AND IEA IMPORT PRICE ASSUMPTIONS

Figure ES.2 Historical Brent crude oil prices

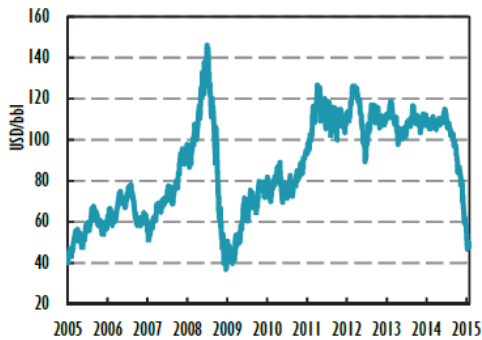
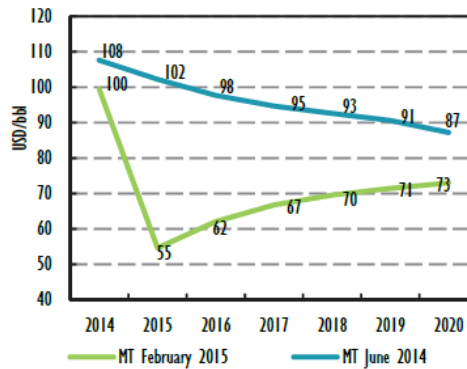


Figure ES.3 IEA import price assumptions



Source: IEA (2014)

As the figure on the left side suggests, the free market traded era starting 2005 has introduced new variables that drive price volatility. While a substantial amount of academic literature now exists that seeks to isolate and analyse the impact of each of these variables: demand /supply dynamics, liquid spot and futures trading, OPEC behaviour and geopolitics and others, it is not a diversion we want to take in this paper.

What illustrates the difficulties of price prediction acutely is the figure on the right which shows two medium term forecasts made by the IEA in June 2014 (when the oil price slide had just begun) and one made in February 2015 a few months apart from each other. The main driving home message is that the activity and market response in the oil industry is now at such high levels that even for institutions like the IEA which have a finger on the pulse of this industry, the probability of getting it absolutely right is quite low.

CURRENT TRENDS

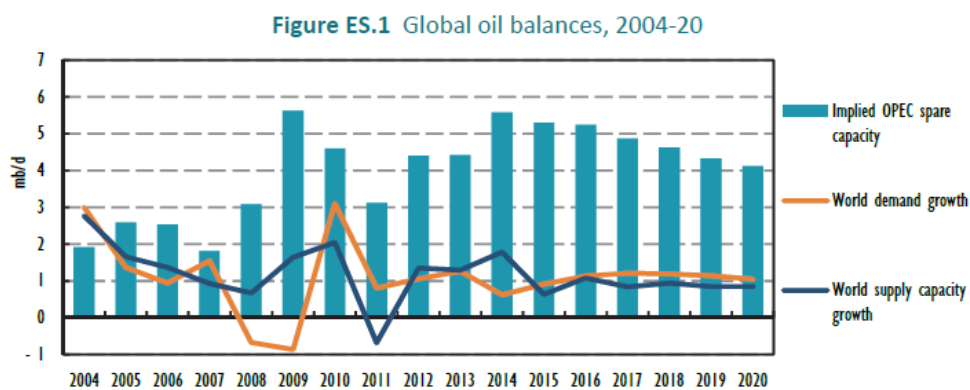
U.S Energy Information Administration estimates that global oil inventories increased by 1.8 mb/d in 2015 marking the second consecutive year of strong inventory builds. Global oil inventories are forecast to increase by an annual average of 1.0 mb/d in 2016 and by an additional 0.3 mb/d in 2017.

Similarly, the IEA in its latest 2016 report says “In 2015, world oil production reached 4,461 Mt (94.2 mb/d), an increase of 3.0% on 2014 (130 Mt, 2.5 mb/d), representing steady growth in the OECD (+4.2%, 47 Mt, 1.1 mb/d) and OPEC (+3.7%, 64 Mt, 1.3 mb/d) and an average lower growth in other producing countries (+1.3%, 19 Mt, 0.4 mb/d). In 2014, OPEC production declined (-1.0%), while the OECD and the rest of the world showed substantial

growths (+8.4% and +1.6%, respectively). Total world production includes crude oil, NGLs, other hydrocarbons and 106 Mt (2.2 mb/d) of liquid biofuels.

The BP Statistics released in June 2016 indicate similar findings. These three sources give us sufficient confidence to suggest that the recovery of the oil price is imminent as we write this paper. The rise, if at all, will be gradual as there is still sufficient spare capacity in the system as shown in Figure 16 below.

FIGURE 16: GLOBAL OIL BALANCES, 2004-2020



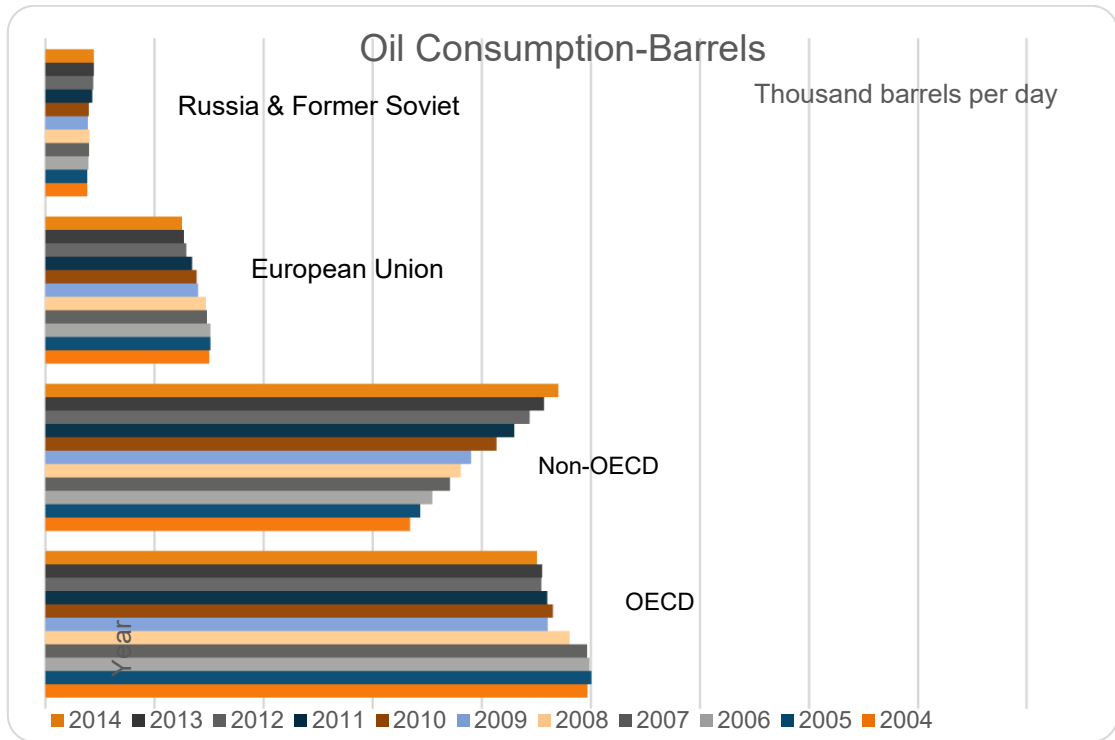
Source: BP (2016)

Global Petroleum and Other Liquids Consumption

U.S Energy Information Administration estimates that global consumption of petroleum and other liquid fuels grew by 1.4 mb/d in 2015, averaging 93.8 mb/d. Global consumption of petroleum and other liquid fuels continue to grow by 1.2 mb/d in 2016 and by 1.5 mb/d in 2017.

The graph below shows 10-year consumption trend by region.

FIGURE 17: 10-YEAR OIL CONSUMPTION TREND



Source: BP

The OECD countries are the leaders in oil consumption though the trend has been declining in gradually from 2004.

Some analysts predict further decline of oil products in US transport sector, mainly due to very cheap natural gas. It is predicted that more and more people will install home refuelling kits to their houses and convert their petrol cars to run on natural gas, so that they could use the existing natural gas infrastructure to fuel their cars. The incentive for doing this is the price difference between oil and natural gas, especially in the US.¹⁴

Global Oil Production

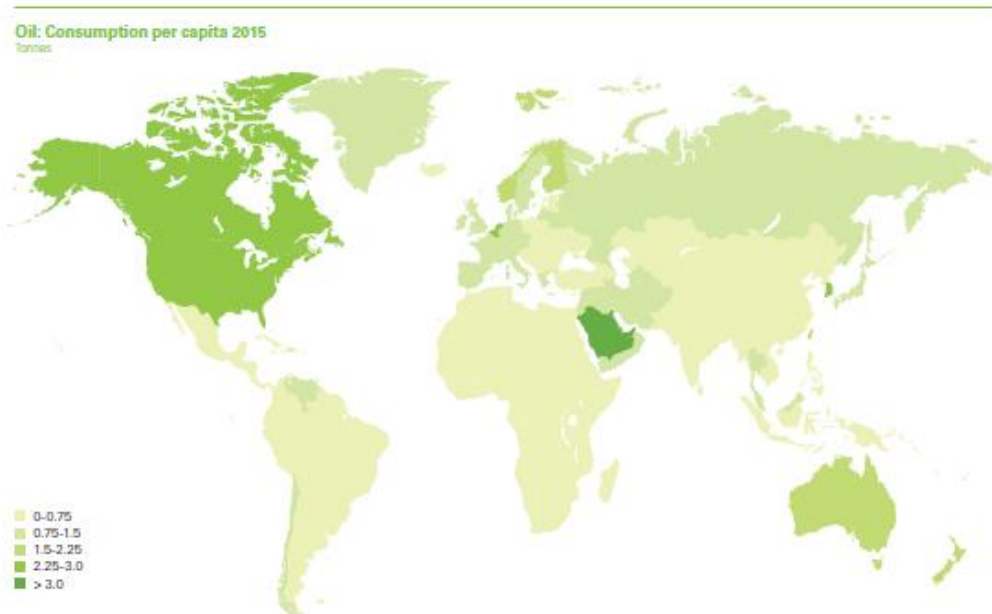
EIA estimates that petroleum and other liquid fuels production in countries outside of the Organisation of the Petroleum Exporting Countries (OPEC) grew by 1.4 mb/d in 2015. The 2015 growth occurred mainly in North America.

¹⁴Riley (2012)

EIA expects non-OPEC production to decline by 0.6 mb/d in 2016, which would be the first decline since 2008. Most of the forecast production decline in 2016 is expected to be in the United States. Non-OPEC production is also forecasted to decline by about 0.2 mb/d in 2017. This data is also confirmed by Wood Mackenzie, whose analysts predict that in 2016 and in 2017 oil production grows only in OPEC (mainly Iran and Iraq) countries and declines elsewhere. Wood Mackenzie sees non-OPEC output declining 1.5 mb/d in 2016. These sources indicate the uncertainty in the markets, but we believe that this uncertainty will remain until the market absorbs the spare capacity until 2020. We therefore conclude our assessment with a caution that non-OPEC, especially US LTO production, will see a short pause in 2016 and 2017 but as early evidence of the first half of 2016 shows, the market is adjusting faster than estimated. We therefore view that non-OPEC production especially US LTO production to be a key trend to watch up to 2020.

The assessment for beyond 2020 is clearly in favour of growth as seen from the figure below; per capital consumption of oil in the non-OPEC and particularly the fast growing Asia Pacific market is still quite low.

FIGURE 18: OIL: CONSUMPTION PER CAPITA 2015



Source: BP (2015) Energy Outlook Report

The graph below shows 10-year production trend by region.

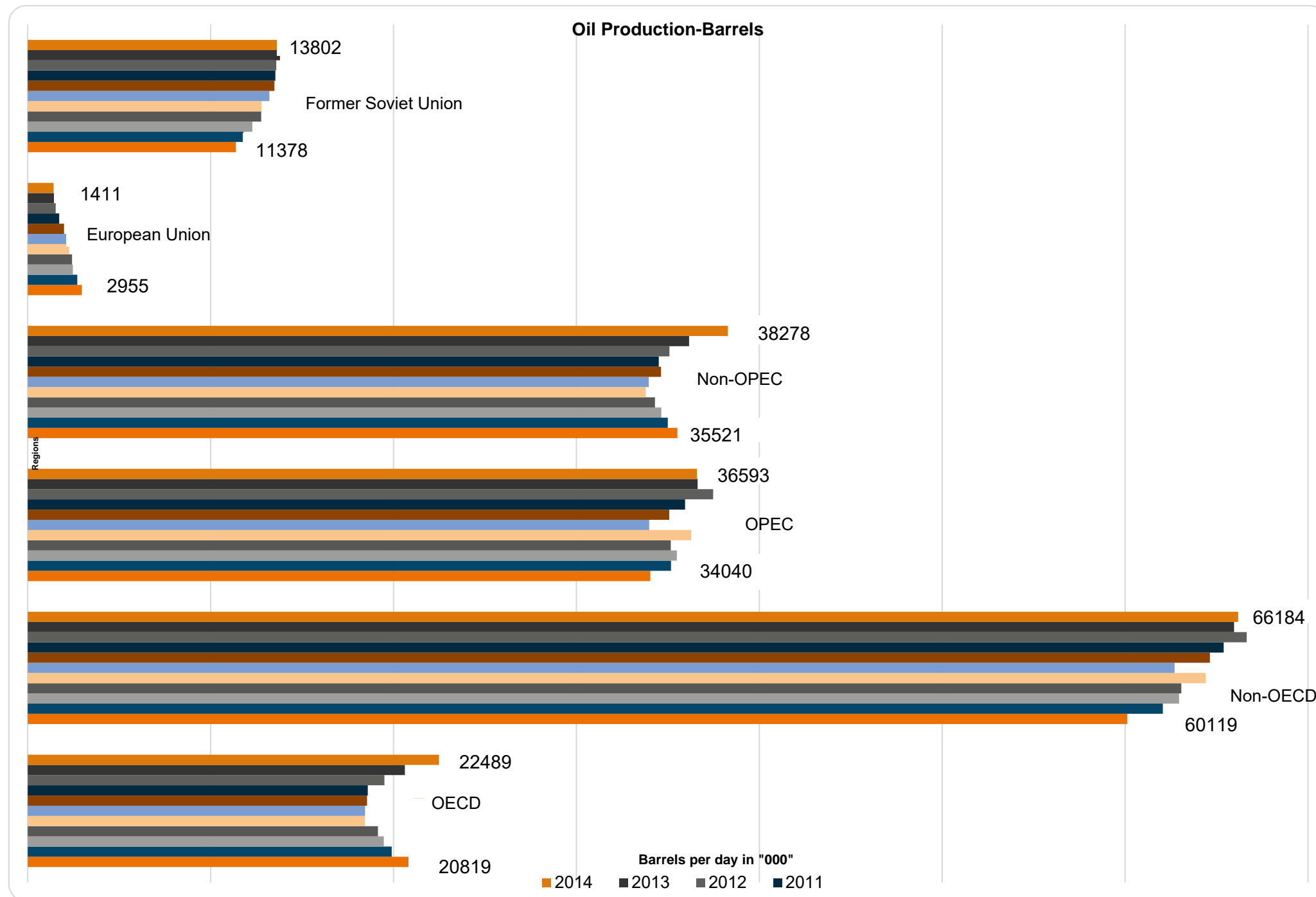


FIGURE 19: 10-YEAR OIL PRODUCTION TREND BY REGION

Source: BP

Crude Oil Prices

The price of oil has been a crucial factor of global economic growth. Oxford Economics has calculated that a US\$20 fall¹⁵ in oil price results in a 0.4% global growth over the next 2-3 years. The same has been estimated by the IMF and has been seen in the past.

According to US Energy Information Administration¹⁶, Brent crude oil spot prices decreased by US\$7/b in January to a monthly average of US\$31/b, the lowest monthly average price since December 2003. Ongoing growth in global oil inventories and uncertainty over future global demand growth continued to put downward pressure on oil prices during January. After growing by an estimated 1.8 mb/d in 2015, global oil inventories are forecast to grow by 1.4 mb/d in the first quarter of 2016.

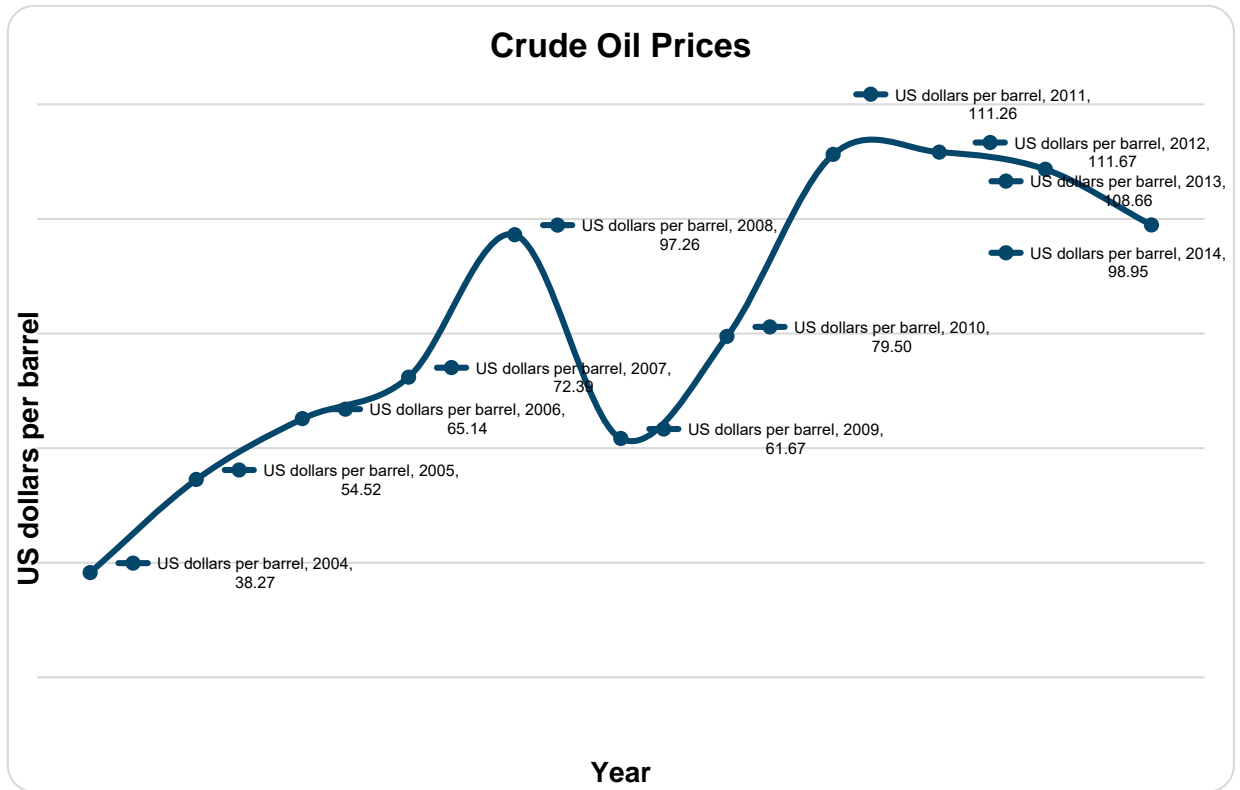
There are of course a wide range of price predictions that continue to be made; e.g. the prediction from Wood Mackenzie is that in the next 5-10 years Brent will reach 80-90 US\$/bbl, as there is not enough 50 US\$/bbl oil in the world to balance the market.¹⁷

¹⁵Giles (2014)

¹⁶ Short-Term Energy Outlook (April 2016)

¹⁷Wood Mackenzie

FIGURE 20: DEVELOPMENT OF CRUDE OILS PRICE FROM 2004 TO 2014



Source: BP

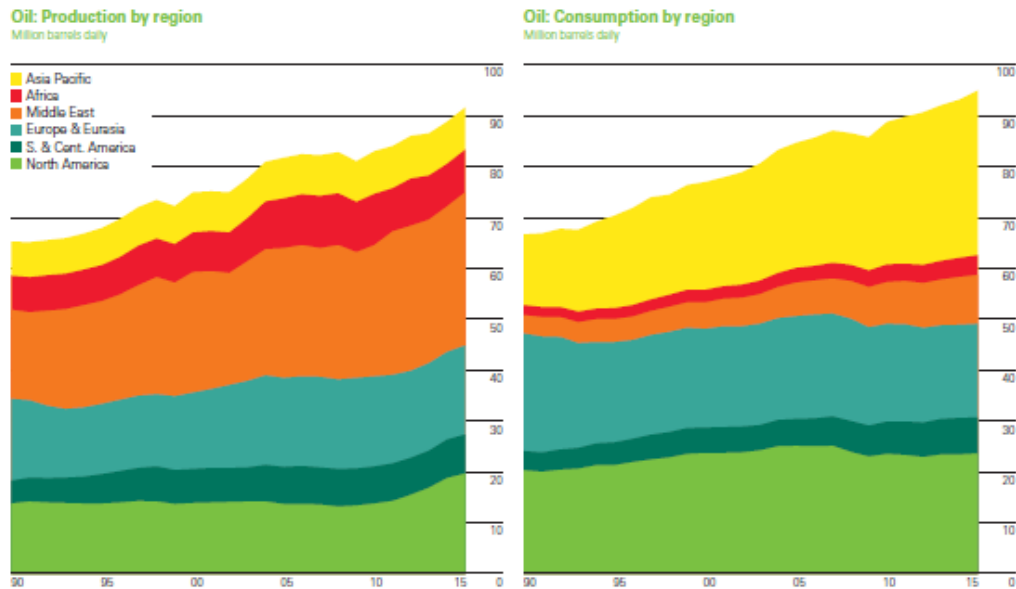
There has been an increase in oil prices until in 2009 when a sharp drop was experienced due to tension in the Gaza strip. The increasing trend continued until late 2015 when the prices started to decline.

A number of experts have said that current low prices are due to Saudi Arabia, others see this rather as a result of increased production in the US. It has been noted that the price collapse began already in September 2014, although the Saudis were producing the same amount of oil per day in 2014 as they were in 2013. During the same period the US production increased by one million barrels per day.¹⁸

¹⁸Gause (2015)

GLOBAL, REGIONAL AND DOMESTIC MARKETS

FIGURE 21: OIL PRODUCTION AND CONSUMPTION, BY REGION



World oil production growth in 2015 significantly exceeded the growth in oil consumption for a second consecutive year. Production grew by 2.8 million b/d, led by increases in the Middle East (+1.5 million b/d) and North America (+0.9 million b/d). Global oil consumption increased by 1.9 million b/d, nearly double the 10-year average, with above-average growth driven by OECD countries. The Asia Pacific region accounted for 74% of global growth, with China once again contributing the largest national increment to global oil consumption growth (+770,000 b/d).

Source: BP (2016) Energy Statistics

Risk Factors and Price Drivers:

Other things that will pull back the crude oil demand growth rate in the long term are the following:

1. Decline in population growth rates in OECD countries
2. Further energy efficiency improvements
3. Dependence on renewable sources of energy

Oil market drivers especially in the growth markets of Asia Pacific Include

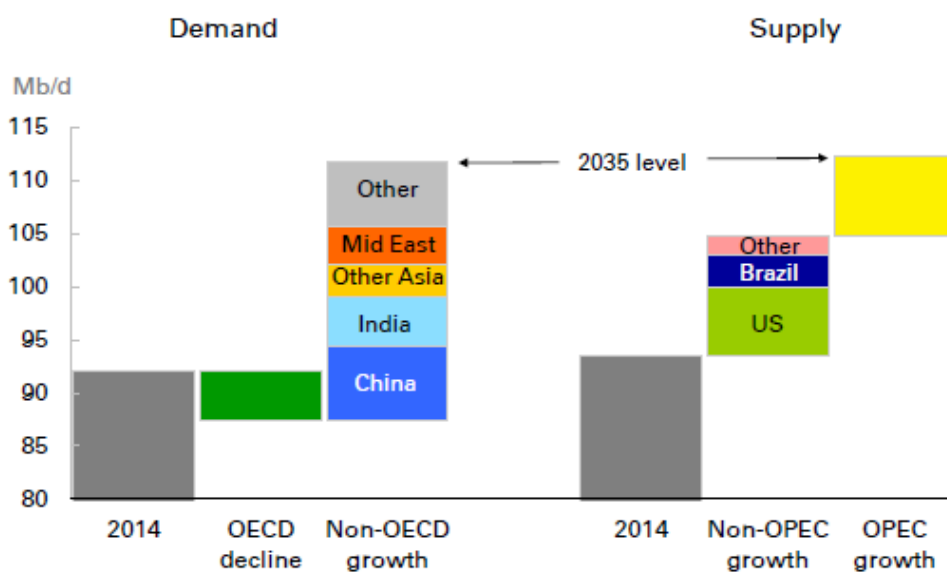
- a) Population growth,
- b) Motorisation in Asia
- c) Growing costs of exploration and production
- d) OPEC policy
- e) Dollar depreciation

We conclude this chapter on Economics with a BP assessment beyond 2020, which of course we will revisit when we revise the paper again for the next congress. What is instructive from the figure below is the clear shift in the centre of gravity of the oil trade towards Asia Pacific.

FIGURE 22: THE CENTRE OF GRAVITY OF OIL TRADE IS SHIFTING EAST

Base case: Fuel by fuel detail

Strong growth in Asia drives increases in oil demand...



Source: BP (2016) Energy Outlook June

OIL SUPPLY AND DEMAND DYNAMICS: ADDITIONAL COMMENTARY

According to Investopedia, the law of supply and demand primarily affects the oil industry by determining the price of oil. The price, and expectations about the price of oil are the major determining factors in how companies in the oil industry allocate their resources. Prices create certain incentives that influence behaviour; this behaviour eventually feeds back into supply and demand to determine the price of oil.

Oil demand and supply curves are steep since oil price is inelastic. The substitutes for oil are relatively few especially in the short run, hence the steep demand curve. The steepness of the supply curve is due to huge investment involved in oil production. This will always allow

for continuous production for companies to recover their costs. The stability of the oil market is influenced by the demand and supply. For example, OPEC stabilised the market in 2008/9 by cutting production by nearly 3 mb/d; this helped to stabilise the prices. Similarly, OPEC raised production sharply in 2004 when global demand suddenly surged.

Global oil price dynamics are subject to many factors, the principal of which are the balance of supply and demand, macroeconomic and geopolitical situation, dynamics of the US dollar exchange rate and conditions on the global financial markets. Technological breakthroughs make it possible to develop huge resources. The increase in unconventional oil and gas production in the US serves as a good example. Taking into account the US oil production progress many analytical agencies lower their long-term oil price forecast.

For example, extended periods of high oil prices lead to consumers shunning vehicles that are not fuel efficient, thus reducing their driving. Businesses and individuals may pay more attention to conserving energy due to its cost. These factors reduce demand.

On the supply side, high oil prices lead to more drilling projects; more research money pours in and sparks innovation in new techniques and efficiencies; and many projects that were not viable at lower prices become viable. All of these activities increase supply.

An example of this circumstance was seen between 2007 and 2014 when oil prices were above US\$100 for the most part. Massive investments poured into the sector via credit and new companies. Production increased in response to high prices, especially with innovations in fracking and oil sands. These investments could only be justified based on high oil prices and contributed to record supply in 2014.

Additionally, great strides were made in efficiency and alternative energy, which contributed to decreasing demand on a per-person basis. In the summer of 2014, there was a deflationary shock due to economic weakness in China and Europe. Given the supply and demand dynamics, oil prices cratered, falling more than 50% in a four-month time frame.

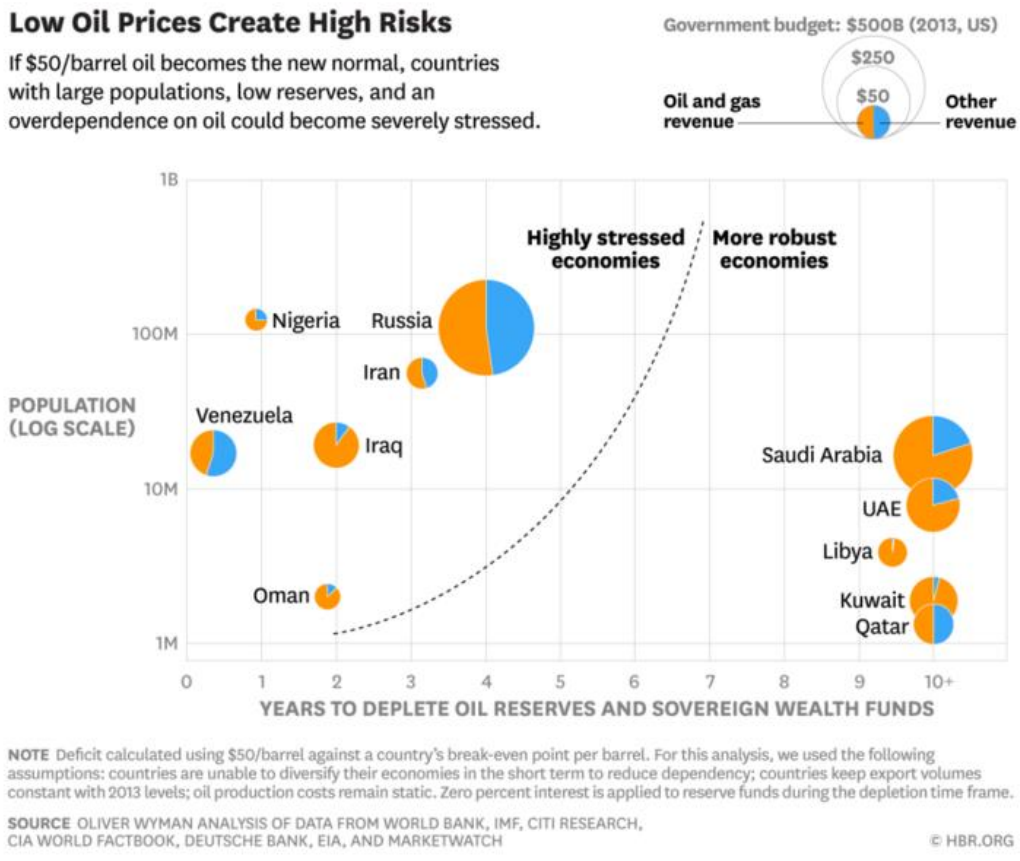
A low oil price creates the opposite set of incentives: companies are slashing their spending on the search for new deposits. That, in turn, could crimp supply years from now. Earlier exploration pullbacks have been blamed for subsequent tight markets. In the late 1990s, oil prices crashed, triggering a round of big consolidation and a pullback in exploration spending. That came back to haunt the world when Asian demand took off just a few years later, and supply growth could not keep up—sending prices soaring.¹⁹

A low oil price creates the opposite set of incentives. Production drops as many companies in the oil industry may declare bankruptcy and projects in development are shut down; this

¹⁹Williams (2015)

crushes supply. Demand also rises as people drive more and focus on efficiency matters less materially because of lower energy costs²⁰.

FIGURE 23: LOW OIL PRICES CREATE HIGH RISKS



Source: HBR

INVESTING IN THE LONG TERM

What to expect in the future:

1. Global demand for liquid hydrocarbons will continue to grow.
2. The growth of population and the consumer class in Asia will support oil demand increase. The main increase in consumption will come from transportation sectors in developing countries.

²⁰ Investopedia

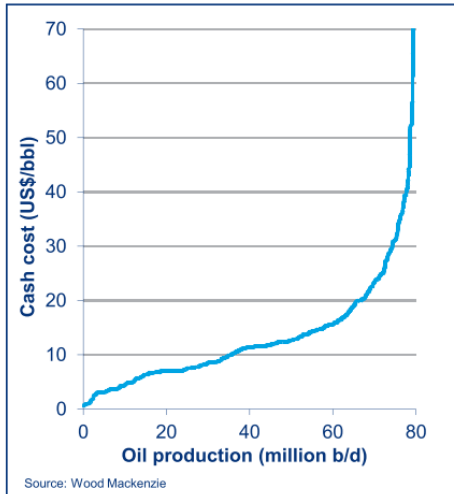
3. Increase of oil production in North America will not lead to a global oil price collapse.
4. Modern methods of evaluation of shale oil reserves allow considerable uncertainty. A number of factors including the growing cost of reserve replacement, the balancing role of OPEC and the depreciation of the US dollar will help to support the current levels of oil prices in the long term.
5. Ongoing trends such as the decrease in US gasoline imports and the commissioning of new highly effective oil refineries in the Middle East and Asia will continue to have a long-term negative effect on European producers.
6. Projects currently planned are unable to compensate the production decline of brownfields. Without large-scale use of new technologies, oil production in Russia will begin to fall in 2016-2017.
7. The Russian oil refining industry will undergo significant modernisation but risks of gasoline deficits remain.
8. Measures taken by the Russian government will promote modernisation of domestic oil refineries but the situation concerning the automotive gasoline market will remain quite tense until 2016-2017.

Addendum on the Production Cost Curve

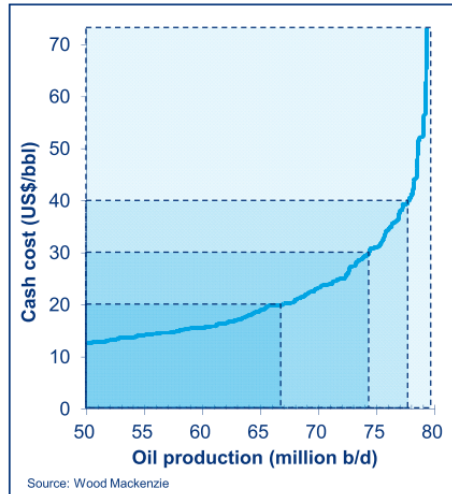
FIGURE 24: THE POST PRODUCTION COST CURVE

The production cost curve

Full operating cash cost curve



Detailed (>50 mb/d) operating cash cost curve



Cash Cost adjusted to Brent pricing.
Production excludes liquids from gas and gas/condensate fields

Cash Cost adjusted to Brent pricing.
Production excludes liquids from gas and gas/condensate fields

The economic pain starts to intensify at US\$50/bbl, below which increasing numbers of producing oil fields turn cash flow negative. At a Brent oil price of US\$40, 2.0 million b/d of production is cash negative; at US\$35, 3.4 million b/d is cash negative; at US\$30, this rises to 5.3 million b/d. If Brent were to fall to US\$25, 7.7 million b/d or 8% of global supply would be cash negative.

Being cash negative simply means that production costs are higher than the price received. It does not necessarily mean that production will be halted. The operator's first response is usually to store production in the hope that the oil can be sold when the price recovers. For others the decision to halt production is complex and raises further issues that we discuss later in this report.

Source: Wood Mackenzie

CASE STUDY FOR ECONOMICS AND MARKETS – LITHUANIA AND IMPACT OF OIL INDUSTRY

Lithuania is one of the Baltic States, which started the State independence's path 26 years ago. The country's economy mostly depends on the external energy resources. After the Soviet Union collapse, the oil refinery company MazeikiuNafta, built in early eighties of last century, went through several owners' hands. Since 2006 PKN ORLEN became the main shareholder, and until now it is with the new name of ORLENLietuva from 2009. It should be noted, that in 1999 the newly built Butinge Terminal started the loading operations, i.e. the oil supply direction has changed from the west instead of the east. Nevertheless, the petrol price from stations of ORLENLietuva is similar or even higher than in other petrol stations or the ones in the Baltic region.

Oil sector is also closely interrelated with the natural gas sector, as their prices correlates. Natural gas is one of the main energy resource for the electricity generation and for the central heating system. Its price is directly reflected in the cost of final product for customers. From the 3rd of December 2014 Lithuania is able to independently meet the demand of natural gas and is no longer dependent on the single external gas supplier. LNG terminal has created an opportunity to develop LNG market in Lithuania. The country has a possibility to purchase natural gas from different suppliers at market prices. Importance of regional and global markets is crucial for the competitiveness of the economy, and the current oil price decrease is welcome. It should be noted, that at the moment the final result of efforts to have competitive conditions in the natural gas sector, was not exactly as expected, and the outcome for end-users remains nearly the same as it was, due to the security investments made and other various reasons, one of which is political. Nevertheless, there could be an optimistic perspective, when in the mid-February 2016 the new agreement signed would allow reduction in the price from LNG terminal by more than one-third. This would lead to decrease of €34 million in energy prices for end-use customers.

It should be noted, that in spite of the reorganisations and privatisations' processes and huge investments in the oil, the natural gas and electricity sectors over the last two decades, at the moment the country's energy competitiveness status has not changed much. The outcome of the high oil and natural gas prices is that they paved the way for the renewable energy resources. Since the adoption of the Law of RES in 2011, their part in national energy balance increased significantly, in spite of the required investments, and it seems, that lower oil prices will not stop this process. It worth mentioning that similar factors influenced the investments to the security means by way of new electricity connections with the new energy systems. As could be seen from the primary results at the beginning of 2016, it may serve future social benefits.

3. SOCIO-ECONOMICS

KEY MESSAGES FOR SOCIO-ECONOMICS

- Oil price decline has positive impacts for oil-intensive industries and oil importing nations, and to a lesser degree for consumers.
- Oil producing nations are facing difficult times trying to balance their budgets and are using up national reserves.
- Oil revenues are associated with negative impacts known as the resource curse.
- Countries are trying to develop their oil and gas supply chains with local content policies.

SOCIO-ECONOMIC IMPACTS OF OIL PRICE VOLATILITY

The price of oil has significant impacts on the global economy. Conventional wisdom states that if the oil price rises too fast, then as a rule of thumb, the global economic growth is hindered, if the oil price drops, this is a boost to the global economy. The rule of thumb is that a 10% fall in oil prices boosts growth by 0.1 - 0.5% points.²¹ Since the large oil price shocks of the 1970s, it has been widely argued that the oil shocks had large effects on the global economy, with nine of the ten post-World War II recessions in the US preceded by episodes of sharply rising oil prices²². However, studies indicate that the sharp oil price booms between 2002 and 2008 did not have the anticipated adverse effect on the global economy²³ or core inflation^{24,25}.

Moreover, the recent oil price plunge by up to 75% had uncertain effects due to the speed and magnitude of the decline. Commentators have introduced the “New Economics of Oil” as key principles seem to no longer apply.²⁶ Even though effects are reversed for oil producers and consumers, the net effect on growth is usually known to be positive as consumers are thought to spend more than producers save, thus stimulating overall economic activity. Recent research now suggests that relationship of oil prices and overall

²¹The Economist (2016), Who’s afraid of cheap oil?

²² Hamilton, 1983

²³ Kilian (2009); Segal (2011)

²⁴ Cecchetti and Moessner (2008)

²⁵ Allsopp and Fattouh (2013)

²⁶Ibid 18

activity has changed as a result of the falling oil-intensity of GDP, increasing labor market flexibility, and better- anchored inflation expectations²⁷. Others argue that adverse shocks in the aftermath of the 2008 financial crisis and smaller response of demand have offset the positive effect usually associated with lower oil prices²⁸. The exact size of the impact however usually depends on the fundamental drivers of the price decline, the extent of pass-through to retail prices for households and firms and how much of it they spend, and not least, policy responses²⁹.

Oil consumers as winners

Oil consumers are generally thought to benefit from the recent oil price plunge. Fossil-intensive industries, such as the agricultural and transport sectors are also gaining from lower fuel prices as input to production. According to a recent study by Oliver Wyman, the US airline industry has operating margins above 15% with lower oil prices³⁰. Petroleum refineries and downstream activities are profiting as the price of their key input has fallen.

Net oil importers such as China, India or Japan are welcoming fall in prices. For example, India spent about US\$125 billion annually during the past five years on the import of crude oil. Now with the price hovering around US\$60/bbl, this huge yearly burden has come down almost 50%, thus saving India nearly US\$65 billion to US\$70 billion every year, thereby reducing its trade deficit substantially³¹. While the windfall gains helped to ease India's current account deficit, and contributed to the macro-economic stabilisation of India's economy, low prices did not find their way to Indian consumers and did not have a positive effect on demand. It is important to note that retail fuel prices have declined globally, on average, by only half as much as world oil prices³². In other words, while there are clear fiscal benefits, net fuel taxes for consumers have increased. In some oil-importing countries, the positive effects of lower global oil prices have also been muted by exchange rate depreciation, and lower non-oil commodity prices, if that country is exporting non-oil commodities³³.

Oil producers as the losers

Even though it depends on the degree of hydrocarbon dependence of a country, oil exporting nations are generally suffering from the oil price collapse. In some countries, the consequent fiscal pressures can be mitigated by large sovereign wealth fund or reserve assets. In Russia, where oil revenues make up about 50% of the federal budget, fiscal revenue shortfalls have resulted in public spending cuts and the state using its reserves to balance the federal budget. The situation is even worse in Saudi Arabia and other countries that have higher degrees of dependence on oil rents. In Saudi Arabia, oil generates up to

²⁷ Blanchard and Riggi (2013)

²⁸ IMF (2015); World Bank (2015)

²⁹ IMF (2015)

³⁰ Hartmann and Sam (2016)

³¹ Kanwar (2015)

³² Ibid 25

³³ Ibid 25

80% of state revenues and represents 45% of GDP.³⁴ The government has also responded to fall in revenues by using up national reserve assets. Even though Saudi Arabia has accumulated US\$600 billion worth of reserves it had ran a record deficit of nearly US\$100 billion since mid-2014.

SAUDI ARABIA'S VISION 2030

The low oil price environment and necessity of diversifying sources of income as well as a new visionary leadership planning ahead for a risky oil future has marked the beginning of an era of economic reform. Saudi Arabia has launched an ambitious National Transformation Program (Vision 2030) that aims at the diversification of its economy and to increase non-oil revenue to more than triple by 2020. The 15-year plan includes economic reforms such as the privatisation of state assets with 5% sale of Saudi Aramco, raising fees and tariffs on public services as well as the introduction of value added tax of 5%. It also involves painful austerity measures with negative implications for the population such as the reduction of subsidies on water and electricity. 35 other oil dependent countries especially in the Gulf Cooperation Council are watching Saudi Arabia's experience, as there might be important lessons to be learned in the future.

The cost of production of oil and the fiscal break-even price to balance the state budget varies across countries and can range from US\$54 per barrel for Kuwait to US\$184 for Libya, but is generally above current market prices at the moment³⁶. Fragile oil exporters who do not have any significant buffers and are unable to hedge effectively against low oil prices are suffering the worst. Nigeria crude sales fund about 75% of the country's budget, and the break-even price for Nigeria lies at around US\$100 causing severe fiscal constraints and adjustment in macroeconomic and financial policies. The social price with welfare cuts is enormous.

Lower oil prices would especially put at risk oil investment projects in low-income countries. Newly emerging oil and gas producers such as Mozambique or Uganda face major challenges with delays in first oil production, weak hiring of people and companies and disappointment among the population with high expectations for the new industry. An estimated US\$380 billion in project capital expenditure has been deferred in new oil & gas projects, resulting in delays of 68 major projects worldwide.³⁷

³⁴<http://time.com/4188317/saudi-arabia-will-be-the-big-loser-from-the-plunge-in-oil-prices/>

³⁵ Sticanti and Al Omran (2016)

³⁶ World Bank (2015)

³⁷ Wood Mackenzie (2016)

Oil revenues and the resource curse

Relying heavily on natural resources might be bad for societies, as this might bring about a phenomenon known as “resource curse”. This may lead to currency appreciation, crowding out of other sectors of economy, fiscal dependence, conflicts, corruption and political power monopolisation. Many studies link high levels of income from natural resources to poor governance and a corrupted political system. Oil curse is an outcome of four distinctive qualities of oil revenues³⁸:

- 1) **Stability** – volatile oil prices make it hard for governments to have long-term policies. They often fall into the trap of pro-cycle spending and are unable to effectively hedge against low oil prices.
- 2) **Scale** – oil revenues are massive, meaning governments of oil producing countries are on average almost 50% larger (measured as a fraction of countries’ economy) than the governments of non-oil countries.
- 3) **Source** – oil funds are not financed by citizens, and governments are not accountable.
- 4) **Secrecy** – deals with international oil majors and budgets of NOCs make it easy to hide revenues.

Solutions to mitigate the negative effects of oil revenue volatility on the country's budget include long-term investments in special funds and limits on how these funds can be used. One of the first examples of sovereign funds for oil revenues comes from 1953 when British authorities established Kuwait Investment Authority. In 2015, a total of 68 national or state sovereign wealth funds manage assets with market value of US\$7.2 trillion.³⁹ While sovereign wealth funds are useful to deposit oil windfalls and to hedge for times of low prices, they require clear and transparent legislation for withdrawal, deposit and investment, independent oversight and an adequate institutional structure.

NORWAY AND THE GOVERNMENT PENSION FUND GLOBAL

The largest sovereign wealth fund in the world is Norway’s Government Pension Fund Global with value of US\$771 billion at end of 2014. 36.5% of the total value has been achieved due to returns on investments. Norway has been investing its revenues from oil sector to avoiding the resource curse. In 2015 NGPFG made more money in the first three months of the year than the government spent in the same period.⁴⁰

Norway has also set up Government Pension Fund Norway with assets valued US\$22.3 billion invested 85% in Norwegian and 15% Nordic region equities (60%) and fixed

³⁸ Ross (2012)

³⁹ Kalev Kallamets, Tallinn University of Technology, RESOURCE REVENUE MODEL FOR A DEVELOPED COUNTRY: CASE ESTONIA

⁴⁰ <http://www.ft.com/cms/s/0/23693448-ee72-11e4-88e3-00144feab7de.html>

income assets (40%). Average annual gross return on the GPFN is calculated at 7.3% from January 1998 to year-end 2014. The fund is managed by specialised fund manager Folketrygdfondet with a clear mandate to invest up to 15% in any single company's equity.⁴¹

To avoid the oil curse, the so-called good governance programmes for more transparency, accountability and anti-corruption have been requested in the national oil and gas sectors. The scale and secrecy of revenues are thought to incentivise rent-seeking behaviour and corruption, if institutions are not providing the necessary checks and balances.

The oil and gas supply chain and local content

A well-developed national oil and gas industry is known to make an important contribution to an economy. The industry across its value chain is a critical source for investments, technological innovation and value addition, as well as high-skilled and low-skilled employment and labour income. For example, the UK oil and gas has a strong domestic oil and gas supply chain that provides employment for over 400,000 people across the UK. However, as a consequence of low oil prices, downsizing strategies have resulted in job reductions, especially in the exploration arm of oil and gas companies.⁴²

In some less developed contexts, domestic oil and gas supply chains have often been underdeveloped and dominated by foreign suppliers. As part of their oil-based industrialisation strategies to develop local supply chains, many countries have introduced localisation requirements over the last five years. Saudi Arabia's Vision 2030 aims to maximise local content to increase its added value, reducing dependence on imports, and creating job opportunities.⁴³ These requirements make a domestic participation in terms of procurement of good and services mandatory.

As local content requirements are perceived as additional costs to projects, some argue this adds to delays and cancellation of projects with low oil prices. Some governments are responding with adjustments in regulations and tax regime to the new normal of oil prices to continue to attract investors. While Norway is facing a 15% fall in investments in its oil industry and consequent job reductions due to the fall in oil prices, its government has so far resisted reducing taxes.⁴⁴

⁴¹Kalev Kallemeets, Tallinn University of Technology, RESOURCE REVENUE MODEL FOR A DEVELOPED COUNTRY: CASE ESTONIA

⁴²Macalister (2016)

⁴³Saudi Arabia's vision to 2030, National transformation program 2020

⁴⁴Holter (2015)

4. ENVIRONMENTAL IMPACTS

KEY MESSAGES FOR ENVIRONMENTAL IMPACTS

- Increased need to control global warming will have a huge impact on the use of fossil fuels as a source of energy. A global agreement to cut global warming to less than 2°C was adopted by consensus on the 12th of December 2015 at the United Nations Climate Change Conference.
- In a bid to preserve the environment and the ecosystem, it is important for the oil industry players to learn from past failures that have damaged the environment.
- Strict precautions should also be applied when using technologies that pose high risk of damage to the environment.
- Regulations, especially in the EU, call for more efficient and environmentally friendly production cycles, which can be achieved by making use of energy production by-products and production waste.

A DETAILED LOOK INTO COP21 AGREEMENT AND THE LIKELY IMPACTS ON FOSSIL FUELS

The 2015 United Nations Climate Change Conference, termed COP21, was held in Paris from 30th November to 12th December, where a global agreement on reduction of climate change was negotiated. The agreement which aims to cut global warming to less than 2°C compared to pre-industrial levels was adopted by consensus on 12th of December 2015, but is not yet legally binding until it is joined by at least 55 countries which together represent at least 55% of global GHG emissions. The signing of the agreement by the parties will be done in New York within a period of one year beginning 22nd of April 2016 and ending on the 21st of April 2017. Parties will also be required to "pursue efforts" to further limit the rise in temperature to 1.5°C above pre-industrial levels which, according to some scientists, will require zero emissions in the second half of the century. Achieving such a reduction in emissions would involve a complete transformation of how people get energy.

FIGURE 25: WORLD LEADERS CELEBRATE VICTORY OF THE PARIS NEGOTIATIONS.

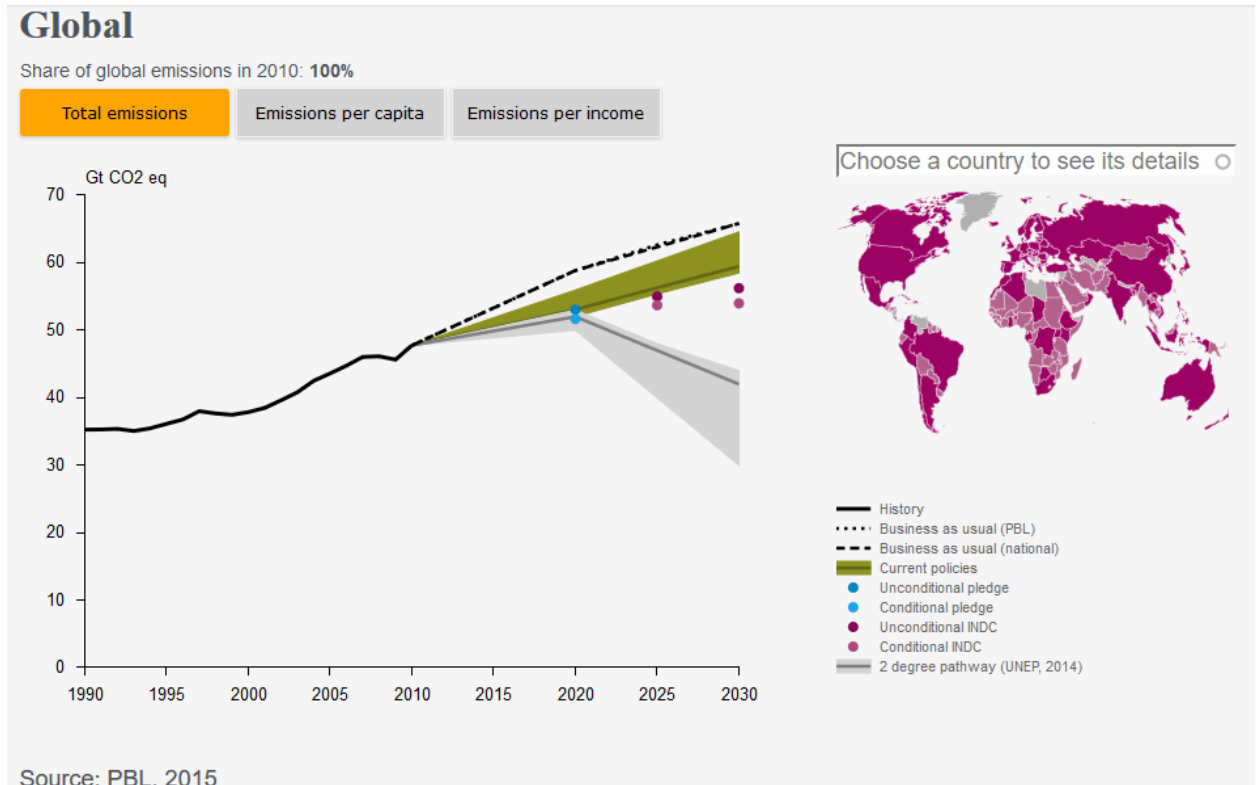


Source: Associated Press

The Paris agreement represents a long awaited breakthrough in climate negotiations. The United Nations (UN) has been working for more than two decades to persuade governments to work together in reducing GHG emissions. The previous international climate treaty, the 1997 Kyoto Protocol, has been seen by many as a big failure with countries such as Canada recently withdrawing from it. The last climate summit, in Copenhagen in 2009, also ended in disarray when countries could not agree on a binding emissions deal. It was therefore a big relief to see the Paris talks come into fruition. “History will remember this day”, said UN Secretary General Ban Ki-moon, “the Paris agreement on climate change is a monumental success for the planet and its people.”

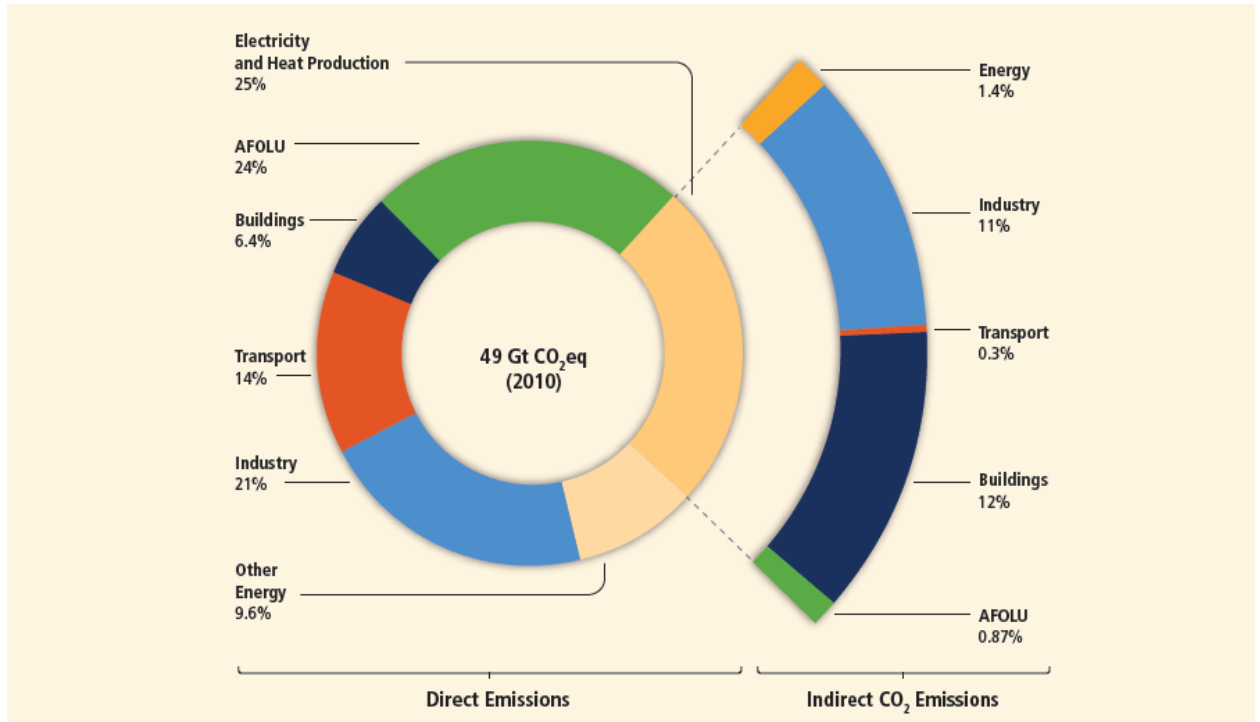
In order to reach the long term goal of making sure global warming stays well below 2°C, countries agreed to set national targets, termed Intended Nationally Determined Contributions (INDCs) for reducing GHG emissions every five years. By 29th November 2015, 184 countries representing about 96% of global GHG emissions had submitted INDCs for the first cycle beginning 2020. According to the PBL (Netherlands Environmental Assessment Agency), if the INDCs are implemented, they will deliver a reduction of 9 and 11 Gt CO₂e by 2030, compared to the business as usual scenario, for the full implementation of all unconditional and conditional INDCs, respectively. The figure below shows the impact of aggregated reductions by the full implementation of all unconditional and conditional INDCs submitted to date, compared to the business-as-usual and current policies scenario.

FIGURE 26: IMPACT OF AGGREGATED REDUCTIONS BY THE FULL IMPLEMENTATION OF ALL UNCONDITIONAL AND CONDITIONAL FULL INDCS SUBMITTED TO DATE, COMPARED TO THE BUSINESS-AS-USUAL AND CURRENT POLICIES SCENARIO



The biggest economic impacts of the Paris Agreement will be felt in the energy sector. As can be seen in the figure below, power generation and transport industry, where alternative low-carbon technologies already exist, will be the hardest hit. The agreement in Paris also means that green technology and renewable energy industry will be the biggest beneficiaries over the next few decades. Analysts at Barclays estimate that approximately US\$21.5 trillion of investment in energy efficiency and US\$8.5 trillion of spending on solar, wind, hydro, and nuclear power will be required by 2040 under the current pledges.

FIGURE 27: TOTAL ANTHROPOGENIC GREENHOUSE GAS EMISSIONS (GTCO2EQ/YR) BY ECONOMIC SECTORS.



Source: IPCC, SPM

According to the equities team at Barclays, out of the three major fossil fuels, crude oil appears to be the most exposed industry if the Paris agreement is implemented in full. They estimated that the industry will incur a total revenue loss of US\$16.4 trillion.

This is based on IEA's World Energy Outlook 2015 report which compares baseline demand (under the New Policies Scenario) with the 450 Scenario (model that keeps CO₂ emission under 450 ppm required to prevent global warming from exceeding an average of 2°C). It shows that the total demand for oil over the next 25 years is estimated to fall from 939.5 to 830.4 billion barrels, which translates to a percentage drop of 11.5% in terms of weighted annual average.

Changes in the modes of transportation will play a key role in the dynamics of crude oil demand over the next few decades. While a lot has been done to replace use of fossil fuels to generate electricity with cleaner energy like renewables and nuclear, 99% of the transport sector still heavily depends on crude oil. But with costs coming down and mileage range improving significantly, electric vehicles (EVs) is attracting great interest from consumers, with annual growth rates ranging from 50-100% in the last 2-3 years.

If growth at such rates could continue, then demand for crude oil will be affected in the near future. However, OPEC and major oil companies seem to expect the current status quo to continue. OPEC maintains that EVs will only constitute 1% of cars in 2040 and that the fossil fuel share of the global energy market will remain dominant at 78% over the next 25 years.

BP in its most recent Energy Outlook 2035, claims that alternative (non-oil based) transport will only have annual growth of 5% over the next two decades, and that all of this growth will essentially be in the gas-powered transport sector.

ExxonMobil in its energy outlook "The Outlook for Energy: A View to 2040" similarly assumes that EVs and fuel cell vehicles (FCVs) will have less than 4% market share by 2040.

Other companies like Chevron have also indicated that majority of their future plans are based on the assumption that the transport sector will basically remain the same for at least the next five decades. Although there are many unknown factors that may hinder a switch to cleaner modes of transport, it is wrong to assume that the status quo will be maintained. As technologies for EVs improve and global concerns about climate change and air pollution escalate, a gradual shift towards electric vehicles will likely follow. But this paradigm shift towards an eventual electrification of transport should bear in mind that electric vehicles are as clean as the energy mix of the environment in which recharges are made.

Additionally, if national governments in response to the Paris Agreement, were to enact policies and put incentives aimed at accelerating a shift to cleaner modes of transportation, then the markets for the conventional internal combustion engines (ICEs) and consequently crude oil will be severely hampered.

In the wake of the Agreement, representatives from over 60 organisations across the world also called for a levy on fossil fuel extraction. This could further lead to a strain on the business models of most crude oil companies. It is difficult to tell whether the Paris Agreement will lead to the end of the fossil age, given the fact that the agreement is not yet binding.

There could still be a dispute over the promised US\$100bn a year of mitigation funding for developing countries where the need for fossil fuels, the cheapest energy options, is more pressing than climate challenges.

But although the likely impacts are still not yet clear, fossil fuel companies should not carry on with business-as-usual. They need to venture into new territories as Total and Shell are already doing, invest in low-carbon technologies and partner with research institutes which are actively looking for ways to sequester excess carbon in the atmosphere.

The Oil industry has expressed its collective support for this effective climate change agreement, with the aim of being part of the solution to help lower the current global

emissions trajectory. In this low-emissions future, oil will continue to be an important part of the broad energy mix needed to deliver affordable and clean energy products and services, and it is intended to help to transform energy systems through, for example, low-emissions technology innovation, including CO₂ capture, utilisation, and storage or energy efficiency.

ECOSYSTEM MODIFICATION

As with most industrial processes, production of shale oil faces a number of environmental challenges. The environmental impacts of above ground (ex-situ) retorting are very technology-specific. For example, technologies using gaseous heat carriers in some cases produce a solid waste containing organic residues, which may pose a threat to the environments in which they are disposed. Most solid heat carrier technologies struggle with higher CO₂ emissions, though this is a challenge for all ex-situ technologies.

In-situ processes require robust heating technology, but none is fully demonstrated at present. Substantial progress has been made on electric heating cables that do not require splices between mineral-insulated cable segments. However, energy efficiency considerations are motivating work on non-electrical systems, including down-hole burners and hot circulating fluid systems such as propane, CO₂, and molten salts. The hot-fluid systems include demonstration of super-insulated piping systems to minimise heat loss from the surface. Geothermic fuel cells are also under development, which can switch from underground heat generation to electric power generation for export depending on the pricing in the power market.

Another environmental issue with unconventional oil is the usage of water. The industry has previously claimed that the water usage is in the range of 1-3 barrels of water per barrel of oil. The higher end was typical to in-situ processes where aquifer remediation was required. More recently, with in-situ processing in the Piceance Basin planned only below the aquifers, the lower range is more appropriate. In 2013 water usage as low as 0.3-1 bbl of water per bbl of oil production was reported⁴⁵. The major reductions came from more aggressive water conservation efforts and the elimination of water needed for ground water flushing after in-situ retorting. Most developers now believe that a bulk of future in situ development will be carried out in areas where there is no mobile ground water, and thus ground water mitigation technology such as a freeze wall will not be necessary.

New generation technologies such as fluidised bed combustion, producing shale oil and electricity from the retort gas, the by-product of shale oil production, are reducing CO₂ emissions from oil shale processing. New oil shale processing technologies should be technically feasible, environmentally acceptable and economically viable.

⁴⁵ Wani, Schroeder, Meyer and Fowler (2013) Low Water Use Technologies – Improvements to Shell's Water Balance, 33rd Oil Shale Symposium, Colorado School of Mines, Golden CO USA

From the perspective of development of the EU environmental policy, only a phase has been completed, which will be followed by other, more stringent requirements, and work on meeting those will continue. Besides activities aimed at achieving regulatory compliance, in 2015 a lot of work was done to make the Group's production facilities more efficient and environmentally friendly. EestiEnergia's strategic objectives are: to derive maximum energy from oil shale, to improve the flexibility and efficiency of its energy production operations and to increase the effectiveness of resource utilisation by making use of energy production by-products and production waste.

Impacts on the ecosystem

Lessons (un)learned from the DeepWater Horizon, more than half a decade later

On the evening of 20th April 2010, a blowout and an explosion occurred on the DeepWater Horizon (DWH) rig, killing 11 people and spewing out an estimated 3.1 million barrels of crude oil into the Gulf of Mexico. The accident happened when a "fail-safe" blowout preventer failed on the Macondo Well releasing the crude for a period of about three months.

FIGURE 28: THE DEEPWATER HORIZON RIG IN FLAMES IN SPRING OF 2010



Source: EPA

At the onset of the spill, environmental activists predicted dire consequences on the environment. Some like Matthew Roy Simmons, a leading proponent of the "peak oil" theory, even predicted that the crude oil would "float all the way to Ireland." However, more than half a decade later, it is evident that those predictions were over-exaggerated. While the accident

led to massive oiling of beaches and marshes, mortality of fish and other sea animals, and subsequent struggling of businesses especially tourism, it is fair to say that it has not been the ecological cliff that anti-petroleum activists predicted. On the spill's five-year anniversary, BP released an extensive report showing that there was no lasting damage to the ecosystem and that "the Gulf has largely recovered". The report shows that as early as August 2010, less than 2% of water samples exhibited more oil-related chemicals than the threshold Environmental Protection Agency (EPA) deems safe for marine life. The report also suggests that "the few areas where there were potentially harmful exposures were limited in space and time, mostly in the area close to the wellhead during spring and summer of 2010". Additionally, BP reports that gulf species such as shrimps and sea-birds have not been significantly affected on the long-term.

While the assessment by BP has not been disproven, the US government and other scientists suggest that it is too soon to make any long term conclusions. Several studies have been done in an attempt to understand both the short term and long term effects of the oil spill.

For example, a study done in 2014 to assess the effects of the oil spill on Bluefin tuna found that the oil toxins can cause irregular heartbeats in the species leading to cardiac arrest. The study, published in the science journal, found that a common form of injury among a broad range of species affected by the spill was linked to PAH cardiotoxicity.

Another study published in 2014 by 17 scientists from the US and Australia, found that tuna and amberjack which were exposed to oil from the spill developed fatal or at least life shortening deformities of the heart and other organs. According to the scientists, predators higher up in the food chain and possibly even humans, whose vital organs are in many ways similar, would most likely be affected in the same way.

Although the long term negative effects remain unclear and highly debateable, key lessons regarding short term environmental impacts of oil spills have been and are continuously being learned. However, there is room for improvement because existing data on the number of offshore drilling and production accidents and near-misses in the past six years are not particularly encouraging.

According to a report published in 2012 by the Institute for Energy and Transport (JRC-IET), the two underlying causes of the major accidents in the industry are "failures of the safety management system and a poor safety culture".

Indeed, several studies of the DeepWater Horizon accident have indicated that, human errors, organisational failures and regulatory challenges were some of the main contributing factors. Over the past six years since the accident, both regulators and the industry have made great strides in trying to address these factors. Most of the regulations and safety reforms that have been carried out have mainly concentrated on spill prevention, containment/response and improved safety culture. The US Bureau of Safety and Environmental Enforcement (BSEE) recently proposed a new rule that tightens safety

standards on offshore well blowout preventers. The rule which mandates redundant shear rams in each preventer to protect against device failure was collectively discussed and agreed upon by both BSEE and industry experts

In October 2011 the European Commission (EC) also published draft legislative proposals to centralise offshore safety and environmental regulations among its member states including Norway which is a member of the European Economic Area (EEA). The proposals were aimed at creating common safety standards across Europe because the Commission believed that "the likelihood of a major offshore accident in European waters remained unacceptably high." The UK oil and gas industry and regulators on their part convened the Oil Spill Prevention and Response Advisory Group (OSPRAG) to review the sector's offshore drilling practices and readiness to respond to major incidents in the UK continental shelf (UKCS). A major two-day drill was also carried out in May 2011 to simulate UK response to a major oil spill incident offshore. This drill focussed on well control, counter-pollution measures at sea and shoreline protection. Additionally, the UK oil and gas industry in July 2011 also successfully tested its ability to deploy a well capping device in the waters west of Shetland. New containment and gathering systems have also been put in standby ready to deploy in case of an emergency.

In terms of improving the safety culture, the industry sponsored the creation of the Center for Offshore Safety (COS). This centre works with the regulators to make sure that the latest advances in safety technologies and practices are shared throughout the industry. However, it is clear from the number of incidents that the safety culture has not been fully implemented. The oil and gas industry should proactively advocate for higher universal safety standards and maintain close relationship with regulators. We should learn from the DeepWater Horizon accident.

EMISSIONS

Unburnable carbon

The theory behind unburnable carbon stems from the reasoning that the cumulative global CO₂ emissions need to be limited to mitigate the effects of climate change.

This CO₂ budget can then be used to calculate the maximum amount of fossil fuels that can be used before the critical limit is reached. The global CO₂ emissions budget is calculated to be in the range of 565-886 billion tonnes (Gt) of CO₂ to 2050⁴⁷.

The world's known fossil fuels hold many times more carbon, by some calculations using up today's known fossil fuels would emit 2,860 GtCO₂. CCS technologies extend the carbon budget by 125 Gt, which is not much. As a result, some more pessimistic analysts predict that 60 - 80% of coal, oil and gas reserves of listed firms are unburnable.

⁴⁷Carbon Tracker (2013)

5. OUTLOOK

ENERGY DEMAND OUTLOOK FOR OECD AND NON- OECD

According to the latest (June 2016) Oil Market Report by IEA, non-OECD economies will contribute 1.2 mb/d of the global 1.3 mb/d expansion, dominating the demand growth in the short term. IMF in its 2016 World Economic Outlook suggested that developing economies and emerging markets carry a sizeable 130% economic growth when compared to advanced economies. Non-OECD countries such as China and India require more oil per unit of GDP because they are generally in a stage of the economy characterised by heavy manufacturing. The demand growth for OECD countries on the other hand is forecasted by IEA to be slower than those of non-OECD countries mainly because more stringent vehicle efficiency assumptions are built into their short-to-medium term models. Although countries such as Korea, the US and Turkey were forecasted to post stronger gains, growth in the second half of 2016 is envisaged to slow down under the influence of higher oil prices and a dull macroeconomic outlook. Elsewhere, there will be a fall in demand in Japan, France, Canada and Italy, while weak conditions in Germany and Spain are not particularly encouraging either. In general, total OECD oil deliveries in 2017 are forecasted to average 46.4 mb/d.

In the long term, China's oil demand is expected to rise by approximately 5 mb/d by 2040, with more than two-thirds of this forecasted to happen by 2025. India, on the other hand, depicts a totally opposite scenario from that of China. There, the IEA predict a total increase of 6 mb/d by 2040, but with two-thirds of this occurring in the second half (2025-2040) of the projection period. This is mainly because India's population is increasing, a big difference from China which has had the one-child policy since the 1980s. IEA also notes that access to electricity and modern type of energy is more widespread in China than it is in India. Additionally, the market for electric vehicles in India is almost non-existent and therefore, sustained growth in the number of internal combustion engine vehicles will lead to consumption of more oil. By 2040, the total energy demand in India is predicted to be nearing that of the US, although the demand per capita remains 40% below the global average.

The long term demand for oil in developed countries (OECD) is forecasted to decline. This is mainly because technological improvements that lead to creation of higher fuel efficiency vehicles are already being implemented in these countries. There is also continued focus on reducing carbon emissions from other sectors of the economy which further leads to less demand for crude oil. IEA expects the current OECD countries to reduce their oil demand by the size of 11 mb/d by 2040.

Countries with large, low-cost reserves, such as Saudi Arabia, are rethinking long-term strategies and recently announced that it is creating a US\$2 trillion mega-sovereign wealth

fund, funded by sales of current petroleum industry assets, to prepare itself for an age when oil no longer dominates the global economy.

Of the four scenarios for the future of the industry outlined in a new set of white papers from the Global Agenda on the Future of Oil and Gas, three of them envisage this type of world. Factors such as technological advancements, the falling price of batteries that power electric vehicles and a post-COP21⁴⁸ push for cleaner energy could even drive oil use below 80 million barrels a day by 2040 – about 15% lower than today.⁴⁹

Globally, there are ample liquid hydrocarbons in terms of both reserves and resources. BGR in its 2015 yearly report estimates that there are about 219 billion tonnes of conventional and unconventional crude oil reserves and 343 billion tonnes of recoverable resources in the world at the end of 2014.

Given current production levels this would imply, that liquid hydrocarbons can be supplied for many years to come. However, the rate at which new supplies can be developed in order to supply a growing market and the break-even prices for those new supplies are changing. In addition, supply interruptions can occur unrelated to peak oil, affecting global oil production levels.

Most importantly, levels of supply are increasingly less dependent on the production policy of OPEC, despite OPEC controlling significant global crude oil reserves and holding between one and six million barrels per day of spare capacity in reserve (IEA).

A combination of sustained high prices and energy policies aimed at greater end-use efficiency, diversification in energy supplies and shifting towards renewables might actually mean that “peak oil demand may occur sometime in the future even before the substantial global liquid hydrocarbon potential is anything like exhausted”⁵⁰.

The increase in US crude oil production during the past years owing to light tight oil (LTO) undoubtedly had an effect on the global oil market, although US tight oil 2014 accounted for just below 5% of the world’s production of crude oil and condensate. Even worse, reserves make up less than 0.5% of the world’s conventional and unconventional crude oil reserves⁵¹. Major areas containing substantial portions of tight oil reserves include the Bakken Shale Formation in North Dakota, Montana, and South Dakota, and the Eagle Ford Shale in Texas. Together, these two shale deposits account for more than 80% of the total tight oil proved reserves in the US⁵².

⁴⁸COP21: COP stands for Conference of the Parties, referring to the countries that have signed up to the 1992 United Nations Framework Convention on Climate Change. The COP in Paris is the 21st such conference

⁴⁹World Economic Forum (2016)

⁵⁰ IEA

⁵¹BGR (2015)

⁵² Chapman (2015)

Hence, over the medium term and under favorable economic conditions, US production of tight oil is projected to be robust. But this might only be a temporary phenomenon⁵³. It appears reasonable to assume that the Middle East will be the major source of future supply growth, long after the US shale oil boom has run its course. Price is important, but whether oil exists at all is even more so⁵⁴.

Brent prices are forecast to average US\$50/b in 2017, with upward price pressure concentrated later in that year. At that point, the market is expected to experience small inventory draws, with the possibility of further draws beyond the forecast period. Brent prices are forecast to average US\$56/b in the fourth quarter of 2017.

What to expect in the future

1. Global demand for liquid hydrocarbons will continue to grow.
2. The growth of population and the consumer class in Asia will support oil demand increase. The main increase in consumption will come from transportation sectors in developing countries.
3. Increase of oil production in North America will not lead to a global oil price collapse.
4. Modern methods of evaluation of shale oil reserves allow considerable uncertainty. A number of factors including the growing cost of reserve replacement, the balancing role of OPEC and the depreciation of the US dollar will help to support the current levels of oil prices in the long term.
5. Ongoing trends such as the decrease in US gasoline imports and the commissioning of new highly effective oil refineries in the Middle East and Asia will continue to have a long-term negative effect on European producers.
6. Projects currently planned are unable to compensate the production decline of brownfields. Without large-scale use of new technologies, oil production in Russia will begin to fall in 2016-2017.
7. The Russian oil refining industry will undergo significant modernisation but risks of gasoline deficits remain.
8. Measures taken by the Russian government will promote modernisation of domestic oil refineries but the situation concerning the automotive gasoline market will remain quite tense until 2016-2017.

It is very hard to accurately predict oil price as it is mostly done by extrapolating historical data. The dangers of extrapolation were, again, spectacularly illustrated by The Economist newspaper (1999) prediction that “the world is awash with the stuff, and it is likely to remain so” and that “\$10 might actually be too optimistic” and oil prices might be heading for US\$5 per barrel. Only nine years later, in 2008, the price of dated Brent reached its historic high of US\$144.2 per barrel on July 3⁵⁵.

⁵³<http://shalebubble.org/key-findings>

⁵⁴ IEA (2014) World Energy Outlook

⁵⁵ Allsopp and Fattouh (2013)

Brent prices are forecast to average US\$50/b in 2017, with upward price pressure concentrated later in that year. At that point, the market is expected to experience small inventory draws, with the possibility of further draws beyond the forecast period. Brent prices are forecast to average US\$56/b in the fourth quarter of 2017.

US\$50 oil puts some producing countries under considerable stress as they grapple with less oil revenue in their national budgets. Venezuela, Nigeria, Iraq, Iran, and Russia could be forced to address substantial budget deficits within the next five years⁵⁶.

VISION STATEMENTS FROM EXPERTS (ENEFIT)

Estonia is celebrating an anniversary in oil shale development in 2016 – 100 years of oil shale mining. Estonia is one of the few countries in the European Union and also in the world, which is self-sufficient in electricity production. Estonia is also the country least dependent on imported energy in the EU. This unique position has been provided for by oil shale, a domestic resource that Estonia has utilised for a century. Through continuous innovation, Estonia has modernised its oil shale industry to significantly decrease the impacts on the environment and create the maximum value from oil shale. Oil shale provides for 4-5% of Estonia's GDP and contributes €300 million annually to the state budget. Estonia is living proof that the oil shale industry can be viable long-term, and has remained so throughout the last century. Smart and innovative choices will guarantee that oil shale energy will continue to be a viable solution for decades.

Short and medium term

How will the oil business look in 5-10 years? Give an overview about expected developments in terms of expected technologies, market structures and the role of oil in the energy business as well.

Over the long term, increased and new technical and economic substitutions for oil would see a decrease in demand. Price remains an important factor, both the general level of energy prices relative to other goods and services, and the relative prices of competing fuels within the overall mix. There have been large increases in the price of energy over the last decade and large changes in relative prices⁵⁷.

US based shale oil producers have improved their drilling and fracturing technology, and they can ramp up production in an appraised field in as few as six months at a small fraction of the capital investment required by their conventional rivals. As a result, shale oil has soared from about 10% of total US crude oil production to about 50%⁵⁸. The question remains for how long the US could maintain high shale oil production levels.

⁵⁶ Hartmann and S. Sam (2016)

⁵⁷ Allsopp and Fattouh (2013)

⁵⁸ Ibid 52

The focus is no longer on running out of fossil fuel in the foreseeable future, but rather who will control its future and how and when will the world transition away from it.

Antoine Halff of Columbia University's Centre on Global Energy Policy told American senators on January 19th that the shale-oil industry, with its unique cost structure and short business cycle, may undermine longer-term investment in high-cost traditional oilfields. The shale producers, rather than Saudi Arabia, could well become the world's swing producers, adding to volatility, perhaps, but within a relatively narrow range.⁵⁹

OPEC's ability to stabilise the market in response to short-lived, temporary shocks remains largely unaffected. The greater responsiveness of US shale means that cyclical movements in shale production should also help to stabilise the market. But OPEC's role remains dominant.⁶⁰ The supply characteristics of shale oil are different to conventional oil: shale oil is more responsive to oil prices, which should act to dampen price volatility. But it is also more dependent on the banking and financial system, increasing the exposure of the oil market to financial shocks.

Leveraging resource: pros and cons of resource vs. other energies

Oil industry vs other industries

This feature of cyclicity is common to other industries as well, but there are three special features that distinguish the oil industry from other industries. First, in countries where proven oil reserves are highly concentrated the decision to extract and develop these reserves is in the hands of governments or state actors. This has important implications, as decisions about whether and how much to invest is affected by economic and political factors and by events both inside and outside the oil market. The oil price is one of the various determinants of investment. Other determinants include political impediments such as sanctions, civil strife or internal conflicts; the nature of the relationship between the owner of the resource and the national oil company responsible for exploiting these reserves; the technical and managerial capability of the national oil company; the degree of access to reserves to foreign investors; and the petroleum regime and the fiscal system that govern the relationship between national and IOCs. One factor that has received special importance in the consumer–producer dialogue is long-term oil demand uncertainty. Oil producers often argue that the policies of consuming governments, both implemented and announced, play an important role in inducing uncertainty and thus, in the face of calls for security of supply, they have coined the concept “security of demand.”

Second, oil projects have long planning periods and can be subject to delays. These delays do not only occur because of the size of the projects and the large capital outlays involved,

⁵⁹ The Economist (2016) The oil conundrum

⁶⁰ Dale (2015)

but can also be due to issues such as access to reserves and the complexity of the negotiations between IOCs, NOCs, and the owner of reserves in both the pre- and post-investment stages. The relationship between the IOCs and the owner of the reserves (the government or state-owned enterprise) is affected by oil price developments, but equally importantly, it affects oil price behaviour through the investment channel.

Finally, producers' investment decisions affect the market structure in a fundamental way. High oil prices do not necessarily induce governments of producing countries to increase investment and productive capacity. In contrast, a combination of high oil prices and limited access to reserves has pushed many IOCs to explore new frontiers. The effect is that the cheapest oil reserves are not necessarily developed first, allowing for the coexistence of both high-cost and low-cost producers, with important consequences for the process of oil price formation.

The dependencies between oil and renewables

There are some paradoxical aspects to this. The deployment of renewables on a large scale, which would almost certainly require subsidies, could lead to low oil prices, leading to the need for even higher subsidies. An alternative, within consumer countries, would be higher taxes on conventional fuels or on their carbon content to make alternatives economic, unless there were spectacular falls in the costs of alternatives and technologies. Countering the problem with higher taxes would have to be international; otherwise cheaper oil would flow to areas where fossil fuels were not taxed. Another, equally unlikely, solution would be for the producers to receive compensation for not producing fossil fuel on the lines of "set aside" schemes often applied in agriculture. There are already a few schemes of this type designed to protect carbon sinks such as rain forests. Such issues are very complex and highlight a core feature of the oil market: the competition over rents between producers and consumers. Consumer governments would prefer to capture the rents involved via domestic taxation or equivalently by cap and trade systems. Producers would rather claim the rents for themselves by maintaining increase⁶¹.

In 2015, more than half a million AFVs were registered in the EU, up 20% compared to 2014. This represents 4.2% of total passenger car registrations. The uplift was fully sustained by the electric (+108.8%) and hybrid electric (+23.1%) markets, while the other alternative fuels declined (-8.4%). Total number of cars in the EU – 280 million. New registrations in EU 14,5 million. New registrations of alternative fuel cars 0,5 million. The age of electric car is still to come.⁶²

⁶¹ Allsopp and Fattouh (2013)

⁶² <http://www.acea.be/statistics/tag/category/key-figures>

CASE STUDY ABOUT SAUDI ARABIA

Saudi Arabia ranked 2nd and 8th in crude oil and gas production respectively as at 2014. In that same year, it consumed approximately one third of the oil produced, ranking it the 4th largest consumer of oil and with increased economic activity, domestic consumption is going to take up 80% of the oil produced by 2032. Majority of this domestic consumption of crude oil is what drives the country's power generation. Such overreliance on crude oil for domestic consumption greatly diminishes oil available for exports.

In a bid to streamline the quantities of oil used for domestic consumption, Saudi Arabia has resorted to improve on the efficiency of the energy system and introduce the use of renewable energy by increasing the involvement of the private sector in the construction and operation of utility plants. In 2014, subsidies in the energy sector accounted for 8% of the GDP. An attempt by the government to reduce subsidies on diesel used in the electricity sector will enable the renewable sector compete with fossil fuels.

Saudi Arabia has great potential for wind and solar energy with projects like the Al- Aflaj 50 MW solar PV plant. It contemplated using approximately 300 MW of solar and wind energy to replace 1 million barrels per day of liquid fossil fuel to generate power in 10 remote areas.

Institutions like K.A CARE (King Abdullah City for Atomic and Renewable Energy), Saudi Energy Efficiency Center (SEEC) and King Abdullah Petroleum Studies and Research Center have been formed to spearhead Saudi Arabia's transition into renewable energy.

6. GLOBAL TABLES

TABLE 3: OIL DATA ON PRODUCTION, PROVED RECOVERABLE RESERVES AND CONSUMPTION, 2014/2015, PER COUNTRY

Country	Oil Production Mt per year 2015/2014*	Proved Recoverable Reserves Mt 2015/2014*	Consumption Mt per year 2015/2014*
Albania	1.4*	26*	-
Algeria	68.5	1536.5	19.3
Angola	88.7	1709.4	-
Argentina	29.7	328.2	31.6
Australia	31.6	441.8	46.2
Austria	0.9*	7*	12.6
Azerbaijan	41.7	958.9	4.5
Bahrain	10.1*	15*	-
Bangladesh	0.2*	4*	5.5
Barbados	< 0.05*	< 0.5*	-
Belarus	1.6*	27*	7.1
Belgium	-	-	30.5
Belize	0.1*	< 0.5*	-

WORLD ENERGY COUNCIL | OIL

Country	Oil Production Mt per year 2015/2014*	Proved Recoverable Reserves Mt 2015/2014*	Consumption Mt per year 2015/2014*
Benin		1	-
Bolivia	3.4*	22*	-
Brazil	131.8	1889.5	137.3
Brunei Darussalam	6.2*	150*	-
Bulgaria	0.1*	2*	4.2
Cameroon	3.7*	18*	-
Canada	215.5	27754.6	100.3
Chad	4.1	215.8	-
Chile	0.3*	20*	16.9
China	214.6	2521	559.7
Chinese Taipei	< 0.05*	< 0.05*	-
Colombia	53.1	333	15.5
Congo	14.5*	190*	-
Congo Dem Republic	1.3*	24*	-
Côte d'Ivoire	1*	14*	-
Croatia	0.7*	7*	-
Cuba	3.7*	3*	-

Country	Oil Production Mt per year 2015/2014*	Proved Recoverable Reserves Mt 2015/2014*	Consumption Mt per year 2015/2014*
Czech Republic	0.7*	2*	9.4
Denmark	7.7	73.9	8.1
Ecuador	29.1	1174.7	11.7
Egypt	35.6	457.5	39.2
Equatorial Guinea	13.5	149.3	-
Estonia	0.7*	-	-
Ethiopia	-	< 0.5*	-
Finland	0.7*	-	8.3
France	0.8*	11*	76.1
Gabon	11.6	273.6	-
Georgia	< 0.05*	5*	-
Germany	2.4*	31*	110.2
Ghana	5.2*	90*	-
Greece	0.1*	1*	14.8
Guatemala	0.5*	11*	-
Hungary	1*	4*	7
India	41.2	763.5	195.5

WORLD ENERGY COUNCIL | OIL

Country	Oil Production Mt per year 2015/2014*	Proved Recoverable Reserves Mt 2015/2014*	Consumption Mt per year 2015/2014*
Indonesia	40	498.3	73.5
Iran	169.2*	21433*	-
Iraq	197	19307.6	-
Ireland	-	-	6.9
Israel	< 0.05*	2*	11
Italy	5.5	81.5	59.3
Japan	0.6*	4*	189.6
Jordan	< 0.05*	< 0.5*	-
Kazakhstan	79.3	3931.8	12.7
Korea Republic	< 0.05*	-	103*
Kuwait	149.1	13980.7	23.6
Kyrgyzstan	< 0.05*	5*	-
Libya	20.2	6297.3	-
Lithuania	0.2*	1*	2.6
Madagascar	< 0.05*	-	-
Malaysia	31.9	471.2	36.2
Mauritania	0.3*	3*	-

Country	Oil Production Mt per year 2015/2014*	Proved Recoverable Reserves Mt 2015/2014*	Consumption Mt per year 2015/2014*
Mexico	127.6	1495.6	84.3
Mongolia	1*	35*	-
Morocco	< 0.05*	< 0.5*	-
Mozambique	-	2*	-
Myanmar	0.8*	3*	-
Netherlands	2*	30*	38.7
New Zealand	1.8*	17*	7.5
Niger	1*	20*	-
Nigeria	113	5002.7	-
Norway	88	994.4	10.2
Oman	46.6	719.9	-
Pakistan	3.7*	50*	25.2
Papua New Guinea	1.7*	24*	-
Peru	4.7	170.4	10.9
Philippines	1*	15*	18.4
Poland	0.9*	15	25.1
Portugal	-	-	11.4

WORLD ENERGY COUNCIL | OIL

Country	Oil Production Mt per year 2015/2014*	Proved Recoverable Reserves Mt 2015/2014*	Consumption Mt per year 2015/2014*
Qatar	79.3	2694.5	10.9
Romania	4	79.9	9.1
Russian Federation	540.7	14024	143
Saudi Arabia	568.5	36617.9	168.1
Serbia	1.2*	7*	-
Sierra Leone	-	60*	-
Singapore	-	-	69.5
Slovakia	< 0.05*	1*	3.8
Slovenia	< 0.05*	-	-
South Africa	0.1*	2*	31.1
South Sudan	7.3	472.3	-
Spain	0.3*	19*	60.5
Suriname	0.7*	12*	-
Sudan	5.2	202.4	-
Sweden	-	-	14.1
Switzerland	-	-	10.7
Syrian Arab Republic	1.5*	340*	-

Country	Oil Production Mt per year 2015/2014*	Proved Recoverable Reserves Mt 2015/2014*	Consumption Mt per year 2015/2014*
Tajikistan	< 0.05*	2*	-
Thailand	17.2	49.2	56.6
Timor-Leste	3.8*	59*	-
Trinidad and Tobago	4.6*	113*	-
Tunisia	2.9	55.3	-
Turkey	2.3*	46*	38.8
Turkmenistan	12.7	82.2	6.4
Uganda	-	136*	-
Ukraine	3*	54*	8.4
United Arab Emirates	175.5	12976	40
United Kingdom	45.3	374	71.6
United States of America	519.9*	6857*	866.6*
Uzbekistan	3	81.4	2.8
Venezuela	157.8*	26807*	-
Vietnam	15.5*	599*	-

* 2014 data

Source: BP Statistical workbook of world energy (2016), BGR (2015) Energy study: reserves, resources and availability of energy resources.

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- Allsopp, C. & Fattouh, B. (2013), *The Handbook of Global Energy Policy*. Wiley-Blackwell
- Bashir, H. n.d., *Crude awakening*, Deloitte, <http://www2.deloitte.com/uk/en/pages/energy-and-resources/articles/crude-awakening.html>
- Carbon Tracker (2013), *Unburnable Carbon 2013: wasted capital and stranded assets*, <http://carbontracker.live.kiln.digital/Unburnable-Carbon-2-Web-Version.pdf>
- Chapman (2015), *Introducing tight oil, the real game changer in unconventional resources*, in *Market Realist*, December 7, <http://marketrealist.com/2015/12/introducing-tight-oil-real-game-changer-unconventional-resources/>
- Dale, S. (2015), *New economics of oil*, *BP*, October 13, www.bp.com/content/dam/bp/pdf/speeches/2015/new-economics-of-oil-spencer-dale.pdf
- Diminishing dependence, shrinking oil imports, www.eiuresources.com/shrinkingusoilimports/
- EIA (2016), *Short-term energy outlook: global petroleum and other liquid fuels*, September 7, www.eia.gov/forecasts/steo/report/global_oil.cfm
- EIA (2012), *Crude oils have different quality characteristics*, July 16, www.eia.gov/todayinenergy/detail.cfm?id=7110
- Fattouh, B. (2010), *Global demand dynamics: determinants and policy issues*, www.oxfordenergy.org/wpcms/wp-content/uploads/2011/02/Presentation45-GlobalDemandDynamicsDeterminantsandPolicyIssues-BFattouh-2010.pdf
- Gause, F. G. (2015), *Sultans of swing? The geopolitics of falling oil prices*, Brookings Institution, www.brookings.edu/wp-content/uploads/2016/06/Falling-Oil-Prices-English.pdf
- Giles, C. (2014), *Winners and losers of oil price plunge*, in *Financial Times*, December 15, www.ft.com/content/3f5e4914-8490-11e4-ba4f-00144feabdc0
- Gordon, D. (2012), *Understanding Unconventional Oil*, no. May
- Greenleaf, J. et al (2009), *Analysis of impacts of climate change policies on energy security*, pp. 1–352.
- Hansen, J. (2013), *The ‘other’ petroleum industry*, *Oil*, p. 54.
- Hartmann, B. & Sam, S. (2016), *What Low Oil Prices Really Mean*, in *Harvard Business Review*, [Online], Available: <https://hbr.org/2016/03/what-low-oil-prices-really-mean>. [Accessed: 29-Mar-2016].
- Holter, M. (2015), *Norway rejects call to cut crude oil taxes as cure for crude cash*, in *Bloomberg*, February 18, www.bloomberg.com/news/articles/2015-02-18/norway-rejects-call-to-cut-oil-taxes-as-cure-for-crude-crash
- IEA (2016), *Oil market report*, www.iea.org/oilmarketreport/omrpublic/charts/
- IEA (2016), *Oil market report*, August 11, www.iea.org/oilmarketreport/omrpublic/currentreport/
- IEA (2016), *Oil Briefing*

- IEA (2016), IEA releases oil market report for february, February 9, www.iea.org/newsroomandevents/news/2016/february/iea-releases-oil-market-report-for-february.html
- IEA (2015), Medium Term Oil Report, www.iea.org/Textbase/npsum/MTOMR2015sum.pdf
- Investopedia (2015), How does the law of supply and demand affect the oil industry? April 9, www.investopedia.com/ask/answers/040915/how-does-law-supply-and-demand-affect-oil-industry.asp
- Investopedia n.d., Unconventional oil, www.investopedia.com/terms/u/unconventional-oil.asp
- IPIECA (2014), Exploring the concept of 'unburnable carbon', www.bp.com/content/dam/bp/pdf/sustainability/issue-reports/IPIECA_Unburnable_Carbon_fact_sheet_2014.pdf
- Kanwar, R. (2015), Oil and gas in the capitals, *World Oil*, 2015. [Online]. Available: www.worldoil.com/magazine/2015/may-2015/columns/oil-and-gas-in-the-capitals. [Accessed: 29-Mar-2016].
- Kearney, A. T. (2013), Refining in 2021 who will the players be?, *Oil*, pp. 14–18.
- Levine, S. et al. (2014), Understanding curde oil and product markets.
- Macalister, T. (2016), BP makes record loss and axes 7,000 jobs, in *The Guardian*, February 2nd, www.theguardian.com/business/2016/feb/02/bp-annual-loss-biggest-for-20-years-axes-thousands-of-jobs-deepwater
- Mearns, E. (2014), Oil price scenarios for 2015 and 2016, in *Oil Price*, December 17, <http://oilprice.com/Energy/Oil-Prices/Oil-Price-Scenarios-For-2015-And-2016.html>
- Milan, M. (2016), Crude oil demand expected to grow from road transportation, <http://marketrealist.com/2016/01/crude-oil-demand-expected-grow-road-transportation/>
- Morse, E.L. (2013), Energy is a water-intensive industry, *Oil*, pp. 28–30.
- NBR (2015), Regional perspectives on trends in global oil markets, www.nbr.org/downloads/pdfs/eta/pes_2015_briefs.pdf
- OPEC, <http://woo.opec.org/index.php/oil-supply-and-demand-outlook-2040/data-download>
- Plummer, M. (2015), Conventional vs. unconventional oil, in *Oil and Gas Investor*, January 28, www.oilandgasinvestor.com/blog/conventional-vs-unconventional-oil-780801#p=full
- PSAC (2013), Conventional vs. unconventional resources, www.oilandgasinfo.ca/wp-content/uploads/Nov_2013_conv_vs_unconv.pdf
- Rapier, R. (2016), The break even cost for shale oil, in *Forbes*, February 29, www.forbes.com/sites/rrapier/2016/02/29/the-break-even-cost-for-shale-oil/#3c485864e792
- Riley, A. (2012), The geostrategic implications of the shale gas revolution, www.gov.uk/government/uploads/system/uploads/attachment_data/file/224434/evidence-alan-riley.pdf
- Ross, M. L. (2012), The past and the future of the oil curse, *Oil*, pp. 18–21.

Saudi Arabia's vision to 2030, National transformation program 2020,
http://vision2030.gov.sa/sites/default/files/NTP_En.pdf

Statoil (2013), Understanding the resources.

Sticanti, M. & Al Omran, A. (2016), Saudia Arabia approves economic reform program, April 25,
www.wsj.com/articles/saudi-arabia-approves-economic-reform-program-1461588979

The Economist (2016), The oil conundrum, June 21,
www.economist.com/news/briefing/21688919-plunging-prices-have-neither-halted-oil-production-nor-stimulated-surge-global-growth

The Economist (2016), Who's afraid of cheap oil? January 23rd,
www.economist.com/news/leaders/21688854-low-energy-prices-ought-be-shot-arm-economy-think-again-whos-afraid-cheap?zid=298&ah=0bc99f9da8f185b2964b6cef412227be

Walker, S. et al., (2015), Recession, retrenchment, revolution? Impact of low oil prices on oil powers, December 30, www.theguardian.com/business/2015/dec/30/oil-iran-saudi-arabia-russia-venezuela-nigeria-libya

Williams, S. (2015), Oil exploration companies scramble to cut costs, in *Wall Street Journals*, August 27, www.wsj.com/articles/oil-exploration-companies-scramble-to-cut-costs-1440676162

Wood Mackenzie (2016), Deferred upstream projects tally reaches 68, January 14,
www.woodmac.com/media-centre/12530462

Wood Mackenzie n.d. Oil markets: the rebalancing begins,
www.cfasociety.org/calgary/Documents/Wood%20Mackenzie%20-%20Oil%20market%20rebalancing%20begins_09%20Feb%202016.pdf

World Economic Forum (2016), Future of oil & gas,
www3.weforum.org/docs/GACFutureofOilandGas_Executive_Summary.pdf

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**World Energy
Resources
Natural Gas | 2016**

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KEY FINDINGS

1. Natural gas plays a significant role in the global energy mix. It is the number three fuel, reflecting 24% percent of global primary energy, and it is the second energy source in power generation, representing a 22% share.
2. Natural gas has the potential to play a significant role in the transition to a cleaner energy future due to its high energy content, which results in lower emissions of carbon and volatile organic compounds (VOCs) at combustion, relative to coal and oil. These characteristics of gas provide substantial environmental benefits such as improved air quality, and reduced CO₂ emissions.
3. Demand projections for natural gas exports to Asia, particularly China and Japan, have been revised down as importing nations push to improve energy security and reduce the impact of volatile commodity markets on domestic energy prices.
4. In particular, unconventional gas, shale and CBM, reflected more than 10% of global gas production in 2014 and is entering global markets as LNG, disrupting the global supplier landscape and creating increased competition in regional natural gas markets.
5. The shifting dynamics in natural gas pricing in recent years can be attributed to regional supply and demand imbalances. North America prices collapsed in 2009, driven by a domestic oversupply, while from 2011-2013, the Japanese nuclear drove prices sky high in Asia.
6. Currently, the fall in demand in Asia and growing export capacity in Asia and North America, have created an oversupply globally. As further supplies come to the market, it appears likely that the current market oversupply and low price environment will continue in the short to medium-term.
7. Opportunities (Headwinds)
 - Advances in supply side technologies have changed the supply landscape and created new prospects for affordable and secure supplies of natural gas.
 - Natural gas markets are becoming more interconnected as a result of gas-to-gas pricing, short-term trade and consumer bargaining power.
 - In meeting COP21 objectives, gas has a key role to play in displacing more carbon intensive fuels in both transport and power generation, especially in rapidly growing economies.

8. Challenges (Tailwinds/chokepoints)

- The future of demand is highly uncertain at current prices. Policy support and reduced cost structures for natural gas projects are needed for gas to become more competitive in importing regions.
- Infrastructure build-out, government support and the closure of regulatory gaps are needed to unlock the socioeconomic and environmental benefits of natural gas.
- Several technologies exist today to create new markets for gas, but many require support from governments to penetrate markets.

INTRODUCTION

Natural gas is the only fossil fuel whose share of the primary energy mix is expected to grow. However, the “Golden Age of Gas” that was once predicted, has failed to take off due to slower demand growth than expected. Whereas in 2013, the market needed more natural gas, namely liquefied natural gas (LNG) to respond to the Japanese nuclear crisis, in 2016, demand for natural gas has slowed in Asia and declined in Europe.

Upstream oil and gas companies in Australia, the Middle East, Africa, and North America who bet on old forecasts for Asian demand growth, capitalized on the period of high commodity prices and large capital budgets to drive technological advances. In particular, advances in the unconventional gas process, enabled suppliers to develop reserves that were once deemed too expensive. New supplies are emerging at a time when demand is slowing, and suppliers with large inflexible investments in natural gas assets are scrambling to stay afloat.

Natural gas has the potential to play an important role in the world’s transition to a cleaner, more affordable and secure energy future. In developing regions, such as sub-Saharan Africa and India, natural gas can be used to electrify growing communities. As the lowest carbon emitting fossil fuel, natural gas also has the potential to serve as a cleaner source of baseload power.

However, natural gas faces a variety of technical, socio-economic and environmental challenges. For example, in importing nations, the economic risks of import dependency and exposure to volatile commodity prices make gas a less attractive fuel source. Industry and regulators have also not managed to fully address issues with land-use, water management, air pollution and methane emissions associated with unconventional gas supplies.

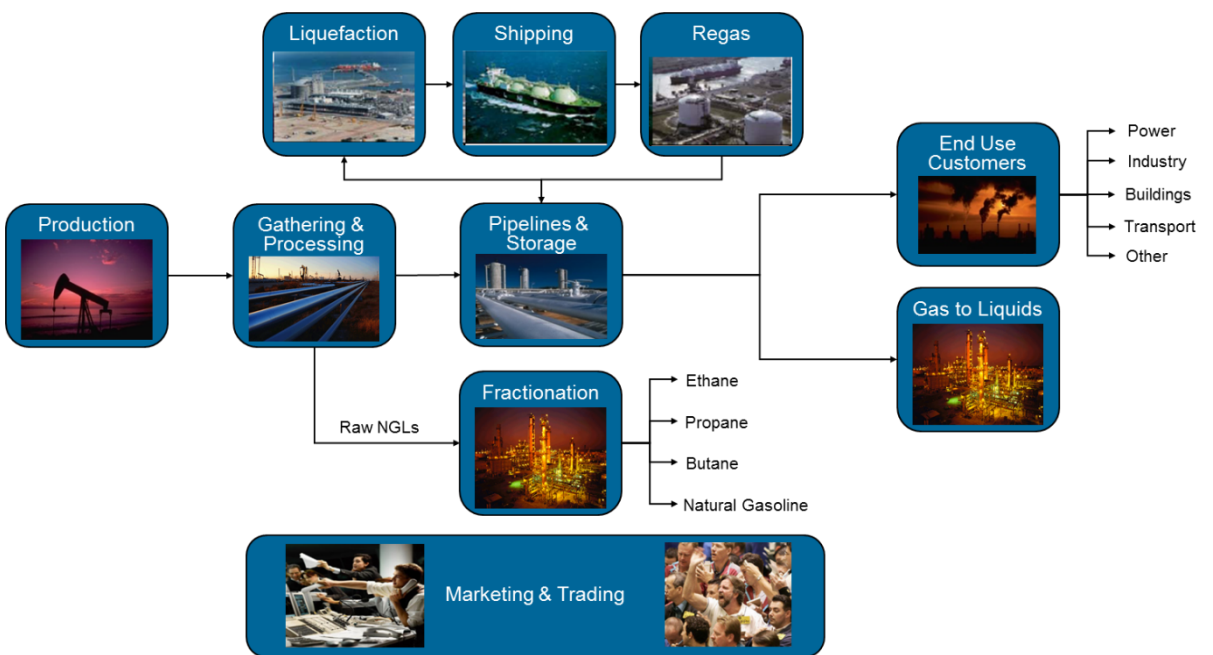
This chapter will summarise key technical, economic, socio-economic, and environmental themes emerging in natural gas. It concludes with an outlook on the future for natural gas. As further supplies come to the market, it appears likely that the current market oversupply and low price environment will continue in the short to medium-term. Whether or not natural gas can achieve price competitiveness will play a significant role in the future demand for natural gas.

1. TECHNOLOGIES

This section will highlight a selected set of technological advances in natural gas.

NATURAL GAS VALUE CHAIN

FIGURE 1: NATURAL GAS VALUE CHAIN



Source: Accenture

Figure 1 outlines the major components of the natural gas value chain. This value chain illustrates that many technology factors impact the transition from production to end use by consumers. Natural gas trade plays a crucial role in the value chain as the supply of natural gas is oftentimes not in the same location as the demand. Additionally, the financial trade of natural gas has also increased in importance and application in recent years.

Exploration and production

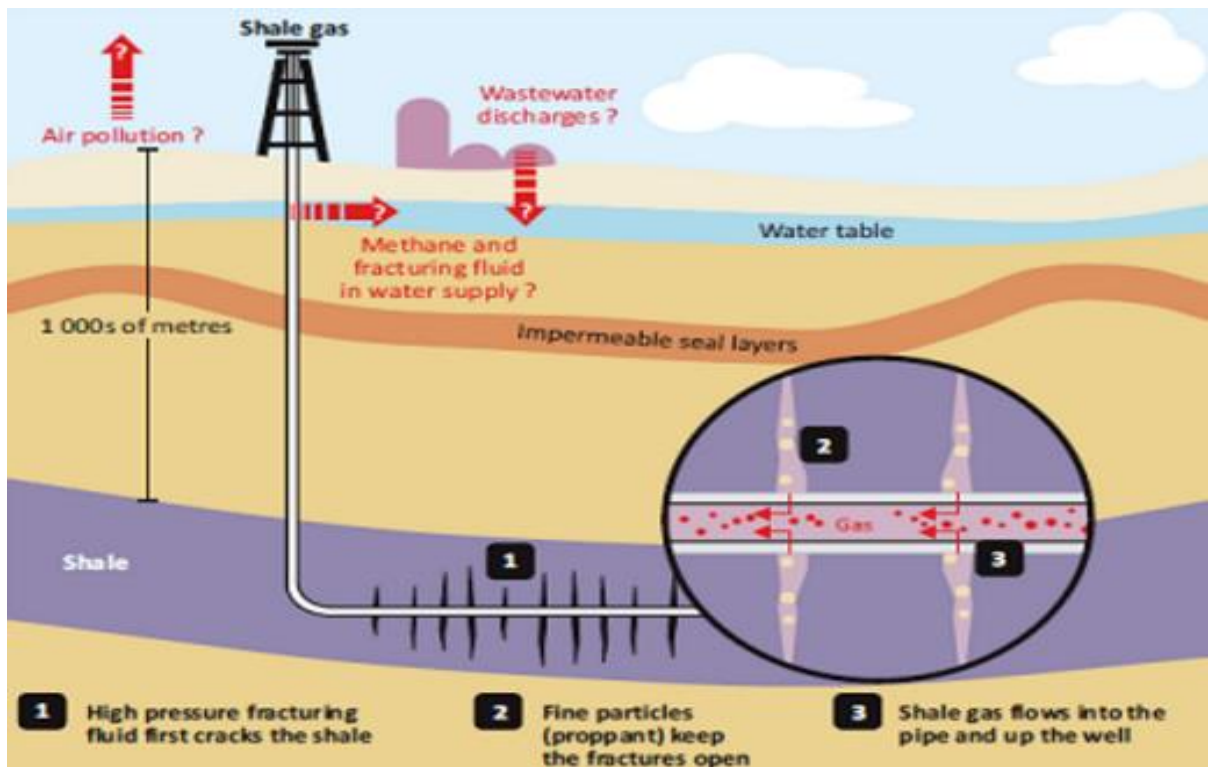
One of the most important recent technological breakthroughs in natural gas development is the progress seen in the drilling and production of unconventional resources. Developments in upstream unconventional gas operations have created substantial

potential for added natural gas supplies. The most impressive results to date are in the US, where in 2015, natural gas production in the US's top seven shale basins reached 461 billion cubic metres (bcm).¹ Additionally, unconventional gas development has made significant progress in Australia, China, and Argentina.

Shale gas

The shale gas value chain consists of additional processing compared to the conventional gas value chain. The drilling process involves many more wells than in a conventional operation and involves multiple rigs for vertical and horizontal well drilling. The completion process requires additional stimulation via hydraulic fracturing. There are many more hand-offs and there is much higher logistical complexity involved in managing materials and equipment on site.

FIGURE 2: SHALE GAS VALUE CHAIN



Source: International Energy Agency (IEA) golden rules for a golden age of gas

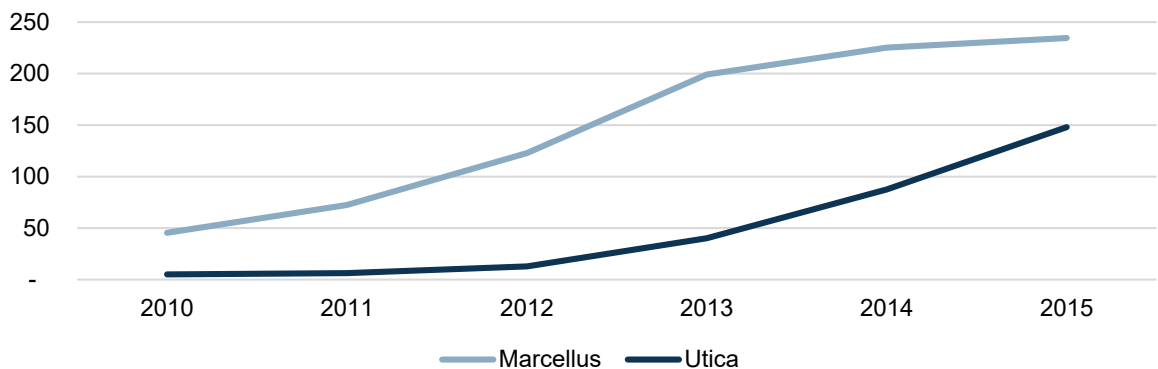
¹ EIA (2016) Drilling Productivity Report

Leading companies have been able to apply technology innovation and manufacturing principles to drive significant time, and therefore cost, improvements in shale and tight oil operations. Cost reductions are driven by reduced drilling and completion times, lower total well costs, and increased well performance (Figure 3).

Drilling technology improvements include longer laterals, improved geosteering, increased drilling rates, minimal casing and liner, multi-pad drilling, and improved efficiency in surface operations. Completion technology improvements include increased proppant volumes, number and position of fracturing stages, shift to hybrid fluid systems, faster fracturing operations, less premium proppant, and optimisation of spacing and stacking.

Looking forward, well costs will trend higher as service companies cut back on discounts in a sustained low price climate. However, the combination of cost reduction and productivity improvements mean that collectively, the unit cost of production in US\$/boe will continue to trend downward.²

FIGURE 3: NEW WELL NATURAL GAS PRODUCTION IN THE MARCELLUS AND UTICA BASINS PER RIG (MCF/D)



Sources: Accenture analysis and us energy information administration (EIA) drilling productivity report

Unconventional projects are considered highly flexible, mainly due to the ability to hold inventory in the form of uncompleted wells. Drilling wells without completing them provides unconventional operators with the flexibility to complete wells and increase supply only when prices are attractive. As of June 2015, the EIA estimated that there are between 2,000 and 4,000 uncompleted wells in the United States representing about 250,000 bpd of production.³

² EIA (2016) Trends in U.S. Oil and Natural Gas Upstream Costs

³ Nülle (2015) Tight Oil Production Trends in a Low Price Environment, EIA

Advancements in technology and efficiency also translate to smaller "footprints", less waste generated, cleaner and safer operations, and greater compatibility with the environment. Section 5, titled Environmental Impacts, discusses in more detail the technologies that can be used to improve water management, methane leakage, and air pollution from operations.

Coal bed methane (CBM)

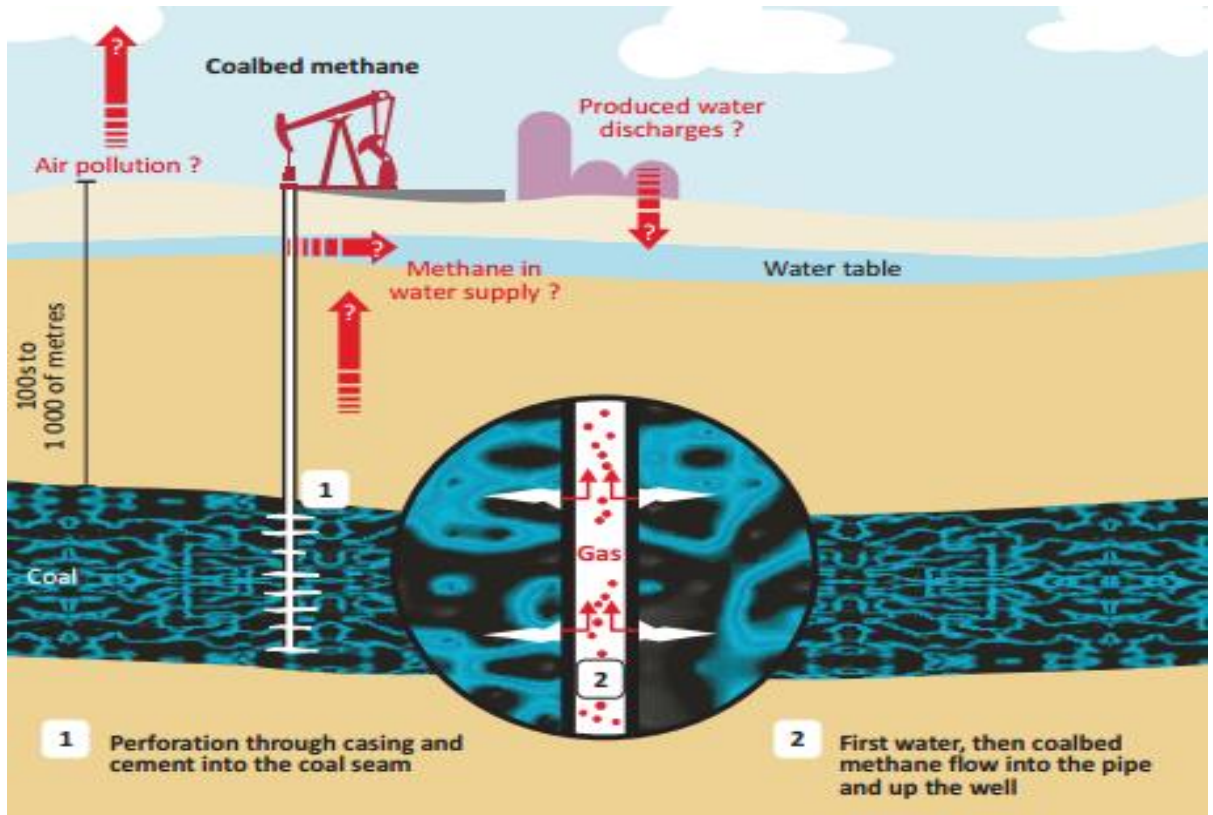
CBM production began as a coal mine degasification and safety technique developed in the US during the 1970's. In 2016, CBM production is commercially well established in several countries and successful production is occurring from a wide range of coal types, ages, and geologic settings. However, in all cases the keys to commercial success are favourable geologic conditions (good coal thickness, gas content/saturation, and permeability); low capital and operating costs; and favourable gas markets and sales prices.

Like shale gas, CBM operations require additional stimulation in the completion process. This technology, has proven most effective in the US, Canada, and Australia, though China, and India also have operations in play. Indonesia also has strong potential for CBM developments due to a very high reservoir quality. Australian operations have been particularly successful and are set to surpass US production by 2020. As of June 2015, Queensland Australia had ~1,141 bcm of CBM reserves. In 2014, Queensland Australia produced ~12.2 bcm of CBM⁴ and China produced 3.6 bcm of CBM. The Chinese Ministry of Land and Resources (MLR) targets production of 30 bcm/year by 2020.⁵

⁴ Queensland Australia (2016) Queensland's petroleum and coal seam gas 2014-2015, Australia.

⁵ Platts (2015) China's 2014 Unconventional Gas Output Soars 42% on Year to 4.9 BCM

FIGURE 4: COAL BED METHANE (CBM) VALUE CHAIN



Source: IEA golden rules for a golden age of gas

Australia is also a pioneer in utilising CBM as a feedstock for liquefied natural gas (LNG exports). The country has started up three CBM to LNG projects since 2014. These three projects (QCLNG, APLNG, and Gladstone LNG) currently represent 21.4 million tonnes per annum (mtpa) of export capacity.⁶ Looking forward, technical advances will continue to improve the economics of the process, and technology holds the best hope for process viability in the future.

Small scale LNG

LNG import terminals and liquefaction plants with a regasification or liquefaction capacity less than 1 mtpa is Small Scale LNG (SSLNG). Other elements of the SSLNG market are bunkering facilities used by LNG fuelled vessels, infrastructure to supply LNG as a fuel for road vehicles and LNG satellite stations. The SSLNG market is developing rapidly,

⁶ BG Group, QCLNG Fact Sheet.
Australia Pacific LNG (2013) The Australia Pacific LNG Project.
Bechtel (2015) Bechtel Delivers First Cargo of LNG for Santos GLNG Project.

especially as a transportation fuel and to serve end users in remote areas or not connected to the main pipeline infrastructure. Significant SSLNG import, break bulk and regasification is already present in China, Japan, Spain, Portugal, Turkey and Norway. Global installed capacity of SSLNG is 20 mtpa across more than one hundred facilities. Further, many terminals are expanding services to include small-scale reloading and bunkering.⁷

Most demand growth for SSLNG is in China where efforts are in place to get clean fuels to fight air pollution in cities. In the US, the price differential between oil and gas is the primary driver for SSLNG. With the abundance of shale gas in the region, prices favour gas over other fuels in transport and power. Stricter regulations on the marine sector are stimulating the use of SSLNG as bunker fuel in Europe and North America. In Latin America, the drivers include monetizing stranded gas supplies and reaching remote consumers.

A transparent and profitable business model is needed to make SSLNG viable. The supply chain is not always economic due to the small scale nature of the deliveries and the relatively small size of the market. However, as technology solutions mature, standardisation, modularisation and therefore competitiveness are expected to increase.⁸

FLOATING TECHNOLOGIES

In the midstream sector, floating technologies are emerging as a flexible solution for importers and exporters who are venturing into the LNG market.

Floating liquefied natural gas

Since 2014, 69 MTPA of floating liquefaction capacity has been proposed globally. Four projects have been sanctioned, accounting for 8.7 MTPA of capacity. Many FLNG proposals announced in the past few years aim to market gas from smaller, stranded offshore fields, which become less attractive in a low price climate, especially when compared to brownfield projects as evidenced in Figure 5. As a result, in the short-term, FLNG project development is expected to slow.

TABLE 1: FLNG PROJECTS UNDER CONSTRUCTION

Project	Country	Capacity (mtpa)	Targeted start-up
Cameroon FLNG	Cameroon	1.2	2017
Caribbean FLNG	TBD	0.5	2016

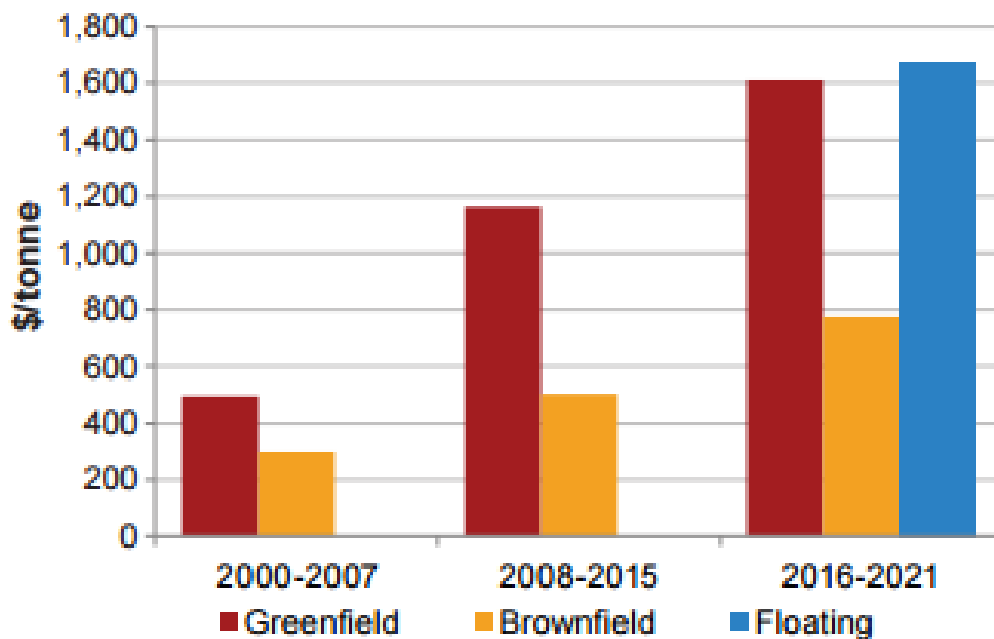
⁷ International Gas Union (2016) World LNG Report

⁸ International Gas Union (2014) Small Scale LNG (SSLNG)

PFLNG SATU	Malaysia	1.2	2016
PFLNG 2	Malaysia	1.5	2018
Prelude FLNG	Australia	3.6	2017

Sources: International Gas Union (IGU) (2015) World LNG Report, Petronas, Golar LNG, and IHS

FIGURE 5: AVERAGE LIQUEFACTION UNIT COSTS 2000-2020 (\$/TONNE)



Source: IGU (2016) World LNG report

Floating regasification

Floating regasification continues to gain popularity as new importers enter the LNG market. Seven new terminals, reflecting 20.4 Mtpa of capacity began commercial operations during 2015, bringing global floating regasification capacity to 77 Mtpa. This accounts for 10% of the total 757 Mtpa in the market. Two floating storage and regasification units (FSRU) were added in Egypt, as well as one in Jordan and one in Pakistan. Four out of the seven new

terminals were FSRUs. Currently, five FSRU projects (in Ghana, Colombia, Puerto Rico, Uruguay and Chile) are in advanced stages.⁹

Challenges of floating technologies

As mentioned previously, the biggest challenge for floating technologies relative to land based technologies is cost. Additionally, there are technical challenges and safety implications of having all the equipment of an onshore LNG processing plant on a vessel that offers roughly one fourth of the space. Separation distances are inevitably reduced and this introduces new risks for operations. The vessel's motion in the water can also create sometimes unpredictable complications for the storage and offloading of LNG. The effects of moving liquids on ships, known as the "sloshing" effect are a well-studied issue for LNG carriers, however when applied to the transfer of LNG from a floating unit to a floating LNG carrier, potentially during rough sea states, the complications grow exponentially. Continued innovation and studies in this space are required to avoid danger and loss of availability in the supply chain.

Additionally, in some cases, political resistance has held back the development of FLNG projects. While the traditional onshore LNG processing option offers a large number of jobs and construction contracts for local people and firms, FLNG plants are built by specialised dockyards, primarily in Korea and China, and manned by specialists; thus they provide far fewer direct economic benefits for the hosting country.¹⁰

DIGITAL PIPELINE INNOVATION

The current global pipeline industry is large and still growing, however it is ripe for innovation as most infrastructure has been in place for decades. For example, 60% of pipeline infrastructure in the US was installed before 1970 and more than 50% of global pipelines were installed between 1950 and 1970.¹¹ This aging infrastructure requires upgrade, particularly as safety concerns become a greater priority. In Europe, projections indicate ~27,610 km of natural gas pipelines will be constructed from 2015-2020, with 71% of this construction in Georgia, Poland, Greece, Russia, and Bulgaria alone.¹²

The penetration of digital solutions to optimise the management of pipelines and plants is revolutionising decision making for pipeline operators. Newfound access to tremendous amounts of near real-time data has the potential to disrupt the midstream sector. Digital solutions are enhancing reliability, providing new ways to evaluate risk, enabling more efficient maintenance, and providing access to new information that can be used to set

⁹ International Gas Union (2016) World LNG Report

¹⁰ Chris (2014) Offshore Technology: does the future float?

¹¹ GE and Accenture (2014) Redefining Pipeline Operations.

GE and Accenture (2014) Redefining Pipeline Operations, Infographic.

¹² Rositano, C (2014) Relying on Russia: an overview of the existing European pipeline industry, Pipelines International.

priorities. Additionally, safety can greatly be improved by allowing proactive maintenance instead of the reactive style commonly used currently.¹³

While digitalisation of pipeline systems creates substantial benefits, it also creates cyber-security risks. The World Energy Council has launched a study on cyber-threats to explore the ways that industry can better mitigate the risks of cyber-attacks.

BIOGAS

Biogas is methane formed through anaerobic digestion. The source material is generally waste such as municipal solid waste in landfills, organic waste in wastewater treatment plants, agricultural plant waste, manure, or food waste. If bio methane waste is not recovered for beneficial use, it is often released as a potent GHG. Capturing and using it has the dual benefit of reducing direct GHG emissions and providing a source of renewable energy.

A transition to biogas methane sources will depend heavily on whether the gas can access pipeline infrastructure to enter markets. Currently, one of the biggest challenges with biogas is bringing the resource to consumers. Landfills or agricultural sites often have minimal energy demand. In other cases, such as a waste water treatment plant, there is sufficient electric and thermal demand for a small CHP facility. In the case where there is no thermal load, a small electric generator may be viable and may be able to sell power to the grid. In most cases, the best alternative will be to feed the biogas into the local natural gas infrastructure, where it can be efficiently sold in the broader gas market. This provides the greatest flexibility for use of the gas and reduces risk of variability in the biogas supply stream.¹⁴ In rural and less connected markets, biogas projects can also play a role in providing micro-grid solutions where natural gas infrastructure does not reach.

POWER GENERATION TECHNOLOGY

Natural gas reflects 22% of global power generation today and is the fastest growing use of natural gas globally. Natural gas power plants usually generate electricity in gas turbines, using the hot exhaust gases of fuel combustion to drive the turbine engine.

Single-cycle gas turbines generally convert the heat energy from combustion into electricity at efficiencies of 35% to 40%. These turbines are highly economic to operate and have the added benefit of being flexible enough to ramp up and down quickly in response to demand fluctuations.

While more expensive to operate, natural gas combined-cycle (NGCC) plants reach efficiencies of 50% or more. NGCC plants first use the combustion gases to drive a gas turbine, after which the hot exhaust from the gas turbine is used to boil water into steam

¹³ GE and Accenture (2014) Redefining Pipeline Operations, Infographic.

¹⁴ International Gas Union (2016) Case Studies Natural Gas and Renewable Energies

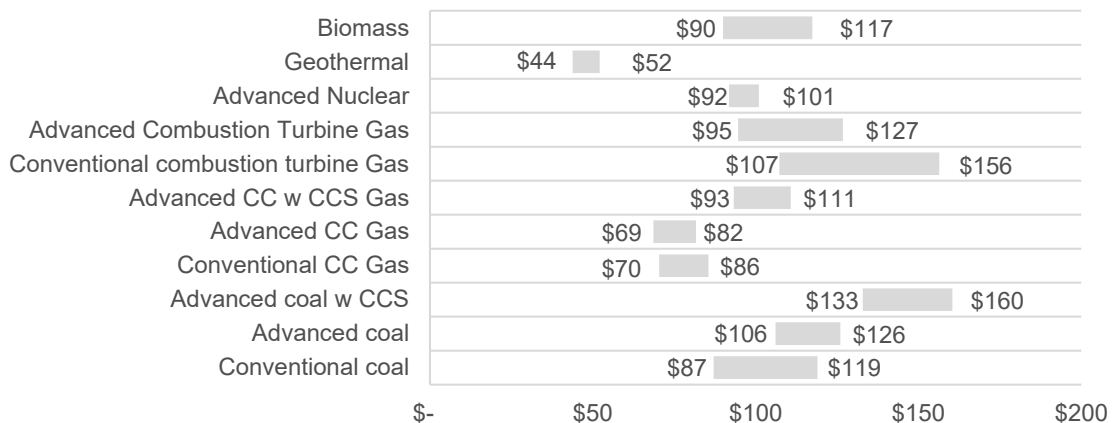
and drive a steam turbine.¹⁵ Many new gas power plants in North America and Europe use combined cycle turbine technologies.

Carbon capture and storage (CCS)

To meet climate targets, CCS is required for coal and natural gas power generation, but absent a CO₂ price or policy mandates, mass adoption will require first mover projects to become commercially viable. Currently 15 projects are operating and seven more are under construction. Three came online in 2015.

In North America, if new laws are enacted, it is highly likely that natural gas CCS projects will lead the way for CCS in the region. The United States Environmental Protection Agency (EPA) has set its first-ever national standards that address carbon pollution from power plants with the Clean Power Plan (CPP) act; the plan requires higher efficiency in coal power generation that essentially mandates carbon capture and sequestration (CCS) on coal plants. The law also establishes a framework to expand standards over time to include natural gas. Although the law has been met with strong resistance and is currently held up in the national court system, the passing of CPP would send strong signals that CCS will eventually be required on both coal and gas generation and given the sheer volumes of natural gas generation in the region, CCS on natural gas plants will be a critical element to meeting these new, more stringent emissions standards. Looking forward, the economics of CCS appear to be more favourable on gas power generation than they are for coal powered generation as exemplified in Figure 6.

FIGURE 6: US UNSUBSIDISED LEVELISED COST OF ELECTRICITY FOR NEW GENERATION SOURCES COMING ONLINE IN 2020



Sources: EIA Annual Energy Outlook (2016)

¹⁵ Union of Concerned Scientists, Uses of Natural Gas

Outside of North America, CCS was dealt a substantial blow in 2015, when the UK government cancelled a £1bn competition for CCS technology just six months before it was due to be awarded. The project was to be the first full-scale commercial natural gas power plant using CCS technology. The plant was originally scheduled to come online in 2018 and would have captured and stored one million tons of CO₂ each year for 10 years.

Power-to-gas conversion

Power-to-gas is a storage solution that can help address grid-stability problems that arise when an increasing share of power is generated from sources that have a highly variable output. The technology is undergoing advanced study and approaching commercial application. A power-to-gas system converts electricity generated during periods of high output and low demand (such as strong wind during off-peak hours) by splitting water molecules into hydrogen and oxygen through electrolysis. The hydrogen is stored for future use as fuel and the oxygen may be sold for industrial use or released into the atmosphere.

There are three potential uses for the stored hydrogen:

- Using hydrogen gas blended with natural gas, or directly, in applications such as power generation or transport fuel
- Feeding fuel cells by injecting hydrogen and oxygen (or air) into the cell to produce a chemical reaction and as a result electricity
- Combining the hydrogen with carbon dioxide to create synthetic methane, which could be used as an alternative to natural gas

The commercial use of power-to-gas technology is primarily being considered in Europe, where it is being reviewed by the European Gas Research Group, as well as the energy departments of several countries. Germany is leading the way, with 18 different experimental programs in progress. Power-to-gas conversion technology is also being evaluated for commercial application in the US by the Southern California Gas Company, in conjunction with the U.S. Department of Energy's National Renewable Energy Laboratory and the National Fuel Cell Research Center at the University of California, Irvine.¹⁶

TRANSPORTATION

Demand from the transportation sector reflects just 3.3% of total natural gas demand, however, natural gas is becoming a more attractive alternative for heavy freight and marine transport. There are substantial economic, environmental and energy security advantages of increasing the utilization of natural gas as a transportation fuel in terms of reducing import dependency and emissions from transport. Additionally, all of the technologies required for a transition exist today: 1) the internal combustion engine (ICE), 2) compressed natural gas (CNG) and 3) liquefied natural gas (LNG). The main choke points are related to

¹⁶ US Energy Information Administration (EIA) (2015) Power-to-gas brings a new focus to the issue of energy storage from renewable sources

the development of infrastructure e.g. pipelines and fuelling stations and finding the optimal mix of transport fuels to reduce the economic burden and maximise emissions outcomes.

Heavy-duty vehicles

The use of LNG and CNG for the heavy duty segment has particular advantages. CNG can now provide 600-mile truck range for long-distance class 7-8 trucking. LNG has two times greater energy density by volume than CNG and provides even longer range. Fuel consumption by heavy duty vehicles is significant due to high annual mileage and low fuel economy, increasing the potential savings and payback period from a fuel cost saving. However, natural gas trucks and buses can cost between US\$30 to US\$70 thousand more than conventional ICE vehicles.

In the US, where natural gas prices are typically 30-50% cheaper per unit of energy than oil, commercial fleet owners who are more focused on life-cycle costs than up-front cost, could see great economic benefits from converting their fleets. LNG technology is more expensive than CNG, but offers higher efficiency and fuel cost savings potentials. Heavy duty vehicles are well-suited to alternative fuel because refuelling takes place at a smaller number of locations, often larger sites outside urban centres. This reduces the infrastructure investment costs to support a material share of fleet.

Marine bunkering

At the moment, LNG is the only marine fuel option that is able to meet existing and upcoming requirements for the main types of emissions (SO_x, NO_x, PM, CO₂) in the MARPOL Annex VI regulations without using marine gas oil. This coupled with a well-supplied global LNG market and increasing plans for LNG bunkering infrastructure in Europe¹⁷ and Asia, has created increasing interest in LNG as a marine transport fuel. Currently, the market is dominated by energy carriers. Shell has one of the largest fleets in the world, operating 44 of the approximately 70 LNG fuelled vessels of all sizes on the global market.

Europe is leading the way with infrastructure build. Between 2015 and 2018, eight projects will come online to supply LNG bunkering loading for vessels¹⁸. Although with low oil prices, current diesel to gas economics, do not favour gas, many vessel owners are taking a long term view on the economics of fuel options, and LNG is well positioned as widely available and affordable energy resource for marine transportation.

CHEMICALS

Industrial natural gas consumption has grown steadily in North America and the Middle East, as relatively low natural gas prices supported the use of natural gas as a feedstock for the production of bulk chemicals.

¹⁷ Gas Infrastructure Europe www.gie.eu/index.php/maps-data/gle-sslng-map

¹⁸ Ibid 17

In the US, industrial facilities, including methanol plants and ammonia or urea-based fertilizer plants, consumed an average of 21.0 billion cubic feet per day (Bcf/d) of natural gas in 2014, a 24% increase from 2009. By the end of 2015, industrial natural gas consumption reached annual average of 21.7 Bcf/d (3.4% above 2014 consumption). Industrial natural gas consumption is expected to increase by another 3.9% in 2016, to an average of 22.5 Bcf/d.¹⁹

Chemical companies use ethane, a natural gas liquid derived from shale gas, as a feedstock in numerous applications. Its relatively low price gives manufacturers an advantage over many competitors around the world who rely on naphtha, a more expensive, oil-based feedstock.

The ratio of the benchmark price of oil to the price of natural gas serves as a real-time proxy for competitiveness, as ethane and naphtha prices are not always readily available. A rough rule of thumb is when the ratio falls below seven, production of ethylene (and its resin derivatives) is relatively disadvantaged, as was the case during much of the 2000s in the US. When the ratio rises above seven, however ethane based petrochemicals are relatively advantaged.

¹⁹ Energy Information Agency (2015) New methanol and fertilizer plants to increase already-growing industrial natural gas use

2. ECONOMICS & MARKETS

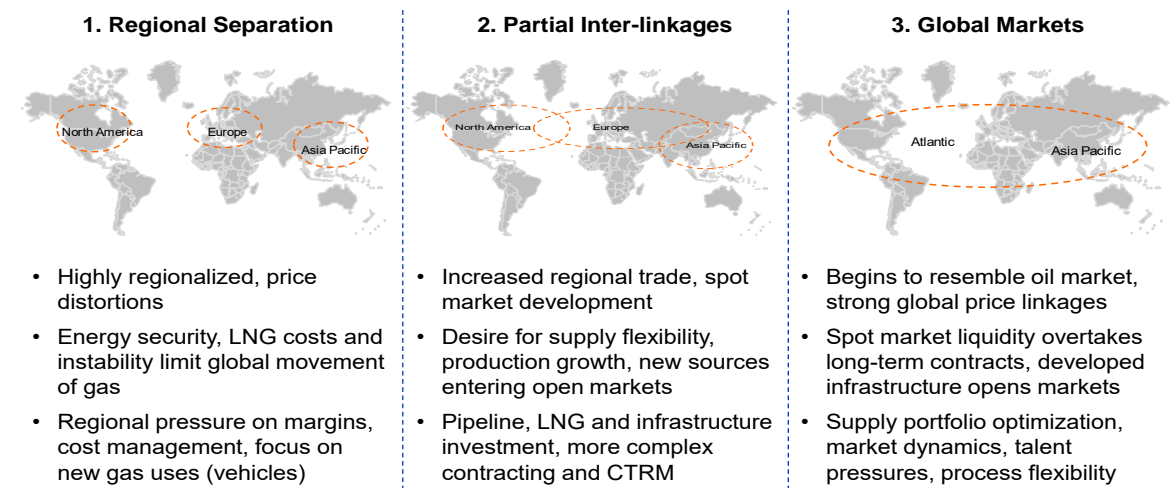
This section will explore economic trends in natural gas markets, and will explore potential outcomes for how market structures will evolve for the industry.

GLOBAL, REGIONAL AND DOMESTIC MARKETS

Natural gas markets have historically operated as three relatively dislocated major regional markets: North America, Europe and Asia. This market structure was driven by the regional nature of pipeline trade, which reflects more than 90% of global natural gas trade. The chart below compares the characteristics of 1) Regionally dislocated/separate, 2) Partially linked and 3) Global natural gas markets. Current market dynamics indicate, natural gas has shifted from separated natural gas markets to markets that are partially linked (one to two), but several uncertainties make it unclear whether this trend will continue or if a global natural gas market will emerge.

Natural gas pricing structures vary significantly across regions currently, and in all three of the key regions, markets are undergoing transformational change. The following sections will provide a brief summary of each of the three major markets.

FIGURE 7: MARKET TRANSITIONS



Source: Accenture research

Source: Accenture strategy

North America

The North America natural gas market is backed by a mature and well integrated physical and financial market structure and substantial domestic natural gas production. Imports have historically faced competition from domestic supplies, which are priced in established trading hubs based on the supply and demand of natural gas in the region.

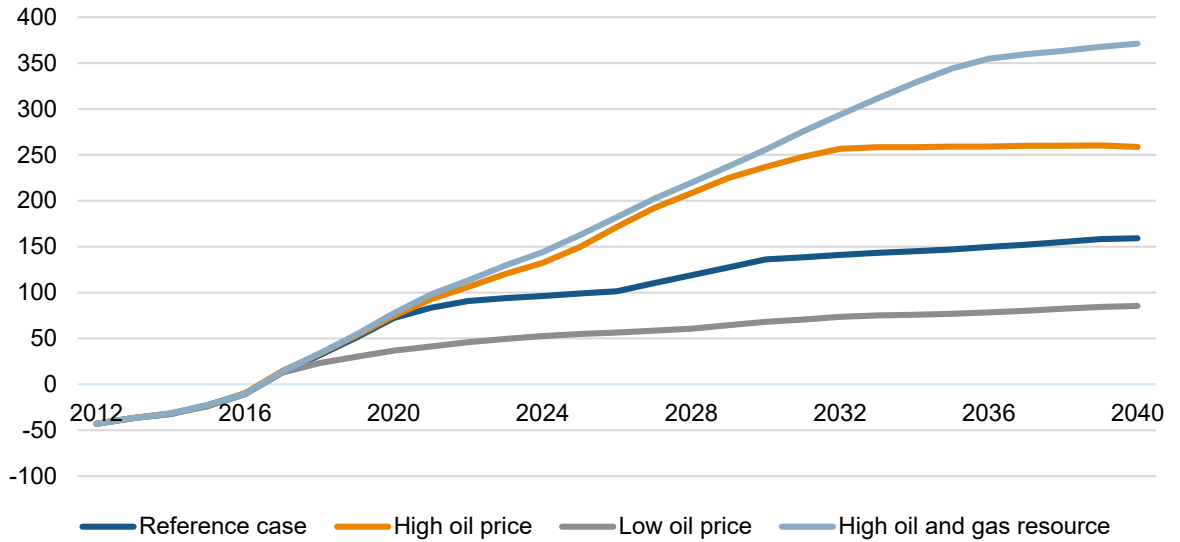
North America is both a large consumer and producer of natural gas, and is dominated by US supply and demand dynamics. The US is currently the world's largest producer and consumer of natural gas globally. Gross production reached ~933 bcm in 2015²⁰, with 49% of this total produced in the nation's top seven unconventional basins.²¹ With the rise of unconventional gas production, supply growth has outpaced demand growth since 2008, resulting in a regional supply glut and a collapse in prices.

Companies and investors looking to capitalise on natural gas price arbitrage opportunities in Europe and Asia, and backed by Asian consumers looking to reduce the premium paid on imported LNG, invested in developing LNG export facilities to enable the movement of US and Canadian natural gas supplies to Asian consumers. The US is now set to become a net exporter before 2020. Later sections of the paper will discuss how this transformation will influence pricing mechanisms in Europe and Asia.

²⁰ EIA (2016) Natural Gas Gross Withdrawals and Production.

²¹ EIA (2016) Monthly Natural Gas Gross Withdrawals, Average of Monthly Production.

FIGURE 8: US NET NATURAL GAS EXPORTS 2012-2040F (BCM)



Source: EIA (2015) Annual energy outlook

Europe

Europe is a mature market, characterised by both intra-regional supplies (~40%) and substantial imports of pipeline gas and LNG (~60%). The liberalisation of the EU’s energy markets in the 1990s made the energy sector more competitive and resulted in increased gas-on-gas competition and led to the emergence of established natural gas trading hubs in the UK, Germany, France, Italy, Belgium, and the Netherlands²².

Europe was the world’s top interregional natural gas importer in 2014, importing 236 bcm from other regions. More than 60% of all imported gas came from Russia via pipeline and 73% of LNG imports were imported from Algeria and Qatar. The European Commission has pushed to diversify the European natural gas supply base in order to improve regional energy security, however, the concentration of Russian imports as a share of total imports has increased in recent years, even as Russian imports overall have declined.²³ Looking forward, cheap LNG supplies from the US and Australia, may offer an opportunity to diversify the European natural gas supply-base.

²² Petrovich (2013) European gas hubs: how strong is price correlation? Oxford Institute for Energy Studies.

²³ Shiryayevskaya (2015) Cheap Russian Gas Tempts EU Buyers as LNG Import Growth Stalls, Bloomberg Business.

European natural gas demand declined for four consecutive years in the period from 2010-2014, reaching 386.9 bcm in 2014, an 11.6% decline over 2013.²⁴ This decline is due to dampened economic growth in the region, geopolitical tensions with Russia, and competition from substitutes such as cheap coal from the US and subsidised renewable energy sources.

Asia and Pacific

Asia has historically relied on oil and coal for energy, but in recent years, it has become the dominant LNG importing region, accounting for ~75% of all LNG imports in 2014²⁵. Key import and export hubs in Asia have very different market structures and dynamics. Japan and S. Korea are well-established, isolated, LNG supplied, and have limited growth opportunities. China and India are emerging markets who plan to obtain supplies through both LNG and pipeline trade.²⁶ Ultimately, this lack of integration means there is no dominant LNG hub in Asia today.

PRICING MECHANISMS

Gas to gas pricing

In North America, where domestic gas competes in mature physical and financial trading hubs, pricing has been historically driven by the mechanics of supply and demand of natural gas.²⁷ The European and Asian markets, were originally rooted in a bilateral-oligopoly pipeline structure that priced gas relative to oil (oil indexation) using long-term contracts.

In Europe, gas-on-gas pricing only represented 7% of pipeline gas trade in 2005, but in 2014, 62% of pipeline gas traded and more than 50% of all natural gas (pipeline and LNG) traded was priced based on gas indexed pricing mechanisms.²⁸ This is due largely to the evolution of several key hubs in the region and market integration spurred by market reforms in the 1990s, which enabled gas-on-gas competition and price transparency in the region.

In Asia, where natural gas is largely imported as LNG, oil indexation remains dominant. This is in part due to a differing market structures and a lack of price transparency and gas-on-gas competition in the region. However, with the current oversupply in the market, a move away from oil indexed pricing models is increasingly apparent. US LNG contracts, which are largely priced with a formula indexed to Henry Hub prices, now reflect the equivalent of 20% of Japanese LNG imports.²⁹ Industry reports also indicate that in 2015,

²⁴ BP (2015) BP Statistical Review of World Energy

²⁵ <http://www.bg-group.com/480/about-us/lng/global-lng-market-outlook-2014-15/>

²⁶ Asian Gas Hub

²⁷ IGU (2015) World Energy Report

²⁸ Platts (2015) Gazprom, Oil-link vs Spot Gas Prices, and Storage

²⁹ Ministry of Economy, Trade and Industry (2015) FY 2014 Annual Report on Energy (Energy White Paper 2015)

there was a pronounced move away from traditional oil indexation to hub-linked pricing and hybrid indexation more broadly in Asia.³⁰

Growing liquidity

Historically, natural gas was traded via long-term contracts (LTCs) to protect consumers from sudden price spikes and to provide security of supply for large importers. LTCs also reduced uncertainty for suppliers making long-term investment decisions. However, since 2010 short-term LNG trade has grown rapidly, driven mostly by Asia Pacific where demand for Spot LNG trade tripled between 2010 and 2014, representing 21% of all global LNG trade in 2014. In 2016, with an oversupplied market, and therefore increased liquidity, short-term trade becomes less risky and a more attractive option for consumers who are unhappy with their current LTCs. Large consumers are likely considering whether to renew LTCs or increase their exposure to the spot market.

Growing consumer bargaining power

Gas-on-gas competition and a more liquid market create the bargaining power for consumers to push back on current market structures and negotiate more flexible contract terms. In 2015, two of the largest utilities in Japan, the number one importer of LNG, said they will no longer sign contracts that restrict reselling cargoes by limiting the destination of shipments they buy.³¹ China Petroleum and Chemical Corporation (Sinopec) was believed to be pursuing changes to contract terms for cargoes from APLNG, its joint venture with

ConocoPhillips and Origin Energy in Queensland Australia.³² India also sought to renegotiate LNG prices with its biggest supplier, Qatar.³³

In Asia, the arrival of US LNG could create the necessary liquidity and competition to establish regional natural gas pricing hubs. China, Japan, and Singapore are all taking steps to launch benchmarks against which both spot and LTCs can be priced. Singapore is expected to launch its first futures and swaps contracts in early 2016 that will be priced against a new benchmark, the Singapore SLInG (after the city's famous cocktail).³⁴ As Asian hubs evolve, pricing will grow to reflect the supply and demand.

Market interconnectedness

Despite the differences in pricing mechanisms across regions, regional prices tended to follow each other relatively closely until 2008 when the North America supply glut led to regional market dislocation and record spreads between the US Henry Hub price and major hubs in Europe and Asia. In 2016, with lower oil prices and weakened Asian demand, the spread between Japanese LNG and United Kingdom (UK) natural gas prices is narrowing.

³⁰ Wood Mackenzie (2015) The stakes are high as LNG players plan their next move

³¹ Stapczynski, S, Inajima, T, and Urabe, E, (2015) Buyers Market for LNG Turns Tables on Producers Amid Supply Glut, BloombergBusiness.

³² Petroleum Economist (2015) Sinopec rattles Origin and ConocoPhillips.

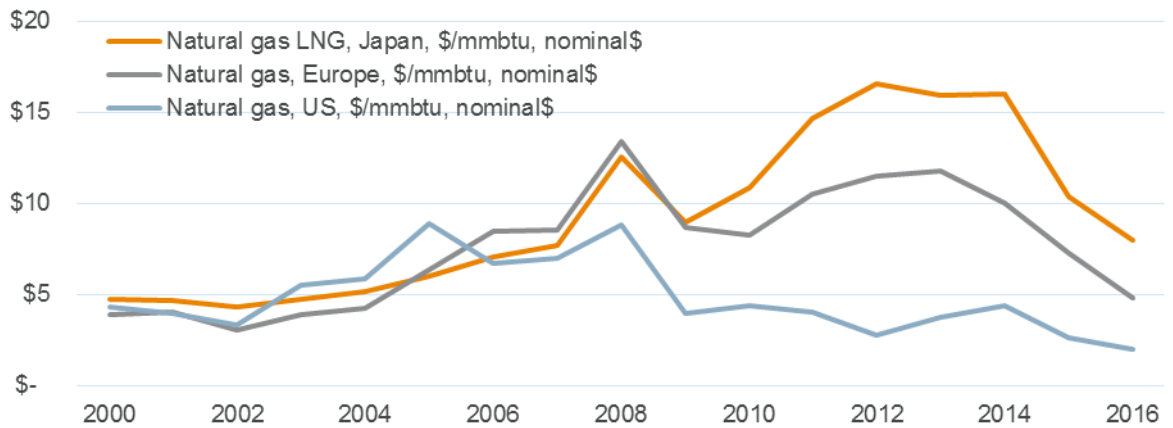
³³ The Economist Intelligence Unit (April 2015) India seeks to renegotiate major LNG contract with Qatar

³⁴ Energy Market Company (2015) SLInG.

The Wall Street Journal (2015) Singapore LNG Futures Could Launch Next Month.

US prices, however, remain significantly depressed due to the continued build-up of domestic supplies.

FIGURE 9: NATURAL GAS PRICES AT MAJOR HUBS (\$/MMBTU) (2000-Q12016)



Source: World Bank (April 2016) Commodities Price Data, The Pink Sheet

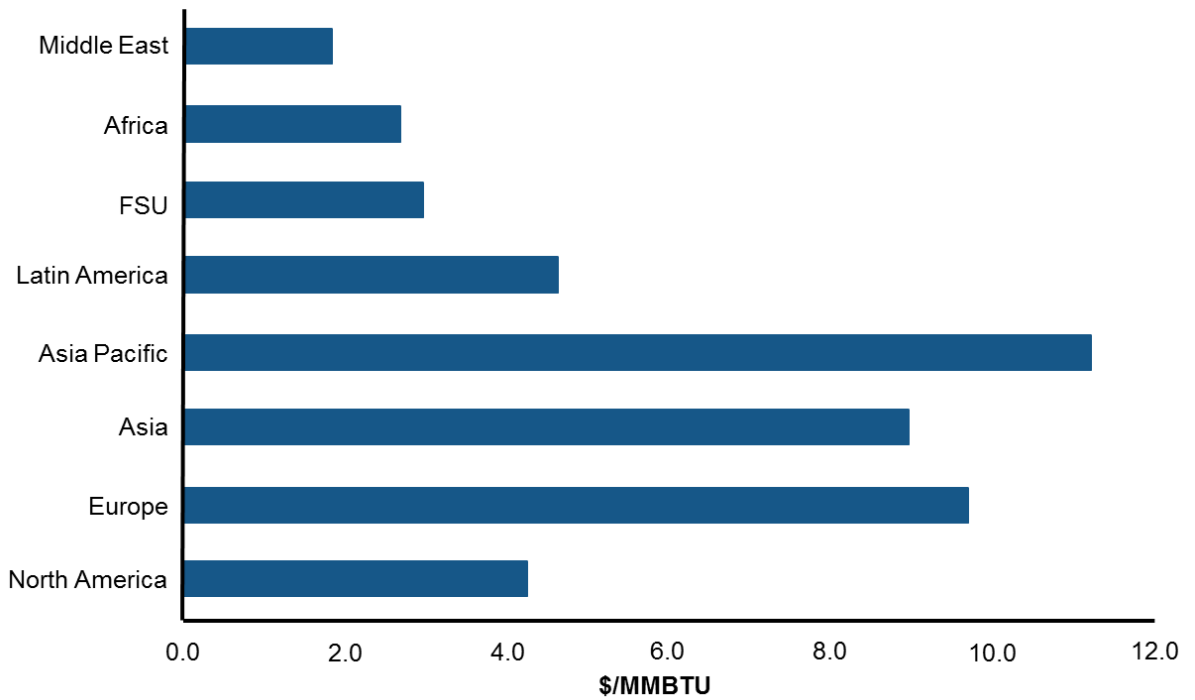
As more and more Australian and US LNG hit the global market, gas on gas competition and liquidity will grow, and there is potential for Asian, European and North American gas prices to converge. Additionally, the export of LNG from the US will serve as a release valve for the build-up of supply that has kept prices depressed in North America since 2008.

Wholesale prices

As a result of the regional nature of global natural gas markets, there is wide disparity in wholesale natural gas prices across regions, with importing regions, especially Asia Pacific and Europe, paying higher prices than resource rich regions as evidenced in Figure 10.³⁵

³⁵ IGU (2015) Wholesale Gas Price Survey

FIGURE 10: AVERAGE WHOLESALER NATURAL GAS PRICE BY REGION 2014



Source: IGU (2015) Wholesale Gas Price Survey

DRIVERS AND KEY DYNAMICS

The shifting dynamics in natural gas pricing in recent years can be attributed to regional supply and demand imbalances. North America prices collapsed in 2009, driven by a domestic oversupply, while from 2011-2013, the Japanese nuclear prices drove prices sky high in Asia. Currently, the fall in demand in Asia and growing export capacity in Asia and North America, have created an oversupply globally. Looking forward, the challenge will continue to be moving natural gas from supply to demand centres.

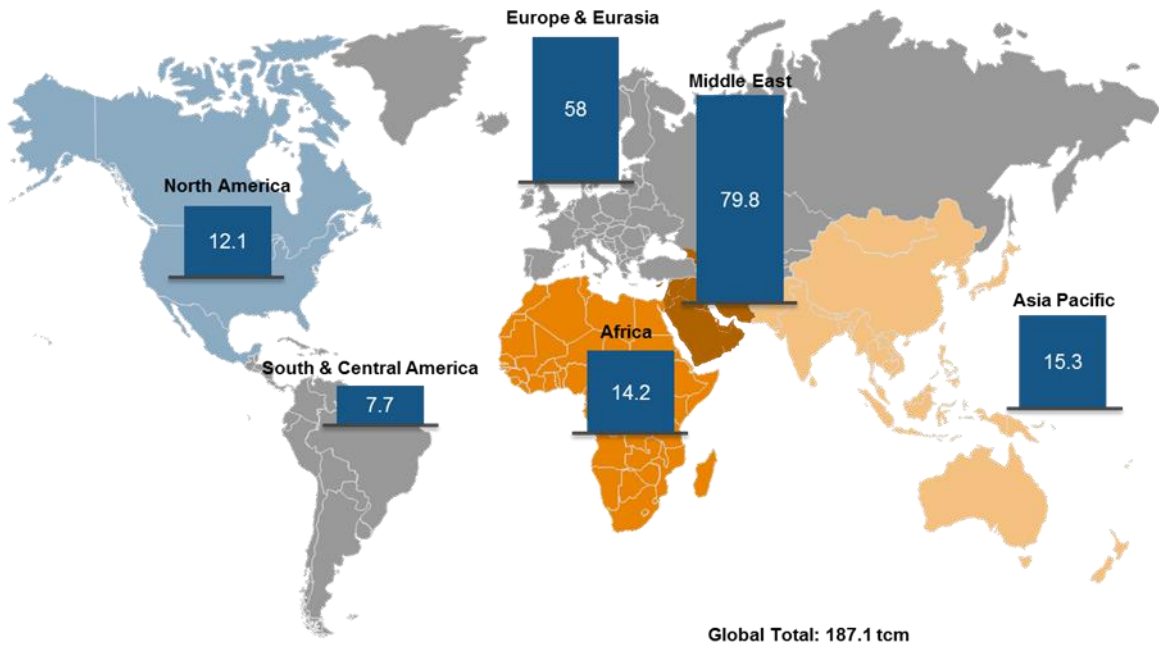
Supply

Reserves

Improvements in exploration and production technology enabled the growth of proved natural gas reserves in the last decade. Namely from unconventional sources. In 2014, there were 187.1 tcm of proved natural gas reserves, a 19.5% increase over 2004 levels. A

majority of these proved reserves are in the Middle East and Russia, with 79.8 tcm and 32.6 tcm of proved natural gas reserves respectively.³⁶

FIGURE 11: GLOBAL PROVED NATURAL GAS RESERVES 2015 (TCM)



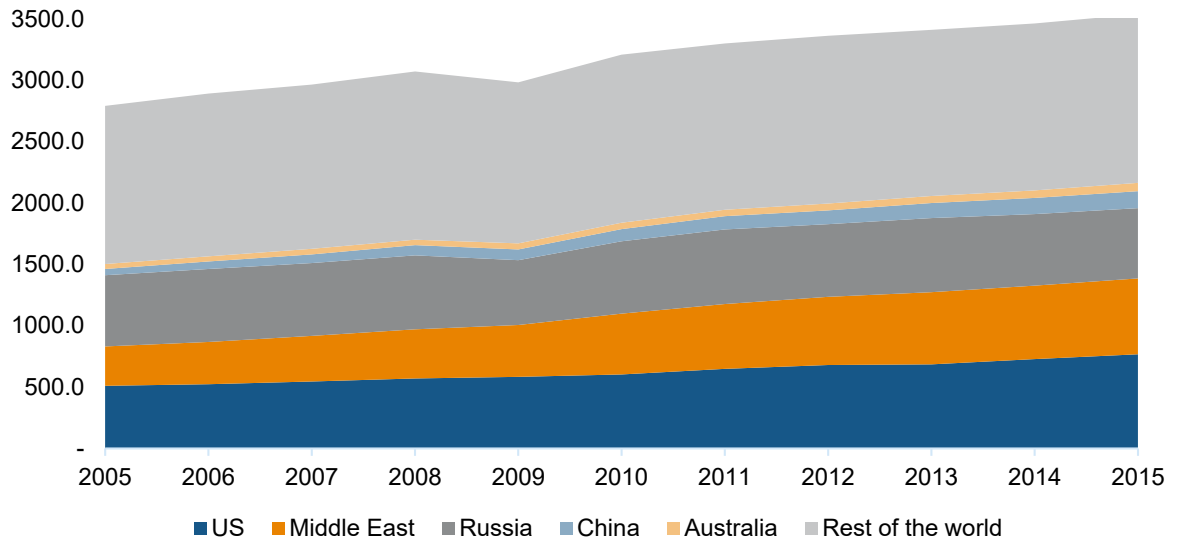
Source: BP (2015) Statistical Review of World Energy

Production

Natural gas production grew at an average rate of 3.3% p.a. from 2009-2013, however with the collapse in oil and gas prices in the last half of 2014, production growth has slowed, reaching 3538.6bcm in 2015, a 2.2% increase over 2014 production levels. Still, several regions including Iraq (13.5% growth in 2015), UK (7.8% growth in 2015), and the US (5.3% growth in 2015) saw substantial production growth in 2015.

³⁶ BP (2015) BP Statistical Review of World Energy

FIGURE 12: GLOBAL NATURAL GAS PRODUCTION 2004-2014 (BCM)

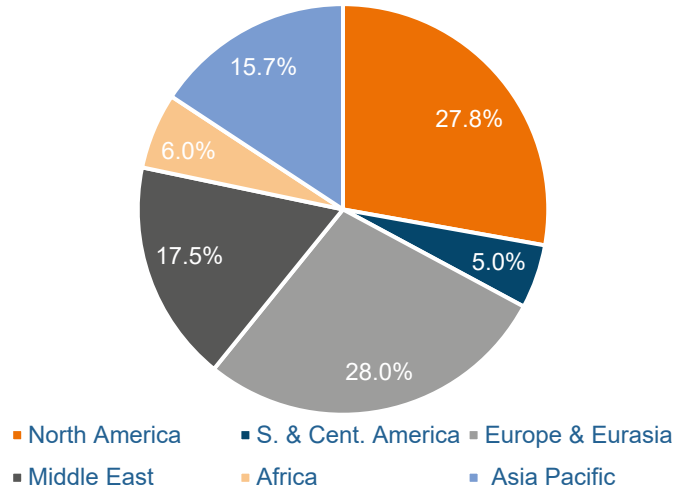


Source: BP (2015) Statistical Review of World Energy

The largest producers of natural gas globally are Russia (573.3 bcm), the United States (767.3bcm), Canada, Qatar and Iran.³⁷

³⁷ BP (2016) BP Statistical Review of World Energy 2016.

FIGURE 13: REGIONAL SHARE OF NATURAL GAS PRODUCTION 2015



Source: BP (2016) Statistical Review of World Energy

North America

North America has seen significant natural gas production growth due to the rise of shale gas in the US. The region produced 984 bcm of natural gas in 2015, which represented 28.1% of global gas production and growth of 3.9% from the previous year. While the US was responsible for a majority of this growth, Canada's production also grew slightly by 0.9% to 163.9 bcm.³⁸

Latin America

Latin America and the Caribbean produced 178.5 bcm of natural gas in 2015. This represented only a growth of 0.7% year-over-year, which was down from the 1.6% average annual growth from 2010-2014.

EU

The EU produced 132.4 bcm of natural gas in 2014, a reduction of more than 9% since 2014³⁹. Production has declined in the region in the last decade, due to a lack of investment in upstream operations in the region. Reductions have averaged about 5% per year in the last decade. Norwegian production, which is not included in the EU total for production, grew by 7.7% from 2014 to 2015, reaching 117.2 bcm in 2015.⁴⁰

³⁸ BP (2016) BP Statistical Review of World Energy

³⁹ EC (2016) Eurostat Database, Primary Energy Production by Resource.

⁴⁰ BP (2016) BP Statistical Review of World Energy 2016.

Russia

Since 2013, Russian gas production has declined by 9.5%. In 2015, production reached 573.3 bcm, a decline of 1.5% over 2014. Declines are driven by economic sanctions, declining prices, and lower gas demand globally.⁴¹

The Middle East

The Middle East has seen substantial gas production growth in recent years and this trend is expected to continue, albeit, at a slightly slower pace than seen in the last five years. Natural gas production increased from 495.6 bcm in 2010 to 599.1 bcm in 2014, averaging an impressive 4.9% average annual production growth rate in the period. The region's 2015 year-over-year production growth was dampened by the global oversupply, reaching 3.1% or 617.9 bcm. Qatar, Iran, and Saudi Arabia are the main gas producers in the region, and all three are poised to continue to grow production through 2020.⁴²

Africa

African natural gas production declined in 2013 and 2014 reaching just 208 bcm of natural gas in 2014 and picked up slightly in 2015 to reach 211.8 bcm of natural gas. Production in Egypt (the region's largest producer) and Algeria fell by 2.7% to reach 128.6 bcm of natural gas. Sub-Saharan Africa is poised to see significant production increases in the coming decades due to large offshore discoveries near East Africa, particularly Mozambique and Tanzania.⁴³

Asia Pacific

The Asia Pacific region produced 556.7 bcm of natural gas in 2015, which represented 4.1% year-over-year growth and was much higher than the 1.8% average annual production growth from 2010-2014. A large portion of this growth came from China, where production grew 6.8% annually on average from 2009-2015, reaching 138 bcm in 2015.⁴⁴

Demand

In 2015, global natural gas consumption grew by 1.7% to 3468.6 bcm, an improvement over 2014 growth rates, but a significant drop off from the 10-year average of 2.3% seen from 2005 to 2015. With import prices falling significantly in 2015, consumption picked up in both Asia and Europe. Still, demand for natural gas remains below expectations in major importing regions due to dampened economic growth, and strong competition from other fuels. In resource rich regions such as the Middle East, Africa and North America, demand continues to grow rapidly to meet new demand and as a substitute for oil and coal in transport, power and non-energy uses such as chemicals production.

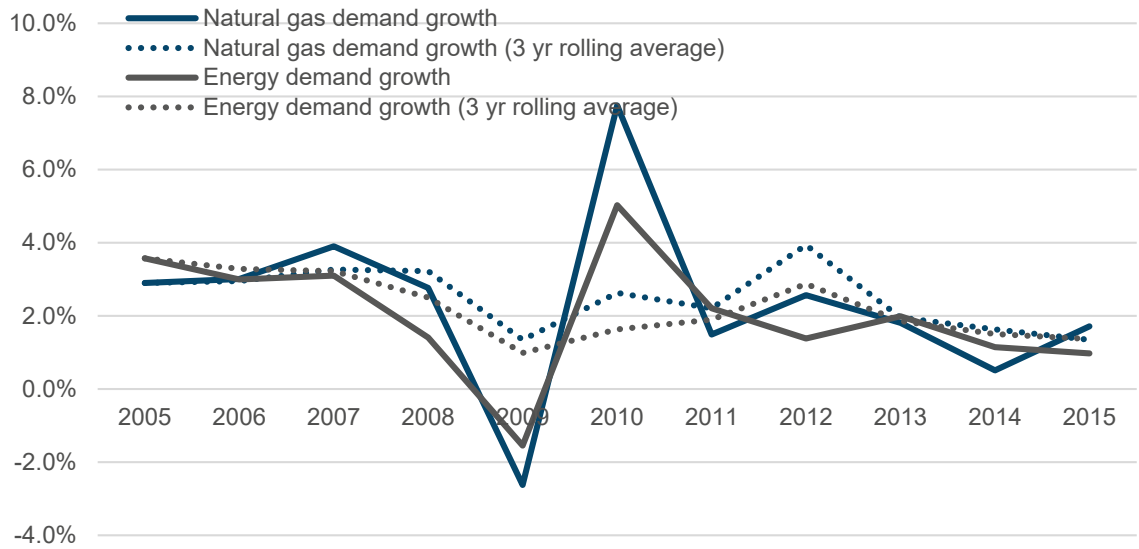
⁴¹ BP, 2016: BP Statistical Review of World Energy 2016.

⁴² Ibid 41

⁴³ Ibid 41

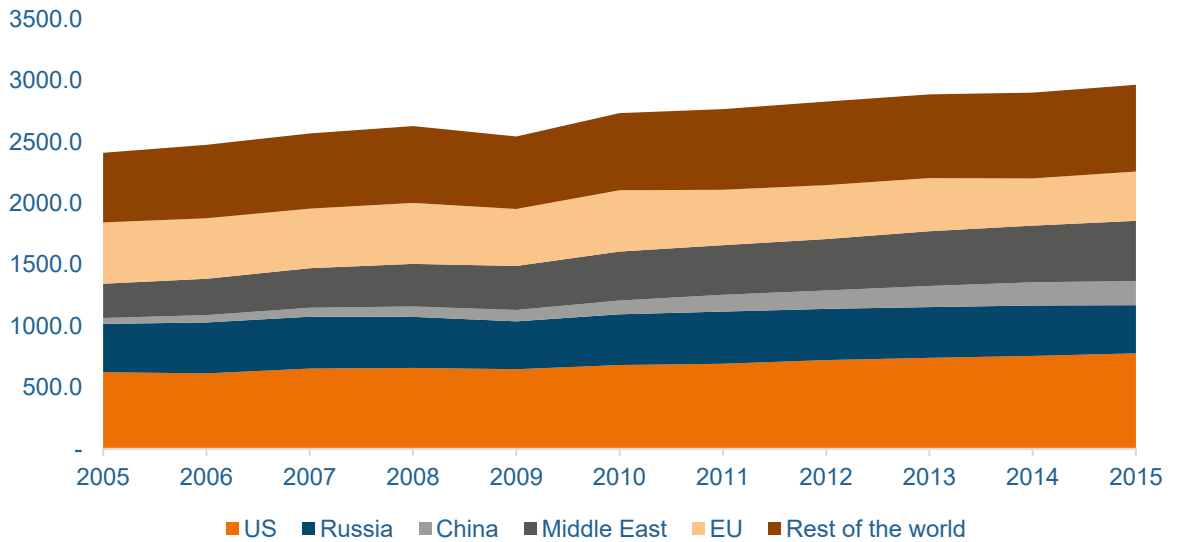
⁴⁴ Ibid 41

FIGURE 14: ENERGY DEMAND GROWTH AND NATURAL GAS CONSUMPTION 2005-2015



Source: BP (2016) Statistical Review of World Energy

FIGURE 15: NATURAL GAS CONSUMPTION 2005-2015 (BCM)



Source: BP (2016) Statistical Review of World Energy

North America

Abundant supplies of cheap natural gas in North America have spurred demand growth in the region. Natural gas consumption grew at a rate of 2.8% p.a. from 2011-2014. In 2015, consumption grew at 1.9%, reaching 963.6 bcm, and reflecting 28.1% of global consumption. With the lowest gas prices seen in over a decade, natural gas has been steadily replacing coal in power and a record number of coal-fired plants have been retired from service because of the high cost of meeting environmental regulations. As a result, natural gas has grown to reflect 31.5% of North America's primary energy consumption in 2015 versus 24.8% in 2005.⁴⁵

Latin America

In Latin America and the Caribbean (LAC), natural gas demand growth regained momentum and increased from 1.1% in 2014 to 3.1% in 2015 to 174.8 bcm. This was in line with the 4.9% average annual growth seen from 2009-2013. Natural gas share in the region's primary energy mix remained flat from 2005 to 2015 with natural gas becoming the number two fuel in the LAC energy mix in 2015, representing 21.9%, overtaking hydroelectric and placing second to oil in terms of share of primary energy.⁴⁶

EU

The EU consumed 444 bcm of natural gas in 2015, roughly 12.8% of global natural gas consumption globally. Lower import prices drove an increase in consumption at a rate of 4.3% from 2014 to 2015, a reversal of the decline in gas consumption seen since 2010.

Russia

Russia consumed 391.5 bcm of natural gas in 2015, a decline of 5.0% over 2014. Natural gas consumption has declined continuously since 2011, with the total decline reaching 7.8% in the period. The decline is driven by a reduction in economic activity as a result of economic sanctions and lower commodity prices. The share of natural gas in the primary energy mix fell from 53.7% to 52.8% from 2014 to 2015, displaced by coal, hydro and nuclear generation.

The Middle East

The Middle East saw a spike in natural gas demand in 2015, which grew at a rate of 6.2% from 2014, reaching 490.2 bcm of consumption. Iran and Saudi Arabia combined accounted for 60.7% of the region's total consumption at 191.2 bcm and 106.4 bcm respectively. The share of natural gas in the energy mix was 49.9% in 2015. The region has seen steady growth since 2010, averaging 4.2% p.a. growth from 2010 to 2015. Consumption growth is driven by ample resources, population growth, strong economic factors, urbanisation, de-salinisation plants, a boom in the petrochemical sector using gas as a feedstock, and policies that have kept end-user prices at very low levels.

⁴⁵ BP (2016) BP Statistical Review of World Energy 2016.

⁴⁶ Ibid 45

Africa

In Africa, natural gas consumption was 135.5 bcm in 2015. From 2002 to 2012, demand grew at 5.8% p.a., but declined in 2013 and started growing again in 2014. The share of natural gas in Africa's primary energy consumption rose from 23.3% in 2004 to 28% in 2015.

Asia Pacific

Asia Pacific's natural gas consumption grew 0.5% year-over-year to 701.1 bcm in 2014, which was a large drop from the 4.8% average annual consumption growth obtained from 2010-2014. Natural gas is still well behind coal and oil in regards to the Asia Pacific's primary energy consumption and only represented 11.5% in 2015.⁴⁷

China has been responsible for a significant portion of the region's growth during both of those time spans. China's natural gas consumption rose 14.1% annually on average from 2010-2014 and the nation consumed 197.3 bcm in 2015, representing 4.7% year-over-year growth.

India's natural gas consumption was 61.9 bcm in 2011 and 50.6 bcm in 2015, which represented a decline of 18.2%. Although the nation is viewed as a potential growth market for natural gas, consumption fell each year from 2011 to 2013, increasing slightly in 2014 before flattening in 2015. Affordability is the biggest challenge for gas in India where coal dominates power and energy equity is a high priority for policymakers.

Demand by sector

Natural gas is largely utilised in the power, industry, buildings, and transportation sectors. In 2013, those four sectors combined made up 87.3% of the 3507 bcm of natural gas used globally.⁴⁸

The power sector is the largest consumer of natural gas and presents the largest opportunity for continued growth in natural gas demand. The power sector utilised 1414 bcm of natural gas in 2013, which represented 40.3% of total end use. Growth in demand for natural gas in power depends strongly on the price at which it is available and its competitiveness versus other fuels, as well as the policy preferences that affect plant operation and investment decisions in new capacity. In resource-rich countries, gas makes a compelling case as a source of power. In countries where gas imports are the major source of supply, the role of gas in power generation tends to be more limited. In these cases, gas demand in power generation is sustained through policies targeting a reduction in air pollution, diversification of the power mix and the need for more flexible peaking capacity.

⁴⁷ BP (2016) BP Statistical Review of World Energy 2016.

⁴⁸ IEA (2015) World Energy Outlook

The industry sector is the second largest end user of natural gas, slightly edging out the buildings sector. This sector was responsible for 22.1%, or 774 bcm, of natural gas's end use in 2013. Within industry, natural gas can effectively be utilised as a feedstock for petrochemicals among other examples. The growth of use of gas in industry will be driven by similar dynamics to those of the power sector, including price competitiveness and environmental policies, but is also influenced by the demand for petrochemicals and the differential between oil and gas prices.

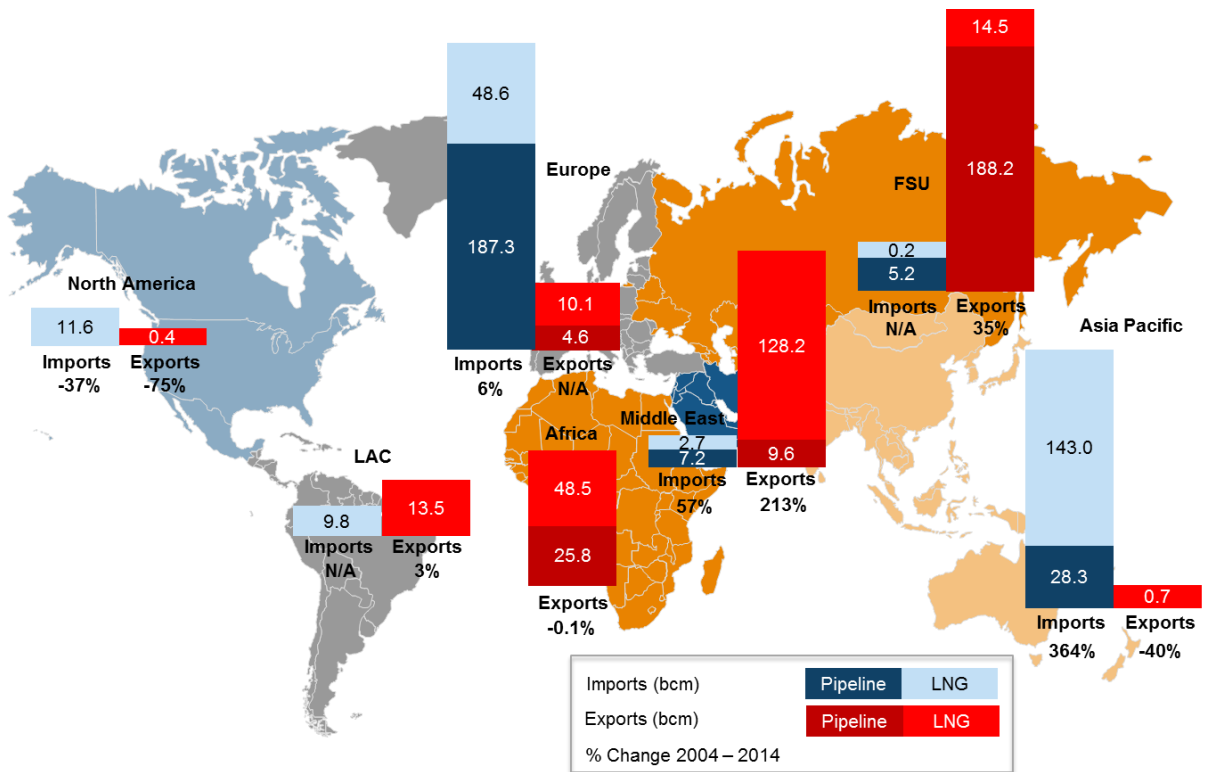
Accounting for 21.6% of natural gas's end use, the buildings (residential and services) sector is the third largest natural gas end user. The buildings sector utilised 758 bcm of natural gas in 2013. Within the buildings sector, over 60% of natural gas use is for space heating. The scope for gas to expand in the buildings sector is limited mainly by efficiency policies in developed and developing regions, which drive down the demand for gas, and promote the substitution of gas in heating with electricity.

The transport sector utilised 116 bcm of natural gas in 2013. This represented 3.3% of natural gas's total end use. Road transportation accounted for 37.1% (43 bcm) of the total natural gas used in the transport sector in 2013. Natural gas vehicles continue to increase as there were over 22 million in 2013. Compressed natural gas (CNG) is often utilised for passenger vehicles, while LNG can be used for both trucks and maritime transportation. The use of gas in transport is driven by the differential between oil and gas price, which incentivise a switch, and also by infrastructure development and the promotion of natural gas vehicle sales.⁴⁹

⁴⁹ IEA (2015) World Energy Outlook

Natural gas trade

FIGURE 16: INTERREGIONAL NATURAL GAS TRADE IN 2014 AND % CHANGE FROM 2004 (BCM)



Source: BP (2015, 2005) Statistical Review of World Energy

LNG trade

The LNG market has grown 7% on average annually since 2000 as countries without developed pipeline systems request more natural gas. Growth opportunities for LNG are tremendous as LNG represented just 10% of global natural gas supply in 2014.⁵⁰ According to analysis by Total, this is projected to grow to 13% by 2020.⁵¹

In 2014, there were 333.3 bcm of LNG deliveries globally and Asian LNG imports represented nearly three-fourths of this LNG trade.⁵² Japan posted record LNG imports, however, in 2015 the nation set forth its plan to revive its nuclear power sector and reduce its dependence on LNG. South Korea’s demand decreased by 7% year-on-year as the

⁵⁰ IGU (2015) World LNG Report

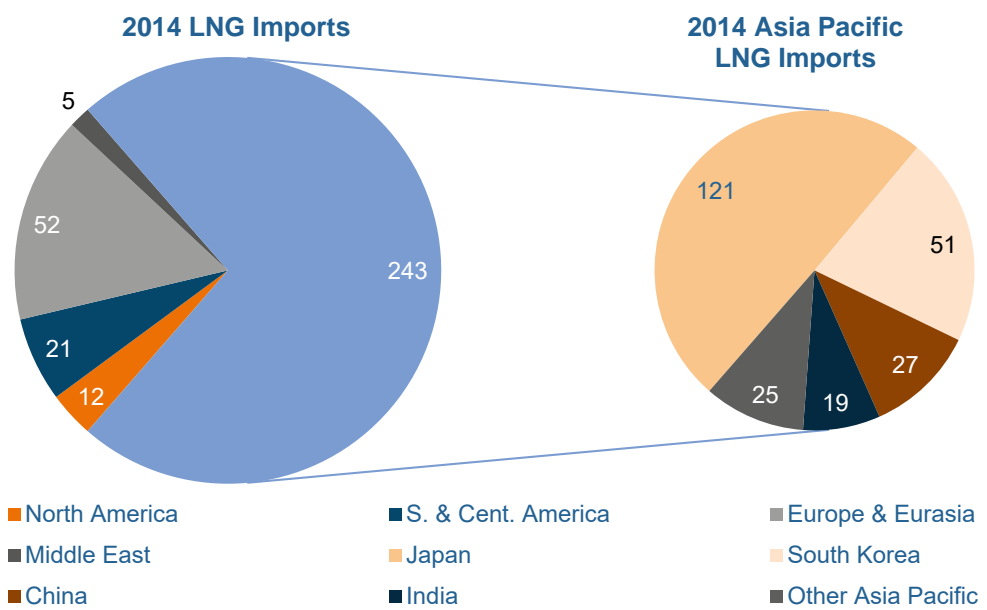
⁵¹ Total (2012) Liquefied Natural Gas: A Booming Industry.

⁵² BP (2015) BP Statistical Review of World Energy 2015.

government took steps to increase energy efficiency and reduce the economic impacts of expensive LNG exports.⁵³

BP projects that China will reach nearly the same level of LNG imports as Japan by 2035 (~124 bcm/year versus ~134 bcm/year), however there are a multitude of factors that could impact China's LNG demand going forward including, reduced energy demand, pipeline trade with Russia and growing domestic production of gas.⁵⁴

FIGURE 17: LNG IMPORT DEMAND (BCM)



Source: BP (2015) Statistical Review of World Energy

In Europe, LNG net imports grew by 16.6 % to 31 mtpa in 2015, as demand for natural gas grew in the region and domestic production declined. In the UK net imports grew by 12.4 % due to colder weather. In both Spain and Portugal, LNG demand was boosted by higher demand for natural gas in the power sector as droughts reduced the availability of hydropower and a heatwave in the summer created a spike in demand for power.⁵⁵

⁵³ BG Group (2015) Global LNG Market Outlook 2014-15.

⁵⁴ BP (2015) BP Energy Outlook 2035.

⁵⁵ LNG World News (2015) Cedigaz European LNG net imports up in 2015

LNG export capacity additions

Unconventional gas from North America and Australia has and will continue to shift the dynamics of the LNG market and the supplier landscape for natural gas. Virtually all added LNG export capacity will be added in the US and Australia through 2020. Less than a decade ago, with natural gas production on the decline, the US was expected to remain an importer of LNG and a potential market of last resort for surplus cargos around the world. However, the massive increase in domestic shale gas production since 2008 has positioned the US to become a net exporter of natural gas by 2017.⁵⁶ The US currently has five projects, reflecting a capacity of 97 bcm of export capacity, under construction.

Australia is set to surpass Qatar to become the number one LNG capacity holder in the world by 2017. The nation exported 31.6 bcm of natural gas via LNG in 2014 and their LNG production capacity is expected to grow to ~119 bcm by 2020 based on projects currently under construction.⁵⁷ Three of the nation's new LNG projects will be fuelled by CBM.

Pipeline trade

In 2014, pipeline trade fell 6.6% to 663.9 bcm. This decline was largely driven by an 11.3% fall in Russian exports to 187.4 bcm.⁵⁸ While Russia has been a long standing supplier in the natural gas industry, security concerns in recent years drove big trade partners in Europe and Turkey to take active steps to diversify away from Russian natural gas imports. The economic sanctions imposed by the US and Europe in an attempt to get Russia to withdraw troops from Crimea, have also resulted in the stalling of major Russian oil and gas projects to supply customers in Turkey and Germany.

However, the current economics of Russia's oil indexed contracts imports make the resource more competitive than LNG imports in Europe. This has been a persistent trend since 2011. Even as Europe's natural gas imports declined 11.3% in 2014, the concentration of Russian pipeline gas has grown to 63% of natural gas imports.⁵⁹ In 2015, Europe increased shipments from Russia as contract prices declined.⁶⁰ While LNG supplies from the US and Australia may provide an alternative, the cost of getting Russian supplies to European borders is significantly lower, which creates a challenge for US and Australian LNG suppliers looking to take significant market share in the region.

⁵⁶ EIA (2015) Projections show U.S. becoming a net exporter of natural gas.

⁵⁷ BP (2015) BP Statistical Review of World Energy 2015

BG Group, QCLNG Fact Sheet.

BG Group (2015) BG Group starts commercial operations from QCLNG Train 2 in Australia, Nov 25 2015.

Santos GLNG (2014) First Cargo Shipped from GLNG.

Chevron (2015) Chevron and SK LNG Trading Sign Gorgon LNG Supply Agreement.

IEA (2015) World Energy Outlook 2015.

⁵⁸ BP (2015) BP Statistical Review of World Energy 2015.

⁵⁹ Ibid 58

⁶⁰ Shiryayevskaya (Sept 2015) Cheap Russian Gas Tempts EU Buyers as LNG Import Growth Stalls, BloombergBusiness.

FIGURE 18: MAJOR EUROPEAN IMPORTERS OF RUSSIAN PIPELINE NATURAL GAS (BCM)



Source: BP (2015) Statistical Review of World Energy

One of the major projects in question for Russia is the Power of Siberia Pipeline system, which would enable Russia to supply substantial amounts of gas to China. Construction began in 2015 on the East Line. However, China is facing a supply glut that is blamed for delays seen in the development of the West Line.⁶¹ The latest announcements indicate that the deal may be signed in 2016.⁶² It is broadly believed that China is reviewing its energy needs due to the economic slowdown. If both the Power of Siberia and Power of Siberia 2 pipelines become operational, China would soon receive up to 68 bcm/year of natural gas from Russia.

⁶¹ RT (Jul 2015) Russia-China deal on 2nd gas route postponed - media.

⁶² Sputnik News (2015) Russia, China Expect to Sign Power of Siberia-2 Deal in Spring 2016.

TABLE 2: MAJOR CHINESE NATURAL GAS PIPELINES

Pipeline	Capacity (bcm/year)	Status	Production Year
Central Asia – Line A/B	30	Operational	2011
China – Burma Pipeline (Sino-Myanmar)	12	Operational	2013
Central Asia – Line C	25	Beginning of production	2014
Russia – East Line (“Power of Siberia”)	38	Under construction	2018
Central Asia – Line D	30	Under construction	2020
Russia – West Line (“Power of Siberia-2”)	30	Delayed	TBA

Sources: RT, China National Petroleum Corporation (CNPC), and IEA

Europe and Eurasia currently represent the largest portion of the pipeline natural gas market globally. The region exported 435.8 bcm of pipeline natural gas in 2014, 92% of which was intraregional. The remaining 8% of exports was split between the Asia Pacific at 28.3 bcm and the Middle East at 6.9 bcm.⁶³

North American pipeline natural gas trade made up approximately 18% of pipeline natural gas trade at 116.9 bcm in 2014. All of North America’s pipeline natural gas trade was

⁶³ BP (2015) BP Statistical Review of World Energy

intraregional. Canada was the region's largest pipeline exporter at 74.6 bcm. The US is the region's largest pipeline importer.

Canada heavily relies on its pipeline relationship with the US as 100% of their natural gas exports are directed towards US via pipeline trade. However, as a result of growth in domestic production, Canadian exports have been displaced and this trend is expected to continue in the coming years. In fact, Canadian pipeline gas exports to the US fell 7% from 2010 to 2014, while US pipeline gas exports to Canada increased 21% during the same time period.⁶⁴ Canada is currently evaluating ways to diversify their natural gas exports as evidenced by the proposed LNG export terminals in British Columbia.⁶⁵

NATURAL GAS INVESTMENT

In many regions, natural gas is an increasingly important part of power generation and upstream portfolios. For example, Anadarko's estimated 2015 sales volumes were 52% natural gas and 14% natural gas liquids (NGLs).⁶⁶ Natural gas accounts for 50% of BPs upstream production globally, and is expected to grow to 60% of their portfolio.⁶⁷ Utility companies such as Engie, are expanding their natural gas portfolios to increasingly include E&P and midstream infrastructure. CEOs from several oil and gas companies also came forward in 2015 to demonstrate their support for gas as a bridging fuel, asking for a clear carbon price signal to reduce the uncertainty surrounding natural gas investments and establish a stronger role in the global energy mix for natural gas in anticipation of COP21.⁶⁸

While activity remains strong in the power sector, the low price environment is causing major upstream oil and gas companies to re-evaluate their spending habits and more critically analyse which investments they can justify financially. In 2015, only upstream and midstream projects already under construction and tied to contracts moved ahead in many regions. With the realisation that oil and gas prices may stay at their current lower level for longer than initially anticipated, companies are reducing capital expenditures and cutting back on virtually all new projects.

US shale oil and gas and LNG projects

EIA data indicates drilling activity has declined 60% in the top 7 US shale basins in 2015. Wood Mackenzie estimated about US\$83 billion in delayed projects in North America shale in the first half of 2015.

Twenty-five US LNG projects have been proposed to move excess supplies of gas out of North America. However, it is likely that only the five US LNG export projects currently

⁶⁴ Natural Resources Canada (2016) North American Natural Gas Market: 2015-2016 Heating Season Outlook.

⁶⁵ Natural Resources Canada (2016) Canadian LNG Projects.

⁶⁶ Cohen (2015) Anadarko Petroleum Reduces Rig Count and Capex, Seeking Alpha.

⁶⁷ Dudley (2015) World Gas Conference 2015 Quote.

⁶⁸ Rochan (2015) Shell and Total believe future is in natural gas and not in coal, International Business Times.

Van Beurden, B (2015) Growing Gas Together, Shell.

under construction will move forward. Current market dynamics make it unlikely that any new projects will move beyond FID before 2020.

Deepwater Projects

The most impacted projects are more technically challenging offshore projects such as arctic and deep-water. According to analysis by Rystad Energy, as of January 2016, nine pre-development offshore gas projects have been delayed since the second half of 2014, of which seven occurred in the second half of 2015 alone.⁶⁹

FIGURE 19: DELAYED OR CANCELLED MAJOR OFFSHORE PROJECTS (DRAFT)

Project	Country	Major Shareholders	Projected Capex (Billion US\$)	Status
Alaskan Arctic	USA	Shell	7 (Spent)	Exited
Bonga South West	Nigeria	Shell	12	Postponed FID
Zinia 2	Angola	Total	Unreleased	Postponed FID
Mad Dog 2	USA	BP	10	In Review (delayed again in early 2015)
Johan Castberg	Norway	Statoil	4	Postponed FID to 2017
Snorre 2040	Norway	Statoil	4	Postponed FID to Q4 2017
Tommeliten Alpha	Norway	ConocoPhillips	2.1	Cancelled

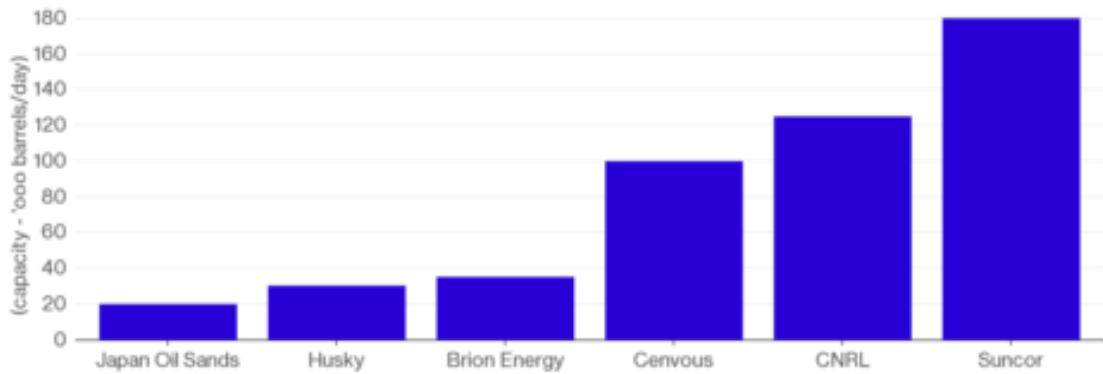
⁶⁹ Islam, (2016) Nearly 230 BUSD earmarked for pre-development projects deferred since H2 2014, delaying over 3 MMboe/d of supply, Rystad Energy.

Sources: Statoil, Reuters, New York Times, Financial Times, and Independent.

Canadian Oil Sands

Most experts agree that capital intensive oil sands projects are not economic at current prices, yet current projects in the oil sands will add at least another 500,000 barrels a day to the already oversupplied North American market by 2017. For companies stuck spending billions in a downturn, the time required to earn back their investments will lengthen considerably, but with much of the capital already sunk, companies must move ahead and try to recover their costs.

FIGURE 20: OIL SANDS PROJECTS UNDER CONSTRUCTION (COMPLETION BY 2017)



Source: Bloomberg.

For projects in the planning phases, companies have had to make big cuts to capital spending. About 800,000 barrels a day of oil sands projects have been delayed or cancelled, according to Wood Mackenzie.⁷⁰

Australian LNG Projects

Australia's massive Greenfield projects have faced delays and cost overruns and are estimated to breakeven at more than double the US\$6 to US\$7 prices seen today at major Asian hubs. In the current climate, no projects that are pre-FID are expected to move ahead.

⁷⁰ <http://www.bloomberg.com/news/articles/2015-09-03/canada-oil-sands-fork-over-billions-for-500-000-unnneeded-barrels>

ConocoPhillips has moved away from pre-FID LNG projects referencing lower returns, low flexibility, and long cycle times.⁷¹ Similarly, Chevron decided that no FID would be made on the Kitimat LNG project in 2015.⁷²

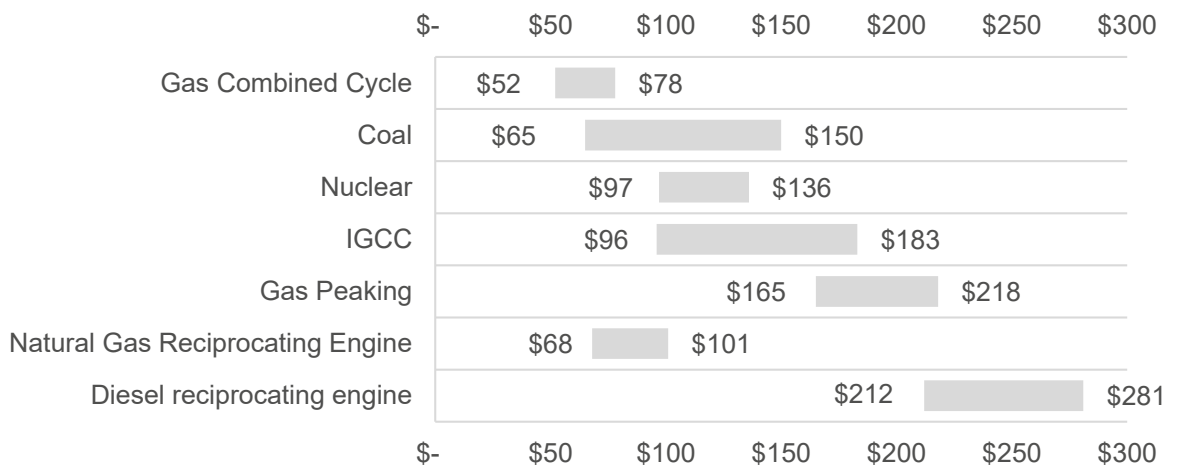
RISK ANALYSIS

The biggest risks to natural gas markets currently is their inability to compete against more economic, secure and environmentally friendly substitutes in transport, industrial use and power.

Affordability

Under current policies, existing coal, nuclear and hydro plants may provide more economic, and for many nations, more secure alternatives to natural gas for baseload power. While in Europe and the US, the levelised cost of generating power from new CCGT is now cheaper than from new coal-fired units, the competitiveness of new gas-fired and coal-fired plants is skewed towards coal in emerging economies that rely on imports for gas supplies. Absent a carbon price and more stringent regulations on air pollution and carbon emissions, natural gas has struggled to take share from cheap coal in these regions. In developing regions that rely heavily on LNG imports, governments must balance environmental sustainability with income and energy equity. In India for example, this has led to a delay in expanding natural gas infrastructure and continued growth in coal generation^[1]. The Indian government has openly stated its views on coal as the current best option to deliver the energy needed to improve the standard of living for millions of people.

FIGURE 21: GLOBAL UNSUBSIDISED LEVELISED COST OF ENERGY



⁷¹ ConocoPhillips (2015) ConocoPhillips Investor Update: May 14

⁷² Chevron (2015) 2015 1Q Earnings Transcript.

Source: Lazard

3. SOCIO-ECONOMICS

This section will breakdown some of the key socioeconomic factors that are impacted by natural gas, with a focus on electrification and the potential improvements to quality of life.

ENERGY ACCESS

Energy access and electrification rates remain a key disparity between developed and developing countries. According to the World Bank, 84.6% of the world has access to electricity in 2012. However, when focusing on the least developed countries based in the UN's classification, access to electricity drops to 34.3%.⁷³

Energy access and electrification will be key to raising the standard of living for billions of people, and supporting continued economic growth, but it is also difficult due to a variety of chokepoints, such as affordability and infrastructure underdevelopment. Natural gas has the potential to play a key role in providing access to energy for all, in particular through the strategic deployment of distributed systems.

Distributed systems

Several of the technologies discussed in Section 2, enable the deployment of off-grid or de-centralised solutions that allow developing regions to overcome infrastructure challenges faster than many industrialised nations have experienced in the past. For example, SSLNG could enable economic activity for small end uses like heavy road transport, bunkering and small industrial processes and can be applied in off grid regions or regions with limited infrastructure, reducing the reliance on inefficient diesel generation. SSLNG and CNG could also enable natural gas use for cooking, small-scale generation projects, and cleaner and more reliable fuels for personal transportation.

Biogas also shows substantial promise for use in de-centralised systems. For Example, in Ethiopia, biogas is being deployed for rural economic development to off-grid communities in selected areas of the country. The modular systems generate 100kW of electricity in addition to 170kW of heat, while occupying less than 3,500 square meters. The goal is to provide adequate uninterrupted and grid independent power to support the achievement of middle-income status by 2025 while developing a green economy.⁷⁴

Sub-Saharan Africa

Natural gas discoveries in recent years in Mozambique and Tanzania appear very promising. Empresa Nacional de Hidrocarbonetos estimates indicate finds offshore

⁷³ World Bank (2016) Access to electricity (% of population)

⁷⁴Chin (2014) Aora to Provide First Solar-biogas Hybrid Power Solution for Off-grid Africa Communities

Mozambique alone could reflect ~7.1 tcm of recoverable natural gas.⁷⁵ Tanzania's Energy and Minerals Ministry estimates that the country has ~1.6 tcm of natural gas reserves.⁷⁶ This natural gas could serve to improve energy access for millions of people, namely for electricity and cooking, where the need is most urgent in the region. The IEA estimates that 90 million people will gain access to electricity in Sub-Saharan Africa through 2040, fuelled in part by added supplies of natural gas. Additionally, natural gas's share of electricity generation in sub-Saharan Africa is projected to increase from 9% to 25% from 2012 to 2040.⁷⁷

The African continent has the opportunity to build a foundation that establishes the development of its vast resource on two pillars for economic growth: 1) exports to boost national coffers and 2) domestic gas to support local and regional development. If policymakers in the region are successful at regional cooperation and energy system integration, sub-Saharan Africa could emerge as an important new hub for natural gas that serves as an intermediary, connecting North America and Asian markets, and feeding growing demand for energy within Africa. This enables the development of strategic infrastructure, limits the need for fossil fuel imports in the region, and provides some protection for the continent against commodity price volatility.

India

India's Vision 2030: Natural Gas Infrastructure plan created by the Petroleum and Natural Gas Regulatory Board, projects natural gas demand to grow in India by 6.8% per year from 2012/2013 to 2029/2030 in efforts to raise the standard of living and electrify the ~300 million people living without access to energy.⁷⁸ In addition, natural gas is vital to meeting India's renewable energy targets. The government has announced 175 GW renewable energy target by 2022, and natural gas has been identified as the best fuel for bridging.

About 53% of the overall demand for natural gas in India comes from regulated segments such as power, fertiliser, and city gas. The government has developed policies for converting all naphtha based fertiliser plants to gas based. The government has also recently announced its plan to create 100 smart cities; this initiative is combined with efforts to grow natural gas transmission infrastructure. India is currently expanding piped natural gas to households from 2.7 million in 2015 to over 10 million households within the next four years to reduce reliance on more harmful biomass stoves.⁷⁹ These initiatives not only provide economic development and cleaner fuels for millions of people, they enable India's aspirations to expand their use of intermittent renewables. However, the issue of affordability remains a challenge, LNG is still currently too expensive for power generation in India, relative to coal.

⁷⁵ Gismatullin (2012) Eni-Anadarko African LNG Plant to Be World's Second-Largest, BloombergBusiness.

⁷⁶ Bariyo (2015) Tanzania Says Gas Reserves Rise 18% to Reach 55 Trillion Cubic Feet, The Wall Street Journal.

⁷⁷ IEA (2014) Africa Energy Outlook 2014.

⁷⁸ Goswami (2015) How India weathered a storm in Paris during COP21 climate summit, The Economist

⁷⁹ Business Standard (2015) PM Modi calls for cut in energy imports by 50% by 2030.

4. ENVIRONMENTAL IMPACTS

This section will detail the impact that natural gas use has on the environment. The environmental concerns with unconventional gas in particular have deterred the development process from expanding beyond its current markets. In order for shale gas drilling to become more prominent in Europe and elsewhere, the process will need to see large improvements in regards to its environmental impact.

METHANE EMISSIONS

Natural gas is the lowest carbon emitting fossil fuel, however a major concern surrounding natural gas is methane leakage. The reduction of methane emissions is important because although methane does not remain in the environment as long as CO₂, it traps 84 times more heat in the short-term. On a 100-year horizon, methane emissions trap 25 times more heat than CO₂.⁸⁰ According to a study by ICF International, stopping a minimum of 45% of leakage globally would help the climate over the next 20 years as much as shutting down one-third of the world's coal-fired power plants.⁸¹

Approximately a third of methane emissions are a result of oil and gas production and transmission⁸². In Europe, methane leakage from the transmission and distribution grids is estimated to be between 0.5% and 0.9% of the total of anthropogenic GHG emission⁸³. Many technologies already exist to detect the leakage of this odourless and colourless gas, however, the main challenge has been developing an appropriately stringent set of norms and regulation to improve the safety of gas infrastructure and reduce leaks. Appropriate regulation coupled with digital technologies, such as drones, sensors and data analytics could play a role in improving monitoring, detection and predicting failures. Recent studies in the U.S., Canada and Mexico by ICF International indicate that existing technology can cut methane leaks by between 40% and 54% at an average cost of a penny per thousand cubic feet of gas produced.⁸⁴

In North America, the shale gas drilling process creates increased opportunity for methane leakage as there are more wells and pipelines involved in operations. As a result, in August 2015, the US Environmental Protection Agency (EPA) took action by issuing proposals that would help combat methane emissions from oil and gas operations. The proposals would require both methane and volatile organic compounds reductions from hydraulically

⁸⁰ Marcogaz (2015) Methane emissions in the European natural gas transmission and distribution sectors

⁸¹Krupp (2016) Fixing the Methane Leaks That Deflate Natural-Gas GainsThe Wall Street Journal

⁸² Patel (2015) Methane Emissions Threaten to Undermine Natural-Gas Offensive, Bloomberg Business.

⁸³ Marcogaz (2016) MARCOGAZ Survey CH₄ emissions for gas transmission & distribution in Europe

⁸⁴Krupp (2016) Fixing the Methane Leaks That Deflate Natural-Gas GainsThe Wall Street Journal

fractured oil wells and would significantly help the EPA in their pursuit of reducing the oil and gas sector's methane emissions by 40-45% by 2025 relative to 2012 levels. If preventative steps are not taken, methane emissions from the sector are projected to see at least a 25% increase by 2025.⁸⁵

Faulty drilling techniques and improper standards for cement well linings and steel casings have also been identified as sources of methane leakage that lead to both water and air contamination. Incidents in Texas, Pennsylvania, and more recently California have led to lawsuits and human displacement. In the case of California, the Porter Ranch leak was attributed to a faulty well, that the operator, SoCal Gas, was forced to permanently shutter by regulators. In other cases, however, regulators and operators have argued that water contamination is caused by naturally occurring instances of methane seeping into drinking water. Fortunately, scientists have identified methods to identify the source of leaks, using the distinctive ratio of methane to salt not found in instances of contamination from fracking wells. Ultimately, the continued evolution of methods to identify the source of leaks, and more stringent standards for well casings and drilling processes, will be needed to reduce the risks of leakage.

WATER

Both water usage and water contamination are important areas of concern in the unconventional drilling and completions processes. The process of drilling and hydraulically fracturing a shale gas well can require between two million and six million gallons of water depending on the well size. Approximately 89% of the water used by the shale gas industry is for the hydraulic fracturing process.⁸⁶ This large water requirement presents problems surrounding the EWF nexus, especially in regions where water is at a premium. Water scarcity issues will require technology advancements in the stimulation process. Saudi Aramco is exploring the use of CO₂, saline aquifers, wastewater, propane, and other hydrocarbons to replace water in hydraulic fracturing. In particular, Saudi Aramco's CO₂ development initiatives could enable the reduction of stimulation water and acid volumes by 30%.⁸⁷

Additionally, water contamination can result from poor management of fracturing chemicals and water, both during the fracturing process and from flowback afterwards. The risks of water contamination throughout the drilling and completion process were discussed in the section on methane leakage and can be managed through improved drilling techniques and higher standards for cement and steel casing. Flowback and produced water quality and the final intended disposition of that water, requires a multitude of different water treatment options, however, in many states in the US, produced water can be disposed of through deep well injection at a cost that can be less than US\$2 per barrel, which makes treatment and re-use technology applications less likely absent a regulatory requirement.

⁸⁵ The White House (2015) Fact Sheet: Administration Takes Steps Forward on Climate Action Plan by Announcing Actions to Cut Methane Emissions

⁸⁶ Zammerilli, (2014) Environmental Impacts of Unconventional Natural Gas Development and Production, US Department of Energy.

⁸⁷ Saudi Aramco (2015) Annual Review 2014.

In the Marcellus shale, where the geology is not favourable to injection sites, produced water is often processed at treatment plants. A more cost-effective alternative is on-site treatment of the produced water to the degree needed for re-use as frac water. Produced water has been successfully treated using Reverse Osmosis (RO) as the primary treatment technology. However, extension of the RO technology to the treatment of flow back from hydraulic fracture operations has required pre-treatment technologies designed to extend the life of the RO unit. New approaches and more efficient technologies are needed to make treatment and re-use a widespread reality.⁸⁸

There is also widespread concern over the protection of groundwater and the responsible management of the large amount of produced water associated with CBM operations. The key difference for CBM wells is that wells initially produce a large volume of water, which declines over time. The methane production starts low, builds to a peak, and then decreases. The proper management of produced water from CBM also includes disposal, storage, or treatment as a waste product. Any beneficial re-use of the water is dependent on a number of factors including its quality, cost of treatment required and pipeline infrastructure. Water of suitable quality can be used for town water, aquaculture, recharging aquifers, wetlands, and recreational lakes or at mining operations and power stations. Poor quality water may be contained in storage ponds. Increasing the volumes of produced water application in a secondary use, will require continued technology advances that improve the commercial viability of treatment and re-use.

CARBON DIOXIDE EMISSIONS

One of the key reasons that natural gas is considered a cleaner form of energy is its benefits with regards to CO₂ emissions. Compared to alternative fuels, natural gas emits significantly less CO₂. For example, new natural gas power plants release 50-60% less CO₂ than new coal power plants, which represents a significant environmental difference.⁸⁹ Furthermore, natural gas emits significantly less sulphur, mercury, particulates, and nitrogen oxides compared to other fossil fuels.⁹⁰

Additionally, natural gas has the potential to play a significant role in the world's transition to a less carbon intensive energy system, serving as an efficient and economic pairing fuel to serve as load balancing against the volatile nature of intermittent renewables. Gas is flexible to meet intermittent (intra-day/intra-week) and seasonal (winter/summer) demand while building out renewable generation. Other means to respond to peak and seasonal demand would be either much more polluting (coal), or more expensive (adding batteries to long term storage assets). Additionally, the continued development of biogas and power-to-gas technologies could bring potential breakthroughs in solving the storage problem and generating gas without all of the associated risks of fossil fuel gas production.

⁸⁸ NETL (2013) Water Issues Dominate Oil and Gas Production

⁸⁹ Union of Concerned Scientists: Environmental Impacts of Natural Gas

⁹⁰ Ibid 89

AIR POLLUTION

Air pollution from natural gas is significantly lower than that of other fossil fuels. The combustion of natural gas produces negligible amounts of sulphur, mercury, and particulates. While burning natural gas does produce nitrogen oxides (NO_x), which are precursors to smog, levels are lower than those of gasoline and diesel used for motor vehicles. Analyses by the US Department of Energy indicates that every 10,000 U.S. homes powered with natural gas rather than coal avoids the annual emissions of 1,900 tons of NO_x, 3,900 tons of SO₂, and 5,200 tonnes of particulates. These pollutants are linked with problems such as asthma, bronchitis, lung cancer, and heart disease and reductions in these emissions translate into public health benefits for hundreds of thousands of people. In developing regions such as China, the Middle East and Latin America, the air quality benefits of natural gas vs. coal power or oil transport solutions have led to significant policy support for the increased use of gas.

In contrast, the complex process of developing unconventional gas affects local and regional air quality. Some areas where drilling occurs have experienced increases in concentrations of hazardous air pollutants and two of the six “criteria pollutants” regulated by the EPA because of their harmful effects on health and the environment. Exposure to elevated levels of these air pollutants can lead to adverse health effects, including respiratory symptoms, cardiovascular disease, and cancer. A recent study found that residents living less than half a mile from unconventional gas well sites were at greater risk of health effects from air pollution from natural gas development than those living farther from the well sites.

LAND USE AND WILDLIFE

The construction of infrastructure and facilities, increased road traffic and land disturbance required for oil and gas drilling can alter land use and harm local ecosystems by causing erosion and fragmenting wildlife habitats and shifting migration patterns. When oil and gas operators clear a site to build a well pad, pipelines, and roads, the process can cause the erosion of dirt, minerals, and other harmful pollutants into nearby streams.

A study of hydraulic fracturing impacts in Michigan found potential environmental impacts to include increased erosion and sedimentation, increased risk of aquatic contamination from chemical spills or equipment runoff, habitat fragmentation, and reduction of surface waters as a result of the lowering of groundwater levels.

EARTHQUAKES

The disposal of fracking wastewater by injecting it at high pressure into deep injection wells, has been linked to earthquakes in the US that have caused substantial economic damage. At least half of the 4.5 million or more earthquakes to strike the interior of the United States in the past decade have occurred in regions of potential injection-induced seismic activity.

Although it can be challenging to attribute individual earthquakes to injection, in many cases the association is supported by timing and location of the events.⁹¹

REGULATION

The regulation of natural gas production processes varies across regions. Shifts in regulatory requirements for the production and consumption of natural gas will play a large role in shaping the future of the industry. Regulation debates have become an even larger factor as new, controversial techniques, such as fracturing shale rocks, have become technologically viable.

US regulation

CBM and shale gas operations are generally regulated at both the federal and state levels by rules for conventional oil and gas development. However, both shale and CBM gas operations are much more complex than conventional gas development and introduce additional risks around waste and water management, air pollution, congestion, dust, etc.

State and federal regulation has been for the most part catching up to the rapidly growing industry. This has created tension with some communities. However, as the industry evolves, new standards are being introduced. In March 2015, the US Department of the Interior (DOI) released new standards that would impact the fracking process, however only on public and American Indian land. These standards represented somewhat of a compromise as they instilled more stringent environmental regulations, without making a major impact on the process. The main purpose of these new standards is to reduce the risk of water contamination as a result of the fracking process. The new rules also increased the requirements for well design, transparency, and liquid waste storage.⁹²

European regulation

European nations overall have been strict on shale drilling. Currently in Europe, five countries have an outright ban or moratorium on fracking, as seen in Table 3. Additionally, Germany approved draft legislation in 2015 that bans fracking for projects less than 3,000 meters and all fracking in national parks and nature reserves, while Austria's shale environmental regulations are so stringent that shale drilling is not financially viable.⁹³ One country that has shown some support for shale drilling is the United Kingdom (UK). However, Scotland and Wales both have a regional ban on fracking.⁹⁴

⁹¹ Union of Concerned Scientists, Environmental Impacts of Natural Gas
<http://extension.psu.edu/natural-resources/natural-gas/issues/economic>

⁹² US Department of the Interior (2015) Interior Department Releases Final Rule to Support Safe, Responsible Hydraulic Fracturing Activities on Public and Tribal Lands.

⁹³ Torry (2015) German Cabinet Approves Anti-Fracking Draft Law, The Wall Street Journal.

The Economist (2013) Frack to the future: Extracting Europe's shale gas and oil will be a slow and difficult business.

⁹⁴ Brooks (2015) Scotland announces moratorium on fracking for shale gas, The Guardian.

Deans (2015) Welsh Government moves to impose a 'moratorium' on all of the planning bids, Wales Online.

TABLE 3: EUROPEAN COUNTRIES OR REGIONS WITH FRACKING BAN OR MORATORIUM

Country/Region	State of ban/moratorium
The Netherlands	2013 (Until 2020 at least)
Luxembourg	2012
Bulgaria	2012
Czech Republic	2012
France	2011
Wales	2015
Scotland	2015

Sources: Reuters, Bloomberg, the Economist, the Guardian, DW, Wales Online, and EJOLT

China regulation

The Chinese government is pushing to increase the role of natural gas use for energy and in particular, unconventional gas will reflect 50% of production by 2030. Overall, regulations for unconventional gas are not well established in China, which has caused some community concerns. Like the US, the nation's regulatory frameworks are based on conventional processes and are still catching up for unconventional gas.⁹⁵

⁹⁵ Feng (2015) China Backpedals on Shale Gas, American Chemical Society.

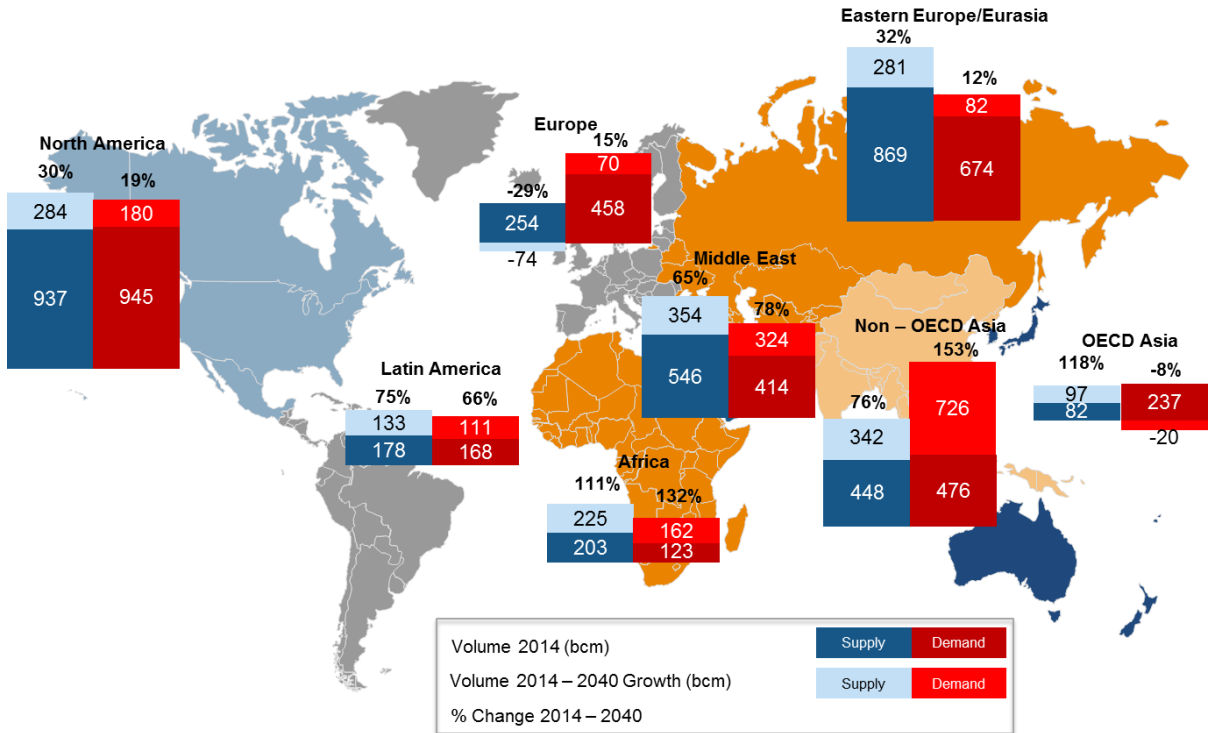
5. OUTLOOK

The current signals in the market, which were discussed in previous sections can be summarised as a few high-level trends:

- Advances in supply side technologies have changed the supply landscape and created new prospects for affordable and secure supplies of natural gas
- Natural gas markets are becoming more interconnected as a result of gas-to-gas pricing, short-term trade and consumer bargaining power
- The future of demand is highly uncertain, new policy frameworks and continued cost improvements will be needed to make gas more competitive
- Infrastructure build out, government support and the closure of regulatory gaps are needed to unlock the socioeconomic and environmental benefits of natural gas
- Several technologies exist today to create new markets for gas, but many require support from governments to penetrate markets

This section will evaluate the implications of the signals discussed in the previous sections of this paper and explore what they mean for the future of supply and demand in the natural gas industry.

FIGURE 22: GLOBAL SUPPLY AND DEMAND FOR NATURAL GAS 2014-2040 (BCM)



Sources: IEA (2015) Natural Gas Medium-Term Report and IEA (2015) World Energy Outlook

SUPPLY

The natural gas market's current oversupply is in part a result of suppliers betting on continuously increasing Asian natural gas demand and in part due to significant advances in supply side technologies. In particular, the rise of unconventional gas production in the US and Australia have shifted the global dynamics of the market. The momentum on the supply side advances coupled with softening demand in key growth markets i.e. Asia, mean it is likely that the market will stay oversupplied in the short to medium-term.

While the current supply dynamic has caused serious concerns over the economics of current and future projects, the long-term implication of this trend is that natural gas markets are becoming more interconnected as a result of gas-to-gas pricing, short-term trade and consumer bargaining power.

The following sections will discuss potential sources of new supplies, for both conventional and unconventional gas.

Conventional gas supply

Conventional supplies will continue to dominate the market, driven by production from the Middle East and Russia. The largest share of new supply additions will likely come from Qatar and Iran.

Iran, the world's largest proved natural gas reserves holder, has the potential to bring on substantial new supplies now that the Iran Nuclear Deal has enabled the lifting of Western sanctions. The nation has begun looking into potential pipeline and LNG export projects and the EC believes that Iran could supply the EU with 25-35 bcm of natural gas annually by 2030.⁹⁶ Projections for Iranian supply growth in the IEA's New Policies scenario suggest production could increase more than 100 BCM to 290 bcm by 2040⁹⁷ (from 176.2 bcm in 2014).⁹⁸

Qatar has been the world's leading LNG exporter since 2006, with 77 mtpa, or a third, of global export capacity and one third of global market share in 2014. By 2017, Australia is set to surpass Qatar as the number one LNG capacity holder with 86.5 mtpa;⁹⁹ however, there is still significant room for Qatar to disrupt the evolution of global natural gas markets.

As an established trade partner, Qatar is already well positioned to supply both Europe and Asia. In 2014, Qatar supplied 45% of all LNG imported to the Eurasia region and 31% of LNG imports to Asia.¹⁰⁰ With the world's largest LNG Trains, Qatar has the ability to produce and process large quantities of gas and can keep its costs far below Australian or US projects. IHS estimates that it costs about US\$2/MMBTU to produce and liquefy gas in Qatar.¹⁰¹ Additionally, at oil prices below US\$50/bbl, Qatar's oil indexed contracts are still cheaper than US Henry Hub indexed contracts and provide QatarGas, the Qatari NOC, with a substantial margin to continue investing in export capacity.

Sub-Saharan Africa could see their natural gas production significantly increase post-2020 due in large part to major offshore natural gas discoveries near the coast of East Africa. Mozambique and Tanzania are the main beneficiaries of these offshore discoveries. Mozambique could have up to ~7.1 tcm of recoverable natural gas according to Empresa Nacional de Hidrocarbonetos, while Tanzania has ~1.6 tcm of natural gas reserves based on estimates from the country's Energy and Minerals Ministry.¹⁰² Although Mozambique and Tanzania are minimal natural gas producers at the moment, they are projected to produce 80 bcm of natural gas combined under the IEA's New Policies Scenario in 2040, which represents massive growth potential.¹⁰³ However, significant investment and

⁹⁶ Steinhauser, G, 2015: Iran Could Become Major Supplier of Natural Gas to EU, The Wall Street Journal.

⁹⁷ BP (2015) BP Statistical Review of World Energy

IEA (2015) World Energy Outlook

⁹⁸ Note: 176.2 BCM of production excludes water, sulfur, flared gas, and injected gas

⁹⁹ IGU (2015) World LNG Report

¹⁰⁰ BP (2015) BP Statistical Review of World Energy

¹⁰¹ Reed (2015) Liquefied Natural Gas Makes Qatar an Energy Giant, The New York Times.

¹⁰² Gismatullin (2012) Eni-Anadarko African LNG Plant to Be World's Second-Largest, BloombergBusiness.

Bariyo (2015) Tanzania Says Gas Reserves Rise 18% to Reach 55 Trillion Cubic Feet, The Wall Street Journal.

¹⁰³ IEA (2015) World Energy Outlook

infrastructure improvements will be necessary in order for Mozambique and Tanzania to take full advantage of their natural gas potential.

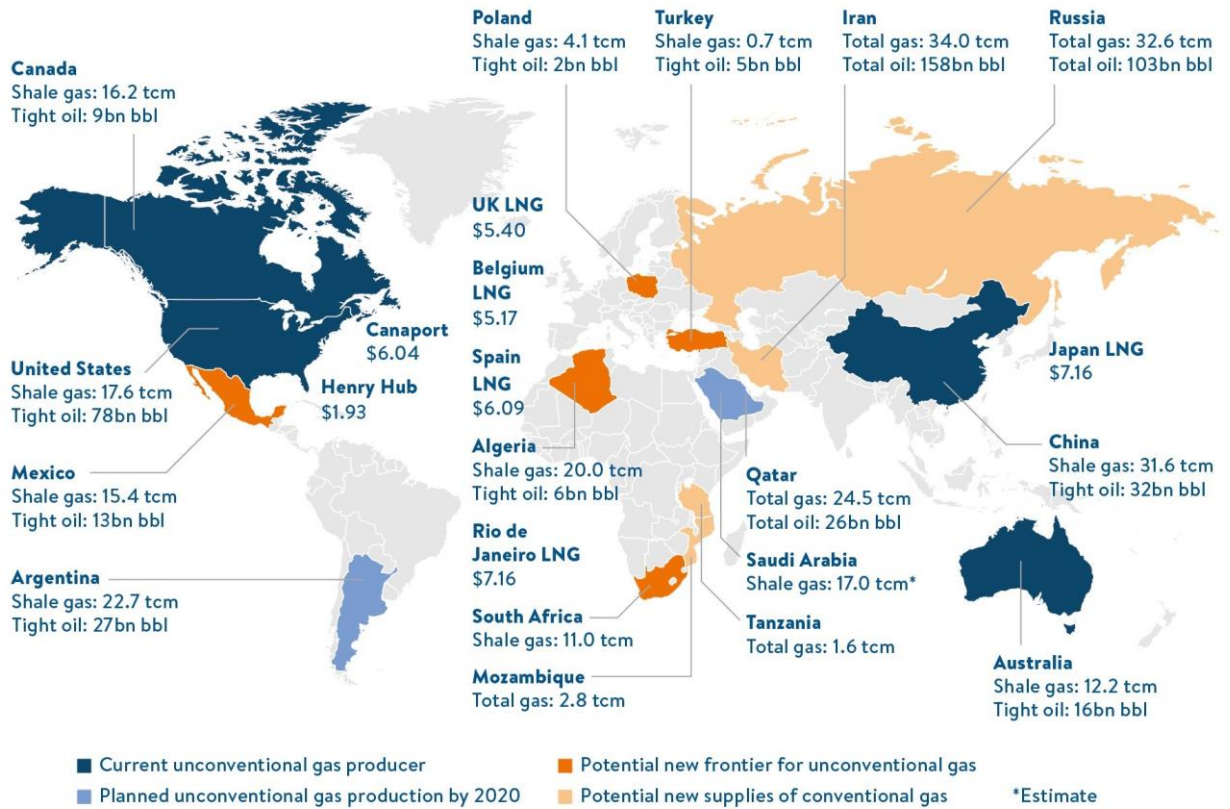
Unconventional gas supply

Despite the low price environment, unconventional gas production will continue to grow in large part due to continued efficiencies seen in US shale operations, continued momentum in the Australia LNG sector and the drive of National Oil Companies (NOCs), striving to bring affordable natural gas supplies to the market.

In particular, the continued development of unconventional gas could be pivotal in bringing affordable supplies of gas to millions of people. On a global scale, the International Energy Agency (IEA) estimated in their 2014 New Policies Scenario, that by 2040, unconventional gas could amount to 60% of all added supplies of natural gas in the period and 30% of total natural gas consumption.¹⁰⁴

¹⁰⁴ IEA (2014) World Energy Outlook

FIGURE 23: NEW SUPPLY LANDSCAPE (TECHNICALLY RECOVERABLE RESERVES)



Sources: BP Statistical Review of World Energy, EIA, FERC, and Reuters

As unconventional gas becomes both more technically and economically feasible, countries will begin to further tap into their unconventional gas potential. Table 4 illustrates the significant opportunity for unconventional gas supply growth as measured by technically recoverable shale gas reserves. Significant unconventional gas production growth is globally expected out to 2040. Unconventional gas production was 632 bcm in 2013 and the IEA projects this to more than double to 1667 bcm in 2040 under their New Policies Scenario.

TABLE 4: INTERNATIONAL TECHNICALLY RECOVERABLE SHALE GAS RESERVES

No	Country	Trillion Cubic Metres (tcm)
1	China	31.6
2	Argentina	22.7
3	Algeria	20.0
4	US	17.6
5	Canada	16.2
6	Mexico	15.4
7	Australia	12.2
8	South Africa	11.0
9	Russia	8.1
10	Brazil	6.9
11	UAE	5.8
12	Venezuela	4.7
	World	241.5

Source: EIA World Shale Resource Assessments

The three largest players for unconventional gas going forward are the US, Australia, and China. The previous chapter discussed the progress made in the US and Australia in developing their unconventional resources. China, while not as mature as the US and

Australia markets, has also made significant strides in developing its unconventional resources. In 2014, China produced 1.3 bcm of shale gas and CBM production was 11.6 bcm from mines and 3.6 bcm from seam operations.¹⁰⁵ 2014 targets from the Ministry of Land and Resources (MLR) indicate shale gas and CBM could grow to reflect at least 50% of domestic natural gas production by 2030.¹⁰⁶

Argentina and Saudi Arabia are both expected to begin commercial shale operations by the end of the decade. Argentina's unconventional potential is heavily tied to their Vaca Muerta formation in the Neuquén basin, which bears a resemblance to the early-stage Eagle Ford. This makes the development process more straightforward and creates potential for production efforts to yield significant returns.

Saudi Arabia is set to become a shale gas producer by 2020¹⁰⁷ and the nation's NOC, Saudi Aramco, recently announced it is investing another \$7bn to develop shale gas resources.¹⁰⁸ Saudi ambitions in shale gas are led by the nation's desire to boost its gas supply and displace the use of liquid hydrocarbons for power.

Table 5 outlines the expected total natural gas production growth out to 2040 in countries where there is unconventional gas potential. Both conventional and unconventional natural gas production will play a role in achieving production growth in these countries.

¹⁰⁵ Xinhua Finance (2014) China to generate 15.2 bcm CBM in 2014 up 10 pct
Platts (2015) China's 2014 Unconventional Gas Output Soars 42% on Year to 4.9 BCM, Singapore.

¹⁰⁶ Platts (2014) China Could Double Oil, Gas Production by 2030 To 700 Mil Mtoe.

¹⁰⁷ Oil and Gas News: Saudi Arabia Review: Aramco deploys rigs for shale.

¹⁰⁸ Business Insider (2015) Saudi Arabia Is Putting Aside Billions for Its Own Gas-Fracking Revolution.

TABLE 5: TOTAL NATURAL GAS PRODUCTION IN 2014 AND 2040 (NEW POLICIES SCENARIO)

Country	2014 Production (bcm)	Projected 2040 Production (bcm)
US	728.3	863
Australia	55.3	175
China	134.5	356
Argentina	39.4	111
Saudi Arabia	108.2	143
Mexico	58.1	125
Algeria	83.3	116

Source: BP (2015) Statistical Review of World Energy and IEA (2015) World Energy Outlook

DEMAND

Globally, estimates for natural gas demand growth have been revised down and range from 1.6% to 1.9% growth p.a. to 2040. Still, the share of natural gas in global primary energy demand is expected to rise from 21% in 2013 to 22% in 2020 and 24% in 2040 under the IEA's New Policies Scenario.

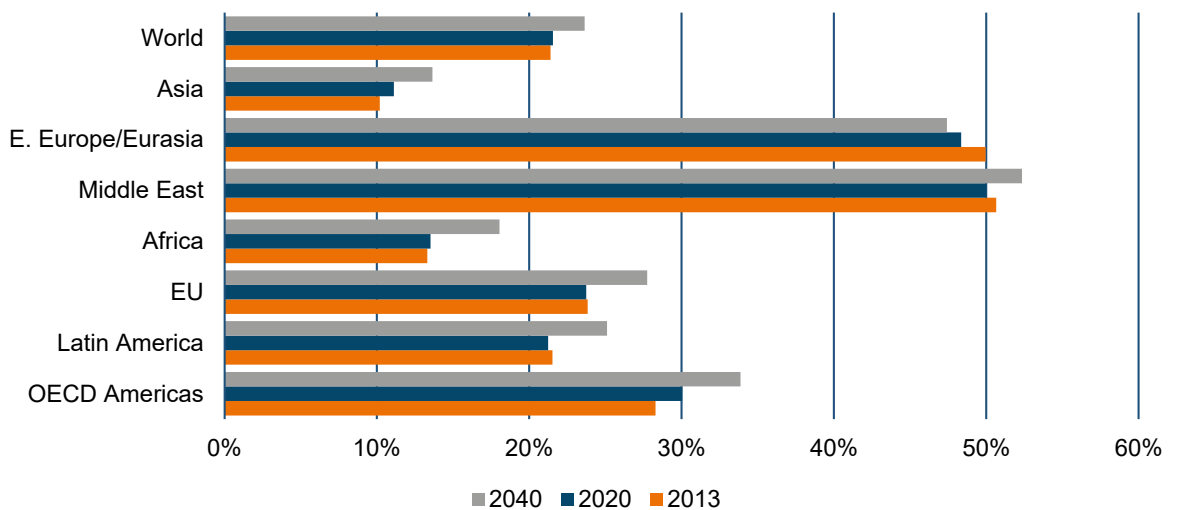
In Europe, future natural gas demand is expected to slow due to growing efficiencies in energy consumption, declining population, security concerns as well as competition from coal and subsidised renewable generation. As a result, little to no natural gas demand growth is expected in the EU out to 2040. The Eastern Europe and Eurasia region is the only region in the world where natural gas's share of primary energy demand is projected to decline from 2013 to 2040.

In Asia, economic growth appears to be slowing more quickly than previously forecasted. A slowdown in the region's economic growth is resulting in reduced projections for overall energy demand and consequently for natural gas demand. However, the region is still

expected to lead the way in terms of future demand growth, driven largely by China and India.

In resource rich regions, natural gas demand growth will remain strong. In North America, natural gas will continue to take share in power generation, industrial and building use. However, more infrastructure build will be needed to push natural gas vehicle adoption on a larger scale. The Middle East, where population growth will continue to drive growth in energy demand, will increase natural gas consumption in order to reduce the use of liquid fuels in power generation. In Sub-Saharan Africa, the stage of economic development and population growth will create demand for energy, and thus demand for natural gas. This region will lead the way for growth beyond 2040.

FIGURE 24: REGIONAL SHARE OF NATURAL GAS IN PRIMARY ENERGY DEMAND IN NEW POLICIES SCENARIO



Source: IEA World Energy Outlook (2015)

6. GLOBAL TABLE

GLOBAL TABLE – RESERVES AND PRODUCTION

Note: Natural gas production values are based on marketed natural gas production.

TABLE 6: GLOBAL NATURAL GAS DATA

2015 (2014*) Country	Proved reserves		Production		R/P Ratio
	Bcm	Bcf	Bcm	Bcf	Years
Afghanistan*	49.6	1750.0	-	-	-
Albania*	0.8	29.0	-	-	-
Algeria	4504.0	159057.4	83.3	2931.1	54.4
Angola*	308.1	10880.5	0.7	25.9	440.1
Argentina	332.2	11732.1	36.5	1288.7	9.1
Armenia*	18.0	635.7	-	-	-
Australia	3471.4	122591.7	67.1	2368.0	51.8
Austria*	9.7	341.0	1.2	44.0	8.1
Azerbaijan	1148.3	40553.1	18.2	641.7	63.2
Bahrain	172.1	6076.4	15.5	548.6	11.1
Bangladesh	232.2	8198.4	26.8	947.2	8.7
Barbados*	0.1	5.0	-	-	-
Belarus*	2.8	100.0	0.2	-	-

WORLD ENERGY COUNCIL | WORLD ENERGY RESOURCES

2015 (2014*) Country	Proved reserves		Production		R/P Ratio
	Bcm	Bcf	Bcm	Bcf	Years
Belgium*	-	-	-	-	-
Belize*	-	-	-	-	-
Benin*	1.1	40.0	-	-	-
Bhutan*	-	-	-	-	-
Bolivia	281.0	9923.4	20.9	736.5	13.5
Bosnia- Herzegovina*	-	-	-	-	-
Botswana*	-	-	-	-	-
Brazil	423.5	14956.1	22.9	809.2	18.5
Brunei	276.0	9746.8	12.7	448.4	21.7
Bulgaria*	5.7	200.0	-	-	-
Burkina Faso*	-	-	-	-	-
Burundi*	-	-	-	-	-
Cambodia*	-	-	-	-	-
Cameroon*	150.0	5297.2	-	-	-
Canada	1987.1	70174.6	163.5	5774.9	12.2
Cape Verde Islands*	-	-	-	-	-
Central African	-	-	-	-	-

WORLD ENERGY COUNCIL | NATURAL GAS

2015 (2014*)	Proved reserves		Production		R/P Ratio
Country	Bcm	Bcf	Bcm	Bcf	Years
Republic*					
Chad*	-	-	-	-	-
Chile*	40.0	1412.6	0.9	32.1	44.1
China	3841.3	135652.7	138.0	4872.1	27.8
Colombia	134.7	4758.0	11.0	389.0	12.2
Congo (DRC)*	1.0	35.0	-	-	-
Congo (Republic of)*	115.0	4061.2	-	-	-
Costa Rica*	-	-	-	-	-
Cote d'Ivoire*	28.3	1000.0	1.3	46.6	21.8
Croatia*	24.9	880.0	1.7	60.6	14.6
Cuba*	70.8	2500.0	-	-	-
Cyprus*	141.6	5000.6	-	-	-
Czech Republic*	4.0	140.0	0.2	8.7	20.0
Denmark	31.0	1094.8	4.6	162.2	6.7
Dominican Republic*	-	-	-	-	-
Ecuador*	10.9	384.9	0.6	20.4	18.2
Egypt	1846.3	65200.0	45.6	1609.6	40.5

WORLD ENERGY COUNCIL | WORLD ENERGY RESOURCES

2015 (2014*)	Proved reserves		Production		R/P Ratio
	Country	Bcm	Bcf	Bcm	Bcf
El Salvador*	-	-	-	-	-
Equatorial Guinea*	36.8	1300.0	6.6	233.3	5.6
Eritrea*	-	-	-	-	-
Estonia*	-	-	-	-	-
Ethiopia*	24.9	880.0	-	-	-
Faroe Islands*	-	-	-	-	-
Finland*	-	-	-	0.1	-
France*	9.7	341.0	0.3	10.3	33.2
Gabon*	28.3	1000.0	0.4	-	-
Gambia*	-	-	-	-	-
Georgia*	8.5	300.0	-	-	-
Germany	39.0	1376.4	7.2	253.9	5.4
Ghana*	22.7	800.0	-	-	-
Greece*	1.0	35.0	-	0.2	-
Greenland*	-	-	-	-	-
Guadeloupe*	-	-	-	-	-
Guatemala*	-	-	-	-	-
Guinea*	-	-	-	-	-

WORLD ENERGY COUNCIL | NATURAL GAS

2015 (2014*) Country	Proved reserves		Production		R/P Ratio
	Bcm	Bcf	Bcm	Bcf	Years
Guinea-Bissau*	-	-	-	-	-
Guyana*	-	-	-	-	-
Hong Kong*	-	-	-	-	-
Hungary*	7.8	277.0	1.9	65.5	4.1
Iceland*	-	-	-	-	-
India	1488.5	52564.9	29.2	1032.0	50.9
Indonesia	2839.0	100260.0	75.0	2650.2	37.8
Iran	34020.0	1201404.8	192.5	6796.7	176.8
Iraq	3694.0	130452.4	1.0	36.3	3,597.9
Ireland*	9.9	350.0	0.4	13.2	24.8
Israel	181.2	6400.0	7.5	265.2	24.2
Italy	45.0	1590.2	6.2	217.6	7.3
Jamaica*	-	-	-	-	-
Japan*	20.9	738.0	5.0	174.9	4.2
Jordan*	6.0	213.0	-	-	-
Kazakhstan	936.0	33055.3	12.4	436.6	75.7
Kenya*	-	-	-	-	-
Korea (DRC)*	-	-	-	-	-

WORLD ENERGY COUNCIL | WORLD ENERGY RESOURCES

2015 (2014*)	Proved reserves		Production		R/P Ratio
	Country	Bcm	Bcf	Bcm	Bcf
Korea (Republic)*	5.7	203.0	0.3	11.4	19.0
Kuwait	1784.0	63001.4	15.0	528.8	119.1
Kyrgyzstan*	5.7	200.0	-	-	-
Laos*	-	-	-	-	-
Latvia*	-	-	-	-	-
Lebanon*	-	-	-	-	-
Lesotho*	-	-	-	-	-
Liberia*	-	-	-	-	-
Libya	1504.9	53145.1	12.8	450.4	118.0
Lithuania*	-	-	-	-	-
Luxembourg*	-	-	-	0.2	-
Macedonia*	-	-	-	-	-
Madagascar*	-	-	-	-	-
Malawi*	-	-	-	-	-
Malaysia*	1169.3	41292.0	68.2	2408.5	17.1
Mali*	-	-	-	-	-
Malta*	-	-	-	-	-
Martinique*	-	-	-	-	-

WORLD ENERGY COUNCIL | NATURAL GAS

2015 (2014*)	Proved reserves		Production		R/P Ratio
Country	Bcm	Bcf	Bcm	Bcf	Years
Mauritania*	28.3	1000.0	-	-	-
Mauritius*	-	-	-	-	-
Mexico	324.2	11447.4	53.2	1879.1	6.1
Moldova*	-	-	-	-	-
Monaco*	-	-	-	-	-
Mongolia*	-	-	-	-	-
Montenegro*	-	-	-	-	-
Morocco*	1.4	51.0	-	-	-
Mozambique*	2831.7	100000.0	5.6	-	765.3
Myanmar (Burma)	528	-	19.6	-	16.9
Namibia*	62.3	2200.0	-	-	-
Nepal*	-	-	-	-	-
Netherlands	674.7	23827.2	43.0	1519.2	15.7
New Caledonia*	-	-	-	-	-
New Zealand*	28.3	1001.0	5.2	182.8	5.4
Nicaragua*	-	-	-	-	-
Niger*	-	-	-	-	-
Nigeria	5111.0	180493.2	50.1	1768.1	102.1

WORLD ENERGY COUNCIL | WORLD ENERGY RESOURCES

2015 (2014*)	Proved reserves		Production		R/P Ratio
Country	Bcm	Bcf	Bcm	Bcf	Years
Norway	-	65575.8	117.2	4137.2	-
Oman	688.1	24300.0	34.9	1231.8	19.7
Pakistan	542.6	19160.2	41.9	1480.1	12.9
Papua New Guinea	141.3	4988.5	0.1*	-	-
Paraguay*	-	-	-	-	-
Peru	414.2	14626.0	12.5	441.2	33.1
Philippines*	98.5	3480.0	3.7	129.3	26.6
Poland	94.5	3337.8	4.1	144.5	23.1
Portugal*	-	-	-	-	-
Puerto Rico*	-	-	-	-	-
Qatar	24528.1	866200.0	181.4	6407.6	135.2
Reunion*	-	-	-	-	-
Romania	110.0	3884.6	10.3	364.2	10.7
Russia Federation	32271.0	1139640.7	573.3	20246.0	56.3
Rwanda*	56.6	2000.0	-	-	-
Saudi Arabia	8325.2	294000.0	106.4	3758.4	78.2
Senegal*	-	-	-	-	-

WORLD ENERGY COUNCIL | NATURAL GAS

2015 (2014*)	Proved reserves		Production		R/P Ratio
	Country	Bcm	Bcf	Bcm	Bcf
Serbia	30.5	1089.3	0.5	16.7	65.3
Sierra Leone*	-	-	-	-	-
Singapore*	-	-	-	-	-
Slovakia*	14.2	500.0	0.1	3.5	142.0
Slovenia*	-	-	-	0.1	-
Somalia*	5.7	200.0	-	-	-
South Africa*	-	-	3.0	107.4	-
Spain*	2.5	90.0	-	0.8	-
Sri Lanka*	-	-	-	-	-
Sudan*	-	-	-	-	-
Suriname*	-	-	-	-	-
Swaziland*	-	-	-	-	-
Sweden*	-	-	-	-	-
Switzerland*	-	-	-	0.7	-
Syria	285.0	10064.7	4.3	152.5	66.0
Taiwan*	6.2	220.0	0.4	13.4	15.5
Tajikistan*	5.7	200.0	-	-	-
Tanzania*	1316.7	46500.0	-	-	-

WORLD ENERGY COUNCIL | WORLD ENERGY RESOURCES

2015 (2014*)	Proved reserves		Production		R/P Ratio
Country	Bcm	Bcf	Bcm	Bcf	Years
Thailand	219.5	7751.7	39.8	1406.0	5.5
Togo*	-	-	-	-	-
Trinidad and Tobago	325.7	11503.0	39.6	1399.8	8.2
Tunisia*	65.1	2300.0	2.6	90.4	25.0
Turkey*	6.8	241.0	0.5	16.8	13.6
Turkmenistan	17479.0	617265.0	72.4	2556.7	241.4
Uganda*	14.2	500.0	-	-	-
Ukraine	604.1	21332.4	17.4	614.4	34.7
United Arab Emirates	6091.0	215101.6	55.8	1969.3	109.2
United Kingdom	206.0	7274.8	39.7	1400.3	5.2
United States	10440.5	368704.0	767.3	27096.4	13.6
Uruguay*	-	-	-	-	-
Uzbekistan	1085.9	38347.2	57.7	2039.4	18.8
Venezuela	5617.2	198368.0	32.4	1145.0	173.2
Vietnam	617.1	21793.0	10.7	376.5	57.9
Yemen	266.3	9403.3	2.7	94.0	100.0
Zambia*	-	-	-	-	-

2015 (2014*)	Proved reserves		Production		R/P Ratio
Country	Bcm	Bcf	Bcm	Bcf	Years
Zimbabwe*	-	-	-	-	-
World	186,874.7	6,599,418.0	3,538.6	124,966.2	52.8

Sources: BP Statistical Review of World Energy (2016), Organisation for Economic Co-operation and Development (OPEC) Annual Statistical Bulletin (2015), EIA International Energy Statistics, Central Intelligence Agency (CIA): The World Factbook, and published national sources

REGIONAL TABLES

TABLE 7: REGIONAL NATURAL GAS DATA SORTED BY REGION

2015	Proved Reserves		Production		R/P Ratio
Country	Bcm	Bcf	Bcm	Bcf	Years
Nigeria	5111.0	180493.2	50.1	1768.1	102.1
Algeria	4504.0	159057.3	83.0	2931.1	54.3
Egypt	1846.3	65200.0	45.6	1609.6	40.5
Libya	1504.9	53145.0	12.8	450.4	118.0
Angola	308.1	10880.5	0.7	25.9	440.1
Rest of region	789.8	27890.5	19.7	694.0	40.1
Africa Total	14064	496666.5	211.8	7479.2	66.4
Australia	3471.4	122591.7	67.1	2368.0	51.8
China	3841.3	135652.7	138.0	4872.1	27.8

WORLD ENERGY COUNCIL | WORLD ENERGY RESOURCES

2015 Country	Proved Reserves		Production		R/P Ratio
	Bcm	Bcf	Bcm	Bcf	Years
Indonesia	2839.0	100260.0	75.0	2650.2	37.8
India	1488.5	52564.9	29.2	1032.0	50.9
Malaysia	1169.3	41292.0	68.2	2408.5	17.1
Vietnam	617.1	21793.0	10.7	376.5	57.9
Thailand	219.5	7751.7	39.8	1406.0	5.5
Japan	20.9	738.0	5.0	174.9	4.2
Korea (Republic)	5.7	203.0	0.3	11.4	19.0
Rest of region	1975.4	69760.7	123.4	4358.7	16.0
Asia Pacific Total	15648.1	552607.7	556.7	19658.2	28.1
Russia Federation	32271.0	1139640.7	573.3	20246.0	56.3
Turkmenistan	17479.0	617265.6	72.4	2556.7	241.4
Norway	1856.9	65575.8	117.2	4137.2	15.9
Kazakhstan	936.0	33055.3	12.4	436.6	75.7
Azerbaijan	1148.3	40553.1	18.2	641.7	63.2
Uzbekistan	1085.9	38347.2	57.7	2039.4	18.8
Netherlands	674.7	23827.2	43.0	1519.2	15.7
Ukraine	604.1	21332.4	17.4	614.4	34.7
Rest of region	722.4	25512.4	78.3	2764.1	9.2

WORLD ENERGY COUNCIL | NATURAL GAS

2015	Proved Reserves		Production		R/P Ratio
Country	Bcm	Bcf	Bcm	Bcf	Years
Europe & Eurasia Total	56778.4	2005109.3	989.8	34955.2	57.4
Venezuela	5617.2	198368.0	32.4	1145.0	173.2
Brazil	423.5	14956.1	22.9	809.2	18.5
Peru	414.2	14626.0	12.5	441.2	33.1
Trinidad and Tobago	325.7	11503.0	39.6	1399.8	8.2
Argentina	332.2	11732.1	36.5	1288.7	9.1
Rest of region	478.7	16905.8	34.5	1218.2	13.9
LAC Total	7591.5	268091.0	178.5	6302.1	42.5
Iran	34020.0	1201404.8	192.5	6796.7	176.8
Qatar	24528.1	866200.0	181.4	6407.6	135.2
Saudi Arabia	8325.2	294000.0	106.4	3758.4	78.2
United Arab Emirates	6091.0	215101.6	55.8	1969.3	109.2
Rest of region	7076.7	249911.2	81.8	2889.0	86.5
Middle East Total	80040.9	2826617.7	617.9	21821.1	129.5
United States	10440.5	368704.0	767.3	27096.4	13.6
Canada	1987.1	70174.6	163.5	5774.9	12.2

WORLD ENERGY COUNCIL | WORLD ENERGY RESOURCES

2015	Proved Reserves		Production		R/P Ratio
Country	Bcm	Bcf	Bcm	Bcf	Years
Mexico	324.2	11447.4	53.2	1879.1	6.1
North America Total	12751.8	450326.0	984.0	34750.4	13.0
Global Total	186874.7	6599418.0	3538.6	124966.2	52.8

Sources: BP Statistical Review of World Energy (2015), OPEC Annual Statistical Bulletin (2015), EIA International Energy Statistics, CIA: The World Factbook, and published national sources

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REFERENCES

- Anadarko (2015), Operations Report First Quarter 2015, Accessed Nov 2015.
- Australia Pacific LNG (2013), The Australia Pacific LNG Project, Accessed Nov 2015, www.aplng.com.au/pdf/factsheets/_APLNG012__Fact_Sheet_The_APL_Project_FINAL.PDF
- Australia Pacific LNG (2012), Australia Pacific LNG second train approved, Accessed Dec 2015, www.aplng.com.au/sites/default/files/APLNG_FID2_ASX_release.pdf
- Bariyo N, (2015), Tanzania Says Gas Reserves Rise 18% to Reach 55 Trillion Cubic Feet, The Wall Street Journal, Accessed Nov 2015, <http://blogs.wsj.com/frontiers/2015/06/08/tanzania-says-gas-reserves-rise-18-to-reach-55-trillion-cubic-feet/>
- Bauerova L, (2012), Czech Government Proposes Temporary Ban on Shale-Gas Exploration, Bloomberg Business, Accessed Dec 2015, www.bloomberg.com/news/articles/2012-09-04/czech-government-proposes-temporary-ban-on-shale-gas-exploration
- Bechtel (2015), Bechtel Delivers First Cargo of LNG for Santos GLNG Project, Accessed Nov 2015, www.bechtel.com/newsroom/releases/2015/10/bechtel-delivers-first-cargo-lng-for-santos-glng/
- BG Group, BG Group – QCLNG Fact Sheet, Accessed Nov 2015, www.bg-group.com/assets/files/cms/BG_Group_QCLNG_Fact_Sheet.pdf
- BG Group (2015), BG Group starts commercial operations from QCLNG Train 2 in Australia, Nov 25 2015, Accessed Dec 2015, www.bg-group.com/~/_tiles/?tiletype=pressrelease&id=835
- BG Group (2015), Global LNG Market Outlook 2014-15, Accessed Nov 2015, www.bg-group.com/480/about-us/lng/global-lng-market-outlook-2014-15/
- BP (2015), BP Energy Outlook 2035, Accessed Nov 2015, www.bp.com/content/dam/bp/pdf/energy-economics/energy-outlook-2015/bp-energy-outlook-2035-booklet.pdf
- BP (2005), BP Statistical Review of World Energy 2005, Accessed Mar 2016,
- BP (2015), BP Statistical Review of World Energy 2015, Accessed Nov 2015, www.bp.com/content/dam/bp/pdf/Energy-economics/statistical-review-2015/bp-statistical-review-of-world-energy-2015-full-report.pdf
- Boersma T, (2015), Algeria field report: Developing shale gas in North Africa, Brookings Institute, Accessed Jan 2016, www.brookings.edu/blogs/markaz/posts/2015/03/24-algeria-field-report-shale-gas-boersma
- Briggs H, (2015), Global climate deal: In summary, BBC, Accessed Jan 2016, www.bbc.com/news/science-environment-35073297
- Brooks L, (2015), Scotland announces moratorium on fracking for shale gas, The Guardian, Accessed Dec 2015, www.theguardian.com/environment/2015/jan/28/scotland-announces-moratorium-on-fracking-for-shale-gas
- Business Insider (Jan 2015) Saudi Arabia Is Putting Aside Billions for Its Own Gas-Fracking Revolution, Accessed Jan 2016, www.businessinsider.com/saudi-arabia-wants-its-own-shale-gas-2015-1

- Business Standard (2015), PM Modi calls for cut in energy imports by 50% by 2030, Accessed Jan 2016, www.business-standard.com/article/economy-policy/must-strive-to-bring-down-energy-import-dependence-to-50-by-2030-pm-115032700319_1.html
- Center for Energy Economics (2016), Brief History of LNG, Accessed Mar 2016, www.beg.utexas.edu/energyecon/lng/LNG_introduction_06.php
- Chambers M, (2015), Inpex unveils Ichthys delays, blowout, The Australian, Accessed Dec 2015, www.theaustralian.com.au/business/mining-energy/inpex-unveils-ichthys-delays-blowout/story-e6frg9df-1227525406104
- Chevron (2015), 2015 1Q Earnings Transcript, Accessed Dec 2015, <http://investor.chevron.com/phoenix.zhtml?c=130102&p=irol-EventDetails&EventId=5190019>
- Chevron (2015), Chevron and SK LNG Trading Sign Gorgon LNG Supply Agreement, Accessed Dec 2015, www.chevron.com/chevron/pressreleases/article/01202015_chevronandsklngtradingsignorgonlngsupplyagreement.news
- Chin S, (2014), Aora To Provide First Solar-biogas Hybrid Power Solution For Off-grid Africa Communities, powerelectronics.com/solar/aora-provide-first-solar-biogas-hybrid-power-solution-grid-africa-communities-0
- Cho MS, Korea sees gas demand falling 5 percent by 2029, Reuters, Accessed Mar 2016, <http://uk.reuters.com/article/southkorea-gas-idUKL3N14H14720151228>
- CIA (2016), The World Factbook, Accessed Mar 2016, www.cia.gov/library/publications/the-world-factbook/
- CNPC (2015), Flow of natural gas from Central Asia, Accessed Dec 2015, www.cnpc.com.cn/en/FlowofnaturalgasfromCentralAsia/FlowofnaturalgasfromCentralAsia2.shtml
- CNPC (2015), More than 160 bcm of shale gas reserves newly proved in Sichuan Basin, Accessed Feb 2016, www.cnpc.com.cn/en/nr2015/201509/71392fa045d7406ab3c8c8f95d12811b.shtml
- Cohen L, (2015), Anadarko Petroleum Reduces Rig Count and Capex, Seeking Alpha, Accessed Dec 2015, <http://seekingalpha.com/article/3001686-anadarko-petroleum-reduces-rig-count-and-capex>
- ConocoPhillips (2015), ConocoPhillips Investor Update: May 14, 2015. Accessed Nov 2015, www.conocophillips.com/investor-relations/Investor%20Presentation%20Documents/Investor%20Travel%20Deck-5142015.pdf
- Deans D, (2015), Welsh Government moves to impose a 'moratorium' on all of the planning bids, Wales Online, Accessed Dec 2015, www.walesonline.co.uk/news/wales-news/end-fracking-wales-welsh-government-8638802
- Dudley B,. (2015), World Gas Conference 2015 Quote.
- DW (2015), What ever happened with Europe's fracking boom? Accessed Dec 2015, www.dw.com/en/what-ever-happened-with-europes-fracking-boom/a-18589660
- EIA (2015), Annual Energy Outlook 2015, Accessed March 2016, www.eia.gov/forecasts/aeo/section_energyprod.cfm
- EIA (2015), Country Reports, Accessed Mar 2016.

- EIA (2016), Drilling Productivity Report, Jan 2016, Accessed Jan 2016, www.eia.gov/petroleum/drilling/
- EIA (2016), Henry Hub Natural Gas Spot Price, Accessed Mar 2016, www.eia.gov/dnav/ng/hist/rngwhhdm.htm
- EIA (2016), International Energy Statistics, Accessed Mar 2016, www.eia.gov/cfapps/ipdbproject/IEDIndex3.cfm
- EIA (2016), Monthly Natural Gas Gross Withdrawals, Average of Monthly Production, Accessed Jan 2016, www.eia.gov/petroleum/drilling/
- EIA (2016), Natural Gas Consumption by End Use, Accessed Mar 2016, www.eia.gov/dnav/ng/ng_cons_sum_dcu_nus_a.htm
- EIA (2016), Natural Gas Gross Withdrawals and Production, Accessed Mar 2016, www.eia.gov/dnav/ng/ng_prod_sum_a_EPG0_FGW_mmcf_a.htm
- EIA (2015), Projections show U.S. becoming a net exporter of natural gas, Accessed Dec 2015, www.eia.gov/todayinenergy/detail.cfm?id=20992
- EIA (2016), U.S. Natural Gas Imports by Country, Accessed Mar 2016, www.eia.gov/dnav/ng/hist/n9100us2a.htm
- EIA (2015), World Shale Resource Assessments, Accessed Jan 2016, www.eia.gov/analysis/studies/worldshalegas/
- EMIS (2015), Argentina Energy: Shale on You, Accessed Mar 2016, www.securities.com/emis/insight/argentina-energy-shale-you
- Energy Market Company (2016), SGX LNG Index Group. Accessed Mar 2016, www.emcsg.com/sling
- European Commission (2012), Competition: Energy and Environment Overview, Accessed Mar 2016, http://ec.europa.eu/competition/sectors/energy/overview_en.html
- ExxonMobil (2016), The Outlook for Energy: A View to 2040, Accessed Mar 2016, <http://cdn.exxonmobil.com/~media/global/files/outlook-for-energy/2016/2016-outlook-for-energy.pdf>
- Feng B, (2015), China Backpedals on Shale Gas, American Chemical Society, Accessed Dec 2015, <http://cen.acs.org/articles/93/i3/China-Backpedals-Shale-Gas.html>
- FERC (2016), North America LNG Import/Export Terminals Approved, Accessed Feb 2016, www.ferc.gov/industries/gas/indus-act/lng/lng-approved.pdf
- FERC (2016), World LNG Estimated January 2016 Landed Prices, Accessed Mar 2016, www.ferc.gov/market-oversight/mkt-gas/overview/ngas-ovr-lng-wld-pr-est.pdf
- Franza L, (2014), Long-Term Gas Import Contracts in Europe, Clingendael International Energy Programme, Accessed Dec 2015, www.clingendaelenergy.com/inc/upload/files/Ciep_paper_2014-08_web_1.pdf
- Froley A, (2015), Gazprom, oil-link vs spot gas prices, and storage, Platts, Accessed Dec 2015, <http://blogs.platts.com/2015/04/23/gazprom-gas-oil-link-spot-prices-storage/>
- Gas Infrastructure Europe, www.gie.eu/index.php/maps-data/gle-sslng-map
- Gazprom (2016), About Gazprom, Accessed Jan 2016, www.gazprom.com/about/

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- GE and Accenture (2014), Redefining Pipeline Operations, Accessed Dec 2015, www.intelligentpipelinesolution.com/industrialpipeline/download/GE-IP-Overview.pdf
- GE and Accenture (2014), Redefining Pipeline Operations, Infographic, Accessed Dec 2015, www.intelligentpipelinesolution.com/industrialpipeline/download/GE-IP-Infographic.pdf
- Gismatullin E, (2012), Eni-Anadarko African LNG Plant to Be World's Second-Largest, BloombergBusiness, Accessed Nov 2015, www.bloomberg.com/news/articles/2012-12-21/eni-anadarko-plan-world-s-second-largest-Ing-plant-in-africa
- Gladstone Observer, Origin reveals \$1.65b cost increase on APLNG project, Accessed Dec 2015, www.gladstoneobserver.com.au/news/origin-reveals-165b-cost-blowout-aplng-project/1766190/
- Gloystein H, (2015), After half a decade apart, global gas prices converge, Reuters, Accessed Dec 2015, www.reuters.com/article/2015/01/27/Ing-prices-global-idUSL6N0V603620150127
- Golar LNG (2015), Golar Cameroon FLNG Project Reaches Major Milestone, Accessed Feb 2016, www.golarlng.com/index.php?name=seksjon/Stock_Exchange_Releases/Press_Releases.html&pressrelease=1955666.html
- Goswami U, (2015), How India weathered a storm in Paris during COP21 climate summit, The Economist Times, Accessed Jan 2016, <http://economictimes.indiatimes.com/news/politics-and-nation/how-india-weathered-a-storm-in-paris-during-cop21-climate-summit/articleshow/50275528.cms>
- Herrero A, (2014), Fracking ban expanding in Spanish regions, EJOLT, Accessed Dec 2015, www.ejolt.org/2014/02/fracking-ban-expanding-in-spanish-regions/
- <http://extension.psu.edu/natural-resources/natural-gas/issues/economic>
- ICIS (2015), China's weak natural gas demand cuts into LNG imports, Accessed Mar 2016, www.icis.com/resources/news/2015/10/07/9930658/china-s-weak-natural-gas-demand-cuts-into-Ing-imports/
- ICIS (2015), Romania likely to end natural gas imports by 2016 - ANRE, Accessed Feb 2016, www.icis.com/resources/news/2015/09/21/9925337/romania-likely-to-end-natural-gas-imports-by-2016-anre/
- IEA (2014), Africa Energy Outlook 2014, Accessed Nov 2015, www.iea.org/publications/freepublications/publication/WEO2014_AfricaEnergyOutlook.pdf
- IEA (2013), Developing a Natural Gas Trading Hub in Asia, Accessed Dec 2015, www.iea.org/media/freepublications/AsianGasHub_WEB.pdf
- IEA (2012), Golden Rules for a Golden Age of Gas, Accessed Dec 2015, www.iea.org/publications/freepublications/publication/WEO2012_GoldenRulesReport.pdf
- IEA (2015), IEA Natural Gas Medium-Term Report 2015, Accessed Jan 2016.
- IEA (2014), The Asian Quest for LNG in a Globalising Market, Accessed Dec 2015, www.iea.org/publications/freepublications/publication/PartnerCountrySeriesTheAsianQuestforLNGinaGlobalisingMarket.pdf
- IEA (2015), World Energy Outlook 2015, Accessed Mar 2016.
- IEA (2014), World Energy Outlook 2014, Accessed Nov 2015.

- IEEJ, Economic and Energy Outlook of Japan through FY2016, Accessed Mar 2016, <https://eneken.iecee.or.jp/en/press/press150710b.pdf>
- IGU (2015), Wholesale Gas Price Survey - 2015 Edition, Accessed Mar 2016, www.igu.org/sites/default/files/node-page-field_file/IGU%20Whole%20Sale%20Gas%20Price%20Survey%20Report%20%202015%20Edition.pdf
- IGU (2015), World LNG Report - 2015 Edition, Accessed Nov 2015, International Gas Network (2015), Thirteen Five: the development of China Natural Gas Industry Analysis, Accessed Mar 2016, <http://gas.in-en.com/html/gas-2276156.shtml>
- Islam R, (2016), Nearly 230 BUSD earmarked for pre-development projects deferred since H2 2014, delaying over 3 MMboe/d of supply, Rystad Energy, Accessed Mar 2016, www.rystadenergy.com/AboutUs/NewsCenter/PressReleases/project-delays-commentary-
- Krupp F, (2016), Fixing the Methane Leaks That Deflate Natural-Gas Gains The Wall Street Journal, www.wsj.com/articles/fixing-the-methane-leaks-that-deflate-natural-gas-gains-1454541892
- LNG World News, (2015), Cedigaz European LNG net imports up in 2015, www.lngworldnews.com/cedigaz-european-lng-net-imports-up-in-2015/
- Macdonald-Smith A, (2015), Chevron's Gorgon LNG faces delay to 2016, The Sydney Morning Herald, Accessed Dec 2015, www.smh.com.au/business/chevrons-gorgon-lng-faces-delay-to-2016-20150731-gioy1r.html
- Macdonald-Smith A, (2015), Origin Energy shares rise as start-up nears of \$24.7b Australia Pacific LNG project, The Sydney Morning Herald, Accessed Dec 2015, www.smh.com.au/business/origin-energy-shares-rise-as-startup-nears-of-247b-australia-pacific-lng-project-20150728-gim1mt.html
- Macdonald-Smith A, (2016), Origin Energy ships first cargo from APLNG plant in Gladstone, The Sydney Morning Herald, Accessed Mar 2016, www.smh.com.au/business/energy/origin-energy-ships-first-cargo-from-aplng-plant-in-gladstone-20160110-gm31rf.html
- Marcogaz, (2015), Methane emissions in the European natural gas transmission and distribution sectors www.marcogaz.org/index.php/environment-health-a-safety
- METI (2015), Long-term Energy Supply and Demand Outlook, Accessed Mar 2016, www.meti.go.jp/english/press/2015/pdf/0716_01a.pdf
- Mitsui Lines OSK, (2015), MOL, Gas Sayago Reach Basic Agreement on Continuing Uruguay LNG FSRU Project, Accessed Feb 2016, www.mol.co.jp/en/pr/2015/15064.html
- Mitsui Lines OSK, (2013), MOL Joining Project in Uruguay – Build and Charter World's Largest FSRU, Accessed Feb 2016, www.mol.co.jp/en/pr/2013/13073.html
- Natural Resources Canada (2016), North American Natural Gas Market: 2015-2016 Heating Season Outlook, Accessed Mar 2016, www.nrcan.gc.ca/energy/sources/natural-gas/17894
- NETL, (2013), Water Issues Dominate Oil and Gas Production, www.netl.doe.gov/file%20library/research/oil-gas/epnews-2013-fall.pdf

- Nülle G, (2015), Tight Oil Production Trends in a Low Price Environment, EIA, Accessed Nov 2015, www.eia.gov/conference/2015/pdf/presentations/nulle.pdf
- Oil and Gas News: Saudi Arabia Review: Aramco deploys rigs for shale, Accessed Jan 2016, www.oilandgasnewsworldwide.com/Article/36791/Aramco_deploys_rigs_for_shale
- OPEC (2015), OPEC Annual Statistical Bulletin 2015, Accessed Mar 2016, www.opec.org/opec_web/static_files_project/media/downloads/publications/ASB2015.pdf
- Patel T, (2015), Methane Emissions Threaten to Undermine Natural-Gas Offensive, Bloomberg Business, Accessed Dec 2015, www.bloomberg.com/news/articles/2015-06-03/methane-emissions-threaten-to-undermine-natural-gas-offensive
- Petrobangla (2011), Planning, Accessed Feb 2016, www.petrobangla.org.bd/corp_planning.php
- Petronas (2015), Petronas Floating LNG, Accessed Feb 2016, www.petronas.com.my/our-business/Upstream/lng/Documents/PFLNG%20brochure.pdf
- Petrovich B, (2013), European gas hubs: how strong is price correlation? Oxford Institute for Energy Studies, Accessed Mar 2016, www.oxfordenergy.org/wpcms/wp-content/uploads/2013/10/NG-79.pdf
- Platts (2015), China's 2014 Unconventional Gas Output Soars 42% on Year to 4.9 BCM, Accessed Nov 2015, www.platts.com/latest-news/natural-gas/singapore/chinas-2014-unconventional-gas-output-soars-42-27013858
- Platts (2014), China Could Double Oil, Gas Production By 2030 To 700 Mil Mtoe, Accessed Aug 2015, www.platts.com/latest-news/oil/singapore/china-could-double-oil-gas-production-by-2030-27807594
- Platts (2015), Gazprom, oil-link vs spot gas prices, and storage, Accessed Feb 2016, <http://blogs.platts.com/2015/04/23/gazprom-gas-oil-link-spot-prices-storage/>
- Platts (2014), India's Natural Gas Demand to Double to 516.97 Mil Cu M/Day By 2021-22: Report, Accessed Jan 2016, www.platts.com/latest-news/natural-gas/mumbai/indias-natural-gas-demand-to-double-to-51697-26778967
- PNG LNG (2015), About PNG LNG, Accessed Feb 2016, <http://pnglng.com/project/about.html>
- Queensland Australia (2016), Queensland's petroleum and coal seam gas 2014-2015, Australia, Accessed Feb 2016, www.dnrm.qld.gov.au/__data/assets/pdf_file/0020/238124/petroleum.pdf
- Reed S, (2015), Liquefied Natural Gas Makes Qatar an Energy Giant, The New York Times, Accessed Jan 2016, www.nytimes.com/2015/08/06/business/energy-environment/liquefied-natural-gas-makes-qatar-an-energy-giant.html?_r=0
- Reuters (2012), Bulgaria bans shale oil and gas drilling, Accessed Dec 2015, www.reuters.com/article/2012/01/18/bulgaria-shalegas-ban-idUSL6E8CI2ML20120118#dCuGbQ98BaOgFC90.97
- Reuters (2015), Hess is mirroring Toyota manufacturing process to slash well costs, Accessed Dec 2015, www.reuters.com/article/2015/04/02/dugconference-hess-idUSL2N0WY2T820150402
- Reuters (2015), Saudi Aramco extends bidding for unconventional gas work -sources, Accessed Jan 2016, www.reuters.com/article/aramcosaudi-arbn-oil-gas-idUSL5N0VS15320150222

- Rochan M, (2015), Shell and Total believe future is in natural gas and not in coal, International Business Times, Accessed Dec 2015, www.ibtimes.co.uk/shell-total-believe-future-natural-gas-not-coal-1504050
- Rositano C (2014), Relying on Russia: an overview of the existing European pipeline industry, Pipelines International, Accessed Dec 2015, http://pipelinesinternational.com/news/relying_on_russia_an_overview_of_the_existing_european_pipeline_industry/89032
- RT (2015), China begins construction of Power of Siberia pipeline for gas delivered from Russia, Accessed Dec 2015, www.rt.com/business/270352-russia-china-gas-pipeline/
- Saudi Aramco, (2015), Annual Review 2014, Accessed Jan 2016.
- Santos GLNG (2014), First Cargo Shipped From GLNG, Accessed Sept 2015, www.santoslng.com/media-centre/media-releases/first-cargo-shipped-from-glng.aspx
- Shek C, (2015), China's gas-import slowdown threatens LNG producers, Aljazeera, Accessed Dec 2015, www.aljazeera.com/indepth/features/2015/06/china-gas-import-slowdown-threatens-lng-producers-150602104833809.html
- Shiryaevskaya A, (Sept 2015), Cheap Russian Gas Tempts EU Buyers as LNG Import Growth Stalls, Bloomberg Business, Accessed Jan 2016, www.bloomberg.com/news/articles/2015-09-09/cheap-russian-gas-tempts-eu-buyers-as-lng-import-growth-stalls
- Sino Gas & Energy (2016), Five Year Plan, Accessed Feb 2016, <http://sinogasenergy.com/china/chinas-12th-five-year-plan/>
- Shell (2013), New Lens Scenarios: A Shift in Perspective for a World in Transition, Accessed Mar 2016, www.shell.com/content/dam/royaldutchshell/documents/corporate/scenarios-newdoc.pdf
- South Korea (2014), South Korea 7th Master Plan for the Supply and Demand of Electricity Power. The Monthly Report on Major Electric Power Statistics 2014, Accessed Mar 2016,
- Spurrier A, (2015), Exmar confirms Caribbean FLNG delivery date, IHS, Accessed Feb 2016, fairplay.ihs.com/commerce/article/4255816/exmar-confirms-caribbean-flng-delivery-date
- Stark M, (2014), International Development of Unconventional Resources: If, where and how fast?, Accenture, Accessed Nov 2015, www.accenture.com/t20150523T024807__w__/dk-en/_acnmedia/Accenture/Conversion-Assets/DotCom/Documents/Global/PDF/Dualpub_2/Accenture-Energy-International-Development-Unconventionals.pdf
- Stark M, (2012), Water and shale gas development: leveraging the US experience in new shale developments, Accenture, Accessed Jan 2016,
- Stark M, Blackford T, Vargas M, Sorice J, & Davis M, (2014), Achieving high performance in unconventional operations, Accenture, Accessed Dec 2015, www.accenture.com/us-en/~media/Accenture/Conversion-Assets/DotCom/Documents/Global/PDF/Dualpub_11/Accenture-High-Performance-Unconventional-Operations.pdf
- Stark M, & Vargas M, (2016), Gas Grows Up, Accenture, Accessed Mar 2016, www.accenture.com/t20160309T024135__w__/us-en/_acnmedia/PDF-7/Accenture-Gas-Grows-up.pdf

- Steinhauser G, (2015), Iran Could Become Major Supplier of Natural Gas to EU, The Wall Street Journal, Accessed Jan 2016, www.wsj.com/articles/iran-could-become-major-supplier-of-natural-gas-to-eu-1442155324
- The Economist (2013), Frack to the future: Extracting Europe's shale gas and oil will be a slow and difficult business, Accessed Dec 2015, www.economist.com/news/business/21571171-extracting-europes-shale-gas-and-oil-will-be-slow-and-difficult-business-frack-future
- The White House (2015), Fact Sheet: Administration Takes Steps Forward on Climate Action Plan by Announcing Actions to Cut Methane Emissions, Accessed Dec 2015, www.whitehouse.gov/the-press-office/2015/01/14/fact-sheet-administration-takes-steps-forward-climate-action-plan-anno-1
- Torry H, (2015), German Cabinet Approves Anti-Fracking Draft Law, The Wall Street Journal, Accessed Dec 2015, www.wsj.com/articles/german-cabinet-approves-anti-fracking-draft-law-1427896555
- Total (2012), Liquefied Natural Gas: A Booming Industry, Accessed Dec 2015, www.total.com/sites/default/files/atoms/file/brochure-gnl-en
- Union of Concerned Scientists: Environmental Impacts of Natural Gas, Accessed Jan 2016 www.ucsusa.org/clean_energy/our-energy-choices/coal-and-other-fossil-fuels/environmental-impacts-of-natural-gas.html#.VmrcMUorKM8
- US Department of Energy: Natural Gas Regulation, Accessed Dec 2015, <http://energy.gov/fe/services/natural-gas-regulation>
- US Department of the Interior (2015), Interior Department Releases Final Rule to Support Safe, Responsible Hydraulic Fracturing Activities on Public and Tribal Lands, Accessed Jan 2016, www.doi.gov/news/pressreleases/interior-department-releases-final-rule-to-support-safe-responsible-hydraulic-fracturing-activities-on-public-and-tribal-lands
- USGS (2000), Coal-Bed Methane: Potential and Concerns, Accessed Dec 2015, <http://pubs.usgs.gov/fs/fs123-00/fs123-00.pdf>
- van Beurden B, (2015), Growing Gas Together, Shell, Accessed Dec 2015, www.shell.com/global/aboutshell/media/speeches-and-articles/2015/growing-gas-together.html
- The White House, 2015: Fact Sheet: Administration Takes Steps Forward on Climate Action Plan by Announcing Actions to Cut Methane Emissions, Accessed Dec 2015, www.whitehouse.gov/the-press-office/2015/01/14/fact-sheet-administration-takes-steps-forward-climate-action-plan-anno-1
- World Bank (2016), World Bank Commodities Price Data (The Pink Sheet), Accessed Mar 2016, <http://pubdocs.worldbank.org/pubdocs/publicdoc/2016/3/633811457027702995/CMO-Pink-Sheet-March-2016.pdf>
- World Bank, (2016), Access to electricity (% of population), Accessed Mar 2016, <http://databank.worldbank.org/data/reports.aspx?source=2&type=metadata&series=EG.ELC.ACCS.ZS>
- www.bloomberg.com/news/articles/2015-09-03/canada-oil-sands-fork-over-billions-for-500-000-unnneeded-barrels
- Xinhua Finance (Dec 2014), China to generate 15.2 bcm CBM in 2014 up 10 pct, Accessed Jan 2016, en.xinfinance.com/html/Industries/Energy/2014/20447.shtml

Zammerilli A, (2014), Environmental Impacts of Unconventional Natural Gas Development and Production, US Department of Energy, Accessed Dec 2015, www.netl.doe.gov/File%20Library/Research/Oil-Gas/publications/NG_Literature_Review3_Post.pdf

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**World Energy
Resources
Uranium and Nuclear
|2016**

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KEY FINDINGS

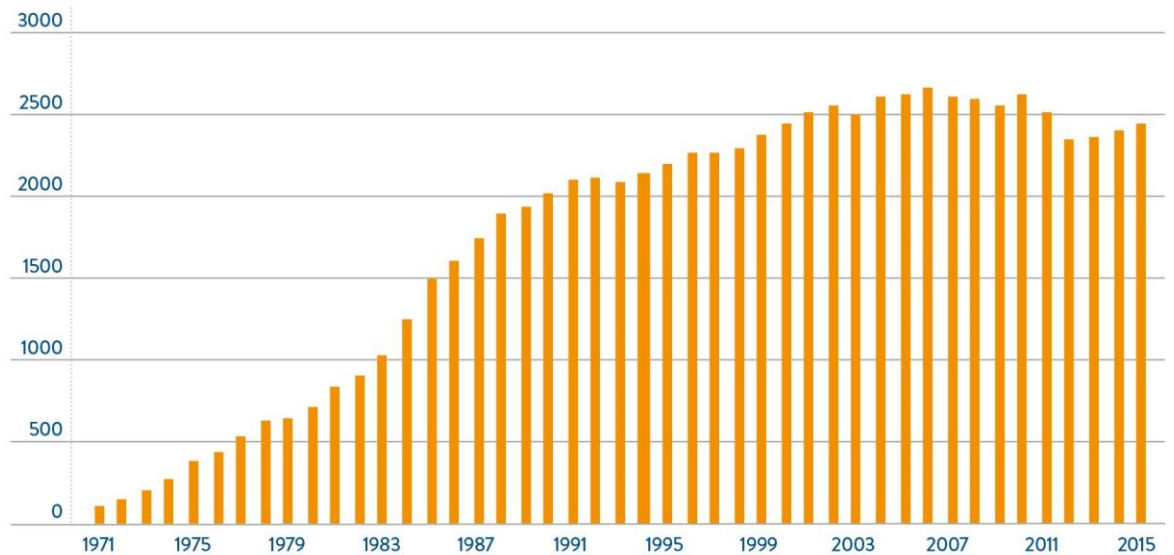
1. Global nuclear power capacity reached 390 GWe at the end of 2015, generating about 11% of the world electricity. As of December 2015, 65 reactors were under construction (6 more than in July 2012) with a total capacity of 64 GW.
2. Construction total is the highest for many years and two-thirds (40) of the units under construction are located in four countries: China, India, Russia and South Korea. Projections indicated that nuclear power generation capacity will increase the fastest in the Far East (China, Japan and the Republic of Korea), and downward shifts are set to occur in North America and Western Europe.
3. China and India are expected to dominate future prospects of nuclear generation. The increasing need to moderate the local pollution effects of fossil fuel use, means that nuclear is increasingly seen as a means to add large scale baseload power generation while limiting the amount of GHG emissions.
4. Currently there are more than 45 Small Modular Reactors designs under development and four reactors under construction. These designs are expected to provide dramatic improvements in reactor flexibility and efficiency.
5. The low share of fuel cost in total generating costs makes nuclear the lowest-cost baseload electricity supply option in many markets. Uranium costs account for only about 5% of total generating costs and thus protect plant operators against resource price volatility. Generation IV reactors promise to remove any future limitation on fuel supply for hundreds of years.
6. Nuclear desalination has been demonstrated to be a viable option to meet the growing demand for potable water around the globe, providing hope to areas in arid and semi-arid zones that face acute water shortages.
7. In the period beyond 2035, it is expected that fast reactors will make an increasing contribution in a number of countries by building on the experience of operating these reactors in Russia and with developing the Generation IV prototypes, such as the Astrid reactor being designed in France.
8. The economic attractiveness of existing nuclear plant economics is confirmed by the appetite of many utilities to extend the life of their existing fleet. In the US, licences to extend to sixty years the licence period have been sought and received for the great majority of reactors. Plans are being developed to apply for 80 year life extensions¹.

¹ In general, high-cycle fatigue is not a life-limiting factor for nuclear power plants (in contrast to fossil-fired plants or even wind turbines), as their thermal parameters are much lower, leaving much greater mechanical margins. Ageing of nuclear plants is more governed by spare part availability (especially for instrumentation

INTRODUCTION

Following the construction of the first nuclear power plants in the 1950s and 1960s, nuclear power enjoyed very rapid growth during the 1970s and 1980s. The promise of low cost nuclear power was bolstered by the oil crisis of the 1970s which led to concerns about security of fossil fuel supply and high fuel prices. Subsequent growth in the 1990s was checked by lower than expected electricity demand growth, reactions to the accidents at Three Mile Island and Chernobyl, and in some countries moves to liberalise the power sector. Starting in the 2000s and driven by Asian economic development, an unexpected revival of nuclear took place. The advantages of nuclear power are being increasingly recognised: a reliable and secure source of power that in many countries is fully competitive, moreover, a technology that in normal operation is environmentally benign and with zero carbon emissions. With the shift of economic gravity towards the rapidly growing countries of Asia, where existing forms of power generation are facing multiple limits to the role that they can play, nuclear power is seen by a number of governments as an important part of the generation mix.

FIGURE 1: WORLD NUCLEAR ELECTRICITY PRODUCTION, TWH



Source: International Atomic Energy Agency, Power Reactor Information System

The Fukushima accident in March 2011 resulted in a developmental hiatus and a nuclear retreat in some countries; however, with the benefit of five years of hindsight the true

and control systems), additional regulatory requirements, and reactor vessel embrittlement due to neutron influx. Nevertheless, the latter are qualified for 60 to more than 100 years, and can also be extended.

proportions of that accident are becoming clearer: a barely perceptible direct impact on public health but high economic and social costs.

Since 2011, and following a series of safety reviews, nuclear development has continued in those countries that were hitherto committed to it. Electricity demand continues to grow rapidly in developing countries and the disadvantages of competing forms of power generation are increasingly being felt. Nuclear can be seen as standing at an historic inflection point where the pessimism of earlier decades has been replaced by an appreciation of the role that nuclear power can play in the portfolio of clean energy sources. Certainly, the industry stands ready to make a greater contribution to meeting future electricity demand than in the recent past. The designs of current reactors are safer and more efficient than previous designs and there are sufficient defined uranium resources to power the current level of capacity for over 100 years. Given the appropriate price signals, many more resources could undoubtedly be defined. Moreover, the development of fast neutron reactors, a technology with more than 100 reactor years of operating experience, could allow current uranium resources to provide power for an effectively indefinite period into the future whilst simultaneously reducing the challenges of waste management and proliferation for future generations.

1. URANIUM

Uranium is a naturally-occurring element in the earth whose traces can be found everywhere. Most reactors are fuelled by uranium, which is mined in significant quantities in twelve countries, even though the distribution of uranium is quite widespread (with a similar concentration within the earth's crust to that of tin). Over 80% of global production is mined in five countries (Kazakhstan, Canada, Australia, Namibia and Niger) and resources in the ground are plentiful.

In conventional mining, ore is mined via underground access workings or by open pits. The ore goes through a mill where it is crushed and then ground in water to produce a slurry of fine ore particles suspended in the water. The slurry is leached with sulphuric acid to dissolve the uranium oxides, leaving the remaining rock undissolved.

In 2015 over half of world mining production uses in situ leaching (ISL), where groundwater injected with a complexing solution and usually an oxidant is circulated through the uranium ore, extracting the uranium. The solution containing dissolved uranium is then pumped to the surface. This mining method does not cause any significant ground disturbance.

Both mining methods produce a liquid with dissolved uranium, which is separated, filtered and dried to produce a uranium oxide concentrate (U₃O₈). The U₃O₈ is only mildly radioactive. The radiation level one metre from a drum of freshly-processed U₃O₈ is about half that experienced from cosmic rays on a commercial jet flight.

The development of ISL mining has reduced the cost base of the uranium mining industry as in most cases ISL mining is cheaper than conventional mining. It can also be developed more rapidly and is less capital intensive. It should be possible in future to adjust mine production from ISL mines to prevailing demand conditions rather more readily than for conventional mines, which have high development and other capital costs that need to be amortized. The spot price for U₃O₈ through 2015 has not been sufficiently high to incentivise new conventional mines or even to maintain production at all existing mines. Continued production at some existing mines is being enabled by long term (legacy) contracts agreed when prices were significantly higher than 2015 levels and by depreciation of local currencies against the US\$ in a number of the main producers.

Global uranium production increased by 40% between 2004 and 2013, mainly because of increased production by Kazakhstan, the world's leading producer. Since 2013, mine production has declined somewhat reflecting the surplus capacity existing in the post-Fukushima world. Several mines have closed, either temporarily or permanently, and the development of a number of projects has been curtailed. Nonetheless, a surplus of mine supply continues to exist reflecting the fact that expectations for increased demand have not been met. It will be several years before equilibrium is established in the uranium market as several new mines are only now coming into production. Cigar Lake in Canada

and Husab in Namibia are two very large mines that along with mine expansions in Kazakhstan are likely to keep any growth of demand well supplied over the next few years.

Uranium resource and production capacity have grown together over the past few years reflecting a 22% increase in uranium exploration and mine development activities between 2008 and 2010, which in 2010 surpassed US\$2 billion. The assessments of global uranium resources made by the International Atomic Energy Agency and the Nuclear Energy Agency show that total identified resources have grown by about 70% over the last ten years. As of January 2015, the total identified resources of uranium are considered sufficient for over 100 years of supply based on current requirements.

Despite its rapid increase, total annual mine production is less than the fresh fuel requirements of all operating reactors in the world. This is a consequence of a “secondary” market for uranium (i.e. a market for already mined uranium) for reactor fuel from nuclear warheads and other military and commercial sources, most notably reprocessing of used fuel and ‘underfeeding’ by enrichment plants (where in response to a favourable price ratio between uranium and enrichment services, more enriched uranium is created from the same amount of ore). The “secondary” market has limited growth in the remaining demand for fresh uranium. At its lowest in the 1990s, the total global production of uranium fell to about 60% of the annual reactor fuelling requirements.

Enrichment

To enable natural uranium to be used in light water reactors, the concentration of the fissile isotope U235 must be increased in enrichment plants from 0.71% to 4-5%. Uranium enrichment capacity markets have also changed. Lower cost centrifuge enrichment has now almost entirely replaced the earlier gas diffusion process but remains concentrated in the EU, Russia and to a lesser extent the US. China, which is using Russian and domestically-designed centrifuges, has reached a capacity of 4.0 million SWUs² (out of a global total of 57m SWUs) and is adding more capacity. Limited enrichment facilities for domestic needs exist in Argentina, Brazil, India and Pakistan.

Fabrication

Total global fuel fabrication capacity is currently over 13 000 tHM/yr (tonnes of heavy metal) for light water reactor (LWR) fuel and about 4 000 tHM/yr for pressurised heavy water reactor fuel (PHWR). Total demand is about 10 400 tU/yr. Some expansion of current facilities is under way in China, Russia, Republic of Korea and the USA. The current fabrication capacity for mixed oxide (MOX) fuel is around 200 tonnes of heavy metal (tHM), with one industrial plant located in France (Melox). Some smaller facilities under construction in Japan and the Russian Federation. Additional MOX fuel fabrication capacity is under construction in the USA to use surplus weapons-grade plutonium. China is also planning for the construction of a large scale reprocessing and MOX fuel fabrication facility in the next decade. Worldwide, 31 thermal reactors currently use MOX fuel.

² Separative Work Unit, a standardised measure of the effort required to separate U235 from other isotopes of uranium.

Used Fuel Management

In principle, most of the energy content of the fuel that is loaded into a reactor remains after the fuel is discharged. Depending on national policy, the nuclear operator faces the choice of whether to send the used fuel to a waste repository or to reprocess the used fuel to extract and re-enrich the fuel as 'enriched recycled uranium' and 'mixed oxide fuel' (MOX which blends the two oxides of uranium and plutonium) for use in specially licenced reactors (respectively 'open' and 'closed' fuel cycles). The total amount of used fuel that has been discharged globally is approximately 320 000 tHM. Of this amount, about 95,000 tHM has been reprocessed, and the rest is stored in spent fuel storage pools at reactors or in away-from-reactor storage facilities. Away-from-reactor storage facilities are being regularly expanded, both by adding modules to existing dry storage facilities and by building new ones. Six countries operate reprocessing facilities and recycle parts of the plutonium in the form of MOX for reuse in nuclear power plants. Some countries manage plutonium with spent MOX fuel which can be recycled for fuelling future fast-breeder programmes. Total global reprocessing capacity is about 5,000 tHM/yr.

PLUTONIUM

Plutonium (Pu94) was discovered in 1940 and is the first element made by men, when scientists were studying how to make atomic bombs. Nearly all the available plutonium is artificial, even though some traces occur in nature as well. There are two types of plutonium: one is used as fuel for reactors, from uranium 238, and the other one to produce nuclear weapon.

Even if plutonium is highly toxic and radioactive, it's also used to power batteries for some heart pacemaker and to fuel some NASA space missions. ³

THORIUM

Thorium was discovered in 1828 by the chemist J. J. Berzelius. It is a slightly radioactive material and it exists in nature in a single isotope (Th-232) which decays very slowly. The energy is released after the exposure to neutrons and thorium undergoes a series of nuclear reactions, becoming U-233, a fissile isotope of uranium.

There are seven types of reactor into which thorium can be used as fuel: Heavy Water Reactors (PHWRs), High-Temperature Gas-Cooled Reactors (HTRs), Boiling (Light) Water Reactors (BWRs), Pressurised (Light) Water Reactors (PWRs), Fast Neutron Reactors (FNRs), Molten Salt Reactors (MSRs), Accelerator Driven Reactors (ADS).

Thorium fuel cycles has attractive characteristics, such as lower levels of waste generation, less transuranic elements in that waste, and a diversification option for nuclear fuel supply. Also, the use of thorium could guarantee extra safety margins. Despite these merits, the extracting costs are still high and the research has faced a slowing down in the recent years.

³ Sources: World Nuclear Association and US NRC.

India is the country with the largest reserve of Thorium (almost 25% of the world's supply) and for this reason is engaging research to build reactors that use thorium instead of uranium. It has developed its unique three stage nuclear power programme for utilising thorium. This involves serial deployment of PHWR (natural U-235), FBR (using Pu-239) and FBR (using U-233).⁴

⁴ Sources: World Nuclear Association and The Open University.

2. TECHNOLOGY

All currently operating nuclear energy facilities utilise the process of nuclear fission. In this process, heavy atomic nuclei split apart to form lighter ones, releasing energy at the same time. Certain isotopes (most notably uranium-235, which is naturally occurring) are fissile, which means that they can be made to undergo fission when bombarded with neutrons. The fission process also produces neutrons, so that a chain reaction can be set up wherein each fission event can initiate another. Nuclear reactors then are designed to maintain this chain reaction in a controlled manner. Fission takes place in the nuclear fuel while the rest of the reactor is designed to convert the thermal energy produced into electricity and to make sure that none of the radioactive material created during the process is released into the environment. Nuclear power plants are thermal plants, similar to gas or coal. They heat water to steam in order to turn turbines. In the case of medical and research reactors, some of the radioactive isotopes created via fission are actually the product of interest. These can be used for medical and industrial purposes.

The amounts of energy released in these nuclear reactions are very large – some 10,000 times larger than chemical processes such as the combustion of fossil fuel. This high energy density is in fact one of the great technical advantages of nuclear energy since it means that much lower volumes of fuel are needed than fossil fuel, refuelling only needs to be carried out periodically, siting of plants can be quite flexible and it is much easier to protect against disruptions to fuel supply. The other advantage is that there is no chemical ‘burning’ going on. There is no need for oxygen and no harmful atmospheric emissions produced. Wastes are contained inside the physical fuel itself.

The chief technical drawback of nuclear technology is that fuel which has undergone fission, used fuel, becomes intensely radioactive. While the level of radioactivity actually diminishes quite quickly, it remains at levels which are dangerous to most living organisms for thousands of years. This used fuel requires shielding, can only be handled remotely and requires special measures for its final disposal. It also continues to generate a significant heat load, both inside the reactor and out, for several years and requires active cooling during this time. If fuel gets too hot it will melt, and the radioactive materials contained will be released. In a very serious fuel melt event the radioactive materials may escape the reactor and containment structures, posing a risk to people and the environment, as happened at both the Fukushima Daiichi and Chernobyl plants. However, it must be said that modern nuclear power plants are constructed with improved systems for maintaining cooling and containing any radioactive material that may be produced in the rare event of fuel damage.

TODAY’S NUCLEAR REACTOR TECHNOLOGY

There are a large number of reactor technology configurations which can achieve and manage fission and in the first generation of nuclear power plants there was significant variation in plant design. Based on the learning from this early experience, the second generation of nuclear power plants (Gen II) settled on a handful of reactor ‘types’

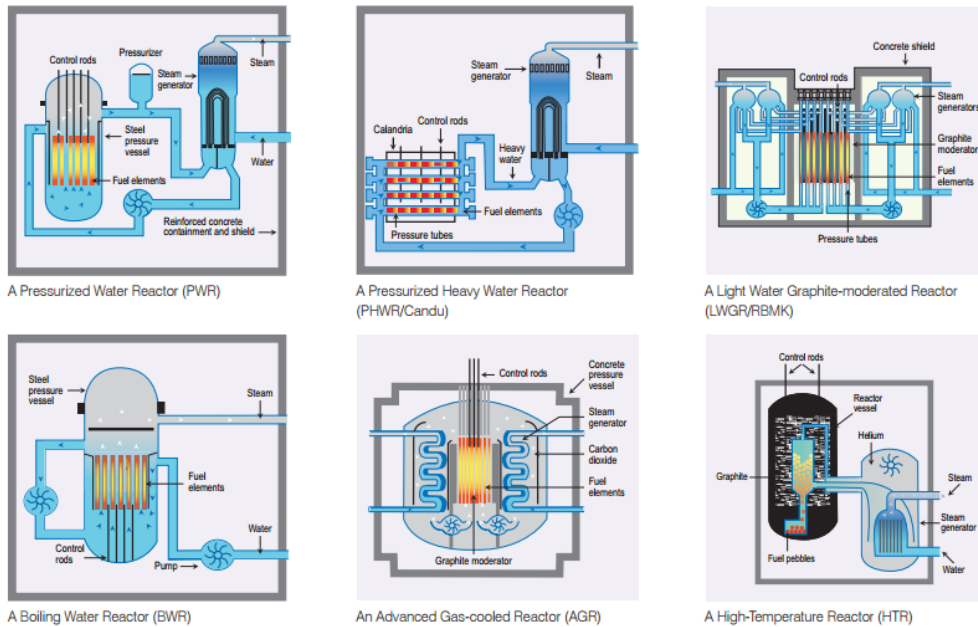
championed by different countries although there was still significant variation in design between plants and not much standardisation in models. These types include:

1. **Pressurised water reactor – PWR.** Pressurised water forms both the moderator⁵ and the coolant. Hot water is kept liquid under pressure and pumped through a primary circuit containing steam generators. These steam generator heat water in a secondary circuit to steam and this steam drives a turbine before being condensed and returned to the steam generators.
2. **Boiling water reactor – BWR.** Water is both moderator and coolant. However, in a boiling water reactor there is only one circuit. Water boils inside the reactor pressure vessel directly and this steam drives the turbine to create electricity.
3. **Pressurised heavy water reactor – PHWR.** These use normal (light) water as a coolant but use heavy water⁶ as a moderator. Their coolant is kept pressurised and they also make use of steam generators. These reactors can be found in Canada, India, South Korea, Argentina and Romania.
4. **Gas-cooled reactor – GCR.** Now only to be found in the UK (with the AGR designs), these employ a gas coolant in the primary circuit and water in the secondary circuit. They use graphite as a moderator.
5. **Light water (cooled) graphite (moderated) reactor – LWGR.** These use normal water as a coolant and graphite as a moderator and steam generators. The remaining LWGRs are all in Russia where they are known as RBMKs.

⁵ In order for a nuclear chain reaction to be sustained in most reactors, it is necessary to slow down the neutrons created to a certain ideal speed. This process is called moderation and it increases the likelihood of a fission reaction taking place in uranium-235. Water is often used for this purpose, but it is not a particularly effective moderator, meaning that enriched fuel needs to be used in these reactor designs. Other moderator materials which are used include graphite and so-called heavy water.

⁶ Water where one or more hydrogen atoms present is deuterium (i.e. has a neutron as well as a proton).

FIGURE 2: REACTORS IN USE



Source: World Nuclear Association (2016)

The currently operating nuclear power plants which can be found in some 30 countries around the world are mostly Gen II now. Over 90% of these are light water reactor designs (pressurised water reactors or boiling water reactors). The other designs have a more limited deployment as noted. The longevity of the Gen II reactors has turned out to be quite remarkable and the performance of these units has improved steadily with time. These days, most plants operate routinely with higher than 80% capacity factors and are expected to be capable of operating for between 50 – 60 years. Studies are currently underway in the US to see whether reactor lives could technically be extended out to 80 years. Life extension of existing nuclear units is one of the cheapest forms of maintaining generating capacity. However, there are questions over material aging (and the effects of radiation on this) that will be only be answered as plants operate for longer and which may mean that some units are capable of operating for longer than others.

Gen III reactors represent an evolutionary development of Gen II and all designs currently available are PWRs, BWRs or PHWRs. They offer improved safety and are supposed to offer improved economic performance over Gen II. They are built with a longer planned lifetime of 60 plus years and operate at greater thermal efficiencies, optimising the use of fuel. In order to achieve these goals Gen III reactors are typically larger than most Gen II designs. Well over half of the reactors currently under construction are Gen III reactors.

A list of the currently commercially available reactor models is provided in the tables below.

**TABLE 1: COMMERCIALY AVAILABLE POWER REACTORS DESIGNS
(WITH UNITS UNDER CONSTRUCTION OR CONSTRUCTED)**

Developer	Reactor	Capacity (MWe gross)	Design progress, notes
GE-Hitachi, Toshiba (USA, Japan)	ABWR (BWR)	1380	Commercial operation in Japan since 1996-7 US design certification 1997 UK design certification application 2013
Westinghouse/Toshiba (USA/Japan)	AP1000 (PWR)	1200-1250	Under construction in China and USA, many units planned in China US design certification 2005 UK design certification expected 2017 Canadian design certification in progress
Areva and EDF (France)	EPR (PWR)	1700-1750	Future French standard, French design approval. Being built in Finland, France and China UK design approval 2012
KEPCO and KHNP (South Korea)	APR 1400 (PWR)	1450	Under construction at Shin Kori in South Korea Under construction at Barakah in United Arab Emirates Korean design certification 2003 US design certification application
CNNC and CGN (China)	Hualong One (PWR)	1150	Main Chinese export design, under construction at Ningde
Gidropress (Russia)	VVER-1200 (PWR)	1200	Under construction at Leningrad and Novovoronezh plants as AES-2006 plant
NPCIL (India)	PHWR-700	700	Under construction at Kakrapar, Gujarat and Rawatbhata, Rajasthan. Several of them planned for deployment in next 10 years.
BHAVINI (India)	FBR-500	500	Under construction at Kalpakkam, Tamilnadu as PFBR

**TABLE 2: COMMERCALLY AVAILABLE POWER REACTORS DESIGNS
(AVAILABLE, BUT NO UNITS UNDER CONSTRUCTION)**

Developer	Reactor	Size (MWe gross)	Design progress, notes
GE-Hitachi (USA/Japan)	ESBWR (BWR)	1600	Planned for Fermi and North Anna in USA Developed from ABWR Design certification in USA 2014
Mitsubishi (Japan)	APWR (PWR)	1530	Planned for Tsuruga in Japan US design application as US-APWR EUR design approval as EU-APWR 2014
Areva and Mitsubishi (France, Japan)	Atmea1 (PWR)	1150	Planned for Sinop in Turkey French design approval 2012

			Canadian design certification in progress
Candu Energy (Canada)	EC6 (PHWR)	750	Improved CANDU-6 model Canadian design certification June 2013
Gidropress (Russia)	VVER-TOI (PWR)	1300	Planned for Nizhny Novgorod in Russia and Akkuyu in Turkey Russian design certification in progress for European Utility Requirements
SNPI (China)	CAP1400 (PWR)	1400	Developed in China from AP1000 with Westinghouse support, for export First unit ready to start construction at Shidaowan

TOMORROW'S REACTORS

There are many future reactor technologies which are various stages of research and development. Of particular note are the class of small modular reactors (SMRs) and fast reactors, which promise dramatic improvements in reactor flexibility and efficiency respectively.

- Small Modular Reactors:** Ranging in size anywhere up to about 300 MW, i.e. are much smaller than reactor models currently on offer, SMRs are designed to take advantage of economies of series production, rather than economies of scale. They have a greater degree of passive safety and are expected to have a wider range of applications than larger reactors as they are more adaptable and easier to transport and fit into smaller grids. They may also be better suited to the replacement of small fossil units, for use in areas where energy demand is mostly flat or growing only very slowly, and in cases where financing larger energy projects is challenging. The modular construction techniques mean more of the components can be factory manufactured with resulting gains in quality control and speed of assembly. The comparatively larger number of orders should hopefully result in a faster rate of learning and corresponding cost reductions than is possible for larger designs. Lastly, SMRs are particularly suited to non-electrical applications such as co-generation and district heating. In arid parts of the world, there are opportunities to use SMRs for desalination. There is a range of SMRs being developed, from the more traditional light water technologies to molten salt reactors, liquid metal cooled reactors and gas cooled reactors. The light-water designs are arguably closest to market and the first models are planned to be operational by 2020. Mass production is envisaged to make these reactors competitive and accessible to a wide range of countries and companies.
- Fast Neutron Reactors:** Classified as Gen IV technology, the main technical differences between fast neutron reactors and those designs described above stems from the absence of a moderator and the use of different fuel and core configurations. Fast neutron reactors use mainly plutonium 239 (instead of uranium 235) which doesn't react efficiently with slow neutrons. Fast reactors are quite remarkable in that they can create or 'breed' more of their own fuel. The excess of neutrons emitted by the fission of plutonium 239 in these reactors converts uranium 238 present in the core into more plutonium 239. Over 99% of natural uranium

consists of uranium 238 compared to about 0.7% uranium 235, meaning that a vast amount of additional energy is available from the same mined resource. The use of mined uranium in these reactors is only 1% or 2% compared with conventional designs, making them a great deal more fuel efficient. Another advantage of this reactor class is that they can run on the used fuel of today's reactors, consuming much of the actinides present, thereby reducing the volume of high-level waste that needs to be disposed of and the length of time it remains radioactive. Unfortunately, the economics of these reactors remain challenging and research is ongoing with test units in several countries and knowledge shared via international collaborations. Nevertheless, it is envisaged that nuclear fleets with a combination of fast and conventional reactors making use of the synergies between the two types might exist later in the century.

3. ECONOMICS & MARKETS

This section begins with a review of the historical costs and technologies, followed by a review of recent developments.

HISTORIC AND CURRENT TRENDS

Nuclear power was first produced in 1954 but did not take-off as a significant source of power generation until the 1970s and 1980s. During these decades, which were characterised by concerns about security of supply and the depletion of fossil fuel resources, nuclear expanded to provide nearly 18% of the world electricity output. Since that time, its share has declined somewhat as generation growth has shifted from the OECD countries to the developing world. Nuclear power is less well established in non-OECD countries and generation in those countries has been met largely by coal and gas. Nuclear accidents have also played a role in slowing the industry's expansion and the Fukushima accident in 2011 led to a decline in global nuclear capacity that is only now being reversed.

The nuclear industry has developed over three distinct periods:

1. The first "fast growth" period between 1970 and 1990 witnessed an average growth rate of about 12 reactors per year following the first oil price shock of 1973-1974.
2. The second period from 1990 to the mid-2000 was a period of low development, averaging additions of 2-3 new reactors per year only. The increasing capital costs of nuclear and low fossil fuel prices were the main factors resulting in the slowdown. The situation was aggravated further by the two major nuclear accidents: Three Mile Island (USA, 1979) and Chernobyl (Ukraine, 1986).
3. The third period from the mid-2000s until the present day once again witnessed a pick-up in growth. In terms of geographical distribution, the growth was no longer in the OECD countries but mainly in the rapidly developing Asian economies (especially China). That growth was justified by nuclear's relative cost-effectiveness compared to fossil fuels. In addition, environmental concerns, political decisions to establish nuclear programmes and public neutrality in the main countries of growth were contributing factors.

Total annual nuclear power generation reached about 2,600 TWh in the mid-2000s after which it fell back somewhat as reactors were taken off-line following Fukushima. The nuclear share of total global electricity production reached 17% by the late 1980s, but since then dropped to 11% in 2013.

Nuclear Economics and Competitiveness

The economics of nuclear power are characterised by high upfront capital costs and low operating costs over a long operating lifetime, finishing with decommissioning costs. The investment cost of a nuclear power plant will constitute more than 60% of the levelised costs of power generation and it is very important for the economic viability of a nuclear power plant that it is utilised as fully as possible, preferably in a supply network that is able to provide a stable power price.

Drawing on the data supplied by the International Energy Agency and Nuclear Energy Agency (IEA/NEA), nuclear capital costs (known as ‘overnight costs’⁷) vary widely between over US\$6,000/kW in Hungary to less than US\$2,000/kW in China⁸. The reasons for such a wide range are numerous, complex and not always well understood. Differences in the costs of labour (especially the highly skilled labour required for nuclear), the materials used and above all the series economies that can be derived from replication of similar nuclear projects are all important to the determination of nuclear capital costs. As with other baseload generating technologies, the economics of building nuclear power plants are very dependent on being able to spread the costs of reactor development over a significant programme of new build and maintaining the human capital required for efficient delivery of a nuclear programme. Recent construction of new reactor designs in the US and Europe have in particular encountered ‘First of a Kind’ problems that have increased costs, although subsequent units are starting to exhibit learning benefits.

Nuclear capital costs have escalated in some countries at various points in the past, with the US recording some of the highest rates of increase. However, capital cost inflation has been far less of a feature in other countries for which data are available, as the table below indicates.

TABLE 3: HISTORICAL CONSTRUCTION COSTS OF GLOBAL NUCLEAR POWER REACTORS

Country	Era (defined by time period in which reactors began construction)	Annualised rate of change in Overnight Capital Cost (percent/year)
USA	1954-1968, 18 demonstration reactors	-14%
	1964-1967, 14 turnkey reactors	-13%

⁷ Capital costs that are assumed to be incurred at a single point in time, that is without incurring financing charges.

⁸ OECD-Nuclear Energy Agency & International Energy Agency (2015) Projected Costs of Generating Electricity

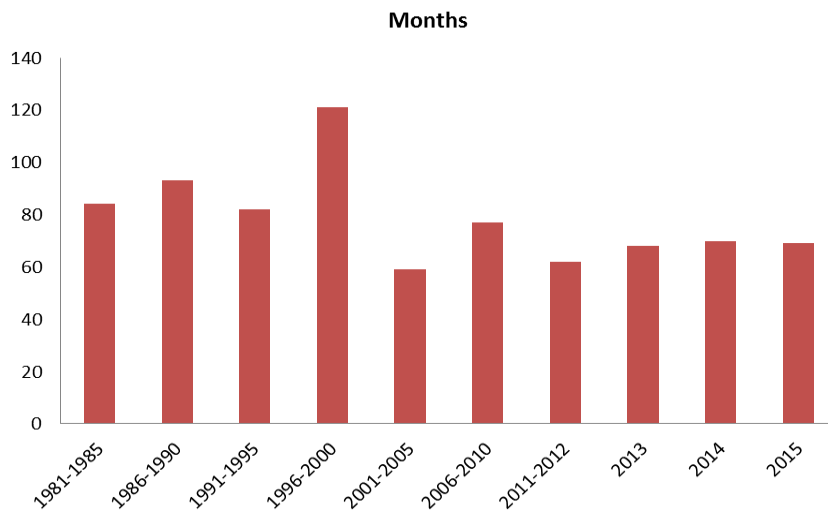
	1967-1972, 48 reactors completed pre-TMI 1968-1978, 51 reactors completed post-TMI	+23% +5 to +10%
France	1957-1966, 7 gas-cooled reactors 1971-1991, 59 light- water reactors	-17% +2 to +4%
Canada	1957-1974, 6 reactors 1971-1986, 18 reactors	-8% +4%
West Germany	1958-1973, 8 reactors 1973-1983, 18 reactors	-6% +12%
Japan	1960-1971, 11 imported reactors 1970-1980, 13 foreign designs 1980-2007, 30 domestic reactors	-15% +8% -1 to +1%
India	1964-1972, 5 imported reactors 1971-1980, 5 domestic reactors 1990-2003, 6 domestic reactors+ 2 imported	-7% +5% -1%
South Korea	1972-1993, 9 foreign designs 1989-2008, 19 domestic reactors	-2% -1%

Source: Lovering, Yip and Nordhaus (2016)
<http://www.sciencedirect.com/science/article/pii/S0301421516300106>

In addition to the differences in overnight costs, nuclear investment costs are governed by the length of time taken for construction. Finance costs are in the order of 30-40% of total investment costs and financing costs increase proportionately with delays to construction schedules. Nuclear power plants are complex engineering projects that are sensitive to delay once construction has started. In addition to strong vendor and/or utility project management capacities, the role of the regulator is critical to delivering good project management as regulator-mandated retrospective specification changes are usually extremely expensive.

The construction record for nuclear is mixed, although arguably no worse than for other large-scale projects of similar complexity and the overall record is skewed by the small number of extremely delayed projects, eg, Watts Bar 2 (US) where construction started in 1973 and Mochovce 4 (Slovakia) started in 1987. The average construction time of the 34 units that started up in the world between 2003 and July 2013 was 9.4 years. However, if the median rather than the mean performance of the industry is evaluated, the picture is very much better and is improving. The median reactor was constructed in 5.75 years in 2015.

FIGURE 3: REACTOR MEDIAN CONTRUCTION TIME



Source: IAEA (2016) Power Reactor Information System

The terms on which finance is forthcoming are critical to the viability of a nuclear project. The predictability of nuclear revenues will have a significant impact on the financing terms available to the operator. In most countries the electricity market is regulated; indeed, national electricity generation and supply systems are typified by single, state-owned generators and distributors of electricity are able to set prices at a level that covers costs and able to obtain finance on public sector terms. Alternatively, deregulated systems are typified by diverse, usually privately-owned operators and separately-owned distribution companies. Generators are to a greater extent price-takers and prices are set by the marginal seller of electricity. The prospects for revenue predictability in the two systems are very different and therefore also the terms governing the availability of finance.

In deregulated markets in particular, the competitiveness of nuclear depends on the marginal costs of alternative generation technologies, concerning which there have been some significant developments in recent years. In the US, unconventional gas has proved to be a very competitive source of fuel and has resulted in falling electricity prices to such an extent that the economic viability of nuclear plants with higher operating costs have been affected (of which two have closed prematurely for purely economic reasons). The absence of a meaningful cost of carbon is a contributor to these low gas prices. So far, the widespread development of unconventional gas has been limited to the US.

In the EU, the principal threat to nuclear arises from the rapid development of renewable generation, in particular wind and solar. These intermittent forms of power, which have been boosted by a generous subsidy regime, have an almost zero marginal cost of production. As a result, they are reducing the capacity factors for competing generation technologies, including nuclear. The above factors have made the nuclear competitive

position country, if not site, specific. The maintenance of the renewable subsidy programmes, the outlook for continued decreases in the capital costs of these technologies and those of the storage technologies needed to compensate for intermittent generation, are questions that will have a significant bearing on the future of nuclear power.

The IEA & OECD-NEA estimate the costs of generating electricity on a lifetime basis, i.e., are levelised. As can be seen from the table below, the competitiveness of nuclear varies from country to country, but is competitive against a range of other generation technologies even when making the conservative assumption of a 10% discount rate.

TABLE 4: LEVELISED COSTS OF POWER GENERATION BY TECHNOLOGY AND COUNTRY (AT A 10% DISCOUNT RATE)

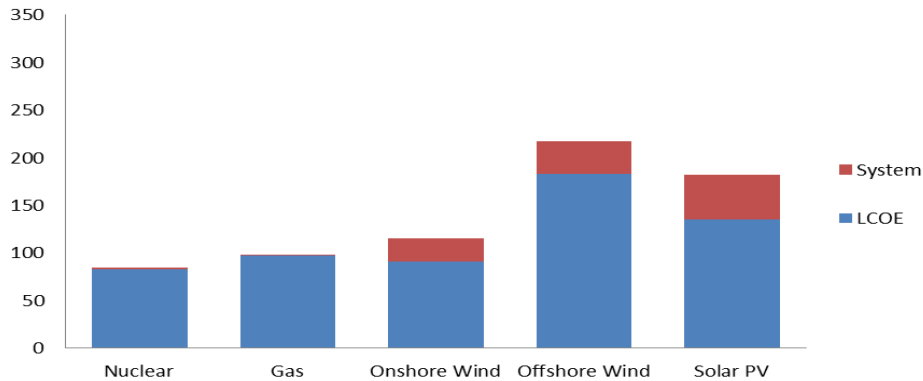
Technology	Country / Regional Data	Levelised Cost (US\$/MWh 2013)
Nuclear	USA	102
	Europe	109-136
	China	49-64
	South Korea	51
Hydroelectric	USA	87-194
	Europe	40-388
	China	28
Onshore Wind	USA	52-79
	Europe	85-151
	China	72-82
	South Korea	179
Offshore Wind	USA	167-188
	Europe	170-261
	South Korea	327
Solar Photovoltaic	USA	103-199
	Europe	123-362
	South Korea	176-269
Gas	USA	71
	Europe	101-263
	China	95
	South Korea	122-130
Coal	USA	104
	Europe	83-114
	China	82
	South Korea	86-89

Source: OECD-NEA and IEA (2015) Projected Costs of Generating Electricity

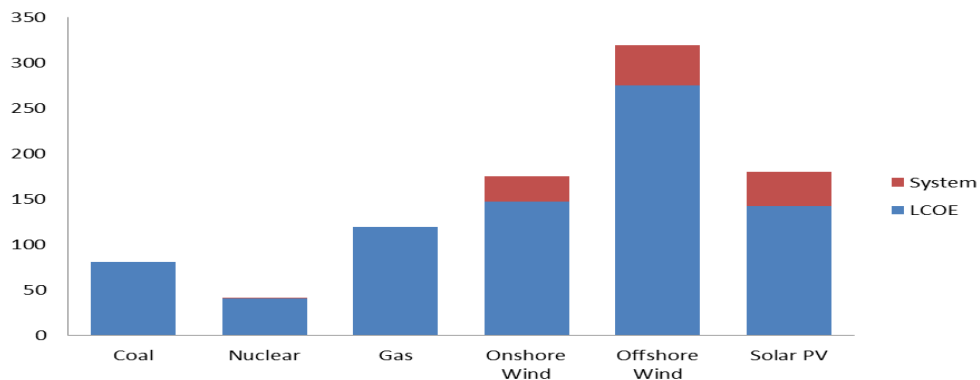
The competitiveness of nuclear is enhanced further when the ‘systems’ costs of different technologies are included. The standard calculation of levelised costs takes the costs at the site boundary (i.e., does not include transmission and distribution costs) and most importantly takes no account of the balancing and adequacy requirements needed to guarantee supply when needed. All technologies have systems costs, but they are most pronounced for intermittent generation technologies. The charts below give an indication of the magnitude of these costs in four countries.

FIGURES 4: PROJECTED COSTS OF GENERATION ELECTRICITY 2015

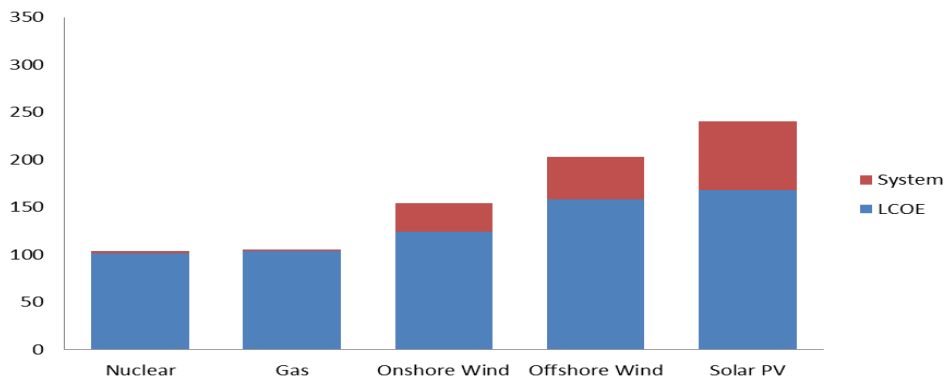
FRANCE: PLANT LCOE PLUS SYSTEM COST \$/MWH, 7% DISCOUNT FACTOR



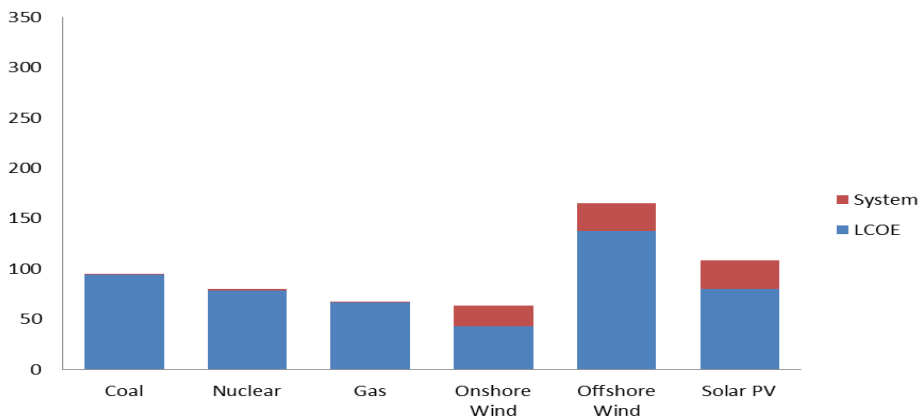
KOREA: PLANT LCOE PLUS SYSTEM COST \$/MWH, 7% DISCOUNT FACTOR



UNITED KINGDOM: PLANT LCOE PLUS SYSTEM COST \$/MWH, 7% DISCOUNT FACTOR



UNITED STATES: PLANT LCOE PLUS SYSTEM COST \$/MWH, 7% DISCOUNT FACTOR



Sources: IEA & OECD-NEA (2015) Projected Costs of Generating Electricity; OECD-NEA (2012) Nuclear Energy and Renewables

A final aspect of nuclear economics concerns the costs of decommissioning. The latter are incurred at the end of an expected 60-year lifetime, followed in some cases by an expected period of closure of as long as 50 years before the costs of dismantlement are incurred. Other countries have opted to dismantle nuclear power plants soon after the cessation of commercial operation. The financial implications of decommissioning are usually very manageable where a fund has been established at an early stage.

KEY DYNAMICS OF NUCLEAR POWER IN DIFFERENT COUNTRIES

The New Nuclear Developers

The development of nuclear power is today concentrated in a relatively small group of countries. China, Korea, India and Russia account for 40 of the 65 reactors that the IAEA records as under construction in December 2015. The countries that have historically accounted for the majority of nuclear power development are now under-represented in new construction.

New nuclear development is taking place in countries that tend to share certain common factors:

- Nuclear power is seen by government as a strategic industrial sector that is important not only to the supply of electricity to the country but also as a driver of innovation, advanced industrial development and as a platform to export high value-added products and services to the rest of the world. National nuclear vendors have been developed and a mature supply chain exists that is becoming more and more international.
- There is a large and sometimes protected national market for nuclear that in a number of cases is characterised by rapidly increased demand for electricity. The production and distribution of electricity is dominated by large, state-owned companies able to set prices for domestic consumers on a cost-plus basis. There is an expectation that the large nuclear construction programmes in these countries will reduce the capital costs of the currently first-of-a-kind nuclear power plants developed by national reactor vendors as development and set-up costs are spread over a large number of constructed reactors.

The Traditional Nuclear Developers

A number of countries with existing nuclear fleets are also considering new nuclear investments as they face constraints related to fossil fuel electricity generation, namely the will to reduce reliance from imported fossil fuel but also due to climate change and other environmental concerns. A growing concern in North America, Europe and Japan is the longevity of the existing reactor fleets as they approach the end of their original lifetime expectations. Research into long term operation has shown that in many cases lifetimes can be safely extended. For example, most of the US nuclear fleet is now licenced to 60 years and operation to 80 years is now being considered. Long term operation of existing plants is often the most economical way of generating electricity.

- In the US, which still has the world's largest nuclear fleet, nuclear capital costs are high, electricity demand growth is low and competing fuels, most importantly shale gas, are making it difficult to justify nuclear projects in the short run. In over half the country, the wholesale electricity price received by the utility is set by market conditions which makes nuclear development with its high upfront costs a less attractive financial proposition, despite the expected competitive lifetime economics

of nuclear plants. Nevertheless, five new reactors are under construction in parts of the country where rates are regulated.

- In Europe, nuclear development costs have been higher than in the US and political opposition makes a nuclear programme all but impossible in a number of countries and risky for utilities in others. Germany, Spain, Sweden and Belgium are among the countries that have imposed specific nuclear taxes which greatly erode or eliminate the profitability of nuclear. Moreover, the favoured means of decarbonising the power supply is to subsidise and otherwise favour renewable power. The rapid growth of intermittent renewables in particular is increasing the volatility, and depressing the level of wholesale prices, which will decrease the profitability of nuclear in the absence of strong scarcity price signals. Beyond these considerations, the demand for electricity is expected to decline on a long-term basis, increasing the financial risks associated with large, capital intensive generating projects. Nevertheless, a number of European countries are strongly committed to new nuclear programmes as a means of increasing energy security and reducing carbon emissions and new reactor construction in the UK and Hungary is expected to add to the four reactors currently under construction in France, Finland and Slovakia.
- In Japan, the regulatory response to the 2011 Fukushima accident was to close the entire nuclear fleet pending the redesign of the regulatory agency and the requirement for each reactor to justify its operation against stringent safety requirements. At the end of 2015, four of the reactors have been shut permanently but two were restarted. The required additional safety-mandated expenditures coupled with reduced expected operating lives, have weakened the economic case for restarts at a number of sites. It is still expected that at least half the fleet will restart operations in the next few years.

The New Nuclear Countries

There are a number of other countries that do not currently have nuclear power, but which are expressing strong interest in the technology. In two of these countries, Belarus and United Arab Emirates, six reactors are currently under construction. In Bangladesh, two reactors have already been ordered for Rooppur Nuclear Power Project, VVER type from Russia Ninh Thuan 1 plant, in Vietnam, was to start by 2014, but the construction time has moved to 2020. The Vietnamese plant will be built by Russia and will be another VVER type. Other countries, including Turkey, Thailand, Indonesia, Jordan, Poland, and Saudi Arabia, are strong candidates to start construction in the next ten years. These countries face rapidly increasing power demand, coupled with a lack of domestic energy resources in some cases. Reactor vendors are operating in an increasingly competitive international market to supply reactors and need to consider including the offer of fuel supply, decommissioning, waste management services and, above all, loans and equity to help finance the reactors in order to provide an attractive offering in many countries.

NUCLEAR RISK ANALYSIS

The commercial risks associated with nuclear are largely focussed on the development of the plant. The IEA and Nuclear Energy Agency, in the 2015 Projected Costs of Generating

Electricity, identify nearly all the risk in their analysis as arising from variability in the Overnight Capital Costs and the cost of capital (as proxied by the discount rate). Uncertainty over the lead time required to construct the plant is also a significant risk. Often these risks are country specific. In countries where there is an established programme of development, reactors are being constructed without undue delay. In countries where financing is made available at attractive rates, then the consequences of capital cost inflation are not so pronounced. Where these conditions are not present, nuclear is relatively disadvantaged against fossil fuel generators that are to a degree able to pass on fuel cost variability and can even temporarily cease generation if required without the penalty of the very high capital service costs that face nuclear operators.

A further risk of great importance to the operator is the risk associated with revenue volatility, a risk that is far greater in deregulated than regulated power markets. Revenue unpredictability is a significant impediment to any project with high fixed costs, as it greatly affects the ability of investors to recover their investment. Revenue uncertainty can be hedged but only over relatively short periods in deregulated markets. In order for investors to have some assurance of investment security, guarantees of future revenue predictability will usually be sought by the utility. The presence or absence of a significant and credible carbon price will also have an effect on revenues and thus on the attractiveness of a nuclear investment.

Political risk is a significant source of risk for a nuclear operator. Political support for nuclear is a precondition for investment but such support can change over the life of a nuclear power plant. In a number of European countries initial support for nuclear has changed towards a more negative view or is being politicised, which has sometimes resulted in increased taxation and premature curtailment of nuclear power plant operation. A related consideration for operators is regulatory risk, which is the risk that regulatory requirements will change in ways that might for example lengthen the plant construction time, shorten operating lifetime or require additional investment and higher operating costs. There is considerable evidence that changes in regulations following the Three Mile Island accident in the US resulted in the escalation of nuclear capital costs.

4. SOCIO-ECONOMICS

FACILITATION OF INDUSTRIAL DEVELOPMENT

In existing nuclear plants, electricity can be generated at low cost compared with most other generating technologies and where this low cost is passed on to customers, enables the greater development of all electricity-using industries as well as the benefits of low cost electricity to households. Continuity of power supply is typical of systems that have a significant nuclear contribution but is noticeable by its absence in many countries, a fact that is a material impediment to their economic and social development. The spread of intermittent renewable generation increases the risk of unreliable electricity supply unless complemented by more reliable generation sources, such as nuclear. Nuclear output can be adjusted to meet varying demand/supply imbalances, as regularly happens in France where nuclear accounts on average for about 75% of electricity supply. Characteristics of nuclear power of assistance to industrial development include:

- **Reliability** – Nuclear power plants typically run continuously. In the US, the capacity factor of the nuclear fleet is over 90% (i.e., it is running over 90% of the time theoretically available to it).
- **Security** – Fuel is available from a number of countries and can readily be stockpiled on site to ensure continuous operation. The fuel in the production pipeline represents a significant reserve of several years, thus qualifying nuclear as a “quasi-domestic” form of energy (in contrast to e.g. imported oil or gas). Fuel reserves are available from the IAEA’s Low Enriched Uranium Bank if necessary.
- **Operating cost predictability** – Fuel is only a small proportion of overall generation costs and other costs are relatively stable.
- **Low emissions** – Nuclear reactors produce virtually zero greenhouse gases and local pollutants such as sulphur dioxide, nitrous oxides and particulates.

EMPLOYMENT CHARACTERISTICS

Nuclear power makes a relatively high contribution to local gross domestic product. Regional Economic Models Inc. has quantified the contribution in Illinois, US, where they estimate that in 2013 the 11.4 GW of nuclear capacity in the state operated by Exelon amounted to US\$8.9bn annually, of which US\$6bn accrued within Illinois. This total contribution can be disaggregated into its constituents, of which the most significant is arguably the employment effect. Nuclear plants employ more people per GWe than almost any other generating technology. The six Illinois nuclear power plants directly employed 5 900, with the majority of these being highly skilled; a high proportion of nuclear employees are graduates. The average salary for nuclear employees in Illinois amounted to US\$105,300, twice the average salary in the state. Indirect employment creation was estimated to total 21,700 in companies supplying products and services to the plants as

well as the indirect employment effect of spending by Exelon employees. Another very significant element of the total economic contribution came from the US\$1.4bn paid in taxes by the nuclear operations in Illinois. Finally, as a long term employer that values a supportive community, the nuclear operations were active supporters of a range of charitable and local community-based projects.

WORKPLACE AND COMMUNITY HEALTH AND SAFETY

As far as workforce safety is concerned, the number of safety incidents at nuclear plants recorded by the US Bureau of Labor Statistics for 2012 was 0.4 per 200,000 hours worked, compared with 2.8 for fossil fuel plants, 3.1 for utilities in general and 3.9 for manufacturing industry. 'Safety culture' is instilled by nuclear operators around the world.

As far as community safety is concerned, there are now over 18,370 reactor-years of operating experience during which three major accidents have occurred. At Three Mile Island (US, 1979), while there were releases of radioactivity, the resulting exposures of the public were negligible. The human health impacts of the latter two accidents have been subject to much international study. They have been assessed extensively by the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) and documented accordingly. Chernobyl (USSR 1986) resulted in two immediate deaths, 28 acute radiation sickness fatalities shortly after the reactor explosion and the Report to the General Assembly⁹ concluded that there were 15 fatalities among young people due to thyroid cancer by 2005, but that to the date of the report, there has been no persuasive evidence of any other health effect in the general population that can be attributed to radiation exposure.

After the Fukushima accident, the 2013 UNSCEAR report¹⁰ concluded that no radiation-related deaths or acute diseases have been observed among the workers and general public exposed to radiation from the accident to date, and that the doses to the general public estimated for their lifetimes are generally low, with the expectation that no discernible increased incidence of radiation-related health effects are expected among exposed members of the public or their descendants. However, this report has made reference to the negative impact on mental and social well-being, related to the natural disaster as well as the fear and stigma associated with the perceived risk of exposure to ionising radiation. Since Fukushima, professional institutions and organisations such as the World Association of Nuclear Operators (WANO) have improved the overall safety based on lessons learned.

⁹ UNSCEAR (2008) Report to the General Assembly,

¹⁰ UNSCEAR (2013) Sources, effects and risks of ionizing radiation

5. ENVIRONMENTAL IMPACTS

Nuclear facilities create environmental impacts, like any energy technology, but compared to alternatives the environmental footprint of nuclear energy is tiny – one of the technology’s major selling points. The production of nuclear energy requires comparatively small amounts of land. Facilities can be sited so as to minimise damage to local wildlife and ecosystems, and many support environmental stewardship programmes designed to protect native and endangered species. Nuclear plants release negligible emissions to water and air during routine operations. While they famously produce high-level radioactive wastes, the volumes are small and these are all actively managed and stored with plans for responsible final disposal – a marked contrast to many other energy-sector waste streams. Arguably the most serious impact of nuclear power plants is to aquatic systems since they require water for cooling and often emit heat to these water bodies as well. However, these water impacts are local and site dependent, and fundamentally the same for all thermal power plants (fossil or biomass). They can be mitigated if necessary. Uranium mining can also impact the local environment, but the scale of mining operations is not large and most of the challenges are not substantially different from other mining activities, being chemical in nature rather than radiological¹¹. All uranium mining impacts can be minimised by implementing good practise.

Such environmental impacts that the technology does cause are tracked and monitored by both industry and regulators.

LAND USE, PLANT SITING AND WILDLIFE

The high energy-density of nuclear technology helps to make it a remarkably discreet and resource efficient electricity generating technology. Nuclear power plants themselves take up a similar land area to coal and gas plants, however they do not require the dedicated fuel transport infrastructure (train lines, pipelines) and large fuel storage facilities. Compared to wind and solar energy, nuclear power plants require only a small fraction of the land in order to produce the same amount of electricity. A large amount of reliable power comes out of very small space. This makes nuclear plants ideal nodes in big centralised grids.

Key siting considerations for nuclear power plants include water access, ground condition/seismology, proximity to demand centres/grid – and perhaps most importantly, local support. In general, there should be no shortage of suitable siting options for nuclear power plants, although some very population dense regions (eg Singapore) have opted against currently available technology due to concerns over the evacuation zones in case

¹¹ There is a radiological risk to miners, who must track their doses. However, the introduction of good mining practise here (such as dust suppression) has over the years eliminated related health impacts

of accidents. Other than this, finding a technically suitable site for a nuclear power plant should not prove any more difficult than for a coal or gas plant, and in fact should prove substantially easier as it is not constrained by the same fuel infrastructure requirements. Where space is not an issue many nuclear facilities maintain large buffer zones. These zones are kept free from development and become natural sanctuaries for wildlife. Many operators have set up biodiversity and conservation programmes, which actively try to protect and foster native plants and animals.

NUCLEAR PLANT EMISSIONS

Nuclear fission is not a combustion process. It does not require oxygen and it does not emit large amounts of CO₂ and any other atmospheric pollutants (eg soot, nitrogen, sulphur dioxide, lead, arsenic, mercury) which come from the combustion process all of which have documented health impacts. Nuclear is heat without fire. It is therefore tempting to call nuclear emission free, but as with renewable technologies there are some small emissions around the margins, and especially across the fuel cycle. A more accurate term would be very low-emission.

One can also assess the GHG emissions avoided through the use of nuclear energy. A life cycle analysis approach demonstrates the climate benefit of nuclear power. A single kWh generated by a nuclear power plant results in the emission, from mine to final storage, of 28 grams of CO₂, roughly the same level as wind energy, and which may be compared with approximately 900 grams per kWh for coal power plants and 500 grams per kWh for gas turbines¹².

While the vast majority of radioactive material is kept within used fuel assemblies, there are very small amounts which accumulate as noble gases, while some tritium is produced inside the water percolating around the reactor vessel and primary circuit of LWRs and PHWRs. These materials are difficult to separate and contain, and so are released in strict accordance with regulation. Radioactive releases from plant circuits are sorted according to their level of radioactivity and their composition; materials are stored and discharged in liquid or gaseous form in amounts that avoid any significant increase in environmental radioactivity. In practice, releases are well below the thresholds set by health regulations.

The operator is responsible for and carries out the measurement and controlled releases of any kind: environmental radioactivity monitoring, groundwater and rainwater monitoring, fauna and flora. The results of these measurements are recorded and transmitted to the safety authority¹³.

NUCLEAR PLANT AQUATIC IMPACTS

The residual heat from generating nuclear electricity needs to be released into the environment. A typical nuclear plant thermal efficiency will be about 30%, meaning that

¹² World Nuclear Association (2011) Comparison of Lifecycle Greenhouse Gas Emissions of Various Electricity Sources

¹³ In France, more than 20,000 measurements are made every year in each nuclear reactor and sent to the Nuclear Safety Authority, which also carries out regular inspections

70% is rather sadly wasted. The ultimate heat sink will either be a nearby waterbody (sea, lake, canal or river), or the atmosphere depending on the cooling technology that is selected. If a suitably large water body, such as the sea or a great lake, is available then this will generally be chosen as the heat sink and nuclear power plants will utilise a once-through¹⁴ cooling system. These extract a large volume of water, but then return it at a different point¹⁵ a few degrees warmer. The volume of the water that is thus 'used' in once-through cooling circuits is very low: 97% of the water withdrawn is returned to the source.

For river based nuclear plants where the water-flow is insufficient, plants are equipped with cooling towers and the atmosphere becomes the heat sink (closed circuit cooling). The amount of water withdrawn is then very low, 2 m³ per second i.e. 10-20 times less than for once through cooling. However, cooling towers come at extra cost and sometimes with a penalty to plant thermal efficiency. There is no universal agreement on best available technology for plant cooling.

The increase in temperature of a water heat sink is measured continuously to minimise any impact on the fauna and flora. Once through cooling also causes a certain level of fish kills. While these numbers may superficially seem high they typically involve small organisms and most studies however demonstrate that these effects are small and do not disrupt the equilibrium of the ecosystems near the plants. This a result of strict guidelines, careful management and good siting.

USED FUEL MANAGEMENT AND DISPOSAL

After it is extracted from the reactor highly radioactive used fuel is typically stored in pools and in some cases (after the heat load has reduced) eventually moved to dry cask storage. The volumes of used fuel produced are not very large and for most plants their lifetime consumption of fuel can easily be stored on site. Different countries are proceeding at different speeds towards final disposal, taking different paths along the way. Some countries, for example, opt to create interim storage facilities which take waste from multiple nuclear sites. In other countries the fuel gets processed and recycled into new fuel assemblies, leaving behind a different kind of high-level radioactive waste. Regarding final disposition, the international consensus is for deep geological disposal. The cost of waste disposal is factored into the general cost of nuclear generated electricity, with funds accumulated over the full operating lifetime of plants.

URANIUM MINING

Nuclear fuel cycle facilities include: uranium mining, enrichment, fuel fabrication, reprocessing and storage of waste. The professions concerned have established guidelines for good practice on all aspects of sustainable development.

Uranium mining occasionally makes the news if for example, there is an overflow of a tailings pond, perhaps caused by a storm, and some material escapes into a nearby river. However, these events are rare and invariably transient and don't pose any danger to

¹⁴ Sometimes called 'open circuit'

¹⁵ Downstream, if on a river.

people or the environment. It is worth noting that natural uranium is not particularly radioactive. In the early days of the industry, there were issues with miner radiation doses, but tight regulations now exist which along with monitoring and a combination of improved mining processes (such as dust suppression) have reduced these down to the order of background levels.

A final note on uranium mining. There are three basic types of uranium mine, open pit, underground and in-situ leach ISL - (sometimes called in-situ recovery). About 50% of the current annual production of uranium now comes from ISL. This is a remarkably environmentally benign mining process which involves pumping a solution through certain permeable deposits, and then recovering the uranium pregnant solution up again at a separate location. The surface geology of these mining sites remains largely undisturbed. There are no tailings, and no milling of ore is required. Remediation and eventual site clean-up will not prove difficult.

HEALTH

Health of the populations living near nuclear power plants and of the employees of the power plants is a top priority and an aspect of the safety culture. The WHO, the IAEA, the national safety authorities, and professional organizations are constantly working on this priority.

Public health protection measures are a component of the way of thinking of nuclear operators, and specific actions are implemented to limit exposure to radiation and the associated health risks in case of emergency.

Any incident is subject to feedback, which aims to: advanced knowledge, improve work methods, develop guidelines, modify the installation and even its design if necessary.

Accidents and incidents can be internal (burst pipe, failure of controls etc.) or external (earthquake, flood etc.). To prevent risks, all feedback is taken into account in the design of facilities, each incident is recorded and analysed, and any necessary modification is carried out not only where the incident occurred but in all similar installations. The 'defence in depth' concept considers systematically the technical, human and organizational potential failures, and seeks to avoid these failures by means of independent, redundant, and the utilisation of different principles for detection. Exchanges are systematically organised in the community of Nuclear Operators (WANO).

In the event of an accident, the first priority is to stop the nuclear reaction and then to remove the residual power, to preserve the integrity of the containment, and to prevent or limit harmful emissions into the atmosphere. The Fukushima accident demonstrated the relevance of these measures: after the damage caused by the tsunami, the absence of hydrogen recombiners resulted in an explosion damaging the reactor and the loss of all water injection for cooling the reactor core led to a meltdown. Following this terrible accident, all nuclear operators have had to test their facilities, and to implement any necessary measures.

MASSIVE NUCLEAR PLANT PLAN NEAR EVERGLADES DELAYED BY COURT

A massive nuclear plant expansion proposed by Florida's largest electric utility must be redone to meet environmental and other concerns near Everglades National Park, a state appeals court ruled Wednesday 20 of April 2016. The 3rd District Court of Appeal in Miami reversed a 2014 decision by Gov. Rick Scott and the Cabinet to approve construction of two nuclear reactors by Florida Power & Light at its Turkey Point plant near Homestead. The project, costing up to US\$18 billion, would add about 2,200 MW of electric power or enough to supply 750,000 homes.

90 miles of transmission lines would run along the eastern edge of the Everglades National Park. Florida Power & Light should bury the power lines at the utility's expense but "presented no competent substantial evidence that the project could satisfy the environmental performance standards" of Miami-Dade County rules panel.

The court found that all the local species would be endangered by the transmission lines. The eastern Everglades has a unique ecosystem, therefore it will be essential to protect it.

The Nuclear Regulatory Commission is focus on addressing concerns, such as how the reactors would handle rising sea levels, if evacuation plans are adequate and whether the reactors might threaten waterways and drinking supplies.

Source: www.floridapolitics.org

6. OUTLOOK

PROSPECTS FOR NEW REACTORS

As of December 2015, 65 reactors were under construction (6 more than in July 2012) with a total capacity of 64 GW. Two-thirds (40) of the units under construction are located in four countries: China, India, Russia and South Korea, all of which have ambitious targets for new nuclear construction. Whilst the construction total is the highest for many years, at least 22 of these projects have encountered construction delays, and for the remaining 43 reactor units, either construction began within the last five years or they have not yet reached projected start-up dates. Many of the plants facing construction delays are Gen III first-of-a-kind designs where some delay is to be expected. The outlook for nuclear up to 2035 will depend largely on the success of the industry in constructing plants to agreed budgets and with predictable construction periods. It is evident in a number of countries that median construction times are stable.

The nature of the regulation of power markets and the success of competing generation technologies will also be critical factors governing the prospects for new reactors. Recognition for the reliability and security of nuclear generation, coupled with a negligible emissions profile, in a world increasingly reliant on intermittent sources of power will assist the growth of the sector.

In the period beyond 2035, it is expected that fast reactors will make an increasing contribution in a number of countries by building on the experience of operating these reactors in Russia and with developing the Generation IV prototypes, such as the Astrid reactor being designed in France.

PROSPECTS FOR EXISTING REACTORS

In general, existing operating nuclear power plants continue to be highly competitive and profitable. The low share of fuel cost in total generating costs makes them the lowest-cost base load electricity supply option in many markets. Uranium costs account for only about 5% of total generating costs and thus protect plant operators against resource price volatility.

The economic attractiveness of existing nuclear plant economics is confirmed by the appetite of many utilities to extend the life of their existing fleet. In the US, licences to extend to 60 years the licence period have been sought and received for the great majority of reactors. Plans are being developed to apply for 80 year life extensions¹⁶. Although such life extension requires a number of investments to be made, it is estimated that the levelised cost of the extended operating period is lower than for almost any competing

¹⁶ In general, high-cycle fatigue is not a life-limiting factor for nuclear power plants (in contrast to fossil-fired plants or even wind turbines), as their thermal parameters are much lower, leaving much greater mechanical margins. Ageing of nuclear plants is more governed by spare part availability (especially for instrumentation and control systems), additional regulatory requirements, and reactor vessel embrittlement due to neutron influx. Nevertheless, the latter are qualified for 60 to more than 100 years, and can also be extended.

technology¹⁷. Indeed, if the decarbonisation of power generation in the developed countries is to be achieved without undue cost and disruption, it is almost essential that the lifetimes of existing reactors are extended.

MARKET TRENDS AND OUTLOOK

Each year, the IAEA updates its low and high projections for global growth in nuclear power¹⁸. In the 2015 update, the low projection for global nuclear power capacity reaches 385 GWe in 2030, compared to a capacity of 376 GWe at the end of 2014. In the high projection it reaches 632 GWe. The projections increase most rapidly for the Far East, a region that includes China, Japan and the Republic of Korea, whereas downward shifts in the projections were made for North America and for Western Europe.

The key drivers and market players defining the future of nuclear power are different from those 20-30 years ago, and the emerging non-OECD economies (mainly China and India) are expected to dominate future prospects. Electricity demand growth is far higher than in the OECD countries and even rapid nuclear development will not unbalance the generating mix in these countries. Moreover, given their relatively poor fossil fuel resource endowment and increasing need to moderate the local pollution effects of fossil fuel use, nuclear will represent a means to diversify the generating portfolio, limit the growth of carbon emissions and secure power supplies. Beyond the requirements of the power sector, the growth of the nuclear sector in China, India, Russia and South Korea is seen as an important aspect of technological and industrial development.

¹⁷ William D'haeseleer (2013) Synthesis on the Economics of Nuclear Energy, Study for the European Commission, DG Energy

¹⁸ International Atomic Energy Agency (2015) Energy, Electricity and Nuclear Power Estimates for the Period up to 2050, Reference Data Series No.1

7. GLOBAL TABLE

TABLE 5: NUCLEAR CAPACITY AND ELECTRICITY SUPPLIED IN 2015

Country	Reactors in Operation		Reactors Under Construction		Nuclear Electricity Supplied [GWh]	Nuclear Electricity Supplied % of Total
	No. of Reactors	Net Capacity [GW]	No. of Reactors	Net Capacity [GW]		
Argentina	3	1.6	1	0.025	6519	4.8
Armenia	1	0.4			2571	34.5
Belarus			2	2.2	NA	NA
Belgium	7	5.9			24825	37.5
Brazil	2	1.9	1	1.2	13892	2.8
Bulgaria	2	1.9			14701	31.3
Canada	19	13.5			95637	16.6
China	31	26.8	24	24.1	161202	3.0
Czech	6	3.9			25337	32.5
Finland	4	2.8	1	1.6	22326	33.7
France	58	63.1	1	1.6	419022	76.3
Germany	8	10.8			86810	14.1
Hungary	4	1.9			14960	52.7
India	21	5.78	6 (including PFBR)	4.3	34644	3.5

Country	Reactors in Operation		Reactors Under Construction		Nuclear Electricity Supplied [GWh]	Nuclear Electricity Supplied % of Total
	No. of Reactors	Net Capacity [GW]	No. of Reactors	Net Capacity [GW]		
Iran	1	0.9			3198	1.3
Japan	43	40.3	2	2.7	4346	0.5
Korea	24	21.7	4	5.4	157199	31.7
Mexico	2	1.4			11185	6.8
Netherlands	1	0.5			3862	3.7
Pakistan	3	0.7	2	0.6	4333	4.4
Romania	2	1.3			10710	17.3
Russia	35	25.4	8	6.6	182807	18.6
Slovakia	4	1.8	2	0.9	14084	55.9
Slovenia	1	0.7			5372	38.0
South Africa	2	1.9			10965	4.7
Spain	7	7.1			54759	20.3
Sweden	10	9.6			54455	34.3
Switzerland	5	3.3			22156	33.5
Taiwan, China	6	5.1	2	2.6	35143	16.3
UAE			4	5.4	NA	NA
Ukraine	15	13.1	2	1.9	82405	56.5
UK	15	8.9			63895	18.9

Country	Reactors in Operation		Reactors Under Construction		Nuclear Electricity Supplied [GWh]	Nuclear Electricity Supplied % of Total
	No. of Reactors	Net Capacity [GW]	No. of Reactors	Net Capacity [GW]		
USA	99	99.2	5	5.6	798012	19.5
Total	441	382.9	67	66.4	2441331	11*

Source: Power Reactor Information System, IAEA, December (2015) *2013 data

TABLE 6: URANIUM PRODUCTION AND RESOURCES

Country	2014 Production tU	Uranium resources(tU)<US\$130/Kg
Australia	5001	1174000
Brazil	231	155100
Canada	9134	357500
China	1500	120000
Czech Republic	193	1300
India	385	not available
Kazakhstan	23127	285600
Malawi	369	8200
Namibia	3255	248200
Niger	4057	325000
Pakistan	45	not available

Romania	77	3100
Russia	2990	216500
South Africa	573	175300
Ukraine	962	84800
USA	1919	207400
Uzbekistan	2400	59400
Other	36	277500
Total	56252	3698900

Source: OECD-NEA & IAEA (2014) Uranium 2014: Resources, Production and Demand; World Nuclear Association (2015) Uranium: From Mine to Mill.

TABLE 7: CHANGE IN WORLD IDENTIFIED URANIUM RESOURCES 2003 – 2013 (THOUSAND TONNES URANIUM)

Cost \ year	2003	2005	2007	2009	2011	2013
<US\$40/kgU	2400	2600	2800	800	681	683
US\$40-80/kgU	1100	1000	1550	2800	2398	1274
US\$80-130/kgU	900	900	950	1600	2248	3946
US\$130-260/kgU				1050	1770	1732

Source: OECD-NEA & IAEA, Uranium: Resources, Production and Demand

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REFERENCES

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- IEA & OECD-NEA (2015), Projected Costs of Generating Electricity
- International Atomic Energy Agency (IAEA) (2015), Energy, Electricity and Nuclear Power Estimates for the Period up to 2050, Reference Data Series No.1, 2015 Edition.
- International Atomic Energy Agency (IAEA) (2015), Power Reactor Information System, December
- International Energy Agency (IEA)
- Loving J, Yip A, & Nordhaus T, (2016), Energy Policy, 91, 371-382 available at <http://www.sciencedirect.com/science/article/pii/S0301421516300106>
- Nuclear Regulatory Commission, US RNC
- OECD-NEA, (2012), Nuclear Energy and Renewables
- Organisation for Economic Co-operation and Development (OECD)
- Organisation for Economic Co-operation and Development (OECD), Uranium: Resources, Production and Demand (various issues)
- Synthesis on the Economics of Nuclear Energy, Study for the European Commission, DG The Open University
- United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) (2013), Effects and risks of ionizing radiation
- United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) (2008), Report to general Assembly
- William D'haeseleer (2013), Energy
- World Nuclear Association (WNA) (2011), Comparison of Lifecycle Greenhouse Gas Emissions of Various Electricity Sources
- World Nuclear Association (WNA) (2015), "Uranium: From Mine to Mill"

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KEY FINDINGS

1. Hydropower is the leading renewable source for electricity generation globally, supplying 71% of all renewable electricity. Reaching 1,064 GW of installed capacity in 2016, it generated 16.4% of the world's electricity from all sources.
2. Significant new development is concentrated in China, Latin America and Africa. Asia has the largest unutilised potential, estimated at 7,195 TWh/year, making it the likely leading market for future development.
3. China accounted for 26% of the global installed capacity in 2015, far ahead of USA (8.4%), Brazil (7.6%) and Canada (6.5%).
4. Technological innovation in hydropower include: a) increasing the scale of turbines (1000 MW turbine in development), b) advanced hydropower control technologies that enable renewable hybrids, c) both conventional and pumped storage hydropower increasingly utilised as a flexible resource for balancing variable renewable resources.
5. Significant advances in sustainable development practices in the sector – through the Hydropower Sustainability Assessment Protocol.
6. Climate bonds market attracts strong hydropower interest as a means to demonstrate sustainability of hydropower.
7. As hydropower has good synergies with all generation technologies, its role is expected to increase in importance in the electricity systems of the future. However, markets and policy will need to evolve to appropriately incentivise investors, particularly where the private sector is expected to engage.
8. There is an increasing trend towards building climate resilience and potential climate change impacts into decision-making processes for hydropower owners and operators.
9. Greater consideration of water management benefits offered by hydropower facilities: flood control, water conservation during droughts or arid seasons.
10. As the pace of new development grows, fuelled by the strong focus on climate change and renewable energy, a shortage of technical specialists can be expected across a variety of needed skillsets, leaving a high demand for experienced engineers, sustainability specialists, and finance and policy specialists.

INTRODUCTION

There has been a major upsurge in hydropower development globally in recent years. The total installed capacity has grown by 39% from 2005 to 2015, with an average growth rate of nearly 4% per year. The rise has been concentrated in emerging markets where hydropower offers not only clean energy, but also provides water services, energy security and facilitates regional cooperation and economic development. The drivers for the upsurge in hydropower development include the increased demand for electricity, energy storage, flexibility of generation, freshwater management, and climate change mitigation and adaptation solutions. On the one hand, there has been significant progress in terms of sustainability practices in the sector and acceptance by external stakeholders such as NGOs and the financial community, which had previously opposed the development of some new projects. On the other hand, criticism of hydropower continues in some stakeholder groups, whose views are mainly biased by past negative experiences and a lack of acknowledgement of sustainable projects successfully built more recently.

As a mature technology, hydropower provides over 16% of global electricity production¹. Since 2004, hydropower development has been on the increase, as emerging markets recognise the benefits that it can bring. In addition to low-cost electricity supply, hydropower provides energy storage and other ancillary services that contribute to the more efficient management of the electricity supply system and balancing of the grid.

An important new driver for global development is hydropower's role as a flexible generation asset as well as an energy storage technology. Storage hydropower (including pumped storage) represents 99% of the world's operational electricity storage². With the increased deployment of variable renewable energy technologies such as wind and solar, hydropower is increasingly recognised as an important system management asset capable of ensuring reliable renewable supply.

Infrastructure for hydropower projects is also used for freshwater management, and projects with reservoir storage generally provide a variety of value-added services. For example, in addition to providing reliable energy supply, hydropower typically brings a variety of macroeconomic benefits such as water supply, flood protection, drought management, navigation, irrigation and recreation. As water management infrastructure, it is also expected to play an increasing role in climate change adaptation. It will be called upon to help respond to expected increases in extreme weather events, including more intense and frequent flood incidents and longer periods of drought.

These multiple services and benefits have reinvigorated interest in hydropower and have altered perceptions of its importance. There have also been significant advances in

¹ REN21 (2016), Renewables 2016 Global Status Report and International Hydropower Association

² IEA, IEA Technology Roadmap: Hydropower

sustainable development practices in the sector - the sector now has a widely recognised and broadly supported tool to assess hydropower project sustainability, as well as to promote improved sustainability performance across the sector³. These factors have combined to improve acceptance and willingness of policymakers and the financial sector to engage in hydropower development, through enabling policy frameworks and, crucially, providing investment and financial support to both public and private entities.

GLOBAL STATUS

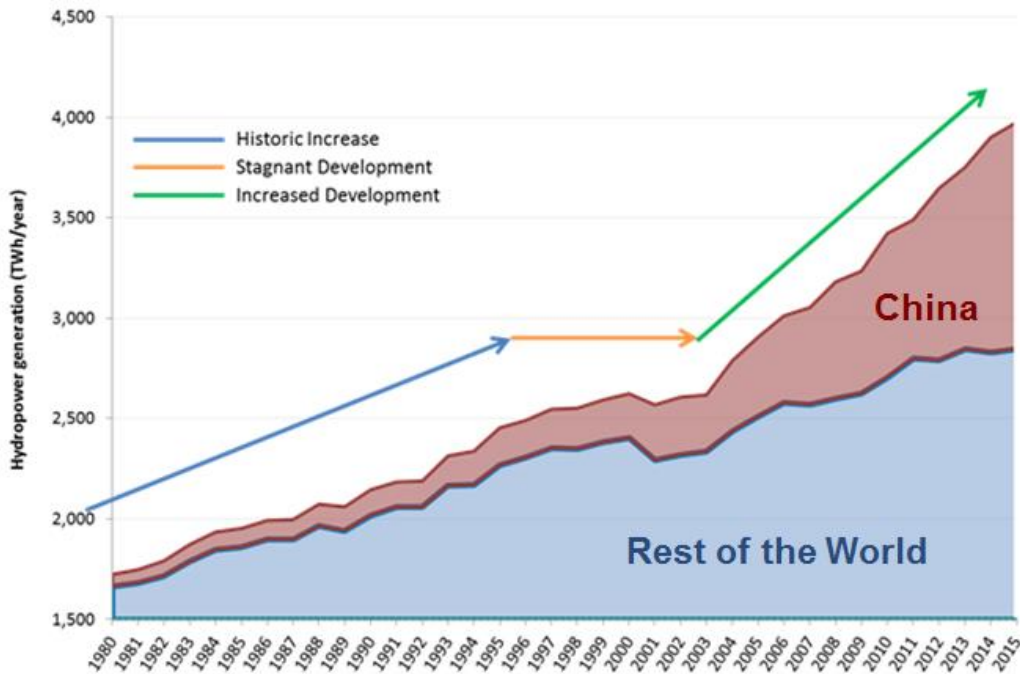
Hydropower is the leading renewable source for electricity generation globally, supplying 71% of all renewable electricity. Reaching 1,064 GW of installed capacity in 2016, it generated 16.4%⁴ of the world's electricity from all sources.

Since 2004, there has been a resurgence in hydropower development, particularly in emerging markets and less developed countries. Significant new development is concentrated in the markets of Asia (particularly China), Latin America and Africa. In these regions, hydropower offers an opportunity to supply electricity to under-served populations and a growing industrial base, while at the same time providing a range of complementary benefits associated with multi-purpose projects.

³ Hydropower Sustainability Assessment Protocol: <http://www.hydrosustainability.org/>

⁴ IHA/REN21, Renewables (2016), Global Status Report

FIGURE 1: GLOBAL TOTAL HYDROPOWER GENERATION SINCE 1980



Source: IHA, EIA

Figure 1 shows the historical growth of hydropower since 1980. The blue arrow represents a general historic increase in hydropower in response to growing demand for electricity worldwide.

From 1999 through 2005 (illustrated by the orange arrow), hydropower development was largely halted worldwide, reflecting the impact of the World Commission on Dams (WCD), which was convened to review the development effectiveness of large dams and develop guidelines for the development of new dams. The report, published by the WCD in 2000, challenged existing practices and proposed stringent guidelines for dams, which in turn caused a sharp decrease in investments while the sector and the financial community considered how to respond to new standards and expectations.

From 2005 onwards (green arrow), hydropower development has seen an upswing in development, which can be attributed in part to the impact of intensive efforts by the International Hydropower Association (IHA) and a multi-stakeholder range of partners in promoting greater sustainability through the development and use of the Hydropower Sustainability Assessment Protocol. The protocol provides an international common language on how these considerations can be addressed at all phases of a project's lifecycle: planning, preparation, implementation and operation. Protocol assessments are delivered by fully accredited assessors who have previous experience of the hydropower

sector or relevant sustainability issues. To receive accreditation, assessors must participate in at least two assessments as trainees prior to attending an accreditation course.

Additionally, growing investments in and by emerging economies (i.e. BRICS, particularly China), continued interest in renewable energy, particularly with storage capacity. Participation in Carbon Markets / Renewable Energy Credits has also contributed to the upswing.

TABLE 1 shows the nations with the largest hydropower capacities in the world. In recent years China has taken centre stage for hydropower capacity, accounting for 26% of global installed capacity in 2015, far ahead of USA (8.4%), Brazil (7.6%) and Canada (6.5%). China has strengthened its dominant position by adding 19 GW in 2015, almost three times the new capacity of the next five countries combined.

TABLE 1: TOP HYDROPOWER CAPACITY AS OF 2015, BY COUNTRY

	Total Capacity end of 2015 (GW)	Added Capacity in 2015 (GW)	Production (TWh)
China	319	19	1,126
USA	102	0.1	250
Brazil	92	2.5	382
Canada	79	0.7	376
India	52	1.9	120
Russia	51	0.2	160

Source: REN21, IHA (2015)

Capacity additions in 2015 have strengthened China’s lead, with new developments progressing at Baihetan (16 GW) and Wudongde (10.2 GW). Total capacity in China is expected to reach 350 GW of pure hydropower and 70 GW of pumped storage by 2020⁵.

⁵ China 12th 5-Year Plan (2011-2015)

Beyond China, significant new deployment took place in the emerging markets of Asia including concentrations in Russia, India, Turkey and Vietnam. Asia has the largest unutilised potential, estimated at 7,195 TWh/year⁶, making it the likely leading market for future development, as illustrated in FIGURE 2. Rapid, concentrated development is expected to continue in India, Turkey, Bhutan and Nepal.

Latin America is another key market for hydropower development. Brazil leads the continent in both installed capacity and new capacity additions, with 91.8 GW installed capacity in total. Hydropower forms the backbone of Brazil's electricity system, supplying 62% in 2015 of the country's needs, although this figure is expected to decline due to a reducing number of sites available to develop and increased investment in fossil fuel generation. However, Brazil looks set to continue hydropower development with plans for construction of up to 19 GW in the next ten years. Other Latin American countries with significant hydropower capacity include Argentina, Chile, Colombia, Paraguay, Peru, Venezuela and Ecuador.

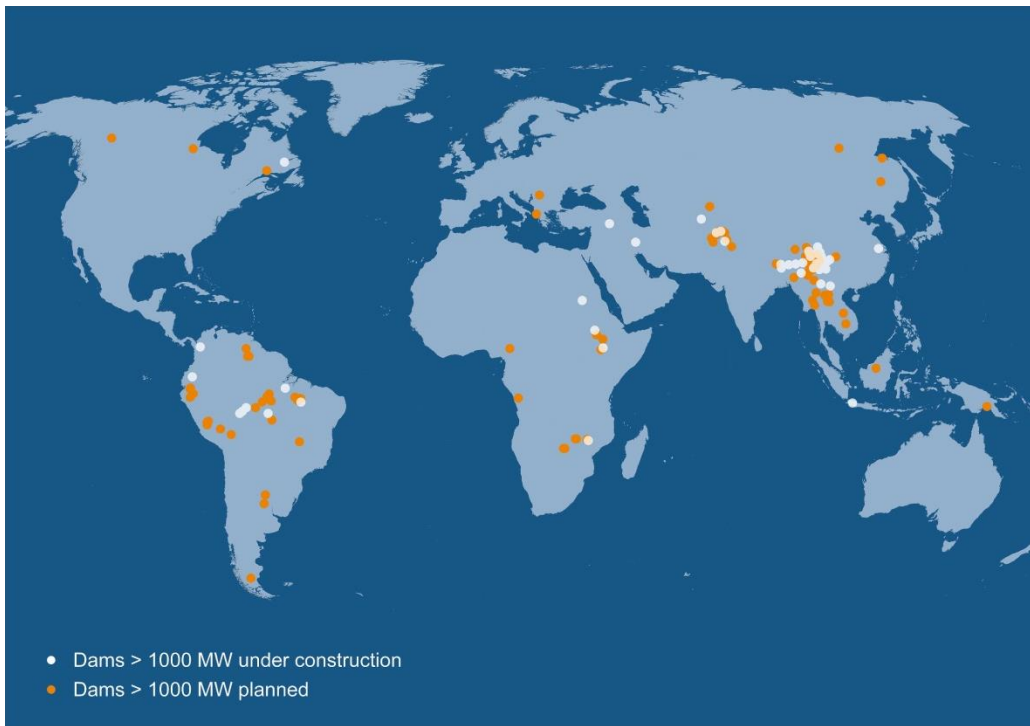
Africa is expected to be a major market for future hydropower activity. With the average electrification rates at only 45%⁷ in 2012, hydropower offers real opportunities for providing electricity on the continent using largely local or regional resources. Significant undeveloped potential remains across all of Africa, with only an estimated 9% of reported hydropower potential developed to date⁸. In particular, the markets of the Democratic Republic of the Congo, Angola, Ethiopia and Cameroon have significant undeveloped potential. Regional African co-operation bodies, including the Eastern Africa Power Pool, the West African Power Pool and the Southern African Power Pool, have the potential to drive further development of hydropower where domestic resources can be developed for export to neighbouring countries with strong demand.

⁶ IHA

⁷ IEA (2014), World Energy Outlook Special Report - Africa Energy Outlook

⁸ IHA

FIGURE 2: GLOBAL DISTRIBUTION OF FUTURE HYDROPOWER DAMS (UNDER CONSTRUCTION OR PLANNED)



Source: Zarfl et al. (2014), A global boom in hydropower dam construction

GLOBAL POTENTIAL

There are many opportunities for hydropower development throughout the world and although there is no clear consensus, estimates indicate the availability of approximately 10,000 TWh/year of unutilised hydropower potential worldwide. TABLE 2 gives an overview of the major unutilised potential globally. How much of that will be developed is a matter of market conditions, government policy and the emergence of other competing renewable options, such as solar PV, wind and biomass. Power pools, increased bilateral trade in electricity, and new customers demanding green energy can enable further growth in hydropower.

Various scenarios look at potential future development, with some indicating a potential to reach up to 2000–2050 GW of installed hydropower capacity by 2050⁹.

⁹ IEA, IHA

TABLE 2: TOP 20 COUNTRIES BY UNUTILISED HYDROPOWER POTENTIAL*

Country	Undeveloped (GWh/year)	Total Potential (GWh/year)	Current Utilisation (%)
Russian Federation	1 509 829	1 670 000	10%
China	1 013 600	2 140 000	41%
Canada	805 111	1 180 737	32%
India	540 000	660 000	21%
Brazil	435 542	817 600	48%
Indonesia	388 289	401 646	3%
Peru	369 058	395 118	6%
DR Congo	306 512	314 381	2%
Tajikistan	299 269	317 000	5%
USA	278 775	528 923	52%
Nepal	205 777	209 338	2%
Venezuela	181 163	260 720	31%
Pakistan	172 820	204 000	14%
Norway	161 000	300 000	45%
Turkey	149 100	216 000	27%
Colombia	151 000	200 000	22%
Angola	147 048	150 000	3%

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Chile	137 428	162 000	12%
Myanmar	134 224	140 000	4%
Bolivia	123 663	126 000	2%

Source: International Hydropower Association

**Undeveloped hydropower potential is a technical figure based on country reporting and analysis, and does not reflect whether or not development of this potential is economically or sustainably feasible*

1. TECHNOLOGIES

TYPES OF HYDROPOWER

Hydropower is the generation of power by harnessing energy from moving water. The current commercially available technologies generate electricity through the transformation of hydraulic energy into mechanical energy to activate a turbine connected to a generator.

It is a versatile energy source, which can respond to different power system requirements while adapting to different physical and environmental constraints as well as stakeholders' interests. Although hydropower plants are highly site-specific (the local topography and hydrology will define the type of facilities that can be built), they can be broadly categorised into four main typologies:

- **Storage hydropower** – a facility that uses a dam to impound river water, which is then stored for release when needed. Electricity is produced by releasing water from the reservoir through operable gates into a turbine, which in turn activates a generator. Storage hydropower can be operated to provide base-load power, as well as peak-load through its ability to be shut down and started up at short notice according to the demands of the system. It can offer enough storage capacity to operate independently of the hydrological inflow for many weeks, or even up to months or years. Given their ability to control water flows, storage reservoirs are often built as multi-purpose systems, providing additional benefits as discussed later in this section. The primary advantage of hydro facilities with storage capability is their ability to respond to peak load requirements.
- **Run-of-river hydropower** – a facility that channels flowing water from a river through a canal or penstock to drive a turbine. Typically, a run-of-river project will have short term water storage and result in little or no land inundation relative to its natural state. Run-of-river hydro plants provide a continuous supply of electricity, and are generally installed to provide base load power to the electrical grid. These facilities include some flexibility of operation for daily/weekly fluctuations in demand through water flow that is regulated by the facility.
- **Pumped-storage hydropower** – provides peak-load supply, harnessing water which is cycled between a lower and upper reservoir by pumps, which use surplus energy from the system at times of low demand. When electricity demand is high, water is released back to the lower reservoir through turbines to produce electricity. Some pumped-storage projects will also have natural inflow to the upper reservoir which will augment the generation available. Pumped-storage hydropower is practically speaking a zero sum electricity producer. Its value is in the provision of energy storage, enabling peak demand to be met, assuring a guaranteed supply when in combination with other

renewables, and other ancillary services to electrical grids. One major advantage of pumped-storage facilities is their synergy with variable renewable energy supply options such as wind and solar power (non-flexible power supply options). This is because pump-storage installations can provide back-up reserve which is immediately dispatchable during periods when the other variable power sources are unavailable.

- **Offshore Marine and other new technologies** – a less established, but growing group of hydropower technologies that use the power of currents or waves to generate electricity from seawater. These include hydrokinetic (river, ocean and wave), tidal barrage and tidal stream, osmotic, and ocean thermal technologies. Although these technologies use the same basic technical concepts as other hydropower applications, due to the novelty of their design and/or application, these will be covered in the Marine Energies chapter of the World Energy Resources publication.

Although there are clear hydropower typologies, there can be overlap among the above categories. For example, storage projects can involve an element of pumping to supplement the water that flows into the reservoir naturally, and run-of-river projects often provide some level of storage capability. Pumped-storage plants, such as Schluchsee in Germany, combine the off-peak surplus energy intake from the system with natural flow.

Hydropower technologies are not bound by size constraints – the basic technology is the same irrespective of the size of the development. Large-scale hydropower installations typically require storage reservoirs as mentioned earlier in this section. Smaller-scale hydropower systems can be attached to a reservoir, or they can be installed in small rivers, streams or in the existing water supply networks, such as drinking water or wastewater networks. Small-scale hydropower plants are typically run-of-river schemes or implemented in existing water infrastructure.

Another source of smaller-scale hydropower capacity is extracted from modernisation of existing hydropower facilities. In cases where it is economically feasible, capacity additions to existing facilities are possible by extending the existing powerhouse to add more units, in addition to the more traditional approach of upgrading the existing generator/turbine sets or increasing the efficiency of turbines.

As with all energy technologies, hydropower facilities are reported on in terms of their installed capacity. Hydropower facilities installed today range in size from less than 100 kW to greater than 22 GW, with individual turbines reaching 1000 MW in capacity.

ROLE OF HYDROPOWER IN THE ENERGY MIX

Hydropower has traditionally been developed to provide low-cost base-load power; the constant flow of water through the generators adds reliable generation into the energy mix. It can also provide peaking power; the ability to release water at short notice can respond to immediate needs for more power on the grid. More recently, the traditional roles of

hydropower are evolving with the increased penetration of variable non-flexible renewable energy sources such as wind power and solar PV installations.

Energy storage is another important function that hydropower plants provide. Reservoirs with storage offer a high degree of flexibility, storing potential energy for later use at timescales ranging from seconds, to days, to several months. At present, it is estimated that 99% of the world’s electricity storage capacity is in the form of hydropower, including pumped storage¹⁰. At times of high solar radiation or strong winds, the energy must be used by either the electricity system, stored for later use, or curtailed. In systems with a significant deployment of renewable energy, when supply is high, pumped-storage hydropower can absorb excess capacity from the grid to pump water into the upper reservoir, thus avoiding curtailment of those assets. This stored renewable energy can then be used later when it is needed. More specifically, when wind turbines or solar panels are injecting energy into a grid, hydropower units can reduce their own output and store extra water in their reservoirs. This storage can then be used to increase hydropower output and fill the gap when the wind drops or the sun is covered by clouds and input from these sources falls. This synergy between hydro storage capability and non-flexible renewable energy resources makes hydropower an important asset for enabling the deployment of other renewable energy systems. TABLE 3 indicates existing capacity for pumped storage.

TABLE 3: PUMPED-STORAGE HYDROPOWER INSTALLED CAPACITY IN 2015, BY REGION

Region	Installed capacity (MW)
Africa	1,580
East Asia	57,999
Europe	50,949
Latin America & The Caribbean	1,004
Middle East & North Africa	1,744
North America	22,618

¹⁰ IEA (2014)

South & Central Asia	6,146
Southeast Asia & Pacific	2,425
World Total	144,465

Source: U.S. DOE Global Energy Storage Database, IHA (2016) Hydropower Status Report

Hydropower, and especially pumped storage, also provides an array of energy services beyond firm power, including black start capability, frequency regulation, inertial response, spinning and non-spinning reserve and voltage support, among others. These ancillary services are increasingly important to the stability of the energy system and may also offer an alternate revenue stream for hydropower generators. These services are priced differently in various markets around the globe, although it is increasingly recognised that they are often not appropriately or sufficiently rewarded by energy markets.

TECHNOLOGICAL DEVELOPMENTS

Hydropower is a mature technology that is reliable and well understood by planners and operators globally. New hydro facilities typically have a high efficiency at 90% to 95% in the conversion from hydraulic to electrical energy, making hydropower one of the most efficient sources of renewable energy. There are significant opportunities for refurbishing existing hydro plants and powering non-hydro dams (e.g. flood control or domestic water supply reservoirs), particularly in more mature markets such as the United States and Western Europe, where greenfield developments are becoming uncommon.

Notwithstanding its maturity, hydropower technology continues to evolve to accommodate changing market conditions, as well as to mitigate the environmental impacts of new and existing stations. Technological innovation over the past few years has focused on increasing the scale of turbines, improving their durability and flexibility, and reducing environmental impacts. Such advances continue to increase generating capacity, and mitigate the negative impact of new and existing stations.

Key recent innovations in the hydropower industry have been:

- Flexible generation:** The 20th century saw huge advances in hydraulic turbine technology, particularly the invention of adjustable rotor blades and inlet guide vanes, providing greater operating range and efficiency. Variable speed pumps are now in operation at new power stations, enabling flexible generation in both pumping and generating mode. Ongoing work in this field aims to enable the retrofitting of existing stations and turbines with similar levels of pumping/generating flexibility, which allows hydropower to deliver more finely tuned ancillary services to the grid. In addition, new developments in automatic voltage regulation are shortening turbine response times,

further improving flexibility and grid stability. Other advances have included new approaches to reduce friction and low-head turbine technologies, enabling hydropower to operate at less traditional sites.

- **Equipment Manufacturing:** Turbines have benefitted from advances in materials science, which includes new alloys, such as tungsten carbide, which are more resistant to erosion and abrasion from sediments. The effect is that turbine parts can be subjected to higher pressure flows, thus generating more power. These materials also enable operation in harsher environments where sediments make up a greater percentage of the flowing water. Hydropower has also benefited from advances in computing power. The integration of computational fluid dynamics (CFD) in the design of turbines has allowed the manufacturing of more efficient turbines. Advancements are also being made in the methods and procedures for maintaining and refurbishing aging hydro power infrastructure to improve performance and reduce outage time.
- **Environmentally conscious designs:** Although hydropower is a low-carbon renewable energy, the construction of a dam inevitably alters the river regime, possibly affecting fish passage, dissolved oxygen concentration, sediment transport and more. New measures are being implemented to counter these impacts, such as: fish-friendly turbines; fish lifts and more effective fish ladders specifically adapted to local species; the selection of turbines with limited impacts on dissolved oxygen; oil-free turbines and bio-degradable lubricants; and the addition of bottom outlet sluices and other sediment management techniques to flush sediment and more.
- **Water management optimisation:** From the generation perspective, stored water is a fuel to be utilised when its value is high and stored when it is low. Yet, unlike fossil fuels, its supply depends on climatic conditions and storage is a function of a variety of constraints such as operating regimes, licence constraints for minimum and maximum water levels, prioritization of water uses (irrigation, power generation, etc.) and required environmental flows. The optimisation of reservoir management is crucial to maximising revenues for power producers. Advances in mathematical modelling have led to the development of highly sophisticated optimisation software and decision-support tools which help inform operational decision making. Also new developments in automatic voltage regulators (AVR), excitation and governor control have improved the speed of response of hydro. This further reinforces hydropower's position as the only renewable capable of reliably offering ancillary services for grid security.

Ongoing work on faster reacting times, broader operating range, improved material resilience, and larger machines will continue to progress hydropower technology over the next several years.

2. ECONOMICS & MARKETS

With the increasing multi-purpose use of freshwater reservoirs and the growing role of the private sector, it is important to analyse both economic and financial performance of hydropower developments.

Investment in hydropower has traditionally been within the realm of the public sector, as hydropower projects are major infrastructure investments. More recently, private players have entered the sector including public–private partnerships, in which risks are allocated to the party best able to manage it.

With regard to financial performance, like many other capital-intensive large infrastructure projects, hydropower has been subject to some criticism on the basis of cost and schedule overruns. However, there are many examples of projects that have been managed successfully from a cost and schedule perspective. For example, Hydro-Québec announced in December 2015 the commissioning of the second and final turbine of the 270 MW Romaine-1 station, eight months ahead of schedule.

Numerous studies have analysed the levelised cost of electricity (LCOE)¹¹ of hydropower in comparison to other energy technologies. A study of 2,155 hydropower projects in the United States found that the LCOE ranged from a low of \$0.012/kWh for additional capacity at an existing hydropower project, to a high of \$0.19/kWh for a 1 MW small hydro project with a capacity factor of 30%¹². The weighted average cost of all the sites evaluated was \$0.048/kWh. The LCOE of 80% of the projects was between \$0.018 and \$0.085/kWh.

The share of the electro-mechanical equipment costs in the total LCOE ranged from a low of 17% to a high of 50%, with typical values ranging from 21% to 31%. Civil works costs ranged from zero (for an existing project) to a high of 63%¹³. These costs are indicative and vary from country to country and project to project as indicated in FIGURE 3.

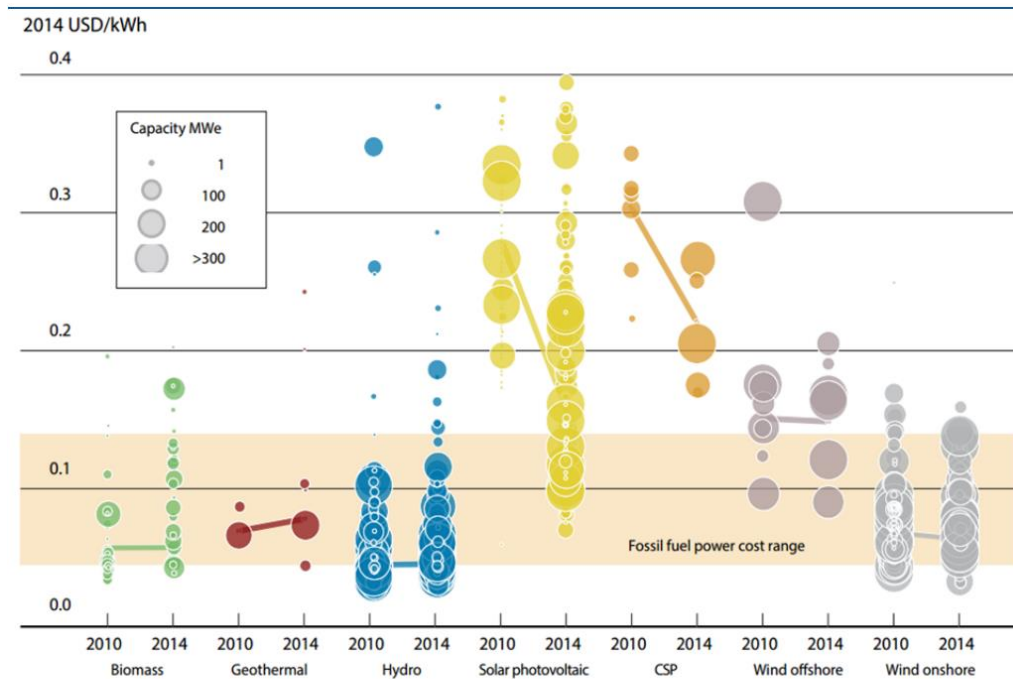
There are several approaches used in the power sector for the estimation of LCOE (IEA, IRENA, PwC). However, each project can have unique circumstances that can result in very specific costs that may fall outside of the typical range; e.g. if a partnership with local communities becomes a major element of capital cost.

¹¹ Levelized cost of energy (LCOE) is defined as the present value (computed at a specified discount rate) of all the resource costs (planning, construction, operating, etc), divided by the present value of the energy (at a fixed price).

¹² IPCC SRREN, IRENA

¹³ IRENA (2014) http://www.irena.org/DocumentDownloads/Publications/RE_Technologies_Cost_Analysis-HYDROPOWER.pdf

FIGURE 3: LEVELISED COST OF ELECTRICITY FROM RENEWABLE POWER GENERATION TECHNOLOGIES, 2010 AND 2014*



**Size of the circle represents the size of the project. The centre of each circle is the value for the cost of each project on the Y-axis*

Source: IRENA (2014)

Hydropower projects of all magnitudes have the similar financial profile of high capital cost, low operation and maintenance cost, no fuel cost and a relatively stable and sustained revenue stream. However, the scale of the project still plays a major role in the LCOE. Small-scale hydropower (installed capacity of less than 10 MW) may cost between \$0.2-0.4/kWh, while a larger scheme of 300 MW and greater is likely to cost significantly less at approximately \$0.1/kWh, which considerably enhances the return to the investor¹⁴.

It is important to note that the revenue stream from a hydropower project is more stable when a long-term power purchase agreements (PPA), bilateral contract or feed-in tariffs have been implemented prior to commissioning the facility. There is greater price risk in liberalised power markets, when not combined with any of the above. In the absence of long term contracts, hydropower operators will make generation decisions on the basis of shorter-term electricity prices, which can in many cases, bring higher returns relative to

¹⁴ IEA ibid

long-term PPAs, however, spot markets can also bring an element of risk to the hydropower operator which must be considered.

Historically, the decision for investment in hydropower is often made on an economic basis; however, another factor that has become increasingly important in the investment decision is the reputational risk of the project. The non-power services that hydropower can bring to a region often cannot be clearly quantified on a return on investment basis. For example, many hydropower projects offer an element of flood protection for the local region and the economic value lies in the value preservation and avoidance of damages. Although it is a highly valued benefit, there is no specific contribution to return on investment for this service. Other multi-purpose benefits include drought management, drinking water supply, irrigation, navigation and tourism, all of which typically do not offer clear and direct revenue streams to reservoir developers. Hydro projects also bring significant macroeconomic and societal benefits, such as employment opportunities, both during and after construction.

ECONOMIC AND FINANCIAL RISK

As with any business, the key elements in the overall risk profile of an investment in large infrastructure projects are the profitability of the project, and the certainty of realising the expected returns. In the case of hydropower, reservoirs can extend to hundreds or even thousands of square kilometres, requiring detailed studies of the hydrology, geology, topography, environmental and social impacts. These studies, along with detailed proposals for the civil works and other technical aspects, form a significant portion of the early capital expenditures. This increases capital requirements, and therefore risk, as some of the studies are undertaken before there is any certainty around project authorisation.

During the construction phase, there is a reasonable certainty about the energy production and resulting revenue generation. At this stage, risk is generally due to cost containment from unforeseen problems.

During the operational phase, hydropower's low maintenance costs and no fuel requirement mean that most capital costs have already been incurred and revenues are typically stable. This, combined with the very long operating life of modern day hydropower facilities (more than 100 years), makes it an attractive prospect for jurisdictions capable of taking on the (long-term) financial risk of hydropower development. However, while risks decline significantly once the plant is put into service, operational risks can include changes in long-term hydrological conditions and more stringent regulatory environments.

Correlating with the changing risk profile through the planning, construction and operation stages of a project, the risk premium on financing for these projects also declines through each stage. In dynamic markets, risk and consequently reward, is taken on by different players throughout these distinct phases. With greater involvement of the private sector, there tend to be more changes in project ownership over the course of the project's lifecycle. Thus the cost of finance correlates with the risk of the specific lifecycle stage.

One of the latest developments in the hydropower sector aiming to assist the investors in the identification of risks and how these correlated throughout the lifetime of the project from planning to operation is the Hydropower Sustainability Assessment Protocol. This tool has been developed through the efforts of the International Hydropower Association in cooperation with a multi-stakeholder range of partners seeking to have the means to assess soundly the sustainability of a hydropower project, both holistically across particular sustainability topics.

FUTURE OUTLOOK

Private investment in the sector has increased over the past decades of high development, where markets have enabled such investment. Investment is also increasingly coming from new international players, both public and private. Chinese entities are investing heavily in Africa, East Asia, and South America. Norway's Statkraft and SN Power have investments in Turkey, Zambia, and Panama. Other notable investments have included South Korean investment in Nepal, Pakistan and the Philippines; Thailand's investment in Myanmar; and Iran's investment in Tajikistan.

3. SOCIO-ECONOMICS

GOVERNMENT POLICIES – REGULATIONS AND INCENTIVES

Water, energy and climate policies have the potential to significantly influence decisions on hydropower developments.

For example, as a renewable energy, in some markets hydropower is eligible for price premiums such as feed-in-tariffs and for quota systems such as renewables obligations. Such government-funded incentive programmes have been shown to be positive drivers of deployment, as well as indirectly inducing hydropower development to help manage the variable output of large quantities of wind and solar coming online as a result of the same programmes. This is the case in Spain and Portugal, where a feed-in-tariff has spurred significant investment in wind and solar technologies, which in turn have led to increased development of pumped-storage hydropower to help balance the system.

It is important to note that hydropower development is highly subject to regulatory environments, related not just to energy, but also to water and environment. These policy spheres are often managed quite separately across various governments, leading to disjointed decision-making and conflicting signals. For example, in Europe, the EU's 20-20-20 legislation directs European countries to achieve a 20% share of renewables in the total final energy consumption by 2020. At the same time, the EU Water Framework Directive mandates actions that have in some cases been shown to deter consideration of hydropower. While targeted policies can be a factor in promoting hydropower, complementarity of policies across the suite of issues relevant to hydropower will also influence how it can be developed.

While there are several socio-economic drivers in play favouring hydropower development, there exist a number of policies hindering hydropower development. For example, despite the clear need for increased storage and other balancing services, most market systems do not appropriately reward these services. In Germany, existing pumped-storage projects have to pay transmission fees as final consumers during pumping operations (but not for generation). Policymakers are partly addressing this for new pumped-storage projects, which are exempted for 20 years. Additionally, any pumped-storage project, which was or is extended after 4 August 2011, by at least 7.5% of installed capacity or 5% of generation, is exempt for 10 years¹⁵.

¹⁵ Section 118 of German energy act (Energiewirtschaftsgesetz) (2014)

Another example of legislation hindering hydropower development is the prohibition of cross-ownership of generation and transmission assets, like in the case of several countries in Europe. The non-cross-ownership legislation is expected to lead to a more efficient use of regional and local electricity networks systems, and more effective performance of the market. Pump-storage hydropower plants are known to be a great asset for assisting to maintain a high quality level of the electricity system/network, and this type of hydropower can be further developed for this purpose. However, the markets do not yet reward fully the value of these benefits, thus posing a higher risk on the return-of-investment for the owner of this type of generation assets under the non-cross-ownership legislation. In contrast, in countries like China, where the legislation allows the state grid to own both transmission and generation assets, recognising the value of pumped-storage projects for a better operation of the electricity network, China is developing 41 GW of pump-storage projects. Alternatively, another possible solution for markets under the no-cross-ownership legislation, the development of pump-storage power plants could find a niche if developed as a “generation packet” in a mix with other renewables, where a given amount of power is guaranteed regardless whether it comes from a solar/wind or pump-storage generation.

Several countries, such as Indonesia, incentivise hydropower development through legislation by requiring feed-in-tariffs and minimum quotas for purchase of renewable energy.

Policy recommendations designed to maximise the potential from hydropower development in more mature markets include the following¹⁶:

- Establishing a level playing field on the energy market between hydropower and other technologies.
- Designing the energy market to reflect the true value of firm and flexible energy capacity in different time frames.
- Prevention of double grid fees for pumped storage plants.
- Removing any obstacles to energy trade across borders and strengthen interconnection infrastructure.
- Recognising within the legislation the value of hydropower to maintain the stability and quality of electricity network supply, as an independent aspect from pure power generation (for demand supply).
- Aligning conflicting policy goals and legislation in the field of water management, renewable energy generation, and climate change mitigation and adaptation.
- Leveraging R&D and technology programmes as a contribution to facilitate innovation in hydropower.

¹⁶ Hydropower sector's contribution to a sustainable and prosperous Europe (2015)

SOCIO-ECONOMIC IMPACTS

Hydropower projects, especially large-scale types, usually tend to be the focus of national policy and public debate. Reasons for this include the high capital investments required, the potential impacts such developments would have on the local environments, the possible displacement of communities from hydropower project sites, and the competing demands between energy, water and land use. While governments generally view hydropower in a favourable light, as they are a means of reducing national emissions, boosting energy security and fostering economic development, hydropower projects can still either enjoy the local support or be met with resistance.

In some cases, public pressure can have a profound effect on the outcome, not only of planned projects, but the entire governing policy on hydropower. The following case study in Chile gives an illustration of this.

CHILE'S HYDROPOWER FUTURE AND PUBLIC SUPPORT

Though a major source of electricity for the country, Chile is rethinking hydropower as a future primary energy supply. The growing unpopularity of large-scale power projects in the country led the national government to halt development of the controversial 2,750 MW HidroAysen hydropower project in the country's Patagonia region in 2014.

The cancellation of the \$8 billion joint venture between Endesa Chile and Colbun S.A. is seen as a victory for environmentalists and the wider Chilean population. There were growing concerns that HidroAysen, which is comprised of 5 separate hydroelectric dams on the Baker and Pascua rivers, would cause significant damage to the environment and wildlife of Chile's rural south. The project also made insufficient provisions for local communities who would be displaced by the project, according to the Ministry of Environment. In response, Endesa Chile admitted the project is no longer in its immediate portfolio, but defended the sustainability of the project, believing the region's water resources are important for Chile's energy development¹⁷.

With its hydropower future uncertain, Chile may need to look to other sources such as LNG and other renewables in meeting its growing energy demands.

There are also examples where hydropower projects have been developed following good practices, receiving full support from the people. For example, the Angostura Hydropower Project, also in Chile, not only accepted but even encouraged by the municipalities of Quilaco and Santa Bárbara, Sernatur and Colbun. Colbun indicated that they did not experience any opposition (in fact the opposite) because the project was seen a touristic project rather than an energy generation project. The

¹⁷ Endesa Chile (2015)

reservoir allowed the development of a tourism industry that was not present before the project and it is bringing economic development to the municipalities. The plant contributed to the creation of the recreational park Angostura del Biobio, and expanded the (previously existing) Angostura park (which included also environmental enhancements). The plant started operations in 2014 and it was the largest hydropower plant built in Chile since 2004.

There are, however, many hydropower projects that score high in the socio-economic impacts assessment made by the Hydropower Sustainability Assessment Protocol, demonstrating successful trade-offs between local and national interests. Their equity partnership with IPs could not be bettered in relation to negotiating and reconciling local and national interests. To illustrate this, it was determined that 71% (12 out of 17) of the assessments made via the Sustainability Protocol have scored 5 (highest) on the project benefits topic. Such benefits can be achieved independently of the economic level for the country: Jostedal (Statkraft, Norway) is an excellent developed-country example, and Miel I (ISAGEN, Colombia) is an example applicable to a developing country. Many assessments show very positive results for local employment. Santo Antonio and Chaglla are good examples of this.

It should also be noticed that local and national interests are sometimes directed at reducing and even eliminating the opposing views on a hydropower development, as it is the case of Program Sava in Croatia, for example, where flood management was a major common interest.

The role of governments on hydropower development is to ensure that projects meet acceptable sustainability requirements – economic, social and environmental – and that all negative impacts that may be incurred from the projects are mitigated to the bare minimum. This is of prime importance to developing and emerging economies considering hydropower development, ensuring that the benefits from hydro projects are enjoyed across the country, and especially in areas where the scarce water resources are being exploited.

INTERNATIONAL IMPACTS

As in many other aspects, international hydropower developments can also face opposition or support, depending whether the interest of the stakeholders across borders are sufficiently taken into consideration.

Water is a cross-boundary resource; 260 of the world's rivers cross at least one national boundary.¹⁸ Countries sharing water resources need to work together to meet their individual needs and potentially boost co-benefits.

Regional co-operation between the involved parties is crucial to ensure that the available water resource is utilised equitably and its potential maximised. Thorough assessments must be undertaken during the pre-project phase of the development, and revisited throughout the lifecycle of the project. This is to analyse the benefits and costs, financial, social and otherwise, of the hydropower project to each of the involved countries. Compensation and other concessions may have to be made to countries that bear sizeable costs compared to any perceived benefits.

CROSS-BORDER CONFLICT AND CO-OPERATION – DAMMING THE NILE IN ETHIOPIA

The under-construction US\$4.2 billion Grand Renaissance Dam (GERD) on the Nile River, close to Ethiopia's border with Sudan, has been a source of contention in North-East Africa since construction began in 2011. The 6,000 MW hydroelectric project, hoped to bring energy self-sufficiency to Ethiopia and alleviate poverty in the country, is of grave concern to Egypt, the most downstream nation on the Nile, which depends greatly on the world's longest river for its agriculture and power. So much so, that Egypt has previously threatened military action on Ethiopia in order to halt construction.

The Nile has long been a focal point for tensions between the nations it flows through. A colonial-era agreement attributes use of most of the river's capacity to Egypt and Sudan, an agreement the ten upstream nations on the Nile do not recognise. In addition, Sudan, naturally Egypt's ally on these matters, appears to have switched allegiances and is now in favour of GERD, upon realising the potential benefits of its operation, including increased irrigation capacity and import of excess generated electricity from the dam.

There have been efforts to ease tensions over the issue recently, and in December 2015, leaders from Egypt, Ethiopia and Sudan signed a legally binding agreement confirming "trust and transparency" between the three states during negotiations. The agreement emphasised the principles of cooperation, development, regional integration and sustainability, mitigating significant damage, exchanging information and building trust.¹⁹ The agreed principles include giving priority to downstream

¹⁸ IHA, Cross-border projects

¹⁹ <http://www.dailynewsegypt.com/2015/12/29/egypt-ethiopia-and-sudan-sign-agreement-on-gerd/>

countries for electricity generated by the dam, a mechanism for resolving conflicts, and the provision of compensation for any damages incurred²⁰.

The dam is expected to enter into operation in 2017.

Three examples of large hydropower projects where the interests across borders were properly considered in the development of the hydropower project, contributing to their successful completion, are the Itaipu project between Paraguay and Brazil, the Nam Theun 2 dam between Lao and Thailand, and the Amistad dam between USA and Mexico.

Multilateral development banks (MDBs), such as the World Bank, have been identified as key players in the reduction of conflict between parties, within the realms of project initiation and financing. The 80 MW Rusumo Falls hydropower project in the Nile Basin region (Rwanda, Burundi and Tanzania) is proof of how multilateral interactions between nations in the region facilitate the relatively smooth progress of a large-scale hydropower project. In this case, the entirety of the project is being developed under the aegis of the African Development Bank (AfDB). The region has a history of conflict in addition to low electrification rates and high levels of poverty. The successful implementation of the Rusumo Falls project is expected to contribute greatly towards economic development and political stability²¹.

SUSTAINABILITY ASSESSMENT OF NAM THEUN 2-LAO

Nam Theun 2 is dedicated to provide Lao and Thailand with competitive CO₂-free electricity and contribute to Lao development as well.

The main sustainability issues addressed during design, construction and operation are: doubling the standard of living for local communities: livelihood, agriculture, health, capacity building, education, drinkable water, irrigation, infrastructures; preserve biodiversity (4000 km² natural reserves, 1 MUS\$/year). The process for taking into account all stakeholders' expectations is as important as the results: 6000 people in local communities as well as 70000 downstream communities are involved in decision making; decisions and compliance were under scrutiny of the civil society, local and global NGOs.

Major results have contributed to demonstrating viability and efficiency of dams to the World Bank and private financial investors i.e. building trust: relocate local communities

²⁰ Al-Jazeera, Egypt, Ethiopia and Sudan Sign Nile Dam Accord

²¹ AfDB, Rusumo Hydro Power Plant

according to culture and religion as well as material expectations; take care of biodiversity (wildlife, elephants, plants etc.); support economic development, employment, and good governance.

Sharing objectives and methodology have been of outstanding importance to start the process, involving the Lao government and public authorities, NTPC, local communities and NGOs,

Among lessons learned, key conditions of success are: focus on making concrete and understandable decisions for all stakeholders, transparency in the decision process, compliance with schedule, and preparation of all stakeholders for dialogue for meeting new challenges appearing during building time and even when the dam is operated.

4. ENVIRONMENTAL IMPACTS

Hydropower development, as with any large infrastructure project, requires a change to the existing environment. This has consequences that impact the local environment, as well as the people living in communities near to the development site. These impacts are well identified, and although not all negative impacts can be eliminated, much can be done to mitigate these impacts. Furthermore, in some cases the impacts are actually positive for the environment.

Hydropower projects are strongly site specific and as such each project will differ in its impacts, positive and negative, depending on issues such as size, geography, surrounding land use and environment. While installed capacity is not a direct determinant on impact, a number of the environmental impacts that arise from the development of hydropower projects are related to the impoundment of a reservoir in storage projects, and largely result from changes to the environment's hydrological characteristics brought about through the introduction of structures.

A good example of a positive environmental benefit is the preservation of large areas of natural habitat that probably would have otherwise been lost. Two projects that score very high in the Hydropower Sustainability Protocol in this aspect are: Itaipu (Paraguay-Brazil), and Chaglla (Peru).

Some examples of positive mitigation measures can also be found in Europe, where many hydro projects have invested heavily in restoring connectivity through fish passage, and the industry is taking the opportunity to modernise e.g. Romanche-Gavet (France), Walchensee (Germany).

LAND USE

Hydropower plants may modify the landscape of their surrounding environments, through the creation of dams and the flooding of land downstream. The land footprint from hydropower development can vary widely, depending on the land topography of the plant and the scale of the project. As in sections above, there are both positive and negative examples of land-use changes due to hydropower development. These should be considered within the overall context of the project's impact.

Two common examples of larger-scale hydropower development with good land utilisation (land/power ratio) are: Chaglla (Peru) with 96 W/m², and Itaipu (Paraguay-Brazil) with 10.37 W/m².

The economic value of land-use changes is difficult to assess. A balanced assessment of land-use changes should also consider the water management benefits offered by hydropower facilities, such as flood control, better irrigation and water conservation during droughts or arid seasons. In the case of flood control, avoiding the costs of losing crops, houses, infrastructure, etc., due to uncontrolled river flooding provides a view of the value added by a hydropower development in this respect, which then can balance out the loss of land used for the reservoir.

Historically, the lack of an adequate methodology to quantify economically these types of services has resulted in practice for these not to be included in the total cost-benefit analysis of hydropower developments. Further research and investigation is necessary to identify suitable methods for economic valuation of land-use change, in order to attain an impartial assessment of a hydropower development.

WATER FOOTPRINT

While hydropower plants produce electricity by diverting water (hence no water withdrawal), water can be lost through evaporation from reservoirs. As a result, there is much debate over how large a water footprint should be attributed to hydropower. In the few studies carried out on this topic, the evaporation rates appear inconsistent, likely due to the variations in site specific conditions for hydropower, local climatic conditions (frequency and direction of prevailing winds) and an immature methodology for calculating evaporation rates. Identified short-comings in much of the published literature to-date include use of gross evaporation rather than net evaporation rates from reservoirs, where the pre-existing evaporation and evapotranspiration rates are not properly accounted for.

A few recent studies carried out in Norway²² (CEDREN – Centre for Environmental Design of Renewable Energy) and Canada²³, conducted by Hydro-Quebec, in conjunction with McGill University and Environment Canada, the water consumption rates are found to be very close to zero (i.e. evaporation from the host environment before and after creation of the hydropower plant are the same), and in some cases was even negative (less evaporation from the environment after the plant was created). These studies boost hydropower's credentials as an energy source with a minimal water footprint. It must be noted, however, that hydropower plants' net evaporation values are expected to vary based on the conditions of the host environment – values are lowest in boreal and temperate regions, and highest in hot and arid regions. More studies need to be conducted around the world in order to confirm this.

Furthermore, in the case of multi-purpose reservoirs with hydropower production, there should be an appropriate allocation of water footprint to each service provided, such as

²² Bakken, Modahl, Engeland, Raadal, and Arnøy (2015)

²³ <http://www.hydroquebec.com/sustainable-development/documentation-center/pdf/studying-net-evaporation-eastmain-1-reservoir.pdf>

irrigation, flood control, recreation and power production. Each one of these uses should be allocated their respective contribution to evaporation (or water footprint). It is a lack of clear guidelines on the allocation of water consumption in the case of multi-purpose reservoirs, which may negatively skew water consumption for power generation. Recent pioneer research from Norway²⁴ is, however, expected to contribute to the development of guidelines.

Much more work needs to be done to establish consistent, defensible methods for determining the net evaporative losses from the pre-impoundment area, which shall be then subtracted from the actual evaporation values determined for the reservoir in question, in order to quantify the net contribution of the project to the water loss due to evaporation.

The methodology for the evaluation of pre-impoundment and post-impoundment consumptive evaporative losses is correlated to the method used for the evaluation of GHG emissions from reservoirs. IHA is leading the G-res project, described in the following section. The G-res tool will be capable of estimating GHG emissions from reservoirs both in the pre-impoundment and post-impoundment state. This technique could be applicable to the development of a better methodology of computing net evaporation from reservoirs.

Numerous initiatives have recently been launched in order to develop a more solid, scientific basis for the calculation of water footprint of a wide range of services and products including hydropower production, where the initiatives by World Water Council and the development of an ISO Water Footprint Standard are among the most prominent.

GREENHOUSE GAS (GHG) EMISSIONS FROM RESERVOIRS

The introduction of a reservoir (for hydropower or other purposes), may have the potential to alter the natural state of greenhouse gas emissions in a river basin. The GHG status of freshwater reservoirs is an area of ongoing scientific research, and policy responses are still evolving as the state of knowledge progresses. There are concerns around the uncertainty in estimates of GHG emissions both pre-impoundment and post-impoundment from reservoir systems, and that these impacts are often attributed to hydropower projects, regardless whether it is a multipurpose or only power generation project.

The GHG footprint of a reservoir is highly dependent on the local climate conditions, as well as the specific human activity in the catchment area. Life-cycle emissions from large-scale hydro plants built in semi-arid regions are relatively low, but could be much higher from plants in tropical regions²⁵. In addition, vegetation along the riverbed at a hydro plant site

²⁴ Bakken, Modahl, Raadal, Bustos and Arnøy (2016)

²⁵ <http://www.internationalrivers.org/environmental-impacts-of-dams>

could decay in the absence of oxygen, leading to a build-up and release of significant amounts of methane²⁶.

Assessment of the effect of the creation of the reservoir on the carbon cycle and related emissions should take into account the emissions from the whole catchment area, before the creation of the reservoir; and compare this to the situation after the reservoir has been built. The result would be the net GHG emissions. Emissions due to unrelated anthropogenic sources (e.g. sewage, agricultural run-off, industry, etc.) should be subtracted to allow an accurate estimate of net emissions.²⁷

Through the UNESCO/IHA GHG Status of Freshwater Reservoirs project²⁸, the International Hydropower Association (IHA) is leading a research project to build a better understanding of the potential GHG footprint of freshwater reservoirs based on local conditions, including preparation of a screening tool to assess potential emissions, as well as building knowledge on how best to mitigate this impact at specific sites when needed. The research will also develop a methodology to properly allocate the GHG footprint of the reservoir to the various services provided by the reservoir. Further work is ongoing by various organisations: IHA is working to provide detailed modelling guidelines for those sites where potential emissions are deemed to be high, following an initial risk assessment. In the near future IHA is expected to complete a tool (G-Res) to measure the GHG emissions from reservoirs.

SEDIMENTATION

The installation of a dam will impact the rate of sediment transport in a river, in many cases leading to sediments becoming trapped behind the dam rather than flowing downstream. This can have a direct effect on the operating life and the electricity output of hydropower plants, and the distribution of sediments and nutrients downstream. Other effects include reduced reservoir and flood management capacity due to the loss of storage, a shortened power generation cycle, and higher maintenance costs. In order to tackle these problems, some countries have a legal obligation to reactivate the sediment transport in rivers. Research undertaken for the World Commission on Dams in 2000 estimated that between 0.5 and 1% of global water storage capacity was lost every year as a result of sedimentation. It should be noted however, that sedimentation impacts vary greatly around the world depending on climate, the location of the project within the basin and the river geomorphology.

The World Bank is developing the RESCON2 tool, which aims to assist sediment management of reservoir projects. While a variety of sediment management techniques are available, work continues on building knowledge in this area and encouraging further action

²⁶ http://srren.ipcc-wg3.de/report/IPCC_SRREN_Ch05.pdf

²⁷ IPCC (2012); IEA (2014); IEA (2011); Harby et al. (2012)

²⁸ UNESCO/IHA GHG Status of Freshwater Reservoirs project, <http://www.hydropower.org/greenhouse-gas-emissions>

to plan for and mitigate sedimentation from the early stages of project planning through to operation.

THE KOKISH RIVER HYDROELECTRIC PROJECT, VANCOUVER ISLAND, CANADA

As social and environmental acceptability becomes increasingly important for the development of greenfield hydropower projects, the partnership between a private energy producer and a Canadian First Nation is a prime example of sustainable development. The Kokish River Hydroelectric Project²⁹, located on north-eastern Vancouver Island, Canada, is a 45 MW run-of-river power plant owned and operated by Brookfield Renewable in partnership with the 'Namgis First Nation ('Namgis).

The Kokish River contains valuable fish resources which are afforded a high level of protection, particularly as healthy fisheries are crucial to the 'Namgis traditional way of life. Fish and fish habitat protection measures extended into every facet of the project, from design and construction, to operations and long term monitoring. The partners developed fish passage systems (instream flow releases, fish ladder, coanda screen) for the Kokish facility, which greatly contributed to the success of this project.

Throughout the project, great emphasis was placed on respecting the riverine environment and providing economic diversification through job creation and signing of a power purchase agreement with the provincial utility, which in return led to providing economic strengthening to the 'Namgis. The 'Namgis participated in project environmental assessment work, including setting the terms of reference for studies, sitting in technical meetings and fields studies, organisation of public meetings, and review of all environmental impact assessment reports. An independent technical advisor was hired by the 'Namgis to assist with the environmental work.

Brookfield Renewable and the 'Namgis are proud of their partnership in completing a project that provides financial benefits for the community while respecting the environment and protecting fish habitat.

²⁹ Namgis First Nation (2014)

5. OUTLOOK

CHALLENGES

Looking forward, there are several challenges that the hydropower sector will need to address as it continues the upward trend in development.

Sector Knowledge and Human Resources

With a fresh influx of investors and developers, there are a number of examples of lessons to be re-learned by new players. Capacity building, networking and knowledge transfer among sector actors, are essential for keeping momentum as well as building and sharing of robust data on good practices in the development and management of hydropower.

As the pace of new development grows, fuelled by the strong focus on climate change and renewable energy, a shortage of technical specialists can be expected across a variety of needed skillsets, leaving a high demand for experienced engineers, sustainability specialists, and finance and policy specialists. Opportunities for skills development and training will be needed to manage risks and ensure safe development and operation of hydropower facilities. The expected rapid pace of hydropower development over the coming decades will only magnify these needs.

In addition to the need for further knowledge building in several areas, and in particular for multipurpose hydropower developments, there is also a need for raising awareness on the macroeconomic benefits of hydropower projects, which in many cases go unaccounted, despite the lack of adequate valuation methodologies.

Energy-Water Nexus

While demand for fresh, potable water is rising, it is important to note that water is a renewable, but fixed resource to be shared. As such, access to potable water worldwide is becoming increasingly strained, with regions such as the Middle East and North Africa already suffering from high water stress (the ratio of total annual water withdrawals to total available annual renewable supply). A global shortage in freshwater supply, equal to 40% of global demand, is predicted by 2030³⁰.

Hydropower plays a crucial role in the energy-water nexus. On the other hand, the versatility of hydropower plants can be exploited to alleviate local water stresses – diverted water can be made available for other purposes such as irrigation and drinking water supply.

³⁰ Water Resources Group, Background, Impact and the Way Forward

Water availability is a local issue; therefore, governments must take a leading role in breaking the cycle of increasing water and energy demand. Co-operation between the energy and water sectors is important, as this is driving the operational efficiencies of the major energy and water consumers. The development of reliable frameworks on the risks of local water availability and quality would better advise governments and the private sector on the undertaking of new developments, as well as foster stakeholder collaboration on such matters. The Water for Energy Framework (W4EF) is a prime example of the tools needed to support addressing the energy-water nexus.

Climate Change Impact

Climate change is expected to have wide-ranging impacts on precipitation levels and regional hydrology. While these impacts will vary by location, generally speaking there is an expectation of increased precipitation and more extreme weather events, including both flood and drought periods. In some regions, climate change will affect water and energy availability as well as electricity demand, which would place a higher premium on water storage; this currently is not always adequately recognised. However, in other regions, climate change will result in increased water flows, such as regions that rely on glacial run-off.

Some organisations within the hydropower sector have recognised the potential impacts of climate change and are developing robust adaptation strategies and building climate resilience into their long range plans. For example, Hydro-Quebec in Canada has partnered with Ouranos a research consortium with expertise in regional climate models and simulations.

OPPORTUNITIES

Regional Hydropower Development

In some cases, the business-case for developing a hydropower project requires cross-border power trade. For mountainous countries such as Bhutan, Nepal and Tajikistan, the export of clean electricity to power-hungry neighbours offers a rare opportunity of substantial investment and revenues. Similar opportunities exist across Africa as well as the nations of the Caucasus, with Georgia keen to develop its estimated 80 TWh hydropower resource. Georgia is already exporting electricity to Turkey, where average wholesale tariffs in each country are US\$0.043/kWh and US\$0.085/kWh³¹, respectively. In 2014, 200 GWh was tendered from 1.3 GW Enguri and 200 MW Vardinili hydropower plants³².

³¹ <http://www.hydroworld.com/articles/print/volume-21/issue-01/articles/russia---central-asia/georgian-hydropower-turns-river.html>

³² <http://www.icis.com/resources/news/2014/07/21/9803129/georgian-electricity-exports-to-turkey-to-fall-in-august-teias/>

In more developed markets, bilateral interconnectors may also be the key to growth. Some hydro-rich Canadian provinces such as Manitoba and Quebec, for example, have abundant hydropower potential, which cannot be developed solely to meet domestic load growth. Therefore, to justify future development, bilateral contracts with the neighbouring US, which has a growing appetite for green energy, can often trigger a new project moving forward. However, access to the US market is dependent largely on building additional interconnections. In other cases, the challenges are likely to be political and environmental, rather than technical, as extremely long high-voltage DC lines such as the 2071 km, ± 800 kV, 6400 MW link connecting the Xiangjiaba Dam to Shanghai have been in operation for some years.

With high-voltage transmission lines, countries with abundant hydropower resources use their reservoirs as 'batteries' to balance the variable generation in neighbouring countries. For example, in the Canadian province of Manitoba, their largely hydro-based system is strongly interconnected with the neighbouring grids of the US mid-west. As such, Manitoba Hydro can utilise their hydropower reservoirs to balance the output of major windfarm developments to the south. Similarly, the Norwegian grid is connected by underwater cables to Denmark, enabling Denmark to use Norwegian hydropower to back up its wind and thermal grid.

Attracting Domestic Markets

Alternate scenarios for hydropower growth in a particular country may follow the Icelandic model, where attracting energy intensive industries to catalyse domestic demand for hydropower serves as a basis for investment. In the case of Iceland, hydropower was developed to attract and build a domestic aluminium industry.

Hydropower is also used to support remote mining operations and associated local grids, for example in Katanga, Democratic Republic of Congo. The Malaysian state of Sarawak is pursuing a similar model of domestic economic and industrial growth, underpinned by the development of local hydropower resources to feed power-intensive industries.

Increasing Demand for Clean Energy and Power

Demand for clean energy will also open new markets. In the aftermath of the Paris Agreement and the adoption of the Sustainable Development Goals in 2015, demand for clean, reliable and affordable electricity is expected to increase and further drive hydropower growth.

In 2013, Facebook opened a data centre in Luleå, Sweden, powered by hydro (100MW installed capacity), as part of its commitment to power operations using clean energy.

Similarly, in 2011, BMW opened a manufacturing facility for its carbon fibre materials for electric vehicles in the US state of Washington, primarily due to the location's abundance of cheap hydroelectricity. Alternatively, regulation encouraging clean energy investment or requiring quotas of clean energy production will also drive hydropower growth.

Evolving Energy Mix and Market Dynamics

As the energy mix continues to evolve, the system will continue to need more energy storage and dynamic capacity to balance grids. As hydropower has good synergies with all generation technologies, its role is expected to increase in importance in the electricity systems of the future. However, markets and policy will need to evolve to appropriately incentivise investors, particularly where the private sector is expected to engage.

Climate Change Resilience and Adaptation Services

Alternatively, hydropower projects may be called on to provide societies with climate adaptation services, where they could offer flood management and drought protection through the use of the storage component of a reservoir. The case study below illustrates the benefits accrued from “multi-purpose reservoirs”. However, plant operators are typically not compensated for these services, and may impact the generation and revenue profile of a particular station. Furthermore, some incentive programs including climate change, offset programmes such as the UNFCCC Clean Development Mechanism; in some cases, effectively discourage development of reservoir storage projects, which will limit the sector's ability to provide climate services, despite increased recognition of such needs.

MULTI-PURPOSE RESERVOIRS –THREE GORGES DAM, CHINA

The world's largest hydropower station is, in fact, not simply a hydropower station. China's Three Gorges Dam, well known for its sheer size at 22.5 GW, generates an average 88.2 TWh of electricity per year. In 2014 the station set a new world record of 98.8 TWh of electricity generated in a year³³, which is roughly equivalent to the energy from 49 Mt of coal.

However, the primary purpose of the dam is to control massive seasonal flooding on the Yangtze River. Each year the river is subject to extreme floods, with major events occurring up to four and five times per year. Before the project's completion in 2007, a single disastrous flood event in 1999 passed through the site, causing economic losses to the region of \$26 billion, equivalent to the total investment cost of the entire Three Gorges Dam project. When a similar flooding event took place in 2010, the dam was able to attenuate the peak flood flows, avoiding billions of dollars of economic damage, not to mention protecting the local communities living in the basin.

In addition to flood control services, the navigation lock built around the dam allows the Three Gorges reservoir to be utilized as a shipping lane, bringing valuable goods upstream to the previously inaccessible municipality of Chongqing and others to the south-west. Navigation has increased by more than four times and the overall cost

³³ The Yearly Electricity Production of the Three Gorges Hydropower Station Was Over 98.8 TWh Which Hit a World Record, retrieved January 2015, <http://www.ctgpc.com/news/news1.php?NewsId=89748>, China Three Gorges Corporation, 2015

of transportation has decreased by a third.

Moving forward, there is a need to fully understand the linkages between climate change and water availability, through the development of accurate models mapping climate-water interactions. Project developers and owners will increasingly be expected to demonstrate climate resilience at the financial and regulatory approval stages. This may include provision of improved data analysis on climate change impacts, increased flexibility in project design to accommodate uncertainty, increased storage volumes, and revised operational regimes.

The sector is increasingly aware of the potential impacts climate change may have on its operations (climate resilience), as well as the potential change in services it may provide in a climate- changed world (adaptation services). Current initiatives across the sector include work on decision-making in the face of uncertainty, analysis of multi-purpose benefits of hydropower, and a “no-regrets” design approach that allows for flexibility and builds climate resilience into hydropower projects.

Hydropower - a Renewable Resource

General concepts like ‘small’ or ‘large’ hydropower are linked to differentiated national policies, and have not been developed on a technical or scientific basis. Hydropower stations of all scales have roles to play in sustainable development. Utilising the natural water cycle, hydropower is an important source of renewable energy. From a 1kW unit to a 1GW hydropower turbine, the physical processes of converting energy in water into clean and dispatchable electricity are exactly the same.

6. GLOBAL TABLE

TABLE 4: HYDROPOWER GLOBAL DATA

Country	Total Hydropower Capacity (MW) in 2015	Pumped Storage Capacity (MW) in 2015	Excluding Pumped Storage (MW) in 2015	Estimated Net Hydropower Generation (GWh) in 2015	Consumption of Hydroelectricity (GWh) in 2015, BP (2016)
Afghanistan	400	-	400	911	145
Albania	1 527	-	1 527	4 000	-
Algeria	228	-	228	320	-
Andorra	45	-	45	102	-
Angola	866	-	866	4 270	-
Argentina	10 118	974	9 144	41 464	42 261
Armenia	1 249	-	1 249	2 180	-
Australia	8 790	740	8 050	13 628	13 707
Austria	13 177	5 200	7 977	39 528	36 744
Azerbaijan	1 116	-	1 116	2 444	1 638
Bangladesh	230	-	230	1 491	898
Belarus	33	-	33	111	121
Belgium	1 427	1 307	120	336	291
Belize	53	-	53	209	-

WORLD ENERGY COUNCIL | HYDROPOWER

Country	Total Hydropower Capacity (MW) in 2015	Pumped Storage Capacity (MW) in 2015	Excluding Pumped Storage (MW) in 2015	Estimated Net Hydropower Generation (GWh) in 2015	Consumption of Hydroelectricity (GWh) in 2015, BP (2016)
Benin	1	-	1	1	-
Bhutan	1 615	-	1 615	7 781	-
Bolivia	494	-	494	2 337	-
Bosnia and Herzegovina	2 504	420	2 084	6 500	-
Brazil	91 650	30	91 620	382 058	360 948
Bulgaria	3 129	864	2 265	3 968	5 788
Burkina Faso	32	-	32	98	-
Burundi	54	-	54	210	-
Cambodia	1 267	-	1 267	1 851	-
Cameroon	741	-	741	4 414	-
Canada	79 202	177	79 025	375 626	383 136
Central African Republic	25	-	25	142	-
Chile	6 622	-	6 622	24 572	23 393
China	319 370	23 060	296 310	1 126 400	1 126 420
China Taipei	4 683	2 602	2 081	4 193	4 470
Colombia	11 392	-	11 392	48 026	44 682

Country	Total Hydropower Capacity (MW) in 2015	Pumped Storage Capacity (MW) in 2015	Excluding Pumped Storage (MW) in 2015	Estimated Net Hydropower Generation (GWh) in 2015	Consumption of Hydroelectricity (GWh) in 2015, BP (2016)
Comoros	1	-	1	5	-
Congo	209	-	209	1 062	-
Costa Rica	1 800	-	1 800	7 411	-
Cote d'Ivoire	604	-	604	2 487	-
Croatia	2 141	293	1 848	6 314	-
Cuba	64	-	64	95	-
Czech Republic	2 259	1 172	1 087	3 070	1 795
Denmark	9	-	9	18	-
Democratic Republic of the Congo	2 495	-	2 495	8 520	-
Dominica	6	-	6	26	-
Dominican Republic	543	-	543	1 427	-
Ecuador	2 413	-	2 413	12 415	13 096
Egypt	2 800	-	2 800	13 700	13 063
El Salvador	472	-	472	1 902	-
Equatorial Guinea	127	-	127	11	-

WORLD ENERGY COUNCIL | HYDROPOWER

Country	Total Hydropower Capacity (MW) in 2015	Pumped Storage Capacity (MW) in 2015	Excluding Pumped Storage (MW) in 2015	Estimated Net Hydropower Generation (GWh) in 2015	Consumption of Hydroelectricity (GWh) in 2015, BP (2016)
Estonia	8	-	8	27	-
Ethiopia	2 552	-	2 552	9 000	-
Faroe Islands	39	-	39	116	-
Fiji	125	-	125	296	-
Finland	3 198	-	3 198	16 538	16 753
France	25 397	6 985	18 412	57 300	53 903
French Guiana	119	-	119	730	-
French Polynesia	47	-	47	288	-
Gabon	170	-	170	804	-
Georgia	2 727	-	2 727	8 807	-
Germany	11 258	6 806	4 452	24 494	19 320
Ghana	1 584	-	1 584	8 670	-
Greece	3 396	699	2 697	5 589	5 584
Greenland	90	-	90	348	-
Guadeloupe	10	-	10	10	-
Guatemala	991	-	991	3 993	-
Guinea	368	-	368	500	-

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Country	Total Hydropower Capacity (MW) in 2015	Pumped Storage Capacity (MW) in 2015	Excluding Pumped Storage (MW) in 2015	Estimated Net Hydropower Generation (GWh) in 2015	Consumption of Hydroelectricity (GWh) in 2015, BP (2016)
Guyana	1	-	1	-	-
Haiti	61	-	61	149	-
Honduras	558	-	558	2 981	-
Hungary	56	-	56	230	233
Iceland	1 986	-	1 986	13 647	-
India	47 057	4 786	42 271	129 000	124 374
Indonesia	5 258	-	5 258	13 741	16 039
Iran	11 196	1 040	10 156	13 785	-
Iraq	2 753	240	2 513	4 403	-
Ireland	530	292	238	806	806
Israel	7	-	7	28	-
Italy	21 880	7 555	14 325	44 751	43 902
Jamaica	23	-	23	124	-
Japan	49 905	27 637	22 268	91 266	96 583
Jordan	12	-	12	59	-
Kazakhstan	2 260	-	2 260	7 325	7 907
Kenya	818	-	818	3 440	-

WORLD ENERGY COUNCIL | HYDROPOWER

Country	Total Hydropower Capacity (MW) in 2015	Pumped Storage Capacity (MW) in 2015	Excluding Pumped Storage (MW) in 2015	Estimated Net Hydropower Generation (GWh) in 2015	Consumption of Hydroelectricity (GWh) in 2015, BP (2016)
Kosovo	36	-	36	126	-
Kyrgyzstan	3 091	-	3 091	13 809	-
Laos	4 168	-	4 168	18 700	-
Latvia	1 576	-	1 576	3 175	-
Lebanon	221	-	221	658	-
Lesotho	80	-	80	694	-
Lithuania	876	760	116	508	345
Luxembourg	1 134	1 100	34	92	-
Macedonia	674	-	674	1 200	-
Madagascar	164	-	164	862	-
Malaysia	5 472	-	5 472	11 984	14 741
Malawi	364	-	364	2 136	-
Mali	157	-	157	289	-
Mauritania	97	-	97	119	-
Mauritius	60	-	60	79	-
Mexico	12 435	-	12 435	30 127	30 051
Moldova Republic	76	-	76	373	-

WORLD ENERGY COUNCIL | WORLD ENERGY RESOURCES 2016

Country	Total Hydropower Capacity (MW) in 2015	Pumped Storage Capacity (MW) in 2015	Excluding Pumped Storage (MW) in 2015	Estimated Net Hydropower Generation (GWh) in 2015	Consumption of Hydroelectricity (GWh) in 2015, BP (2016)
Montenegro	658	-	658	1 800	-
Morocco	1 770	464	1 306	2 517	-
Mozambique	2 187	-	2 187	12 000	-
Myanmar	3 140	-	3 140	5 776	-
Namibia	341	-	341	1 792	-
Nepal	753	-	753	3 635	-
Netherlands	37	-	37	90	87
New Caledonia	78	-	78	328	-
New Zealand	5 254	-	5 254	24 290	24 549
Nicaragua	123	-	123	550	-
Nigeria	2 040	-	2 040	5 898	-
North Korea	5 000	-	5 000	13 140	-
Norway	30 566	1 351	29 215	139 000	137 452
Pakistan	7 264	-	7 264	31 180	34 554
Panama	1 655	-	1 655	5 073	-
Papua New Guinea	234	-	234	861	-
Paraguay	8 810	-	8 810	59 425	-

WORLD ENERGY COUNCIL | HYDROPOWER

Country	Total Hydropower Capacity (MW) in 2015	Pumped Storage Capacity (MW) in 2015	Excluding Pumped Storage (MW) in 2015	Estimated Net Hydropower Generation (GWh) in 2015	Consumption of Hydroelectricity (GWh) in 2015, BP (2016)
Peru	4 190	-	4 190	26 060	23 301
Philippines	4 235	685	3 550	9 951	9 824
Poland	2 351	1 782	569	2 361	1 832
Portugal	5 902	1 343	4 559	9 784	8 654
Puerto Rico	100	-	100	96	-
Reunion	121	-	121	498	-
Romania	6 705	92	6 613	14 482	16 322
Russian Federation	50 624	1 360	49 264	160 171	169 941
Rwanda	99	-	99	182	-
Samoa	12	-	12	54	-
Saint Vincent and the Grenadines	7	-	7	26	-
Sao Tome and Principe	4	-	4	7	-
Serbia	2 835	614	2 221	11 500	-
Sierra Leone	54	-	54	114	-
Slovakia	2 522	916	1 606	3 792	4 067
Slovenia	1 479	180	1 299	4 106	

WORLD ENERGY COUNCIL | WORLD ENERGY RESOURCES 2016

Country	Total Hydropower Capacity (MW) in 2015	Pumped Storage Capacity (MW) in 2015	Excluding Pumped Storage (MW) in 2015	Estimated Net Hydropower Generation (GWh) in 2015	Consumption of Hydroelectricity (GWh) in 2015, BP (2016)
South Africa	2 251	1 580	671	1,058	952
South Korea	6 447	4 700	1 747	5 855	3 004
Sri Lanka	1 624	-	1 624	5 121	-
Spain	18 561	5 268	13 293	32 010	27 786
Sudan	2 250	-	2 250	6 307	-
Suriname	189	-	189	728	-
Sweden	16 184	99	16 320	73 927	74 529
Swaziland	60	-	60	268	-
Switzerland	15 635	1 817	13 818	39 000	37 589
Syria	1 505	-	1 505	2 769	-
Tajikistan	5 190	-	5 190	17 731	-
Tanzania	562	-	562	2 560	-
Thailand	4 510	1 000	3 510	11 684	3 761
Togo	65	-	65	97	-
Tunisia	66	-	66	52	-
Turkey	25 886	-	25 886	66 900	66 903
Turkmenistan	1	-	1	3	-

WORLD ENERGY COUNCIL | HYDROPOWER

Country	Total Hydropower Capacity (MW) in 2015	Pumped Storage Capacity (MW) in 2015	Excluding Pumped Storage (MW) in 2015	Estimated Net Hydropower Generation (GWh) in 2015	Consumption of Hydroelectricity (GWh) in 2015, BP (2016)
Uganda	706	-	706	1 484	-
Ukraine	6 785	1 315	5 470	11 021	6 294
United Kingdom (UK)	4 443	2 744	1 699	8 648	6 320
United States of America (USA)	101 755	22 441	79 314	250 148	253 705
Uruguay	1 538	-	1 538	8 266	-
Uzbekistan	1 731	-	1 731	10 311	10 833
Venezuela	15 393	-	15 393	79 557	76 345
Vietnam	15 211	-	15 211	62 627	63 821
Zambia	2 272	-	2 272	13 931	-
Zimbabwe	765	-	0 765	5 495	-
World Total	1 212 300	144 500	1 067 900	3 969 115	3 946 250

Source: International Hydropower Association IHA (2016) and BP Statistical Review of World Energy 2016 Workbook

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REFERENCES

- Abbas, A. (2015) 'Egypt, Ethiopia and Sudan sign agreement on GERD', in *Daily News Egypt*, December 29.
- African Development Bank Group (2013) *AfDB commits to US \$113 million to Regional Rusumo Falls Hydropower Project*.
- Aljazeera America (2015) *Egypt, Ethiopia and Sudan sign Nile dam accord*, March 23, <http://america.aljazeera.com/articles/2015/3/23/Egypt-Ethiopia-Sudan-sign-Nile-dam-accord.html>
- Bakken, T.H., Modahl, I.S., Raadal, H.L., Bustos, A.A. and Arnøy, S. (2016) 'Allocation recommendations for multipurpose reservoirs – results for water consumption', *Water Policy*. doi:10.2166/wp.2016.009.
- Bakken, T.H., Modahl, I.S., Engeland, K., Raadal, H.L. and Arnøy, S. (2015) 'The life-cycle water footprint of two hydropower projects in Norway', *Journal of Cleaner Production*. <http://dx.doi.org/10.1016/j.jclepro.2015.12.036>.
- British Chamber of Commerce in China (2011) *China's Twelfth Five-Year Plan (2011-2015)*.
- China Three Gorges Corporation (2015) *The yearly electricity production of the Three Gorges Hydropower Station was over 98.8 TWh which hit a world record*.
- Germany Energy Act (Energiewirtschaftsgesetz) (2014) Section 118.
- Hydro-Quebec (2014) 'Studying net evaporation from the Eastmain-1 Reservoir', *Hydro Review*.
- Hydropower Sustainability Assessment Protocol (2016) *Hydropower Sustainability Assessment Protocol*, <http://www.hydrosustainability.org/Protocol.aspx>
- Independent Chemical Information Service (2014) *Georgian electricity exports to Turkey to fall in August – TEIAS*, July 21.
- Intergovernmental Panel on Climate Change (2012) *Managing the risks of extreme events and disasters to advance climate change adaptation*.
- Intergovernmental Panel on Climate Change (2011) *Special report on renewable energy sources and climate change mitigation, Chapter 5 – Hydropower*.
- International Energy Agency (2014) *World Energy Outlook Special Report – Africa Energy Outlook: Focus on energy prospects in Sub-Saharan Africa*.
- International Energy Agency (2014) *Technology Roadmap – Energy Storage*.
- International Energy Agency (2012) *Technology Roadmap – Hydropower*.
- International Hydropower Association (2016) *Cross-border projects*.
- International Hydropower Association (2015) *Endesa Chile*.
- International Hydropower Association, *Greenhouse gas emissions*.

- International Hydropower Association (2016) *Hydropower Status Report*, https://www.hydropower.org/sites/default/files/publications-docs/2016%20Hydropower%20Status%20Report_1.pdf
- International Hydropower Association (2015) *Hydropower Status Report*.
- International Hydropower Association (2015) *Study: The hydropower sector's contribution to a sustainable and prosperous Europe*.
- International Renewable Energy Agency (2014) *Renewable power generation costs in 2014*.
- International Rivers, *Environmental impacts of dams*.
- Namgis First Nation (2014) *Kokish Run of River Power Project*, Brookfield Renewable Energy Partners, Kokish Hydro Facility, <http://www.namgis.bc.ca/Kokish/Pages/default.aspx>
- Renewable Energy Policy Network in the 21st Century (2016) *Renewables – Global status Report*.
- Sandia National Laboratories – U.S. Department of Energy *Global Energy Storage Database*.
- Tavdumadze, L. (2013) 'Georgian Hydropower turns river flow into cash flow', in *Hydro World*, January 2.
- The Water Resources Group (2012) *Background, impact and the way forward*.
- United Nations Educational, Scientific and Cultural Organisation and International Hydropower Association (2009) *The UNESCO/IHA measurement specification guidance for evaluating the GHG Status of man-made freshwater reservoirs*.
- United Nations Sustainable Energy 4 All, *Global tracking Framework 2013*.
- World Energy Council (2011) *Global transport scenarios 2050*.
- World Health Organisation and United Nations Children's Emergency Fund (2014) *Progress on drinking water and sanitation 2014 update*.
- Zarfl *et al.* (2014) 'A global boom in hydropower dam construction', in *Aquatic Sciences*. DOI: 10.1007/s00027-014-0377-0

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KEY FINDINGS

1. Bioenergy is a versatile energy source. In contrast to other energy sources, biomass can be converted into solid, liquid and gaseous fuels.
2. Bioenergy is the largest renewable energy source – 14% out of 18% renewables in the energy mix.
3. Bioenergy supplies 10% of global energy supply.
4. Bioenergy is shifting from a traditional and indigenous energy source to a modern and globally traded commodity.
5. The consumption pattern varies geographically:
 - Biofuels in Americas
 - Fuel wood and charcoal in Asia and Africa
 - Combined heat and power generation in Europe
6. Bioenergy can be the result of activities with varying levels of environmental impact, ranging from the smaller-scale gathering of wild plants or deadwood right up to large-scale bio-crop farms.
7. Countries with high share of renewables also have a high share of bioenergy in their energy mix.
8. Climate change and energy independency are major drivers for bioenergy development.
9. Bioenergy employs thousands of people globally along the complete value chain.
10. Biofuels are the most viable and sustainable option in replacing oil dependency.
11. International trade is driven by pellets (27 million tonnes in 2015) and liquid biofuels.
12. The future will be led by the need for renewables in transport followed by heating and electricity sectors.

INTRODUCTION

Bioenergy is energy from organic matter (biomass), i.e. all materials of biological origin that is not embedded in geological formations (fossilised). Biomass can be used in its original form as fuel, or be refined to different kinds of solid, gaseous or liquid biofuels. These fuels can be used in all sectors of society, for production of electricity, for transport, for heating and cooling, and for industrial processes.

The World Energy Council defines bioenergy to include traditional biomass (example forestry and agricultural residues), modern biomass and biofuels. It represents the transformation of organic matter into a source of energy, whether it is collected from natural surroundings or specifically grown for the purpose.

In developed countries, bioenergy is promoted as an alternative or more sustainable source for hydrocarbons, especially for transportation fuels, like bioethanol and biodiesel, the use of wood in combined heat and power generation and residential heating. In developing countries bioenergy may represent opportunities for domestic industrial development and economic growth. In least developed countries traditional biomass is often the dominant domestic fuel, especially in more rural areas without access to electricity or other energy sources. There are multiple challenges and opportunities for bioenergy as a potential driver of sustainable development, given enough economic and technological support.

Bioenergy comprises a uniquely local set of resources and its use varies from region to region and from country to country. However, in the past couple of years, the increasing trade of biomass in the form of pellets and liquid biofuels for transport has made bioenergy a global energy commodity.

While the use of biomass for energy in the overwhelming majority of cases is carried out sustainably, some concern has arisen regarding risks for overexploitation and other possible negative effects. Therefore, to safeguard the environment, and to meet desired social and economic criteria; sustainability standards have been put in place for bioenergy including ENplus, RSB, WBA, GBEP and ISO. It is important to develop internationally agreed upon standards incorporating all the available schemes. The standards should also be correlated with the UN Sustainable Development Goals. Updated data on bioenergy is crucial.

This chapter includes a high-level global and regional overview pertaining to bioenergy's role in the energy matrix, its production and consumption. It also offers a review of commercially available technologies and notes likely new developments. A brief analysis of bioenergy markets is included and an assessment of issues related to the environmental impact of bioenergy in its various forms. This chapter also focuses on the interaction of the bioenergy industry and bioenergy as an energy source with wider political and economic factors. Specifically, it will elaborate on the land-use and water-use implications of

bioenergy's current usage along with climate benefits of bioenergy. Case studies from different parts of the world will be highlighted.

The supply of biomass can be classified into three sections – forestry, agriculture and waste. Since the 2013 edition of the World Energy Resource report, Waste-to-Energy is a separate resource chapter. Although globally, some of the waste is mixed with materials of fossil origin, like fossil-based plastics, most waste consists of a large share of biogenic material (paper, wood, biogenic textiles, rubber, bio plastics, etc.), and there are large streams of waste and residues from agriculture, forestry, fishing, the food chain, and all connected industries. In most countries, the first step in developing a modern bioenergy sector is to better utilise these resources from wastes and residues. Further discussion is available in the Waste to Energy chapter.

BIOENERGY SUPPLY

Forest

Around the world, woody biomass is used for cooking, production of electricity and heat for industries, towns and cities and production of liquid biofuels. The primary energy supply of forest biomass used worldwide is estimated at about 56 EJ, which means woody biomass is the source of over 10% of all energy supplied annually. Overall woody biomass provides about 90% of the primary energy annually sourced from all forms of biomass (Figure 1).

Woody biomass used is in the form of cut branches and twigs, wood chip and bark, and pellets made from sawdust and other residues. Some of it is wood from demolition and construction, from urban parks and gardens and from industrial wood waste streams (broken pallets, building form work and industry packing crates). Wood is also the source of more than 52 million tonnes of charcoal used in cooking in many countries, and for smelting of iron and other metal ores.

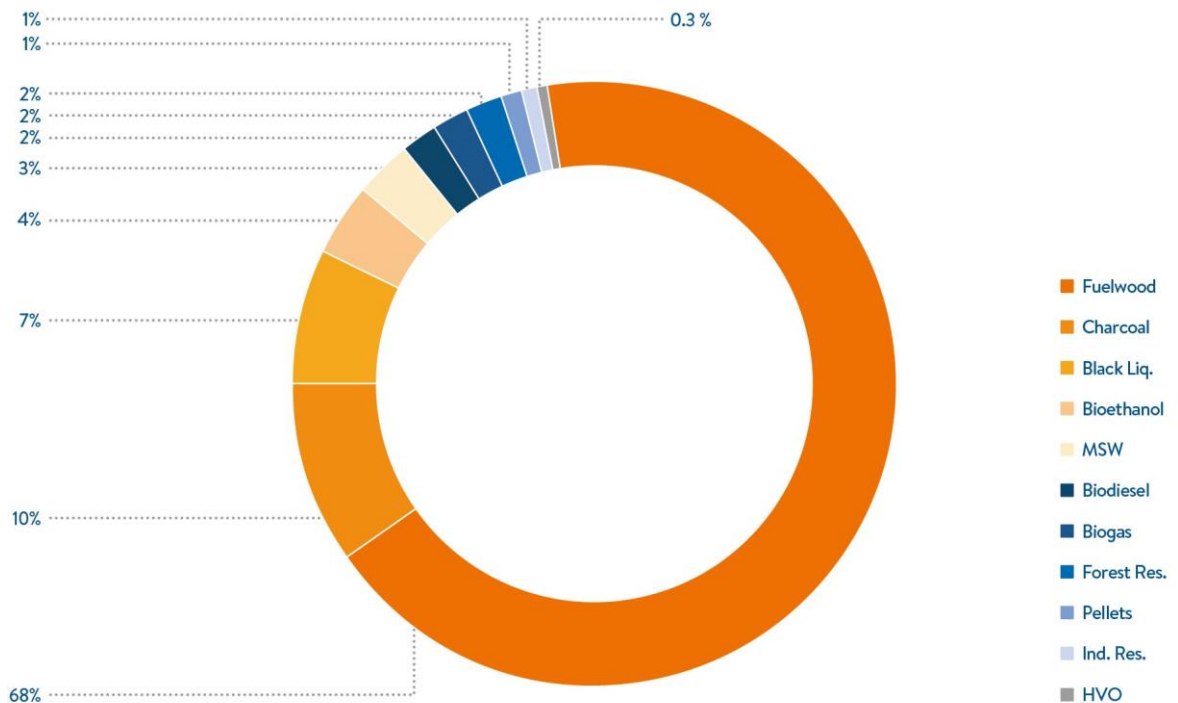
While this utilisation of woody biomass has real scope to increase and to become much more efficient, there is understandable concern about the sustainability of this renewable energy source globally. However, many initiatives are in place and being developed to ensure that at least, the woody biomass that is traded internationally (in the form of woodchip, pellets, charcoal, pyrolysis oil, and other semi-processed forms) is certified by one or other recognised programs as being sustainably sourced.

Production of woody biomass on agricultural land does not automatically displace the amount of food or fibre produced per unit area, as there are many alternative ways to have production of both biomass and other outputs from the same land. It is common practice in many countries to establish dispersed multi-purpose plantings on farmed land that shelter livestock, crops and pastures, while sequestering carbon, reducing wind erosion and drying of surface moisture, and adding to habitat and wildlife linkages. These properly planned plantings of suitable species produce yet more biomass in a sustainable way, as well as round wood for sawmills and other end uses such as for pulp and paper, or for fencing.

It is hard to conceive of a more sustainable practice that produces more side benefits, than agroforestry. The world's forests have been over-cleared (100 million hectares in Australia alone), and worldwide hundreds of millions of hectares of this farm land could be planted back to indigenous biodiverse species using a multi-purpose shelterbelt model, without loss of food and fibre production.

In some countries, including Brazil, USA, Turkey, New Zealand, China, Australia, South Africa, and elsewhere, the replanting is often done across entire landscape. While the suitability of species chosen and sustainability of some of these plantings can be questioned, this is not a new practice, and similar plantings or reversion of cleared land to forest has occurred in the past in southeast Sweden, the north-eastern states of the USA, and elsewhere. In general, the long-term outcomes of these earlier reforestation programs have been good, despite the loss of production from those farms. So, land use changes need to be assessed using a short list of rational criteria to weigh up the benefits and costs.

FIGURE 1: PRIMARY ENERGY SUPPLY OF BIOMASS RESOURCES GLOBALLY IN 2013 (WBA GLOBAL BIOENERGY STATISTICS 2016)



Source: Based on data from World Bioenergy Association (2016)

Agriculture

While it has been suggested that biomass produced on land inevitably displaces the growing of food, this is rarely the case in practice. On the contrary, biomass almost always is a by-product, waste product or residue produced during the production of food, fibre or timber products. One of the few exceptions could be with some first generation biofuels, such as ethanol from wheat, corn or sugar beet; although, even in these cases the biofuel is made from a component that is a small fraction of the feedstock, and so is only one of several products made from that feedstock. Nowadays, 2nd generation ethanol using lignocellulosic feedstock is being produced on an industrial scale in USA, Brazil and Italy etc.

Straw is one example of biomass that is a residue from food production. Straw is produced during production of annual cereals and usually at a ratio of about 0.6-0.8 tonnes of straw per tonne of grain yield. In countries where yields are high (of the order of 8-10 tonnes of grain per hectare), the amount of straw per hectare might be six to eight tonnes and most of this has to be removed to allow cultivation for the following year's crop. As an example, of Denmark's straw production of about six million tonnes a year, over one million tonnes is used to fuel district heating or combined heat and power plants, another million tonnes is used for animal bedding or other on-farm uses (including for heat production), about two million tonnes finds other commercial uses including to be pelleted, converted to ethanol or used in mushroom production. The balance of about two million tonnes is incorporated back into the soil (along with millions of tonnes of the cereal roots), where it is rapidly broken down into greenhouse gases by bacteria and fungi which is then converted to bioenergy.

Around the world, billions of tonnes of straw (and similar plant material including stalk, seed husks and foliage) are annually available but the utilisation is very low. Less than 100 million tonnes is utilised for energy each year and the rest is generally free-burned or allowed to rot, with consequent release of greenhouse gases. This applies whether the crop is rice in Asia, sugar cane in Brazil, wheat in Australia, soybean in Argentina, cotton in Egypt or palm oil in Indonesia. This also applies to the vast amount of higher moisture-content biomass around the world, such as manures, abattoir wastes, and green leafy material.

All production of food, fibre or wood products results in production of biomass, with the amount of this often as much or more than the dry weight of the product. This biomass can be efficiently converted into energy, including on-demand electricity, by mature technologies. While at present final energy from biomass is about 50 EJ of energy or 14% of the world's final energy use, the realistic potential for final energy from biomass worldwide could as much as 150 EJ by 2035¹. According to IRENA, about 38 – 45% of total supply is estimated to originate from agricultural residues and waste while the remaining

¹ IRENA (2014) REmap 2030 Global Bioenergy Supply and Demand Projections

supply is shared between energy crops and forestry products and residues. According to WBA, the estimated potential of using agricultural residues for energy ranges from 17 EJ to 128 EJ. This high range of values is due to the dependence on various factors including moisture content, energy content of the residues etc. The highest potential for using agricultural residues is in Asia and Americas due to the high production of rice and maize respectively.

BIOENERGY CONSUMPTION

Bioenergy is a versatile energy source. In contrast to other energy sources, biomass can be converted into solid, liquid and gaseous fuels. Moreover, bioenergy can be used for heating homes, electrifying communities and fuelling the transport sector. Globally, bioenergy (including waste) accounted for 14% of the world's energy consumption in 2012² with roughly 2.6 billion people dependent on traditional biomass for energy needs³. The consumption pattern of bioenergy varies geographically.

USA and Brazil lead the world in production and consumption of liquid biofuels for transport (accounting for almost 80% of production). In the transport sector, the production of corn ethanol in USA and sugarcane ethanol in Brazil has increased significantly. The production of all biofuels in the Americas increased from about 16 billion litres in 2000 to 79 billion litres in 2012⁴. A significant sector for future use of biofuels is the aviation sector. Liquid biofuels are the only sustainable and viable option for replacing aviation fuel and efforts are underway where airlines, airports, finance institutions, and universities are coming together to explore sustainable aviation pathways. Commercial airlines using biofuels have already flown transatlantic routes. Other important sectors include heavy road and maritime where biofuels can play a big role.

The use of biomass for electricity is prominent in Europe and North America – predominantly produced from forestry products and residues. Cogeneration plants enable the use of biomass with increased efficiency, so much so that the combined efficiency of producing heat and electricity crosses 80%. The Europe and Americas continent contribute more than 70% of all consumption of biomass for electricity. In 2013, 462 TWh of electricity was produced globally from biomass⁵. In the past few years, biomass is seeing increasing uptake in developing countries in Asia and Africa where significant population lacks access to electricity. Biogas and decentralised bioenergy systems are becoming more cost competitive. Already cogeneration plants using agricultural residues like Bagasse in India, Mauritius, Kenya and Ethiopia are successful.

² WBA (2014) Global Bioenergy Statistics

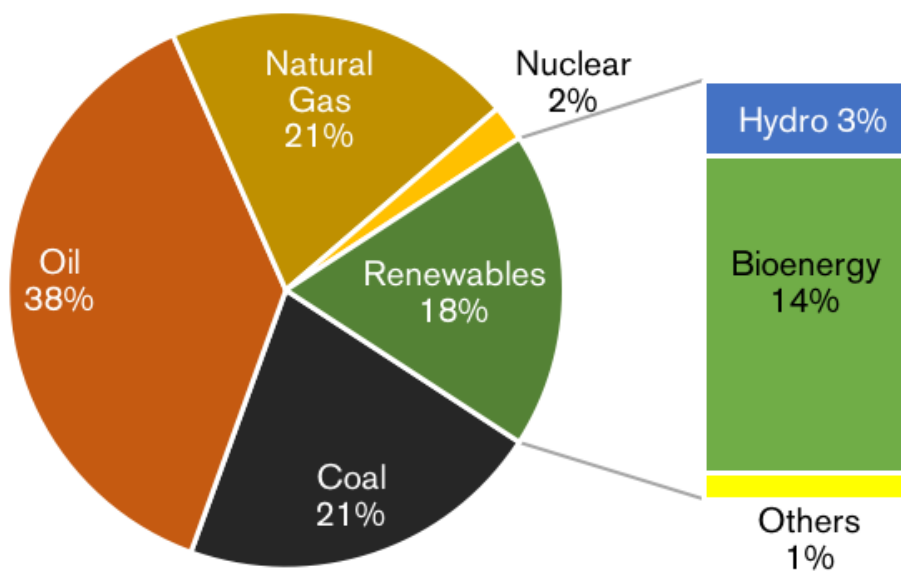
³ IEA Database worldenergyoutlook.org/resources/energydevelopment/energyaccessdatabase/

⁴ WBA (2014) Global Bioenergy Statistics

⁵ Ibid 4

Since time immemorial, biomass has been the major energy source for heating. Currently, the major use of biomass is in the form of heat in rural and developing countries. About 90% of all the bioenergy consumption is in the traditional use. It includes the use of fuelwood, charcoal, agricultural residues etc. for cooking and heating. This will soon change as rapid urbanisation, inefficient use of biomass leading to deforestation, climate goals and increasing energy demand will lead to a shift towards improved conversion efficiencies and modern bioenergy sources like biogas, pellets, liquid biofuels etc.

FIGURE 2: GLOBAL FINAL ENERGY CONSUMPTION IN 2013 (WBA GLOBAL BIOENERGY STATISTICS 2016)

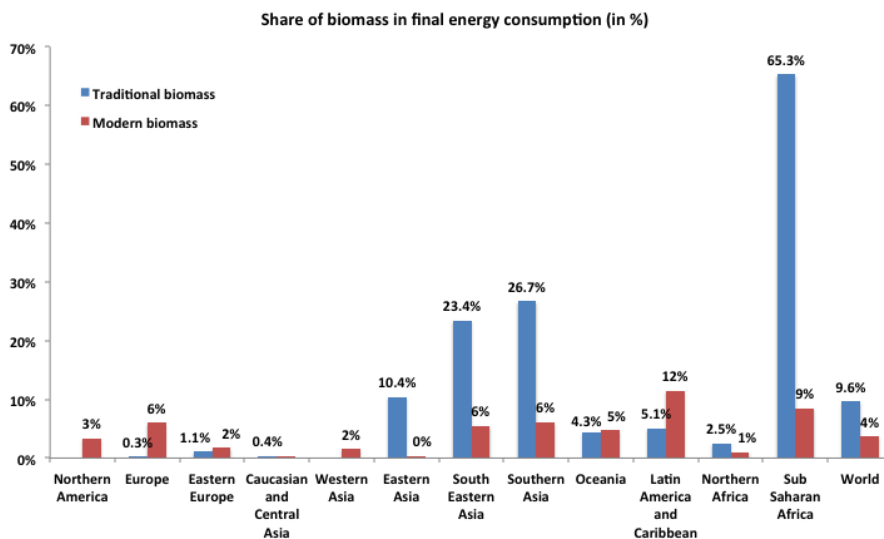


Source: Based on data from World Bioenergy Association (2016)

1. TECHNOLOGIES

For the purpose of this report, bioenergy is divided into three broad categories: solid biomass (e.g. wood, harvesting residues), liquid biofuels (e.g. bioethanol, biodiesel) and gaseous biofuels (e.g. biogas). Further classification of biomass sources is divided into traditional and modern. The line between “traditional bioenergy” and “modern bioenergy” is not so well defined. In many developed countries, firewood and other small-scale use of bioenergy (in a sense, traditional) is still a relatively large energy source for heating and cooking. This is not only a use in “more isolated and rural areas”. The technology is well developed with high efficiency and low emissions. A modern wood boiler is as good as a modern pellet boiler.

FIGURE 3: SHARE OF BIOMASS IN FINAL ENERGY CONSUMPTION IN 2010 (IN %) (WBA GLOBAL BIOENERGY STATISTICS 2015)



Source: World Bioenergy Association (2016)

TRADITIONAL BIOMASS

Organic matter such as wood or charcoal has been used as fuel for fires, cooking and industry, which dates back to the early history of human civilisation. In more isolated or rural areas with no energy access, it remains a key source of domestic primary energy despite the health and environmental problems associated with its inefficient burning. The scale of its

use is impractical to measure to any degree of accuracy, however according to the 2010 Water for Energy report: “a general rule of thumb has been that an additional 10% can be added to global energy consumption for traditional biomass”⁶. According to International Energy Agency, 10% of global energy consumption is due to the use of traditional biomass for heating and cooking.

Some of the problematic aspects associated with the use of traditional biomass in inefficient equipment includes health related issues (inhalation of smoke), pollution, deforestation and safety. Replacing biomass use in traditional conversion devices with more technologically advanced solutions such as advanced biomass stoves, will result in improved efficiency (using less fuel and better ventilation) and stoves that use cleaner fuels such as biogas or electricity, will reduce local emissions, especially particulate emissions⁷.

Larger scale use of traditional biomass, such as small-scale industry, would also benefit from more modern biomass technology to improve energy efficiency and reduce or mitigate harmful emissions. However, for many people across the world, traditional biomass remains the only viable energy option as it tends to be readily available, free, simple and easy to use.

MODERN BIOMASS – BIOMASS TO ELECTRICITY AND HEAT

Biomass using modern technology differs from traditional biomass in two key characteristics; firstly that the source of organic matter should be sustainable and secondly, that the technology used to obtain the energy, should limit or mitigate emissions of flue gases and account for ash residue management. Also, the efficiency of conversion is higher leading to less use of fuel. Modern biomass is largely used in some regions, notably in northern Europe and parts of North America. In Finland, about 60% of bioenergy is produced in forest industry using black liquor, bark, sawdust, and other industrial wood residues. In Sweden, about 40% of bioenergy use is in the forest industry, using residues such as bark, chips, black liquor and tall oil. A similar development occurred in the ethanol and sugar industry where bagasse and straw are used for the processes and power production.

Modern biomass technologies include liquid biofuels used to power automobiles and to produce heat in boilers, industrial and residential cogeneration and bio-refineries used in generating electricity, liquid biofuels and pellet heating systems. Combined heat and power (CHP) or cogeneration means the simultaneous production and utilisation of heat and/or steam and electricity. CHP, particularly together with district heating and cooling (DHC), is an important part of greenhouse gas (GHG) emission reduction strategies, due to higher efficiency and a reduced need for fuels in comparison to stand-alone systems. Electricity production can be fuelled by solid, liquid or gaseous biofuels, with the biggest fraction of biopower today being produced using solid biofuel.

⁶ World Energy Council (2010) Water for Energy report – p18

⁷ Global Alliance for Clean Cookstoves: <http://TOE.cleancookstoves.org/our-work/the-solutions/cookstove-technology.html>

Thermochemical Biomass Gasification is a high temperature process that produces a fuel gas, which after cleaning, can provide a good environmental performance and high flexibility in applications. The process is used to convert biomass (solid biomass, wastes) into a combustible gas that can be used for different purposes. Typical feedstock for gasification is cellulosic biomass such as wood chips, pellets or wood powder, or agricultural by-products like straw or husks.

Pellets are another form of modern bioenergy source. Pellet is a term used for a small particle of cylindrical form produced by compressing an original material. At present, pellets are mainly produced from wood residues, though the volume of pellets produced from agricultural by-products such as straw, husks of sunflower seeds and stalks and corn leaves etc. are increasing. A key advantage of pellets compared to unprocessed biomass is the high density and high energy content per unit volume, which is convenient for long distance transportation. The largest pellet mills are located in 21 countries, where the majority are found in North America and Europe. The combined yearly capacity of the mills when plants under construction or planned are considered is likely to be above 42 million tonnes⁸. The current production (in 2014) was 27 million tonnes and North America and Europe accounted for 97% of all the production volumes. In these regions, bioenergy is often also integrated with the pulp and paper industries. For example, wood pellets are used in residential heating (particularly in Italy, Germany and Austria), district heating (e.g. Sweden, Denmark and Finland) and large scale power generation (e.g. Belgium, the Netherlands and the UK)⁹.

Examples of other modern biomass plants include biomass crops, trees or other fast growing energy plants and forest residue matter gathered in a sustainable manner (See Box: Belize's Bagasse Power Plant case study). In some regions biomass plants commonly have combined heat and power technology to increase the total energy efficiency of energy production and to make productive use of both the electricity generated by the biomass combustion process and the waste heat, which would otherwise be emitted.

The use of heat in such a plant requires either a local customer, for example an industrial plant requiring substantial volumes of heat or steam or a district heating network to take the water to a residential user to be used in space heating and heating of domestic hot water.

⁸ IEA (2013) Large Industrial Users of Energy Biomass.

⁹ World Energy Council (2013) World Energy Resources 2013 report, p. 7.18

BELIZE'S BAGASSE POWER PLANT

The construction on the 31.5 MW Belcogen cogeneration or CHP (combined heat and power) plant was completed in 2009 by a subsidiary of Belize Sugar Industries Limited (BSI) in Belize, Central America. The feedstock used is bagasse which is a fibrous material obtained after the juice from sugarcane has been extracted.

The plant uses a complete combustion process, electrostatic air cleaners, and high operating standards in order to limit the amount of pollutants. An advantage to the local economy is in the creation of new jobs in construction and operations and also encouraging the agricultural sector. This project's success was because of the collaboration from stakeholders. An initial investment of US\$27.8 million was provided by BSI and US\$35.3 million was secured from international loans from various sources including the Caribbean Development Bank.

Source: Arthur Goodland, "A New Push for Renewable Energy in Belize," ReVolt (Worldwatch Institute blog), <http://blogs.worldwatch.org/revolt/a-new-push-for-renewable-energy-in-belize/>

Dolezal, A. et al, (2013), The way forward for renewable energy in Central America.

Biomass co firing

The goal of CO₂ emissions reductions and the subsequent renewable energy incentives have led some power plant operators to broaden their fuel palette to include various carbon-neutral biomass fuels. Co-firing of fossil fuels and various types of biomass is a mature technology and is currently being successfully practiced globally. With technological advances, many limitations associated with it have been overcome. Many coal-fired plants have been converted or retrofitted to accommodate co-firing with limited impact on efficiency, operations or lifespan. However, there is much more to co-firing than simply adding a secondary fuel. Boiler technology and design remain critical issues when evaluating the maximum share of biomass that can be used without compromising boiler performance (output, efficiency, and power-to-heat ratio) or the lifetime of the boiler components.

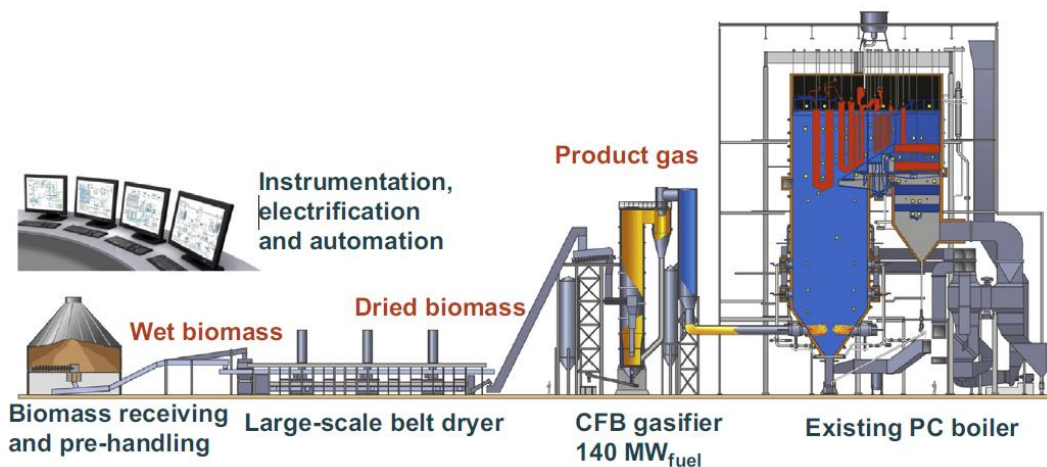
Various technologies have been developed to enable co-firing biomass with coal in pulverized coal (PC) boilers. The vast capacity of existing PC boilers offers great potential for increasing biomass utilization and economic benefits compared to new stand-alone biomass power plants, which also are usually significantly smaller than PC plants. Utilising biomass in an existing thermal power plant can be accomplished through direct or indirect co-firing.

Direct co-firing is the most straightforward, most commonly applied and lowest-cost concept for partially replacing coal or other solid fossil fuels with biomass. In direct co-firing, biomass

and coal are burned together in the same furnace using the same or separate fuel handling and feeding equipment, depending on the biomass, targeted biomass share and site-specific characteristics. The share of biomass that can be successfully employed in direct co-firing is modest and the type of biomass is limited mostly to pellet-type fuels. With torrefied biomass, however, higher shares are expected, up to tens of percentages. Three different main configurations can be distinguished for direct co-firing: the first option is to mix the biomass and coal and co-mill them in the same mill. With typical fuels this is restricted to fairly low co-firing shares of typically 5–10% and specific biomass types. In the second option, the biomass is pulverised in dedicated mills and is injected in the coal powder stream somewhere between coal mills and burners. This enables higher co-firing shares and wider selection of acceptable fuels but necessitates investments. In the third option, dedicated burners for biomass are also installed allowing burners to be optimised for both fuels independently but increasing the investment costs further.

Indirect co-firing consists of converting the solid biomass to a gas or liquid prior to combustion in the same furnace with the other fuel. This allows for greater amounts of biomass to be used, up to 50%. However, this approach requires greater investment and a larger footprint at the plant site. An example of this kind-of-system is presented in Figure 4.

FIGURE 4: VASKILUOTO 560 MW_{TH} PC BOILER EQUIPPED WITH A 140 MW_{FUEL} CFB GASIFIER

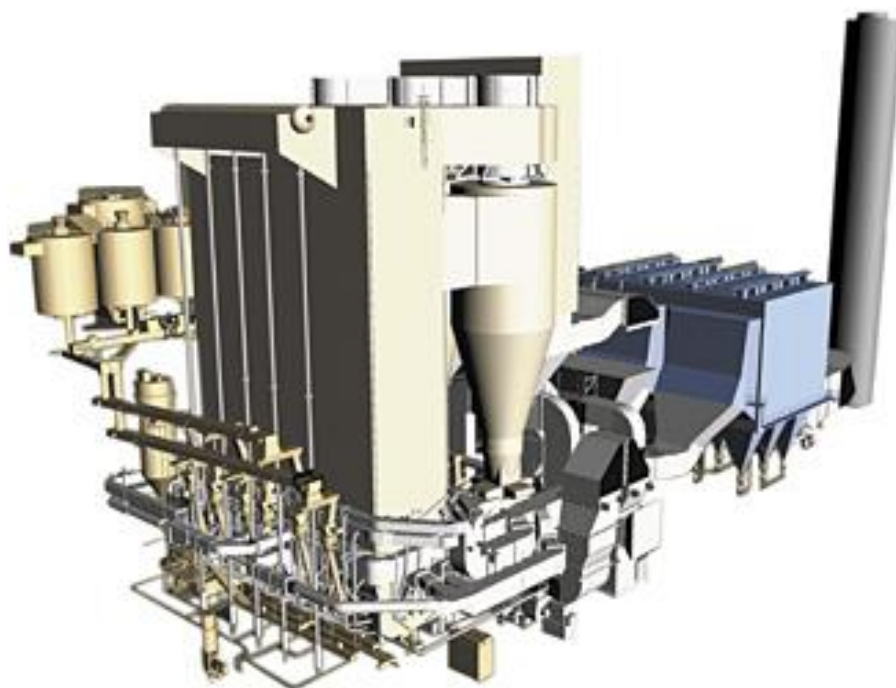


Source: Valmet Power

In general, fluidised bed boilers offer the best fuel flexibility. If properly designed, biomass fuels can be used with coal in any percentage from 0–100% in circulating fluidised bed (CFB) boilers. The variety of biomass fuel options is increasingly diverse, although the availability of some biomass fuels can be limited. Power plants with high fuel flexibility can

adapt to the prevailing fuel market by optimising the fuel mix accordingly. An example of this plant type is presented in Figure 5.

FIGURE 5: ALHOLMENS KRAFT CHP PLANT IN FINLAND IS ONE OF THE LARGEST BIOMASS FIRED PLANTS IN THE WORLD



Note: The design by Valmet Power Oy allows great fuel flexibility; the boiler will be able to burn all mixtures of wood and coal from 100% wood to 100% coal. Thermal output is 550 MW_{th} with steam parameters: 194 kg/s, 165 bar and 545 °C.

Source: Alholmenskraft

One possibility to utilise biomass in existing PC boilers is to convert them into bubbling fluidised bed (BFB) boilers. These retrofits are routine for the major fluidised bed boiler technology suppliers, and numerous such conversions have been conducted, especially in Europe. For example, at least eight conversions to enable pure biomass combustion have been carried out in Poland since 2008, with capacities in the 100–200 MW_{th} range.

The costs associated with biomass co-firing are mainly due to the higher prices of biomass fuel in comparison to coal, higher plant investment, and higher O&M costs. The use of biomass increases O&M costs of the co-firing retrofit plant through negative effects on the availability of the boiler (i.e. boiler-related issues cause increased plant down time) and increased maintenance work and consumables. When considering a retrofit option for biomass, the feasibility of the investment and the willingness to invest are affected also by the remaining lifetime of the plant and the annual operating hours.

LIQUID BIOFUELS

The conversion of bioenergy crops such as corn and sugar cane, into biofuels, synthetic equivalents for oil products such as gasoline or diesel, has a long-established history. Production of ethanol from crops dates back as far as the development of the automotive industry and was in use as a mix additive to oil derived fuels, until the low price of gasoline led it to dominate after the Second World War¹⁰. Biofuels returned to commercial-scale use in the 1970s, triggered by the oil crises of the decade when Brazil took the lead in the production of ethanol from sugar cane.

Liquid biofuels for transport are part of important strategies to improve fuel security, mitigate climate change and support rural development. Conventional biofuels (also referred to as first generation biofuels usually include ethanol from corn, sugarcane etc. and biodiesel from canola, jatropha etc.) are being produced globally with a current production volume of more than 100 billion litres annually. To complement the conventional biofuels, recent advances are focused on the next generation of biofuels. Advanced biofuels, generally referred to as second or third generation biofuels are produced from a broad spectrum of predominantly non-edible biomass feedstock. Some of these are “drop-in” biofuels that can be applied in existing distribution infrastructure and engine platforms. By-products of advanced biofuel production include bioelectricity, bio heat, bio-chemicals and protein based feed. However, some bioenergy experts are sceptical to use the term as many of the first generation plants are very advanced and have very good carbon footprint.

Apart from the technologies of fermentation (ethanol) and esterification (biodiesel), there are various alternative pathways. For example, in biomass gasification, biomass is converted into a combustible gas. The gas can be used, after upgrading, as a transportation fuel or can be further processed into liquid biofuels. Pyrolysis is another technique where oxygen starved environment leads to the conversion of biomass into bio char, bio liquids and non-condensable gases. The bio liquids can then be refined to be used as transportation fuels, heating fuels, or for production of chemicals. Finally, algal biofuels (otherwise called as third generation biofuels) are being explored as a sustainable alternative to fossil fuels. Algae are an alternative feedstock that uses sunlight, carbon dioxide, nutrients and water to produce oils that can be used as feedstock for biofuel production. However, the technology is not yet cost competitive and production is energy intensive.

In the Latin American region, local climate and economic drivers dictate feedstock for bioenergy production. Sugarcane is the dominant crop for ethanol production, particularly in Brazil, Mexico and Colombia (82%, 7% and 4% of regional production respectively in 2013¹¹). Palm oil has a developing role for the production of biodiesel and is grown mainly in Colombia, Brazil and Ecuador (51%, 18% and 18% of regional production respectively in 2013).

¹⁰Antoni, Zverlov & Schwarz (2007) Biofuels for microbes.

¹¹ FAOStat database: <http://faostat.fao.org/site/567/DesktopDefault.aspx?PageID=567#ancor>

More recently in the 2000s, there was a surge in production of liquid biofuels in the Americas and in Europe. This was a result of security of supply concerns over oil supplies overseas that led governments to enact policies favouring the expansion of biofuel use. In the European Union, the directive 2009/28/EC mandates for all member states that the share of transport fuels from biofuels or other sustainable sources be increased to 10% minimum by 2020. However, Finland made a national decision to set the renewable target for transport by 2020 to 20% as a part of its National Renewable Energy Action Plan. The EU directives include a stipulation that such biofuels should be from sustainable sources without “negative impact on biodiversity and land use”¹² and therefore the EU has set a limit for the first generation biofuels, which could be used to reach the 10% target. In addition, to support the market penetration of second generation biofuels, they are so-called double counted in the national targets. This has led to uncertainty in investments in the biofuels sector in EU.

Similarly, in the USA, the Renewable Fuel Standard (P.L. 109-58 §1501) mandates a nine-fold increase of biofuels production from 15 billion litres in 2006 to 136 billion litres in 2020¹³. In total, 32 countries are listed as having a mandatory biofuels blend either nationally or regionally in a recent REN21 report¹⁴.

¹² 2009/28/EC http://ec.europa.eu/energy/renewables/biofuels/biofuels_en.htm

¹³ Yacobi, Congressional Research Service (2012) Biofuels Incentives: A Summary of Federal Programs

¹⁴ REN21 (2015) Global Status Report, p156

TABLE 1: TEN COUNTRIES FOR ETHANOL AND BIODIESEL MANDATORY MIX

Country	Ethanol blend percentage	Biodiesel blend percentage
Paraguay	25%	1%
Brazil	27.5%	7%
United states	National: The Renewable Fuels Standard 2 (RFS2) requires 136 billion litres of renewable fuel to be blended yearly with transport fuel by 2022.	
Philippines	10%	5%
Costa Rica	7%	20%
Argentina	10%	10%
India	5%	-
Jamaica	10%	-
Canada	National: 5%	National:2%
China	10% (in nine provinces)	-
EU	10% (food crop biofuels limited to 7%)	

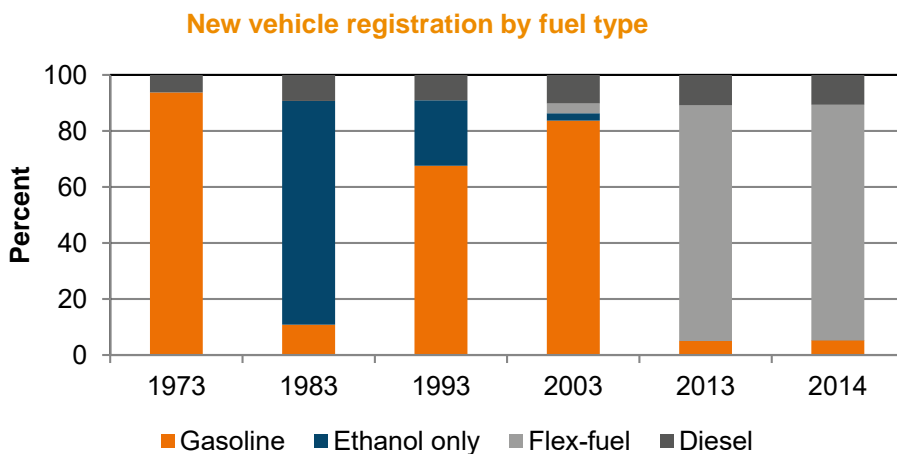
Source: REN21¹⁵¹⁵ REN21 (2015) Global Status Report, p156

Table 1 I lists some countries for current mandatory biofuel blends, where ethanol or biodiesel, as appropriate, is blended with majority petroleum products. The biofuel blends are likely to change significantly by 2020, as many other countries have stated goals of increasing the adoption of biofuels blending to reduce national dependency on imported supplies, for example, India plans to increase its blending mandate to 20%.

BRAZILIAN BIOFUELS

Since the 1970s, Brazil has rapidly increased biofuel production, both bioethanol and biodiesel. In particular, newer technological developments such as flex fuel vehicles have further increased bioenergy’s role in the transport sector. Since 2003 vehicles that can run equally on gasoline or bioethanol have risen from zero to almost 80% market share within four years, replacing traditional gasoline powered vehicles (Figure 6). Today all gas stations have biofuel and traditional fuel pumps, with market prices and consumer choice dictating which fuel individuals choose to buy. The growth of the sugarcane and bioenergy industries has led to innovation not only in the transport sector but also in agriculture, biochemical and electricity generation.

FIGURE 6: EVOLUTION OF BRAZILIAN TRANSPORT SECTOR, NEW VEHICLE REGISTRATIONS BY YEAR AND FUEL



Source: ANFEA Annual Report (2015)

The growth of the sugarcane and bioenergy industries has led to innovation not only in the transport sector but also in agriculture, biochemical and electricity generation.

BIOGAS

“Biogas” is a gas produced by anaerobic fermentation of different forms of organic matter and is composed mainly of methane (CH₄) and carbon dioxide (CO₂). Typical feedstock for biogas production are manure and sewage, residues of crop production (i.e., straw), the organic fraction of the waste from households and industry, as well as energy crops including maize and grass silage. Biogas is supplied to a variety of uses or markets, including electricity, heat and transportation fuels. In many countries, the gas is used for direct combustion in household stoves and gas lamps are increasingly common. However, producing electricity from biogas is still relatively rare in most developing countries. In industrialized countries, power generation is the main purpose of most biogas plants; conversion of biogas to electricity has become a standard technology. Leading countries in producing biogas include Germany, India and China. The use of biogas for transport is dominant in the EU region.

Another proven conversion technology for obtaining biogas is the creation of synthesis gas (known as syngas) via thermochemical gasification. The gas produced when biomass is the feedstock is called BioSNG that can be used in gas turbines to generate electricity and/or heat.

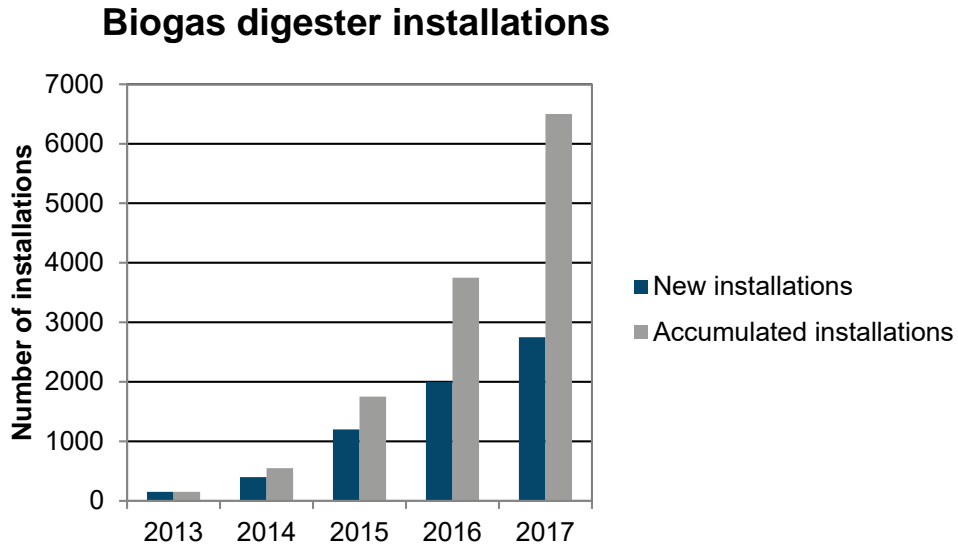
The economics for biomass to syngas conversion will depend greatly on demand levels, regional gas markets and also the pace of growth for gas demand in those same markets. With technological advances and ongoing research and development to commercialise the use of biogas for power generation, the generation market is looking to take some positive steps in the next years. A good example of this is the recent partnership between Dong Energy and Novozymes, Novo Nordisk and Bigadan in the investigation of the possibility of creating biogas from biomass¹⁶. Also, a 20 MW plant is in operation in Gothenburg since 2014, using wood pellets to produce bio-methane.

BOLIVIAN NATIONAL BIOGAS PROGRAMME

In Bolivia, a National Programme for Biogas was enacted in 2013. It aims to organise the installation of 6,500 domestic biogas digester units by 2017 and to establish a viable market for the supply and maintenance of these units for the long term. The stated side-benefits of this plan include a reduction in the use of firewood for domestic energy needs with associated improvements in domestic environment and health conditions, plus improvements in small-scale agricultural productivity from easier access to a modern and sustainable form of energy.

¹⁶ Power technology (2015) Dong Energy joins Danish team to explore producing biogas from biomass.

FIGURE 7: PLANNED BIOGAS DIGESTER INSTALLATIONS FOR BOLIVIAN NATIONAL PROGRAMME FOR BIOGAS



Source: SNVWorld 2013¹⁷

BIOGAS IN TURKEY

Biogas is one of the most promising technologies in Turkey. The number of active biogas plants in the country has increased to 64 with a total installed capacity of 322 MW_e. The ratio to total electricity capacity is only 0.44% while the annual production has increased to 1.57. All the 64 plants are also grid connected with the smallest (Cargill Tarim Bursa Bioenergy Power Plant) having an installed capacity of 0.12 MW to the largest (Odayeri Municipality Waste Power Plan) having a capacity of 28 MW. Biogas, produced from municipal waste is seen as a viable and sustainable alternative to replacing fossil fuels and to deal with the problem of waste in cities.

¹⁷ SNVWorld (2013)

GORGE FARM AD IN KENYA

The Gorge Farm AD power plant is the largest in Africa and the first to be connected to the grid. At 2.8 MW installed capacity, the plant will be delivering 2.4 MW output to the farm and the local grid. This power is enough to light up 8,000 households. The plant was constructed in less than 12 months with an investment of US\$6.5 million. The plant utilises about 50 kilo tonnes of organic crop waste each year and it will produce at least 35 kilo tonnes of rich natural fertiliser as a by-product from the biogas process. The Farm will utilise the rich natural fertiliser to improve soil conditioning and crop yields. This is estimated to displace about 20% of synthetic fertiliser use and improve the farm's bottom line.

The Gorge Farm AD plant is an example of utilising local feedstock and labour to help promote energy and food security in Kenya.

ADVANCED BIOFUELS

Advanced biofuels are generally referred to as second or third generation biofuels. The feedstock includes lignocellulose-based ethanol, hydrogenated vegetable oil (HVO), algae based biofuels and biogas. The production capacity of all advanced biofuels plants stood at 5.4 billion litres in 2013¹⁸. However, due to uncertainty in biofuel and fossil oil markets, and in policy domains, a number of large-scale facilities are reportedly idle at the current time. In 2014 – 2015, a number of full-scale cellulosic ethanol plants came into production in U.S. and Brazil, using corn stover, straw and bagasse.

BIOMASS AS STORAGE

Dispatchable energy sources are those sources that can be dispatched at the request of power grid operators or of the plant owner, meaning they can be ramped up or shut down in a relatively short amount of time based on the current need for energy. The global energy supply is currently in transition, with increasing amounts of weather dependent renewable energy sources connected to grid. Need for balancing and adjusting the supply could refer to time intervals of a few seconds up to a couple of hours, in addition to demand side management. The role of grid management is expected to increase in the future to ensure that customers will continue to receive the required amount energy at the required time, and therefore technical solutions for production, grid management and supply are needed. The need for balancing the production and use of energy is relevant on wide temporal variation and scale requirements. Biomass can renewably address the whole spectrum of

¹⁸ IEA (2015) Tracking Clean Energy Progress

requirements, from frequency control solutions and reserve capacity to seasonal storage of energy.

Bioenergy, as the only currently existing large-scale dispatchable form of renewable energy in addition to hydropower, can be used as a climate friendly option to store energy and to make grid operation more stable on system level. In addition to the ability of balancing electric grid with large shares of weather dependent renewable electricity production, it brings carbon neutral balancing elements also to heating and transport sectors. Bioenergy as energy carrier is stable and therefore the use in power generation will have new roles for peak demands and adjusting generation for secure and reliable grid operation. Bioenergy can be used to balance the grid in existing installations, and especially existing CHP infrastructure to operate as peak and balancing power plants. This brings an additional benefit of balancing the electric grid with bioenergy. Biomass can also be utilised as a refined energy carrier, such as bio-methane or bioliquid, and used in gas turbines, engines or dedicated burners for peak demand. The use in thermal power plants also increases possibilities for balancing the system in the form of turndown ratio and also using thermal storage.

2. ECONOMICS & MARKETS

In the past, local political or economic issues have driven development of bioenergy. Prime drivers of the development of bioenergy in particular have included mandates to reduce the emissions resulting from fossil fuel use, policies to drive improved energy efficiency and security of supply concerns. In the case of raw biomass materials, they generally have a limited storage life and are thus likely to be harvested as needed. Biomass for commercial use is converted into a more compact and durable form such as biomass pellets.

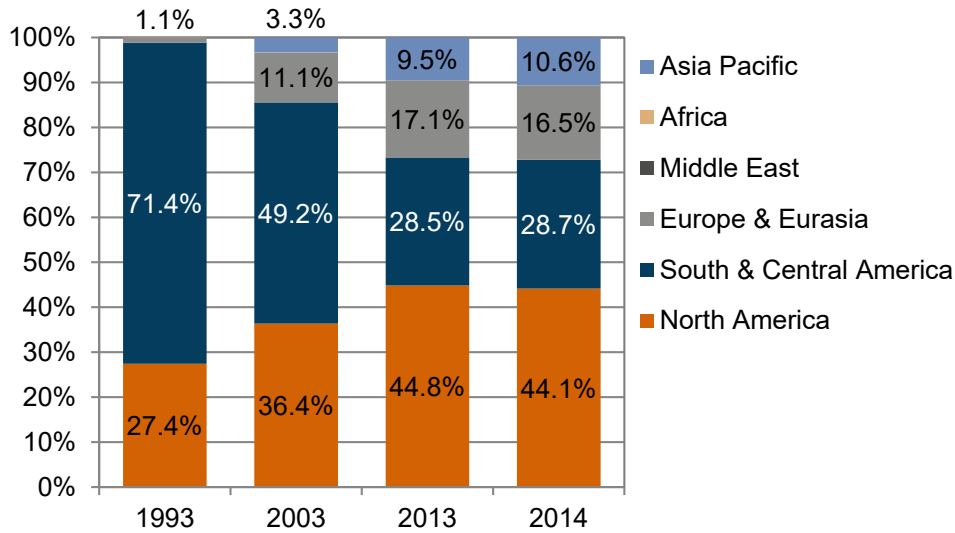
DRIVERS AND DYNAMICS

A major driver for development of bioenergy markets has, in recent years, been the GHG mitigation. Earlier, the main argument was often security of supply and high import costs of fossil fuels. Now, the substitution of fossil fuels, and the reduction of fossil carbon emissions are major arguments and benefits for bioenergy.

With the recent historic climate agreement in Paris at COP21, renewed focus on renewables will drive the investments in bioenergy. The agreement will provide much needed impetus in shifting from fossil fuels to renewables.

Another major driver is the carbon taxes, a key instrument for energy transition. Carbon tax is a simple and effective tool to reduce fossil fuel use and increase energy efficiency. It can be tax neutral as other taxes like income tax can be reduced. This will also lead to a more sustainable lifestyle and investment for the future. To put the Paris agreement into concrete action, there has been a global call for introduction of carbon pricing. It was one aspect in which everyone was in agreement including companies, NGOs, governments etc. Efforts are underway for initiating a global carbon price. Many countries, for example Sweden, have successfully implemented the carbon tax leading to an increase use of bioenergy.

FIGURE 8: SHARE OF BIOFUELS PRODUCTION BY REGION



Source: BP (2015) Statistical Review of World Energy

Finally, bioenergy offers countries that do not have significant natural hydrocarbon resources a potential opportunity to become net producers of energy products for export. To do this however, they need to develop the necessary industry and infrastructure and have sufficient land and water resources to support the economic production of the feedstock crops. An example would be Finland with its long experience of forestry and of converting forestry by-products into forms of bioenergy. Sweden is another example where bioenergy accounts for almost 33% of all final energy consumption. Although historically bioenergy has been developed to address domestic energy demand or national policy concerns, some developed countries have already started to develop bioenergy as a more export-oriented industry.

INTERNATIONAL TRADE

Some trade of biomass products within and even between countries does occur at the regional level. In the past couple of years, there is increasing evidence of international trade of biomass in the form of pellets and liquid biofuels. For example, table 1 of the Bioenergy chapter of the World Energy Resources 2013 report¹⁹ describes the trade in wood chips for energy between Europe, Turkey and Japan. Total trade has risen from 788 PetaJoules in 2004 to 1148 PJ in 2011, a rise of 46%. In the past few years, the intercontinental trade in pellets has risen rapidly. The trade is mostly from North America to Europe and is expected to grow in the near future. In 2014, the production of wood pellets by the EU was 13.5 million

¹⁹ World Energy Council (2013) World Energy Resources 2013 report, p 7.18

tonnes while the consumption was almost 19 million tonnes²⁰. The remaining was imported predominantly from North America.

Biofuels on the other hand have similar characteristics to oil products, such that both fuels can be transported and sold through the same mechanism and utilised by vehicles such as “flex” cars. Both fuels (biofuels and gasoline) have good lubricating properties and high octane number, which is the measure of the compressibility of a fuel before igniting, in addition it is right to state that both fuels represent a burgeoning industry. Production and consumption have been limited to local consumers, however the transportability of biofuels and biogas represent a potential for a more widespread trade of these products in the future. Economic factors will decide the development of any such market, with the costs of production compared with conventional and unconventional oil and gas being the primary restraint on such growth. Production of biofuels globally has grown unevenly over the last 20 years. There has been continued growth in production in South & Central America; however, North America as a region now accounts for 45% of overall production. USA and Brazil account for almost 80% of all production of liquid biofuels.

HARVESTING AND LOGISTICS

Long distance biomass trade is in full swing. Beginning with the first major pellet export from British Columbia (BC) in Canada to Helsingborg Sweden on the “Mandarin Moon” in 1998²¹, North American pellet exports to the EU have increased to 5.3 million tonnes in 2014²². While Canada dominated in North American exports in the 2000-2010 period, lower wood costs and shorter transportation distance allowed the US South East to overtake Canada as the export leader in the last 5 years. From 2013 to 2014, US exports to the EU grew from 4.69 MT to 5.15 MT, while Canadian exports to the EU fell from 1.91 MT to 1.26 MT²³. Historically, most Canadian pellets have been transported 16,600 km from BC through the Panama Canal to Europe, however exports are projected to swell from Quebec in 2015 with the ramping up of the 400,000 tonne capacity Rentech plant in Wawa Ontario exporting from the new pellet terminal in Quebec City²⁴. Canada is moving to enhance competitiveness with the opening of the Westview terminal in Prince Rupert BC, which has all the rail siding, storage and loading capacity to fill Panamax ships. Canada is also increasing pellet exports to Asia, with exports to Japan increasing from 91,000 tonnes in 2014 to 124,000 tonnes in 2015²⁵. Japan also imported 51,000 tonnes from China. The Korean pellet market is very price driven, and 75% of its imports come from Vietnam²⁶.

²⁰ FAO statistics. <http://faostat3.fao.org/browse/F/FO/E>

²¹ John Swaan

²² EPC Survey- Hawkins-Wright, FAO

²³ Ibid EPC

²⁴ Canadian Biomass Magazine, Amie Silverwood, 5082

²⁵ Gordon Murray (2016) Western Forest Industry Conference- Jan 28

²⁶ Ibid 25

Long distance trade in black and brown pellets is also growing. Trade started in 2012, when New Biomass Energy shipped just under 5,000 tonnes of torrefied pellets 200 km by truck from its plant in Quitman Mississippi to the gulf port of Mobile and then by ship to a customer in Europe²⁷. In 2014, New Biomass Energy launched a joint venture with Solvay to expand the plant to 250,000 tonnes. In August 2015, Zilkha made its first commercial shipment of black pellets to Rouen in France from its new 275,000 tonne plant in Selma, Alabama. Arbaflame has been manufacturing black pellets at its 25,000 tonne plant in Norway since 2003. In 2014 it shipped 7,500 tonnes to the OPG generating station in Thunder Bay, Canada, which was recently converted to black pellets.

Ensyn has been manufacturing pyrolysis oil in the US since 1989. Since building its flagship plant in Renfrew Ontario in 2006, Ensyn has shipped pyrolysis oil by truck to customers in Wisconsin, and recently the plant began exporting to New Hampshire, where it is used to heat hospitals. Fortum opened its Joensuu Finland pyrolysis oil plant in 2014. It ships to customers in Finland, and even shipped 160 tonnes across the Baltic to Sweden, the first time pyrolysis oil has been shipped in volume across a sea.

Bioenergy in Aviation sector

Jet aviation fuel makes up between 6-8% of world refinery output annually, and its total usage worldwide is over 200 million tonnes/year; with this amount increasing at over 3% per year. It is estimated that the combustion of this fuel in flight makes up about 3% of the human-produced CO₂-e emissions generated annually. Due to these facts, the international commercial aviation industry is under pressure to limit the increases in GHG emissions created over the coming years and decades, and to develop processes to significantly reduce these overall net emissions through 2050. Pressure is imposed by EU legislation on EU-based airlines and the members of the International Air Transport Association (IATA) have pledged to commence the necessary measures. However, reduction of emissions from a growing commercial aviation sector will be far easier said than done.

The development of production of jet biofuels has some major obstacles. These are principally the logistical issues of bringing together the enormous amounts of biomass feedstocks required, the cost of production, and the system of distribution in parallel with fossil-sourced jet fuel. Presently there is no subsidy or system of cross-transfer of excise duty to help the cost of jet biofuels at the refuelling point become competitive with the cost of fossil jet fuels. By contrast, the production of land transport biofuels is driven both by mandates, legislation and by national systems of taxation on the import of petroleum-derived fuels or on carbon emissions. In general, the biofuel production options for land vehicles are more simple, feasible and economic than for aviation jet fuels. Blending mandates may be as low as 2-5% for diesel-fuelled vehicles and rarely over 10% of ethanol at present in most countries for spark-ignition engine vehicles. The parameters of the specifications of land transport biofuels are relatively undemanding in terms of freezing point, flash point, or even

²⁷ IEA Task 40 (2014) Low Cost Long Distance Biomass Supply Chains

stability in storage. Additionally, in many regions, and particularly in the EU, the retail price for petroleum-derived vehicle fuels is far higher than the production cost, due to an array of duties and other taxes that are imposed.

However, for jet biofuels the situation is quite different. Petroleum-derived jet fuel is sold internationally at little above cost of production and distribution. Specifications for fuel qualities are extremely strict due to the operating conditions of commercial jet planes. The process of making fuels to these exacting specifications requires very large production scale and very technically advanced plant, and for the more economic technologies (in terms of final cost per litre produced) it requires bringing enormous volumes of the biomass feedstock to the processing plant.

For example, to produce 50 million litres (about 40,000 tonnes) a year of jet fuel by the Fischer-Tropsch process requires in the order of one million tonnes a year of wood or straw coming annually to the plant. And to produce 40,000 tonnes a year of bio-jet by the HEFA process requires at least 50,000m³ of vegetable oil, which is the output from at least 10,000 hectares of oil palm plantations. The EU-based airlines use about 20 million tonnes a year. The two million tonnes of bio-jet a year that will be needed from 2020 for the EU-based airlines alone will require an amount 50 times this 50 million litre volume, and so the issues of producing this scale of supply can be seen. This is without any consideration of the demand for bio-jet from the world's other airlines, with their current usage of over 180 million tonnes a year of fossil jet fuel.

Bioenergy in Maritime sector

Up to 90% of the world's goods and materials are moved by commercial shipping. The global maritime fleet consists of bulk carriers and general cargo/tankers using about 70% of the world's marine fuel, and container ships and chemical/product tankers which use the balance of about 30%. The commercial maritime sector uses about 200 million tonnes of fuel a year (a similar amount as the commercial aviation sector). It is similarly estimated to produce about 3% of anthropogenic greenhouse gas emissions. Ships of less than 6,000 tonnes displacement are usually fuelled by a marine distillate similar to truck diesel, while the main engines of larger ships usually use heavy fuel oil (HFO). This is the highly viscous residual product that remains when all other fractions have been boiled off the initial crude oil in the refining process. Accordingly, since most cargo and bulk commodity volume is carried in larger ships, 80-90% of the total volume of marine fuel presently used world-wide is heavy fuel oil. HFO is cheap, but it is so thick that it has to be pre-heated to 104°C-127°C for it to flow to the engine or in transfer. It normally has relatively high sulphur content, contains some level of impurities, and its use produces high levels of particulate matter (PM). The estimate is that fuel use, and hence GHG emissions, from global shipping will both approximately double from 2014 to 2030.

Because of these issues the world maritime fleet owners are under pressure to begin use of cleaner fuels, so that the fleet footprint is reduced in terms of PM, GHG emissions and sulphur oxides (SO_x) emissions. Legislation applies to levels of SO_x emissions in an

increasing number of delineated waters (Emission Control Areas, or ECAs), and so ships entering these waters, and otherwise for entering ports for loading and unloading, will carry two grades of fuel, one for unrestricted waters and one that allows compliance with tighter emissions standards of the ECAs. Examples of ECAs are the Baltic Sea (listed in 2006), the English Channel (2007), the North Sea (2007), North American coastal waters (2012) and the Caribbean (2014). The latter two ECAs have prescribed limits on nitrous oxides (NO_x) and PM, as well as SO_x.

While some shipping lines are trialling liquefied natural gas (LNG) as a fuel in smaller ships, the more usual emissions reduction option entails either switching to use of low-sulphur heavy fuel oil (LSHFO) or to a lighter fuel oil (this may be a blend of HFO or LSHFO and marine distillate). In the longer term the use of some blend of 'green' diesel is seen as a likely pathway that commercial shipping will begin to adopt. As for jet aviation fuel, the cost of bunker oil is relatively untaxed and so any alternate biofuel will need to be relatively low cost and able to be blended without any operational difficulty. It will also have to be stable in storage and be simple to distribute within present fuel distribution systems. Fuels produced from carbon-rich sources including biomass and municipal wastes show some potential to fit within parameters of energy density, stability in storage, cost and blending qualities.

Two possible production systems are either the HEFA process producing drop-in diesel from vegetable oils or animal fats, or pyrolysis oil produced from woody biomass or straw and then refined. A third option would use a high temperature zero oxygen breakdown (flash pyrolysis) of a feedstock of refuse derived fuel (sorted non-recyclable dry municipal wastes) or dry biomass into synthesis gas (a mix of H₂ and CO), and subsequent cleaning, reforming and refining. Both the pyrolysis oil and synthesis gas pathways would yield marine grade fuel oil along with other grades of biofuels in varying proportions.

LOW OIL PRICE RISK

In the recent past, one of the major risks affecting development of bioenergy was the drop in oil prices. During June 2014 – December 2015, the oil prices dropped from US\$112 per barrel to US\$38 per barrel, a decrease of more than 65%. Early January 2016, it touched a low of US\$28. Although the production and consumption of bioenergy (pellets, liquid biofuels, wood chips etc.) hasn't been affected much. However, bioenergy equipment manufacturers have experienced a lot of trouble. In a recent survey²⁸, equipment producers reported struggling with lower investments, lower profit margins and less financial resources available for bioenergy development.

Also, according to the survey, the decrease in the oil price had few positive impacts. The lower prices improved the economic conditions in agriculture as farmers can invest in improved machinery leading to increased farm productivity. For bioenergy producers, the transportation costs are lower leading to lower project costs. Some countries have increased

²⁸ WBA (2015) Oil price survey

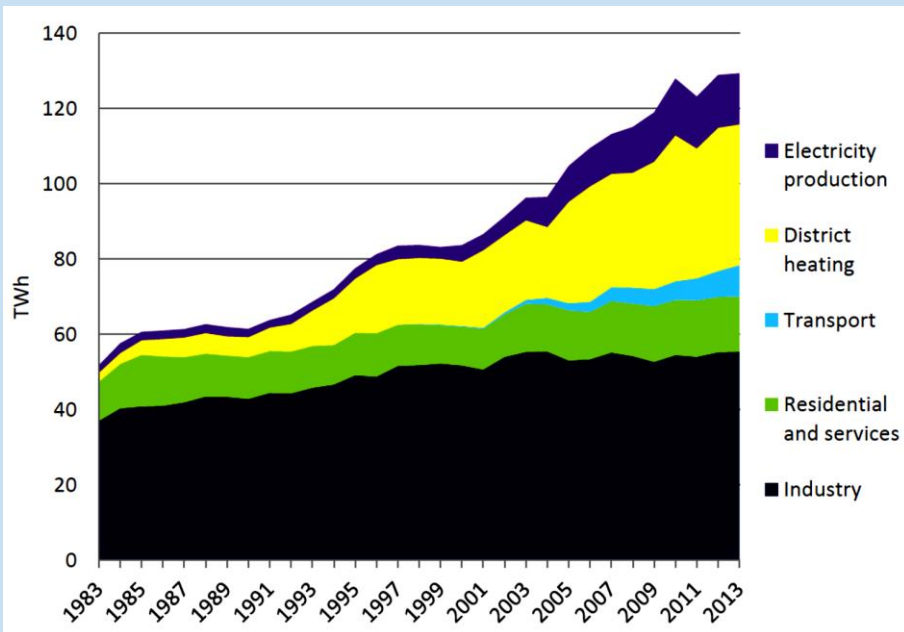
the excise duty on fossil fuels leading to less than observable decline in pump costs for consumers. Also, markets with strong blending mandates were less impacted. It also leads to easing of inflation in developing countries, which are highly dependent on fossil imports. All these may lead to higher spending in infrastructure and renewables.

In the end, there is a need for policy makers to work towards eliminating fossil fuel subsidies globally and increase investments in renewable energy. Carbon taxes and increasing mandatory blends of biofuels are some of the steps needed.

SWEDEN – A LEADER IN BIOENERGY

Bioenergy today accounts for 34% of the final energy use in Sweden. Bioenergy overtook oil as the leading energy source in 2009. The use of biomass has grown steadily in recent decades for both electricity and heat production, as well as within the transport sector. In 1970, imported oil provided almost 80% of the energy supply in Sweden. Biomass accounted for 11% or 52 TWh of the total energy supply in 1983. In 2013, the use of biomass has increased to 129 TWh, which is equivalent to 23% of the total supply. For example, Swedish industry primarily uses biomass and electricity as energy carriers. In 2013, these respectively constituted 38 and 35% of industry's final energy use.

FIGURE 9: USE OF BIOMASS PER SECTOR 1983 – 2013, TWh



Source: Swedish Energy Agency & Statistics Sweden

There are several factors behind “the Swedish bioenergy wonder”:

- When oil prices started climbing in the 1970's, there was strong political support for a policy of reduced energy import dependence. This policy of energy security has prevailed ever since with broad support across the party lines.
- Sweden introduced a carbon dioxide tax in 1991. This tax has been raised several times since, and has made fossil fuels expensive on the market. The combination of powerful policy instruments such as the carbon tax and the electricity certificates scheme introduced in 2003 and compared to the country's size a generous budget for energy related research are part of the success. Biomass became exempt from both energy and carbon dioxide taxes, which has contributed to a sharp increase in the use of biomass. The carbon tax is about 100 €/ton. The green certificate scheme promotes electricity production from renewable energy sources and biomass accounts for about 4.7 TWh within the system.
- Sweden has a strong forest industry, with large volumes of forest residues and by-products that can be used for energy.
- Sweden already in the 1970's had a large district-heating sector, at that time mainly using oil as fuel. Almost all of this oil has been replaced by domestic biomass and waste, and the grids have expanded to supply more than half of all space heating today. Another part of the success story is the expansion of district heating in the 1970's using mostly biomass and a decreasing share of fossil fuels. Nowadays fossil fuels used for heating purposes account for roughly two TWh.
- As all fossil fuels are imported, there is no domestic fossil fuel lobby and no jobs threatened by the change. Instead, the bioenergy sector has created many new jobs throughout the country.

Bioenergy dominates the heating sector, and energy use in the large Swedish forestry sector. In recent years, production of biopower in combined heat and power plants (CHPs) has also increased. Sweden is also leading in the EU when it comes to biofuels for transport. Ethanol, biodiesel and biogas are used for transport, accounting for 12% of the transport fuel market in 2014. In recent years, HVO from forest by-products has shown a strong market growth²⁹. Sweden was then the EU country with the highest percentage of biofuels in the transport sector, and

²⁹Andersson K, (2015), Bioenergy – the Swedish Experience, second edition, Svebio

according to preliminary statistics for 2014; the percentage of renewables has increased further.

In the future, Sweden aims for a fossil fuel independent transport sector in 2030, as well as an energy system without net carbon emissions by 2050. A goal of the current government is a completely renewable energy system.

3. SOCIO-ECONOMICS

The socio-economic impacts of bioenergy are as locally specific as the potential applications of the available technologies. Contrary to popular belief, bioenergy leads to increasing food production, create jobs and improve local productivity.

JOB CREATION

Bioenergy is a local technology with one or more intermediate processing stages prior to use. This can encourage the development of complementary industries beyond the farming and bioenergy plant operations. Generally, bioenergy development will require large scale semi-automated farming and the plants are not particularly manpower intensive, therefore the sector requires skilled workers but not large numbers of workers. The Renovação project³⁰ in Brazil offers an example of large-scale up skilling of agricultural workers to offer new opportunities in a modernised industry. This encompasses basic education in mechanised, agricultural and industrial activities in the sugarcane industry.

The jobs can be seen as “local” or as strengthening the rural and regional economies, creating additional income and jobs in farming and forestry. There is also a potential for added cash income for farmers and forest owners. The bioenergy industry will employ people and jobs will be added for transports of feedstock and products.

The jobs can be both “large scale” and “small scale” but like all jobs in farming and forestry they will be spread over large areas. This is different from mining or fossil fuel production where the job’s creation is limited to certain spots or regions.

Bioenergy impacted the European renewable energy landscape in creating 489,880 jobs and an annual turnover of €48 billion. In comparison to wind (304,000 jobs and €35 billion) and solar (300,000 jobs and €35 billion), bioenergy was significantly higher³¹. These values consist of solid biomass, biofuels and biogas for energy production. In the global scenario, more than 3 million people were employed in the bioenergy sector³²- predominantly in the biofuels sector in Brazil.

LOCAL ECONOMIC DEVELOPMENT

The increasing use of bioenergy leads to better coordination between farmers, landowners and the bioenergy industries. For example, in India, the biofuels policy has led to sugarcane farmers linking up with oil manufacturing companies on supply of cane molasses for ethanol.

³⁰ Renovação project: <http://TOE.unica.com.br/renovacao-project/>

³¹ BioenergyNW (2015) Half a million jobs, €78 billion per year: The socio-economic impact of the European bio-based industry

³² IRENA (2015) RE Jobs review 2015

The increasing revenues lead to local economic development. Apart from biofuels, the use of agricultural residues like straw, rice husk, etc. generates extra revenue streams for farmers. Integration of the supply of residues with bioenergy installations like gasifiers will lead to providing much needed reliable electricity access to rural communities as well. This will also reduce the dependence on expensive and polluting fuels like kerosene and diesel. The development of bioenergy hence supports rural development, increase farmer income and eliminate energy poverty.

EDUCATION, HEALTH AND WOMEN

The dependence of Sub Saharan Africa countries on traditional biomass in their final energy is more than 65%. These are the countries with high levels of poverty, low income and lack of development. The use of traditional biomass will remain in prominence in the near future affecting health and energy efficiencies. Hence, it is imperative that off grid modern bioenergy sources like biogas, liquid biofuels, pellets/briquettes are promoted along with improving conversion efficiencies. This will increase electricity access in rural communities leading to better education. The need for skilled labour in the complete biomass supply chain will lead to improved training centres in the local communities. Local youth will have the opportunity to continue education and obtain employment.

The use of inefficient cook stoves and heating devices in rural communities using traditional biomass causes millions of deaths annually. Open fire burning of wood and charcoal etc. lead to almost four million deaths due to harmful emissions. This particularly affects women and children. The shifting of focus from traditional sources to modern bioenergy would lead to lower emissions improving their health. Use of efficient cook stoves means less fuel usage which translates to less time needed in collecting firewood etc. Women can then avoid frequent trips and also spend the gained time in other income generating activities.

Overall, an integrated systems approach is needed. Efficient forest management, replacing traditional fuels and low efficient equipment to modern energy sources, improved efficiency and increased awareness is crucial.

ADDAX BIOENERGY PROJECT IN SIERRA LEONE

The Addax project in Sierra Leone illustrates the potential for biofuel production in developing countries. Addax produces 85 million litres of ethanol from sugar cane yearly, and employs 3,600 people directly during high seasons. The planted area is 10,000 hectares and the land is leased from the local villages. 340 kilometres of roads have been built in the area. Co-generation of power and process heat gives a surplus of 15 MW of electricity that is delivered to the national grid, this accounts for one fifth of the power production in Sierra Leone. Addax has educated a couple of thousand local farmers in better farming practices (60 percent of them women) and the food production has increased markedly in the area. The project has had a

clear positive effect for the economic development in the region.

Addax Bioenergy is certified by the Roundtable for Sustainable Biomaterials (RSB).³³

³³ TOE.addaxbioenergy.com

4. ENVIRONMENTAL IMPACTS

Bioenergy is closely linked with environmental management since the main feedstock is plants or trees. Bioenergy can be the result of activities with varying levels of environmental impact, ranging from the smaller-scale gathering of wild plants or deadwood right up to large-scale bio-crop farms.

LAND-USE

The production of bioenergy feedstock often requires significant areas of land, either for the plantation of crops or fast-growing trees. These feedstock plants are grown and harvested to provide the raw materials for direct-use or processing to convert them into the fuel for the relevant bioenergy process. However, in some cases bioenergy can be produced from other activity such as the forestry management. For example, the residues from wood milling or materials harvested as part of thinning³⁴ would not have a significant additional land-use impact. Feedstock can come from existing management in forestry and agriculture (residues, thinning material, straw, etc.) through higher yields (more from existing crops on existing land), or through dedicated crops. There is a lot of abandoned farmland in developed countries, for example in Eastern Europe and North America. Managed forestry could be employed in more regions. The general growth of forests (the terrestrial carbon sink) is three times higher than the loss of CO₂ through deforestation.

As well as the impact on land-use from the growing of the crops, there is also the additional issue of deforestation, which is certainly not limited to the bioenergy industry but applies to its further expansion nonetheless. In developing countries in particular there may be economic or political pressure to clear natural forests³⁵ or other non-productive land for the growing of bioenergy crops, this can threaten biodiversity if uncontrolled. Of particular concern is the clearing of natural/virgin rainforest for sugar cane and other similar crops that are well suited to the production of biofuels. However, deforestation is usually a result of bad governance or poverty. More use of forest products where the forest will get a higher value, will also lead to better protection of the forests, with replanting and less deforestation. Land use regulation (ownership) and land reform is important to protect the forests. In many parts of the world, forest areas are increasing, with the resulting higher potential for biomass for energy.

Many international organisations have stated the current and future focus of using crops should be for both food and fuel production. There is no competition and various methods

³⁴ Thinning is the planned removal of trees to promote woodland health: <http://ext.wsu.edu/forestry/Thinning.htm>

³⁵ Natural Forests Standards: <http://TOE.naturalforeststandard.com/nfs-standard/definitions/>

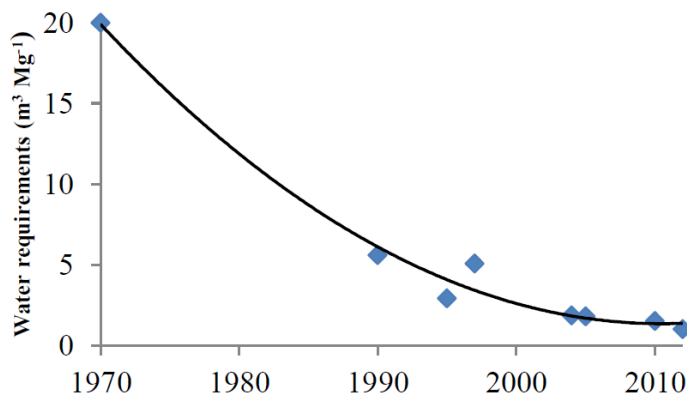
like: increasing crop yields, using marginal lands etc. can lead to sustainable production of both food and fuel.

Policies to encourage the expansion of bioenergy, for instance mandatory mixes of bioethanol or biodiesel to reduce domestic consumption of traditional fossil fuels, may lead to increased domestic production of the necessary feedstock crops and as a result an increasing acreage of land in use for the growing of these crops. The potential for higher yields are very high in most developing countries, not least in Africa and Latin America.

WATER-USE

Bioenergy's water footprint as a form of energy when compared to other resources is considerable. Water is required to grow the feedstock crops and in the case of biofuels in the transformative process to convert the raw feedstock into an end-user fuel. However, these issues do not differ for bioenergy crops compared to regular agriculture and forestry. The methods must adapt to the climatic conditions.

FIGURE 10: EVOLUTION OF SUGARCANE INDUSTRY WATER REQUIREMENTS IN BRAZIL



Source: Scapera et al. (2013)

In Brazil and other parts of the world the processing of ethanol from sugarcane requires large amounts of water. The usage of water is about 87% which covers cane washing, juice evaporation, fermentation cooling and ethanol distillation condenser cooling. In the 1990s, the reuse of water within a closed loop and substituting dry cane cleaning with wet cane washing has brought about a four-fold decrease in water requirement when compared to the 70s (Figure 10)³⁶.

³⁶ Scarpere F.V (2013) Bioenergy and water: Brazilian sugarcane ethanol

The impact bioenergy has on water resource varies based on the type of bioenergy system and also on the region. Some countries have unfavourable water footprint, far above the global average. For example, sugar cane production in Egypt, Pakistan, India, and Vietnam heavily rely on fresh surface and ground water for irrigation³⁷. However, in the case of India, the focus is on using molasses, a by-product for conversion to ethanol instead of using sugarcane juice.

Bioenergy demand can be met in several ways, such that it improves the situation with regards to water usage. For example, *Eucalyptus rameliana* and *pachyphylla* occupy arid habitats with annual precipitation of less than 350mm which can be a potential feedstock for bioenergy in areas where droughts are common³⁸. *Sorghum bicolor* also has a tolerance for drought and this does not affect the ethanol yield produced³⁹.

Water with high salinity can be used to cultivate crops which in turn will minimise the stress on fresh water. Some crops show more salinity tolerance than conventional agricultural crops such as *Andropogon gerardii*. This crop poses good germination rates under increased levels of salinity when compared with other crops with the same carbon fixation pathway⁴⁰. Other plants with good salinity tolerance are *Arundo donax*⁴¹ and *Robinia pseudoacacia*⁴².

CLIMATE BENEFITS

The major benefit of using bioenergy is the climate. The substitution of fossil fuels and the following reduction of GHG emissions are significant. Although the process of harvesting, transportation, conversion and use of biomass might include some fossil inputs, the overall life cycle benefits of the supply chain are better than using fossil fuels in most cases.

In the debate on the climate neutrality of bioenergy, it is important to differentiate between the supply and end use of bioenergy. Considering the forestry sector, if the same amount of forestry is harvested as is grown annually, i.e. a continuous forest, then the biomass is carbon neutral. There is no net addition of emissions to the atmosphere. This is a basic tenet of sustainability in forest laws around the world with a varying degree of enforcement. The other part is the use of bioenergy. The options include leaving it within the forests, thus leading to carbon sequestration and reducing its concentration in the atmosphere. Otherwise, the biomass can be instead used to produce material (furniture, paper and pulp

³⁷ Gerbens-Leenes, TOE.P. and Hoekstra, A.TOE. (2013) Water footprint quantification of energy at a global level.

³⁸ Lauren D.Q., Kaitlin C.S., Jia G., Gary K., Lee D.K., Thomas B.V. (2015) Stress-tolerant feedstocks for sustainable bioenergy production on marginal land.

³⁹Ibid 38

⁴⁰Ibid 38

⁴¹ Schmer M.R., Xue Q., Hendrickson J.R (2012) Salinity effects on perennial, warm-season (C-4) grass germination adopted to the northern Great Plains.

⁴²Meng F.J., Wang Q.TOE., Wang J.Z., Li S.TOE., Wang J.J. (2008) Salt resistance of tetraploid *Robinia pseudoacacia*. *Zhiwu Shengtai Xuebao*.

etc.) or energy (heat, electricity and transportation fuels). The use of bioenergy can thus replace fossil fuels leading to climate benefits.

If we consider the environmental assessment, there have been various studies on the criteria of net energy and emissions of bioenergy. The final climate benefit depends on various factors – water requirement, fertiliser use, human labour, grid electricity composition and transportation fuel used etc. In general, biomass cultivated in tropical regions (for example Brazil, India, Vietnam etc.) usually has higher benefits due to abundant rainfall, less energy intensive manual labour, high solar radiation etc. For example, ethanol produced using sugarcane in Indonesia leads to a 67% emission reduction in comparison to gasoline in the complete life cycle⁴³.

Whichever pathway is chosen, it is important to perform life cycle analysis exploring the social, environmental and economic benefits of each pathway.

⁴³ Dilip K., Bharadwaj K. V., Semida S., Francis X. J. (2016) Energy and GHG balances of ethanol production from cane molasses in Indonesia, *Applied Energy* Vol. 164, pp. 756 – 768

5. OUTLOOK

Bioenergy has been successful in many developed countries and to a certain extent, some developing countries as well. Countries with high share of renewables also have a high share of bioenergy in their energy mix. Bioenergy has enabled countries in a gradual decarbonisation of the energy system and reduced dependency on fossil fuels. Countries like Sweden and Finland are leading the way in this transition by their successful utilisation of bioenergy. The sustainable use of forestry and forest products has led them to be world leaders in renewables. Countries like Brazil are becoming independent of oil by increasing their blending of biofuels in the transportation sector. This transition has been possible because of effective policies such as carbon taxes, blending mandates and investments in research and development. These policies have been driven by strong support from the universities, associations and companies.

New technologies and pathways are reducing the costs of bioenergy, increasing conversion efficiencies and expanding the base of biomass feedstock. The development of bioenergy is leading to a viable transition in greening the energy system. Co-firing of biomass with fossil fuels and other biomass feedstock has become a mature technology and is being practiced globally. The innovation in R&D has enabled the construction and operation of large-scale bioenergy plants using various feedstock and technologies.

The ease of access of biomass feedstock in countries in sub-Saharan Africa and Asia has led to an increasing dependence on biomass. It has provided much needed energy to rural areas and is the source of livelihood in many countries. In some cases, the unsustainable use of fuelwood and charcoal along with ineffective forest and land management has led to large-scale deforestation and degradation. In the future, wood fuel will still be a major energy source and the solution is to increase the transfer of best practices in effective management of forests and land. The increasing use of forest and agricultural residues along with improvements in the biomass supply chain and improved bioenergy equipment are important. Increasing yields will enable the production of more food and fuel.

Apart from various environmental benefits, the use of bioenergy has enormous socio-economic benefits as well. Bioenergy employs thousands of people globally along the complete value chain. The increased use of bioenergy will generate more jobs, provide added income to farmers and strengthen the local economies. The health and safety of women and children is interlinked with bioenergy. Improving equipment efficiencies and supply chain management will improve the living conditions and enable women to be involved in income generating work.

One of the most important benefits of biofuels is in the transportation sector. Electrification is another viable option. However, to reduce the emissions and to limit global warming to within

2°C in this century, biofuels are the most viable and sustainable option in replacing oil dependency. The share of biofuels has to be increased much more than the current 3% globally. Countries around the world have recognised this need and are increasing biofuel-blending mandates. India, Indonesia, Malaysia and Brazil are some of the leading countries in increasing the use of biofuels in the transportation sector. The EU is lagging behind due to confusion and uncertainties in the policies. There is a need for clear and consistent policy framework for better investments. Advanced biofuels from cellulosic feedstock will have to contribute significantly. The recent technological advances have led to countries like USA, Brazil and Italy to test the technology commercially.

An often ignored sector in global climate discussions is aviation and maritime. Biofuels can replace jet fuel and heavy fuel oil in these sectors to reduce pollution and the use of fossil fuels. However, there are significant challenges in implementation due to the cost of production, integration with existing infrastructure, logistics of sourcing biomass and the large scale of consumption. Efforts are already underway in the aviation sector. Flights have already flown transatlantic using biofuel blends while airports are integrating the biofuels into their existing fuel supply chains. More investment is needed.

Bioenergy in the past was largely viewed as a local commodity with local use of resources and consumption occurring domestically. Even though large share of biomass is still traditional in a sense, bioenergy trade is becoming important. The trade of pellets and biofuels is enabling the transfer from regions with high biomass potential (USA, Canada, Russia) to regions with high renewable energy targets like the EU. The pellet trade will continue to grow rapidly in the near future. Strict sustainability standards ensure that the biomass is procured sustainably.

With the increasing use of renewable energy sources, grid intermittency is a challenge. Storage is the key to a rapid green transition. Batteries, solar and large hydro are the current storage options, but bioenergy can become a climate friendly option to stabilise the grid. As an energy carrier, biomass is stable and can be stored easily in the form of pellets, bio-liquid and bio-methane etc.

Development of new technologies, pathways and feedstock could be the future for an increased use of bioenergy in the energy mix. The focus of attention should be on a successful and sustainable integration of all renewables including solar, wind, geothermal, hydro and bioenergy.

6. GLOBAL TABLE

Argentina	
Gross electricity generation from biomass in 2013, TOE	212038
Biomass production in 2013, TOE	2261919
Liquid biofuels production in 2014, kt	3682
Australia	
Gross electricity generation from biomass in 2013, TOE	73259
Gross electricity generation from biogas in 2013, TOE	93896
Biomass production in 2013, TOE	4405322
Biogas production in 2013, TOE	337729
Liquid biofuels production in 2013, kt	307
Austria	
Gross electricity generation from biomass in 2014, TOE	295529
Gross electricity generation from biogas in 2013, TOE	54257
Gross heat production from biomass in 2013, TOE	833859
Gross heat production from biogas in 2013, TOE	6330
Gross heat production from liquid biofuels in 2013, TOE	263
Biomass production in 2014, TOE	4376995
Biogas production in 2014, TOE	292205
Liquid biofuels production in 2014, kt	442
Belarus	
Gross electricity generation from biomass in 2013, TOE	7395
Gross electricity generation from biogas in 2013, TOE	2924
Gross heat production from biomass in 2013, TOE	454644
Gross heat production from biogas in 2013, TOE	2771
Biomass production in 2013, TOE	1505136
Biogas production in 2013, TOE	9101

Belgium	
Gross electricity generation from biomass in 2014, TOE	226226
Gross electricity generation from biogas in 2013, TOE	66553
Gross electricity generation from liquid biofuels in 2014, TOE	7567
Gross heat production from biomass in 2013, TOE	24243
Gross heat production from biogas in 2013, TOE	5207
Gross heat production from liquid biofuels in 2013, TOE	3392
Biomass production in 2014, TOE	1104090
Biogas production in 2014, TOE	206292
Liquid biofuels production in 2014, kt	785
Benin Republic	
Gross electricity generation from biomass in 2013, TOE	86
Biomass production in 2013, TOE	2230917
Bolivia	
Gross electricity generation from biomass in 2013, TOE	4816
Biomass production in 2013, TOE	999403
Brazil	
Gross electricity generation from biomass in 2013, TOE	3438264
Gross electricity generation from biogas in 2013, TOE	39295
Biomass production in 2013, TOE	67195353
Biogas production in 2013, TOE	96399
Liquid biofuels production in 2014, kt	23794
Bulgaria	
Gross electricity generation from biomass in 2014, TOE	11866
Gross electricity generation from biogas in 2013, TOE	1376
Biomass production in 2014, TOE	1086510
Biogas production in 2014, TOE	10390
Liquid biofuels production in 2013, kt	55

Cambodia	
Gross electricity generation from biomass in 2013, TOE	946
Biomass production in 2013, TOE	3999929
Cameroon	
Gross electricity generation from biomass in 2013, TOE	5847
Biomass production in 2013, TOE	4778184
Canada	
Gross electricity generation from biomass in 2013, TOE	373517
Gross electricity generation from biogas in 2013, TOE	75753
Gross heat production from biogas in 2013, TOE	932
Biomass production in 2013, TOE	11468425
Biogas production in 2013, TOE	236960
Liquid biofuels production in 2014, kt	1633
Chile	
Gross electricity generation from biomass in 2013, TOE	491918
Gross electricity generation from biogas in 2013, TOE	3440
Biomass production in 2013, TOE	10235383
Biogas production in 2013, TOE	13352
China	
Gross electricity generation from biomass in 2013, TOE	3293208
Gross heat production from biomass in 2013, TOE	275700
Biomass production in 2013, TOE	200962120
Biogas production in 2013, TOE	7866844
Liquid biofuels production in 2013, kt	2500
Chinese Taipei	
Gross electricity generation from biomass in 2013, TOE	24506
Gross heat production from biomass in 2013, TOE	502
Biomass production in 2013, TOE	211116

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Biogas production in 2013, TOE	6067
Liquid biofuels production in 2013, kt	176
Colombia	
Gross electricity generation from biomass in 2013, TOE	170164
Biomass production in 2013, TOE	3929947
Liquid biofuels production in 2014, kt	936
Costa Rica	
Gross electricity generation from biomass in 2013, TOE	15736
Gross heat production from biomass in 2013, TOE	674501
Biogas production in 2013, TOE	96
Cote d'Ivoire	
Gross electricity generation from biomass in 2013, TOE	5847
Biomass production in 2013, TOE	9640896
Croatia	
Gross electricity generation from biomass in 2014, TOE	4300
Gross electricity generation from biogas in 2013, TOE	6621
Gross heat production from biomass in 2013, TOE	5924
Gross heat production from biogas in 2013, TOE	2723
Biomass production in 2014, TOE	1374702
Biogas production in 2014, TOE	26202
Liquid biofuels production in 2013, kt	33
Cuba	
Gross electricity generation from biomass in 2013, TOE	58470
Biomass production in 2013, TOE	1235049
Liquid biofuels production in 2013, kt	393
Cyprus	
Gross electricity generation from biogas in 2013, TOE	4214
Gross heat production from biogas in 2013, TOE	3612
Biomass production in 2014, TOE	8503
Biogas production in 2014, TOE	11298

Liquid biofuels production in 2013, kt	2
Czech Republic	
Gross electricity generation from biomass in 2014, TOE	171282
Gross electricity generation from biogas in 2013, TOE	197249
Gross heat production from biomass in 2013, TOE	119495
Gross heat production from biogas in 2013, TOE	11632
Biomass production in 2014, TOE	2300994
Biogas production in 2014, TOE	608007
Liquid biofuels production in 2013, kt	286
Denmark	
Gross electricity generation from biomass in 2014, TOE	254343
Gross electricity generation from biogas in 2013, TOE	33448
Gross heat production from biomass in 2013, TOE	1006545
Gross heat production from biogas in 2013, TOE	33415
Gross heat production from liquid biofuels in 2013, TOE	16887
Biomass production in 2014, TOE	1304505
Biogas production in 2014, TOE	122791
Liquid biofuels production in 2013, kt	111
Ecuador	
Gross electricity generation from biomass in 2013, TOE	25452
Biomass production in 2013, TOE	554481
Liquid biofuels production in 2013, TOE	168
El Salvador	
Gross electricity generation from biomass in 2013, TOE	34136
Biomass production in 2013, TOE	779450
Estonia	
Gross electricity generation from biomass in 2014, TOE	62855
Gross electricity generation from biogas in 2013, TOE	1720
Gross heat production from biomass in 2013, TOE	192869

Gross heat production from biogas in 2013, TOE	1553
Biomass production in 2014, TOE	1122099
Biogas production in 2014, TOE	9602
Finland	
Gross electricity generation from biomass in 2014, TOE	943079
Gross electricity generation from biogas in 2013, TOE	11952
Gross heat production from biomass in 2013, TOE	1687566
Gross heat production from biogas in 2013, TOE	9268
Biomass production in 2014, TOE	8066400
Biogas production in 2014, TOE	99695
Liquid biofuels production in 2014, kt	68
France	
Gross electricity generation from biomass in 2014, TOE	140843
Gross electricity generation from biogas in 2013, TOE	129493
Gross heat production from biomass in 2013, TOE	530119
Gross heat production from biogas in 2013, TOE	16815
Biomass production in 2014, TOE	9073899
Biogas production in 2014, TOE	440504
Liquid biofuels production in 2014, kt	3242
Gabon	
Gross electricity generation from biomass in 2013, TOE	860
Biomass production in 2013, TOE	1262850
Germany	
Gross electricity generation from biomass in 2014, TOE	1020465
Gross electricity generation from biogas in 2013, TOE	2513672
Gross electricity generation from liquid biofuels in 2014, TOE	31299
Gross heat production from biomass in 2013, TOE	534012
Gross heat production from biogas in 2013, TOE	116486
Gross heat production from liquid biofuels in 2013, TOE	3249
Biomass production in 2014, TOE	11424692
Biogas production in 2014, TOE	7434294
Liquid biofuels production in 2014, kt	3834

Greece	
Gross electricity generation from biogas in 2013, TOE	18573
Gross heat production from biogas in 2013, TOE	24
Biomass production in 2014, TOE	869208
Biogas production in 2014, TOE	86893
Liquid biofuels production in 2013, kt	152
Guatemala	
Gross electricity generation from biomass in 2013, TOE	154515
Biomass production in 2013, TOE	7561432
Honduras	
Gross electricity generation from biomass in 2013, TOE	62425
Biomass production in 2013, TOE	2258073
Hungary	
Gross electricity generation from biomass in 2014, TOE	146346
Gross electricity generation from biogas in 2013, TOE	22958
Gross heat production from biomass in 2013, TOE	91598
Gross heat production from biogas in 2013, TOE	2174
Biomass production in 2014, TOE	1402790
Biogas production in 2014, TOE	76001
Liquid biofuels production in 2013, kt	423
Iceland	
Biogas production in 2013, TOE	1696
India	
Gross electricity generation from biomass in 2013, TOE	1795443
Gross electricity generation from biogas in 2013, TOE	79794
Biomass production in 2013, TOE	187380004

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Biogas production in 2013, TOE	398969
Liquid biofuels production in 2013, kt	212

Indonesia	
Gross electricity generation from biomass in 2013, TOE	19605
Biomass production in 2013, TOE	54240686
Liquid biofuels production in 2013, kt	2180

Iran	
Gross electricity generation from biogas in 2013, TOE	1978
Biomass production in 2013, TOE	498448
Biogas production in 2013, TOE	6473

Ireland	
Gross electricity generation from biomass in 2014, TOE	22528
Gross electricity generation from biogas in 2013, TOE	16080
Biomass production in 2014, TOE	210400
Biogas production in 2014, TOE	52212
Liquid biofuels production in 2013, kt	25

Israel	
Gross electricity generation from biogas in 2013, TOE	7223
Biomass production in 2013, TOE	4371
Biogas production in 2013, TOE	20350

Italy	
Gross electricity generation from biomass in 2014, TOE	328719
Gross electricity generation from biogas in 2013, TOE	640413
Gross electricity generation from liquid biofuels in 2014, TOE	373345
Gross heat production from biomass in 2013, TOE	517412
Gross heat production from biogas in 2013, TOE	201037
Gross heat production from liquid biofuels in 2013, TOE	23407
Biomass production in 2014, TOE	6539410
Biogas production in 2014, TOE	1960997

Liquid biofuels production in 2014, kt	616
Jamaica	
Gross electricity generation from biomass in 2013, TOE	16681
Biomass production in 2013, TOE	493838
Japan	
Gross electricity generation from biomass in 2013, TOE	2760706
Biomass production in 2013, TOE	8461069
Kenya	
Gross electricity generation from biomass in 2013, TOE	15392
Biomass production in 2013, TOE	15522428
Latvia	
Gross electricity generation from biomass in 2014, TOE	27430
Gross electricity generation from biogas in 2013, TOE	24678
Gross heat production from biomass in 2013, TOE	153889
Gross heat production from biogas in 2013, TOE	14188
Biomass production in 2014, TOE	2046098
Biogas production in 2014, TOE	74903
Liquid biofuels production in 2013, kt	69
Lithuania	
Gross electricity generation from biomass in 2014, TOE	25194
Gross electricity generation from biogas in 2013, TOE	5074
Gross heat production from biomass in 2013, TOE	268272
Gross heat production from biogas in 2013, TOE	2270
Biomass production in 2014, TOE	1116605
Biogas production in 2014, TOE	20900
Liquid biofuels production in 2013, kt	140

Luxembourg	
Gross electricity generation from biomass in 2014, TOE	1806
Gross electricity generation from biogas in 2013, TOE	4816
Gross heat production from biomass in 2013, TOE	3105
Gross heat production from biogas in 2013, TOE	1123
Biomass production in 2014, TOE	65803
Biogas production in 2014, TOE	16696
Malaysia	
Gross electricity generation from biomass in 2013, TOE	95271
Gross electricity generation from biogas in 2013, TOE	1978
Biomass production in 2013, TOE	3505040
Biogas production in 2013, TOE	7906
Liquid biofuels production in 2013, kt	546
Malta	
Gross electricity generation from biogas in 2013, TOE	516
Gross heat production from biogas in 2013, TOE	502
Biogas production in 2014, TOE	1601
Liquid biofuels production in 2013, kt	1
Mauritius	
Gross electricity generation from biomass in 2013, TOE	40671
Gross electricity generation from biogas in 2013, TOE	1720
Biomass production in 2013, TOE	209015
Biogas production in 2013, TOE	5733
Mexico	
Gross electricity generation from biomass in 2013, TOE	87619
Gross electricity generation from biogas in 2013, TOE	13844
Biomass production in 2013, TOE	8867632

Biogas production in 2013, TOE	47053
Liquid biofuels production in 2014, kt	76

Netherlands	
Gross electricity generation from biomass in 2014, TOE	180568
Gross electricity generation from biogas in 2013, TOE	84265
Gross heat production from biomass in 2013, TOE	39577
Gross heat production from biogas in 2013, TOE	3750
Biomass production in 2014, TOE	1290103
Biogas production in 2014, TOE	312698
Liquid biofuels production in 2014, kt	2065

New Zealand	
Gross electricity generation from biomass in 2013, TOE	33964
Gross electricity generation from biogas in 2013, TOE	20465
Biomass production in 2013, TOE	1081471
Biogas production in 2013, TOE	67928
Liquid biofuels production in 2013, kt	4

Nicaragua	
Gross electricity generation from biomass in 2013, TOE	41445
Biomass production in 2013, TOE	1456865

Norway	
Gross electricity generation from biomass in 2014, TOE	1032
Gross electricity generation from biogas in 2013, TOE	860
Gross heat production from biomass in 2013, TOE	80229
Gross heat production from biogas in 2013, TOE	1099
Gross heat production from liquid biofuels in 2013, TOE	4610
Biomass production in 2014, TOE	840499
Biogas production in 2014, TOE	23097
Liquid biofuels production in 2013, kt	40

Panama	
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Gross electricity generation from biomass in 2013, TOE	2838
Biomass production in 2013, TOE	427391
Liquid biofuels production in 2013, kt	12

Peru

Gross electricity generation from biomass in 2013, TOE	45658
Gross electricity generation from biogas in 2013, TOE	7739
Biomass production in 2013, TOE	2750598
Biogas production in 2013, TOE	22165
Liquid biofuels production in 2014, kt	94

Philippines

Gross electricity generation from biomass in 2013, TOE	13070
Biomass production in 2013, TOE	7793375
Liquid biofuels production in 2013, kt	183

Poland

Gross electricity generation from biomass in 2014, TOE	787705
Gross electricity generation from biogas in 2013, TOE	59330
Gross electricity generation from liquid biofuels in 2013, TOE	86
Gross heat production from biomass in 2013, TOE	371931
Gross heat production from biogas in 2013, TOE	9005
Biomass production in 2014, TOE	6179493
Biogas production in 2014, TOE	207104
Liquid biofuels production in 2014, kt	994

Portugal

Gross electricity generation from biomass in 2014, TOE	217541
Gross electricity generation from biogas in 2013, TOE	21411
Biomass production in 2014, TOE	2684103
Biogas production in 2014, TOE	81996
Liquid biofuels production in 2014, kt	351

Republic of Korea

Gross electricity generation from biomass in 2013, TOE	42993
Gross electricity generation from biogas in 2013, TOE	52365
Gross heat production from biomass in 2013, TOE	51830
Gross heat production from biogas in 2013, TOE	13137
Biomass production in 2013, TOE	952542
Biogas production in 2013, TOE	236864
Liquid biofuels production in 2013, kt	348
Romania	
Gross electricity generation from biomass in 2014, TOE	39037
Gross electricity generation from biogas in 2013, TOE	4300
Biomass production in 2014, TOE	3645696
Biogas production in 2014, TOE	19299
Liquid biofuels production in 2013, kt	178
Russia	
Gross electricity generation from biomass in 2013, TOE	3182
Gross heat production from biomass in 2013, TOE	766624
Biogas production in 2013, TOE	3029785
Senegal	
Gross electricity generation from biomass in 2013, TOE	5074
Biomass production in 2013, TOE	1732063
Slovakia	
Gross electricity generation from biomass in 2014, TOE	78762
Gross electricity generation from biogas in 2013, TOE	18315
Gross heat production from biomass in 2013, TOE	168793
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REFERENCES

- Silverwood A, Canadian Biomass Magazine
- Antoni, Zverlov & Schwarz (2007), *Biofuels for microbes*, *Applied Microbial Technology*
- Goodland A, *A New Push for Renewable Energy in Belize*, *ReVolt (Worldwatch Institute blog)*
<http://blogs.worldwatch.org/revolt/a-new-push-for-renewable-energy-in-belize/>
- BP (2015), Review of World Energy <http://TOE.bp.com/en/global/corporate/energy-economics/statistical-review-of-world-energy/renewable-energy/biofuels-production.html>
- BioenergyNW (2015), Half a million jobs, €78 billion per year: The socio-economic impact of the European bio-based industry. <http://bioenergy-nw.eu/socio-economic-impact-of-european-bio-based-industry/#.Vkr3aXbhBhE>
- Dolezal A, et al (2013), *The way forward for renewable energy in Central America*
- FAO statistics, <http://faostat3.fao.org/browse/F/FO/E>
- Global Alliance for Clean Cookstoves,
<http://TOE.cleancookstoves.org/our-work/the-solutions/cookstove-technology.html>
- Gordon Murray (2016), Western Forest Industry Conference
- Kjell Andersson (2015), *Bioenergy – the Swedish Experience, second edition*, Svebio
- IEA (2014), Low Cost Long Distance Biomass Supply Chains, Task 40
- IEA (2013), Large Industrial Users of Energy Biomass
<http://TOE.bioenergytrade.org/downloads/t40-large-industrial-biomass-users.pdf>
- IEA Database,
<http://TOE.worldenergyoutlook.org/resources/energydevelopment/energyaccessdatabase/>
- IRENA (2014), Remap 2030 Global Bioenergy Supply and Demand Projections, Working paper
http://TOE.irena.org/remap/IRENA_REmap_2030_Biomass_paper_2014.pdf
- IRENA RE_Jobs review 2015,
http://TOE.irena.org/DocumentDownloads/Publications/IRENA_RE_Jobs_Annual_Review_2015.pdf
- Natural Forests Standards, <http://TOE.naturalforeststandard.com/nfs-standard/definitions/>
- Power technology (2015), Dong Energy joins Danish team to explore producing biogas from biomass. <http://TOE.power-technology.com/news/newsdong-energy-joins-danish-team-to-explore-producing-biogas-from-biomass-4682491>
- REN21 (2015), Global Status Report, p.156, http://TOE.ren21.net/wp-content/uploads/2015/07/REN12-GSR2015_Onlinebook_low1.pdf
- Renovação project, <http://TOE.unica.com.br/renovacao-project/>

SNVWorld (2013), http://TOE.snvworld.org/download/publications/snv-cimne-hivos_2013_-_plan_nacional_de_biodigestores_de_bolivia.pdf

Thinning is the planned removal of trees to promote woodland health,
<http://ext.wsu.edu/forestry/Thinning.htm>

Tracking Clean Energy Progress (2015), IEA. <http://TOE.iea.org/etp/tracking2015/>

World Energy Council (2010), Water for Energy report

WBA (2014), Global Bioenergy Statistics
<http://TOE.worldbioenergy.org/content/wba-gbs>

WBA (2015), Oil price survey
http://worldbioenergy.org/sites/default/files/150206%20WBA%20Oil%20price%20drop%20summary%20%28Feb%202015%29_0.pdf

World Bioenergy Association (2016), <http://worldbioenergy.org/content/wba-gbs>

World Energy Council (2013), World Energy Resources report

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KEY FINDINGS

1. Treating residual waste with various Waste-to-Energy (WtE) technologies is a viable option for disposal of Municipal Solid Waste and energy generation. There are many factors that will influence the choice of technology and every region will have to properly assess its specific context to implement the most reasonable solution.
2. The global WtE market was valued at US\$25.32 billion in 2013, a growth of 5.5% on the previous year. WtE technologies based on thermal energy conversion lead the market, and accounted for 88.2% of total market revenue in 2013.
3. The global market is expected to maintain its steady growth to 2023, when it is estimated it would be worth US\$40 billion, growing at a CAGR of over 5.5% from 2016 to 2023.
4. Europe is the largest and most sophisticated market for WtE technologies, accounting for 47.6% of total market revenue in 2013. The Asia-Pacific market is dominated by Japan, which uses up to 60% of its solid waste for incineration. However, the fastest market growth has been witnessed in China, which has more than doubled its WtE capacity in the period 2011-2015.
5. Biological WtE technologies will experience faster growth at an average of 9.7% per annum, as new technologies (e.g. anaerobic digestion) become commercially viable and penetrate the market.
6. From a regional perspective, the Asia-Pacific region will register the fastest growth over this period (CAGR of 7.5%), driven by increasing waste generation and government initiatives in China and India; and higher technology penetration in Japan.
7. It is estimated that global waste generation will double by 2025 to over 6 million tonnes of waste per day and the rates are not expected to peak by the end of this century. While OECD countries will reach 'peak waste' by 2050, and East Asia and Pacific countries by 2075, waste will continue to grow in Sub-Saharan Africa. By 2100, global waste generation may hit 11 million tonnes per day.
8. The need to increase the share of renewable energy and reduce GHG emissions, along with raising environmental consciousness to protect the environment from polluting and unsustainable practices such as landfilling, will have a positive impact on WtE market development.
9. WtE remains a costly option for waste disposal and energy generation, in comparison with other established power generation sources and for waste management, landfilling.

10. Combustion plants are no longer a significant source of particulate emissions owing to the implementation of governmental regulations on emission control strategies, reducing the dioxin emissions by 99.9%.
11. At a global level, the influence of WtE on energy security may well be on a limited scale, especially in terms of power generation. While waste production is projected to increase, WtE suffers from limited levels of resource availability and hence power generation capacity, in comparison with the conventional energy resources.

INTRODUCTION

Waste is an inevitable product of society, and one of the greatest challenges for future generations is to understand how to manage large quantities of waste in a sustainable way. One approach has been to minimise the amount of waste produced, and to recycle larger fractions of waste materials. However, there still is a considerable part of undesired end-products that must be taken care of, and a more suitable solution than simple landfilling needs to be found.

The waste management sector faces a problem that it cannot solve on its own. The energy sector, however, is considered to be a perfect match, because of its need to continuously meet a growing energy demand. Waste is now not only an undesired product of society, but a valuable energy resource as well. Energy recovery from waste can solve two problems at once: treating non-recyclable and non-reusable amounts of waste; and generating a significant amount of energy which can be included in the energy production mix in order to satisfy the consumers' needs.

The interaction between waste management solutions and energy production technologies can vary significantly, depending on multiple factors. Different countries across the world choose to adopt different strategies, depending on social, economic and environmental criteria and constraints. These decisions can have an impact on energy security, energy equity and environmental sustainability when looking at the future of the energy sector. If waste-to-energy (WtE) technologies are developed and implemented, while following sustainability principles, then a correct waste treatment strategy and an environment-friendly energy production can be achieved at the same time, solving challenges in both the waste management and energy sectors.

DEFINITIONS AND CLASSIFICATIONS

Municipal Solid Waste (MSW) is classified and defined in various ways depending on the country and what waste management practices are employed. For example, Eurostat (2012) identifies MSW as produced by households or by other sources such as commerce, offices and public institutions. The waste is collected by or on behalf of local authorities and is disposed of through the waste management system¹. The differences in MSW definitions create uncertainty when assessing waste management and national performance, but also inconsistency in data collection as there are overlaps between waste categories across countries, making disaggregation difficult².

¹ Eurostat (2012a) 'Generation and treatment of municipal waste (1 000 t) by NUTS 2 regions',

² European Environment Agency (2013)

When considering waste as an energy resource, it is important to take into account the composition of the different types of available waste. Municipal Solid Waste (MSW) from residential, industrial and commercial sources is the most common waste stream used for energy recovery. However, construction waste, bio-waste from agriculture and forestry activities, hazardous waste and many others also can be considered feasible for energy recovery, depending on their specific composition, their energy content and the specific needs of society in terms of waste disposal. Table 1 shows the different recognised sources of waste and their respective compositions.

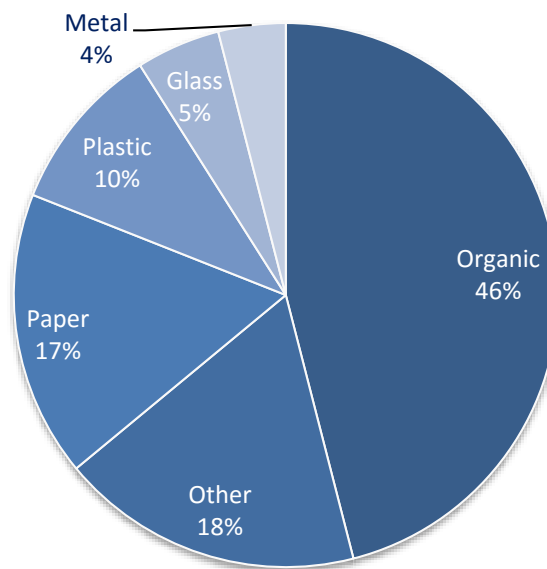
TABLE 1: TYPES AND SOURCES OF WASTE

Source / type		Composition
Municipal solid waste (MSW)	Residential	Food wastes, paper, cardboard, plastics, textiles, leather, yard wastes, wood, glass, metals, ashes, special wastes (e.g. bulky items, consumer electronics, white goods, batteries, oil, tyres), household hazardous wastes, e-wastes.
	Industrial	Housekeeping wastes, packaging, food wastes, wood, steel, concrete, bricks, ashes, hazardous wastes.
	Commercial & institutional	Paper, cardboard, plastics, wood, food wastes, glass, metals, special wastes, hazardous wastes, e-wastes.
	Construction & demolition	Wood, steel, concrete, soil, bricks, tiles, glass, plastics, insulation, hazardous waste.
	Municipal services	Street sweepings, landscape & tree trimmings, sludge, wastes from recreational areas.
Process waste		Scrap materials, off-specification products, slag, tailings, top soil, waste rock, process water & chemicals.
Medical waste		Infectious wastes (bandages, gloves, cultures, swabs, blood & bodily fluids), hazardous wastes (sharps, instruments, chemicals), radioactive wastes, pharmaceutical wastes.
Agricultural waste		Spoiled food wastes, rice husks, cotton stalks, coconut shells, pesticides, animal excreta, soiled water, silage effluent, plastic, scrap machinery, veterinary medicines.

Sources: Hoorweg & Bhada-Tata (2012); ETC/SCP (2013)

The major fractions of solid waste include paper, organic material, plastics, glass, metal and textiles. Figure 1 illustrates the composition of solid waste worldwide. As can be seen, nearly half of the produced waste from society is organic. Specific waste products deriving from construction, industrial and commercial waste are not specified in this figure, but in some cases can represent the majority of a region's waste production.

FIGURE 1: COMPOSITION OF GLOBAL MSW



Source: Hoorweg & Bhada-Tata (2012)

There are numerous technical criteria that have to be met for WtE adoption, and take precedence over other considerations to ensure the reliable operation of a would-be WtE facility. Some of the commonly considered factors are mentioned below.

Waste as a Fuel

The choice of WtE technology will be largely dependent on the nature and volume of the incoming waste stream. A key factor is the energy content (calorific value) of the waste, which determines how much energy can be extracted from it. Table 2 shows approximate net calorific values for common fractions of MSW.

TABLE 2: APPROXIMATE NET CALORIFIC VALUES FOR COMMON MSW FRACTIONS

Fraction	Net Calorific Value (MJ/kg)
Paper	16
Organic material	4
Plastics	35
Glass	0
Metals	0
Textiles	19
Other materials	11

Source: ISWA (2013)

For example, as a general rule, WtE incineration should only be considered if the incoming waste stream has an average net calorific value of at least 7 MJ/kg (i.e. combustion process is self-sustaining). In addition, for optimal operation of the plant, the supply of combustible MSW should at least amount to 100,000 tonnes / year (but could be lower for plants in isolated areas)³. Seasonal changes in waste quality, such as during holidays and festivals, and local traditions which may impact the nature of waste must also be taken into consideration.

These requirements represent a specific challenge for WtE implementation in developing and emerging countries; where waste has significant water content and the organic fraction of the waste is relatively high, and sophisticated waste collection and transportation structures are not in place. In these cases, biochemical methods of energy conversion should be the preferred option. Meanwhile in China, improvements to existing incineration technology have enabled it to unleash the potential of WtE in the country, as described in the following case study.

³ ISWA (2013)

WTE INCINERATION FOR CHINA

Waste is a subject of growing concern in China, as is the case in many emerging economies. The country generates about 300 million tonnes of MSW annually, and this figure is expected to exceed half a billion tonnes per annum by 2025⁴. In addition, simple landfilling of waste is leading to secondary pollution – either through methane leakage or by the contamination of groundwater.

Since the turn of the century, China has made a concerted effort to utilise WtE as a part of its waste management strategy. However, even this is not straightforward. MSW has a high proportion of food waste, resulting in high moisture content and a relatively low net calorific value (3-5 MJ/kg on average, compared to 8-11 MJ/kg in Europe). The waste also has seasonal variations, giving it complicated heating properties.

Incineration technology originated in Europe is not well suited to treat waste with the mentioned properties. Therefore, research in China has developed new incineration plants based on circulating fluidised bed (CFB) technology to recover energy from its waste. CFB technology is proven to be better suited for high moisture content waste, hence making it potentially attractive for implementation in other emerging economies. Dioxin levels reported from these new plants are lower than EU standards. The plants are also capable of processing sewage sludge and other waste sludges, of which China produces 40 million tonnes a year, once the waste is pre-dried. Ongoing research is targeted towards reducing the amount of sewage-sludge ash produced from incineration, and integrating the pre-dried ash with MSW to produce more fuel for the plant.

There are currently 28 CFB WtE plants in operation in China, the largest of which was built in 2012 and processes 800 tonnes of waste per day⁵.

Waste, as a fuel, cannot compete with fossil fuels due to its low calorific value and heterogeneous composition. The Table 3 below shows as an example calorific values of selected fuels.

⁴ Coolsweep, 2014, Global analysis of the waste-to-energy field

⁵ Zhejiang University, 2015

TABLE 3: CALORIFIC VALUES OF SELECTED FUELS

Fuel	Calorific Value (MJ/kg)
Natural gas	36-50
Diesel	46
Black coal, various types	29-32.7
Lignite briquettes	21
Refuse derived fuel, in Germany	13-23
Wood	15
Crude lignite	10
Residual waste, unsorted, in Austria	8-12
Residual waste, unsorted, in China	3.5-5

Source: Ecoprog (2015⁶)

APPLICATIONS

Electricity

Electricity can be produced from waste through direct combustion, and the released heat is utilised to produce steam to drive a turbine. This indirect generation has an efficiency level of about 15% to 27%, with modern plants reaching the higher end of the range. The electrical efficiency rate from incineration is usually higher than from gasification due to lower operating temperatures, steam pressure and overall energy required to run the plant.

Gasification and pyrolysis processes produce a combustible synthetic gas (syngas) that can either be used to produce electricity through the process presented above, or further refined and upgraded to for direct generation in a gas turbine or engine. Greater efficiency

⁶ Ecoprog (2015)

is realised from direct combustion in gas turbines or engines, rather than from a steam turbine⁷.

Heat

The conventional method to generate heat from waste is through combustion or syngas expanded in a boiler system to produce steam. Technological advancements made possible the upgrade of syngas to methane that can be injected in the gas network and utilised in domestic boilers. This procedure could be more effective as the heat is produced in a high efficiency boiler where it is needed. However, a more efficient method of up to 90% is to burn waste in cement kilns where the heat is directly used in the process, though the market potential is small. Tackling challenges of finding long term customers for the heat produced and finances to support the infrastructure costs is essential to make this process commercially viable⁸.

Combined Heat and Power (CHP)

WtE plants can produce heat and power simultaneously using a CHP unit that raises the overall efficiency to up to 40%. In this context, the heat that is generated during electricity production is captured and utilised. A constant demand for the heat will yield the highest economic benefits, and it depends on the location of the plant and the possibility to transfer the heat to, for instance, industrial sites that utilise heat in their operations or district-heating systems that can send it to the neighbouring community or commercial properties.

The challenge of operating CHP systems in the optimal way is to know the relative value of electricity and heat in order to prioritise what should be produced more according to demand. This happens because there is a trade-off between heat and electricity, meaning that as more heat is produced, the output of electricity will decrease due to less amount of energy available. Conversely, gas engines are not affected in the same way⁹.

Transport Fuels

WtE processes can also generate fuels that can be utilised in the operation of transport vehicles. The syngas produced by gasification and pyrolysis technologies can be consumed in vehicle engines if upgraded to bio-methane. Syngas can also be used to make synthetic diesel and jet fuel. Other fuels include hydrogen, ethanol and biodiesel. Oil can be produced through pyrolysis that requires further treatment to be converted to petrol or diesel. Transport fuels can be a more efficient method of utilising energy from waste if the energy requirement for making the fuels is low. However, this is not always the case and an example of an energy intensive process is the purification of syngas necessary for making it effective to run an engine.

⁷ Defra (2014)

⁸ Defra ibid

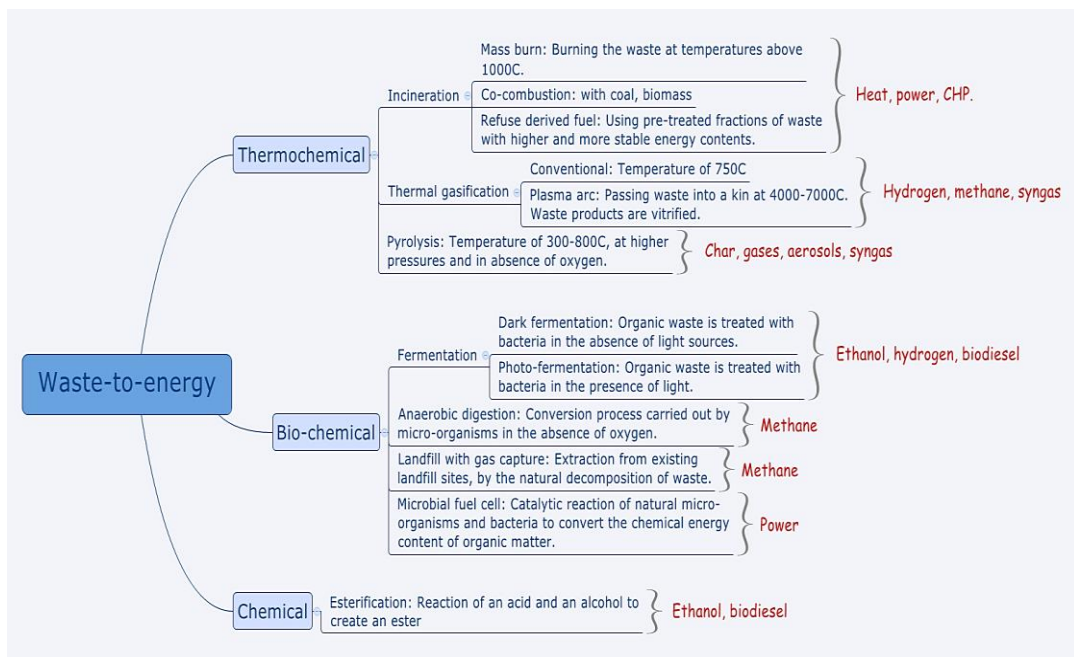
⁹ Defra ibid

1. TECHNOLOGIES

Energy conversion from waste can be obtained by utilising different technologies. Each one of these WtE solutions has specific characteristics, and can be more or less feasible depending on many parameters. Factors include the type and composition of waste, its energy content, the desired final energy form, the thermodynamic and chemical conditions in which a WtE plant can operate, and the overall energy efficiency.

The following list of WtE technologies¹⁰ gives an overall picture of the available options on the market. There are also new developments and research projects aimed at promoting alternatives to the most mature and established technologies.

FIGURE 2: CURRENT TECHNOLOGIES



THERMOCHEMICAL CONVERSION

Thermo-chemical conversion technologies are used to recover energy from MSW by using or involving high temperatures. They include combustion or incineration, gasification and

¹⁰ Lo Re, Piamonti, & Tarhini (2013)

pyrolysis. The main difference among these technologies is the amount of excess air and temperature within the process that leads to the conversion of final product CO₂ and water, or to intermediate useful products keeping aside other technological differences. The dry matter from MSW is most suitable feedstock for thermochemical conversion technologies.

Combustion

Combustion of MSW is the complete oxidation of the combustible materials contained in the solid waste fuel, and the process is highly exothermic. During combustion of solid waste, several complex processes happen simultaneously. Initially, the heat in the combustion chamber evaporates the moisture contained in the solid waste and volatilises the solid waste components. The resulting gases are then ignited in the presence of combustion air to begin the actual combustion process. The process leads to the conversion of waste fuel into flue gas, ash and heat. The heat released is used to produce a high-pressure superheated steam from water, which is sent either to the steam turbine that is coupled with generator to produce electricity, or used to provide process steam. It is important to note that the bottom and fly ashes that are formed by the inorganic constituents of the waste affects the energy balance through its mean heat capacity, even though it is not particularly participated in the combustion process¹¹. Depending on the bottom ash treatment options, ferrous and non-ferrous metals can also be recovered and the remaining ash can be further enhanced to be used for road construction and buildings¹².

Gasification

Solid waste gasification is the partial oxidation of waste fuel in the presence of an oxidant of lower amount than that required for the stoichiometric combustion¹³. The gasification process breaks down the solid waste or any carbon based waste feedstock into useful by-products that contain a significant amount of partially oxidised compounds, primarily a mixture of carbon monoxide, hydrogen and carbon dioxide. Furthermore, the heat required for the gasification process is provided either by partial combustion to gasify the rest or heat energy is provided by using an external heat supply¹⁴. The produced gas, which is called syngas, can be used for various applications after syngas cleaning process, which is the greatest challenge to commercialise this plant in large scale. Once the syngas gas is cleaned, it can be used to generate high quality fuels, chemicals or synthetic natural gas (SNG); it can be used in a more efficient gas turbines and/or internal combustion engines or it can be burned in a conventional burner that is connected to a boiler and steam turbine¹⁵. However, the heterogeneous nature of the solid waste fuel makes the gasification process

¹¹ Consonni, & Viganò (2012)

¹² Grosso, et al. (2011)

¹³ Arena (2012), Higman, (2011), Eremed et.al. (2015)

¹⁴ Arena (2012), Higman (2011)

¹⁵ Arena (2012)

very difficult together with the challenges of syngas cleaning, and there are not many large-scale stand-alone waste gasification plants in Europe.

Pyrolysis

Pyrolysis of solid waste fuel is defined as a thermo-chemical decomposition of waste fuel at elevated temperatures, approximately between 500°C and 800°C, in the absence of air and it converts MSW into gas (syngas), liquid (tar) and solid products (char). The main goal of pyrolysis is to increase thermal decomposition of solid waste to gases and condensed phases. The amount of useful products from pyrolysis process (CO, H₂, CH₄ and other hydrocarbons) and their proportion depends entirely on the pyrolysis temperature and the rate of heating¹⁶.

It is important to note that the mechanical treatment ahead of gasification, sensitivity to feedstock properties, low heating value of waste fuel, costly flue gas clean-up systems, difficulty of syngas clean-up and poor performance at small scale have been a great challenge during gasification of MSW¹⁷.

Table 4 describes the main differences between the waste thermal processes described above.

TABLE 4: COMPARISON BETWEEN PYROLYSIS, GASIFICATION AND COMBUSTION

Pyrolysis	Gasification	Combustion
Normally no air	Sub stoichiometric air Exothermic/Endothermic	Excess air Very exothermic
Only heat (external or internal)	Lower total volumetric flow	Higher volumetric flowrate
Want liquid, gases not desired	Lower fly ash carry over	Fly ash carry over
Pollutants in reduced form (H ₂ S, COS)	Pollutants in reduced form (H ₂ S, COS)	Pollutants in oxidised form (Sox, Nox etc)

¹⁶ Higman. (2011)

¹⁷ Consonni, & Viganò (2012)

Higher char	Char at low temperatures Vitrified slag at high	Bottom ash
Scale: ~10 tonnes/day	Scale: ~100 tonnes/day	Scale: ~1500 t/day
No additional oxygen (only heat)	Some additional oxygen (or air)	Much additional oxygen (or air)

Source: Asme (2013¹⁸)

BIOCHEMICAL CONVERSION

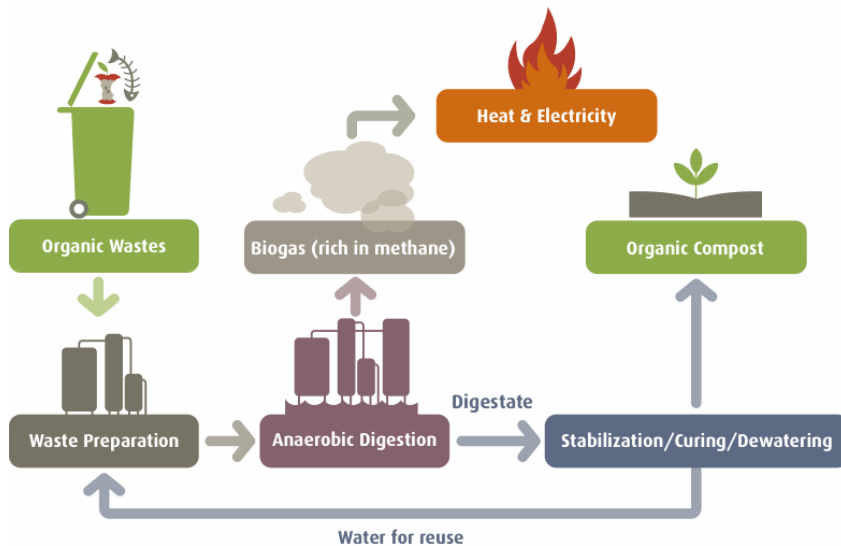
Biological conversion technologies utilise microbial processes to transform waste and are restricted to biodegradable waste such as food and yard waste. Accordingly, the wet matter from the MSW (the biogenic fraction) and agricultural waste are the most suitable feedstocks for biochemical conversion technologies.

Anaerobic Digestion (AD)

AD is a process by which organic material is broken down by micro-organisms in the absence of oxygen, producing biogas, a methane-rich gas used as a fuel, and digestate, a source of nutrients used as fertiliser. The time of operation per cycle, meaning how long it takes for the organic waste to be processed by an AD plant, is usually 15 to 30 days. The biogas naturally created in sealed tanks is utilised to generate renewable energy in the form of electricity or heat with a combined heat and power unit (CHP). The bio-fertiliser is pasteurized to make it pathogen free and can be applied twice a year on farmland, successfully replacing the fertilisers derived from fossil fuels. The technology is widely used to treat wastewater and can also be effectively employed to treat organic wastes from domestic and commercial food waste, to manures and biofuel crops¹⁹.

¹⁸ Goff, Norton and Castaldi (2013)

¹⁹ <http://www.biogas-info.co.uk/about/>

FIGURE 3: ILLUSTRATION OF AD PROCESS TREATING BIODEGRADABLE MSW

Source: Iona Capital (2016)

The anaerobic digestion process occurs in multiple steps and involves a community of micro-organisms, as follows:

- Hydrolysis – complex polymers are broken down by hydrolytic enzymes into simple sugars, amino acids and fatty acids
- Acidogenesis – simple monomers are broken down into volatile fatty acids
- Acetogenesis – the products of acidogenesis are broken down into acetic acid
- Methanogenesis – methane and carbon dioxide are produced

There are many types of AD systems that operate in different ways as well. They are usually classified as follows:

- **Mesophilic or Thermophilic:** The former system operates at temperatures between 25-45°C, while the latter process requires higher temperatures of 50-60°C. Thermophilic systems have a faster biogas production per unit of feedstock and m³ digester, and are more effective at clearing the digestate of pathogens. As they need more energy for heating, these systems have higher costs and require more management than mesophilic ones.
- **Wet or Dry:** this refers to the AD feedstock, but the difference between the two is not significant. Wet AD is 5-15% dry matter and can be pumped and stirred; while dry AD is over 15% dry matter and can be stacked. Dry AD tends to be cheaper to operate as there is less water to heat and there is more gas production per unit of feedstock. In contrast, wet systems require lower capital costs for installation, but dry systems tend to be favoured for MSW treatment.
- **Continuous Flow or Batch Flow:** most AD plants operate with a continuous flow of feedstock because the costs are lower and tend to give more biogas per unit of

input. It is technically challenging to open the digester and restart the system from cold every few weeks. However, there are dry systems that operate on batch flow, and multiple batch digestors with staggered changeover time can be used to overcome peaks and troughs in gas production.

- **Single or Multiple Digestors:** AD occurs in different stages, and wet systems may require multiple digestors to ensure efficiency of the process. Multiple digestors have higher capital and operating costs, require more management, but can offer more biogas per unit of feedstock.
- **Vertical Tank or Horizontal Plug Flow:** Vertical tanks take feedstock in a pipe on one side and digestate overflows through a pipe on the other. Horizontal plug flow is chosen when there is more solid feedstock. The former is cheaper and simple to operate, but presents the risk of having the feedstock for inappropriate periods of time resulting in possible economic losses. The latter is expensive to build and operate, but the rate of feedstock flow in the digester can be highly controlled²⁰.

The choice of AD technology will depend on many factors such as type of feedstock, co/single digestion, space (e.g. plants will have to have a small footprint in urban areas), desired output (e.g. more biogas for energy production, waste mitigation, bedding, digestate), infrastructure and available grants/financing. It is very flexible as it can be designed in multiple ways, according to the context in which is intended to operate.

The feedstock usually requires pre-treatment, depending on the kind available. For instance, waste food from supermarket will require removal of all packaging and screening for contaminants such as plastics and grit; while others such as manure or waste crops will need to be homogenised to reach the consistency desired for optimum fuel output²¹.

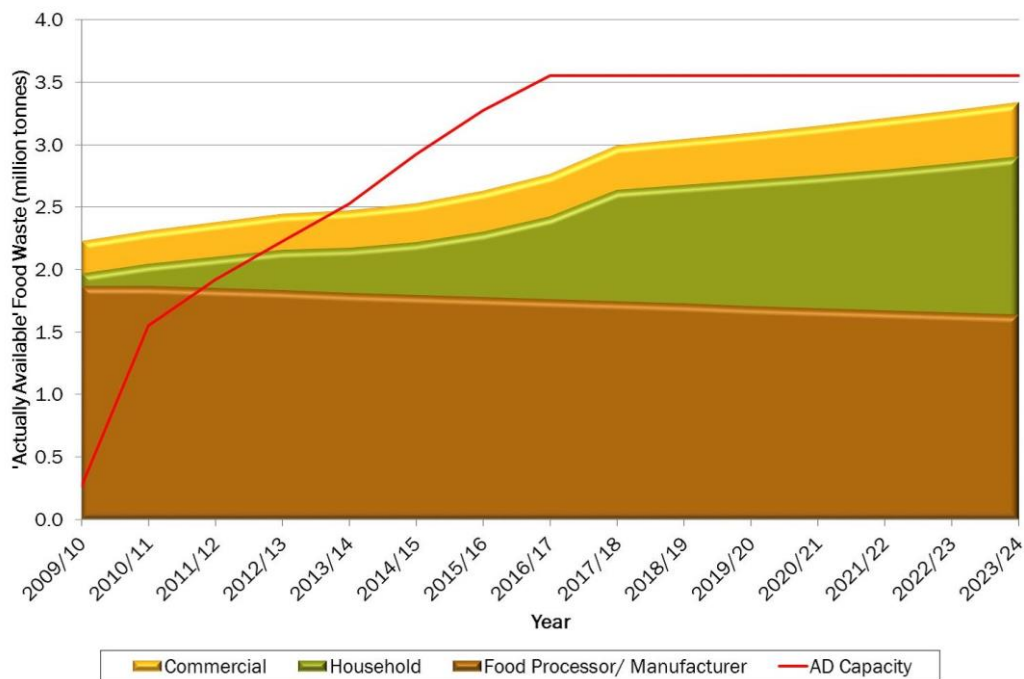
AD is a promising technology with multiple benefits for a wide range of stakeholders ranging from the local community, farmers to government. It is considered to be the optimum method for handling food waste in an environmentally safe way. While it is not a new technology, since it dates from as back as 1800s, and experienced continuous growth and technical development throughout the recent years, the market is rather small with huge room for expansion. In the UK for instance, the biggest drawback for development is the lack of feedstock access. This is not given by a lack of organic waste in general, but by the inability to readily access the streams of waste, a large proportion of it remaining in the residual waste streams. It has been observed that the AD capacity exceeds the 'actually available' food waste, even though it is estimated that UK produces 15 million tonnes of food waste per year. As of 2014, there were 2.8 million tonnes of AD capacity in the United Kingdom designed to treat organic waste from food processing and manufacturing,

²⁰ <http://www.biogas-info.co.uk/about/ad/>

²¹ WRAP (2016)

household and commercial enterprises. The capacity is forecasted to increase to 3.5 million tonnes in 2016/2017 and stall until 2023/2024. Figure 4 below shows that there is already an excess of AD capacity on the market, and not enough feedstock available to readily support the new facilities. Appropriate regulation to incentivise more effective separation of waste at source and preventing the disposal of organic waste in landfills is necessary to increase feedstock, which will enable better use of existing AD capacity²².

FIGURE 4: CAPACITY GAP BETWEEN ‘ACTUALLY AVAILABLE’ FOOD WASTE AND AD CAPACITY IN UK



Source: Eunomia Research & Consulting (2014²³)

Fermentation

Fermentation is a process by which organic waste is converted into an acid or alcohol (e.g. ethanol, lactic acid, hydrogen) in the absence of oxygen, leaving a nutrient-rich residue. Fermentation for the production of bio-ethanol, which is of great importance in the transport sector as it is a clean fuel, is done by pure cultures of selected yeast strains. Yeast fermentations are carried out both as continuous and batch fermentations, although often the batch process is preferred due to less probability of contamination. Practical bio-ethanol

²² Eunomia (2014)

²³ Eunomia Ibid

fermentation plants are large, and an optimal sized plant produces about 200,000-300,000 tonnes of ethanol per year.

Bio-ethanol production in Europe and USA is mainly from starchy substrates such as corn, wheat and triticale, whereas in Brazil the substrate is mainly sourced from sugarcane. There is a focus on developing the effective utilisation of lignocellulosic biomass as substrate because it allows a major increase of renewable substrate availability, without diminishing the availability of food plants. However, this is still significantly more expensive since pre-treatment of cellulosic substrates is required through enzymatic, thermal and acid treatments. Research attempts to increase enzyme activity and reduce enzyme costs to allow economically viable, large-scale enzyme applications. Recent processes to disintegrate biomass developed to raise ethanol yield and decrease the energy demand include alkaline, acid and solvent treatments. The by-product of ethanol fermentation is residual silage after distillation and is usually used for animal feeding, with recent focus on finding ways to recover the energy contained in it²⁴.

TABLE 5: COMPARISON BETWEEN AD AND FERMENTATION

Anaerobic Digestion	Fermentation
Hydrolysis is the initial step	Hydrolysis is the initial step
Final process step is methanogenesis	Final process step is distillation
Primary output product is biogas	Primary output products are alcohols
Currently utilised worldwide to treat MSW as well as other feedstocks	Currently, few facilities exist worldwide for MSW; facilities using other feedstocks do.

Landfill with Gas Capture

Landfills are a significant source of greenhouse gas emissions, and methane in particular can be captured and utilised as an energy source. Organic materials that decompose in landfills produce a gas comprised of roughly 50% methane and 50% carbon dioxide, called landfill gas (LFG). Methane is a potent greenhouse gas with a global warming potential that is 25 times greater than CO₂. Capturing methane emissions from landfills is not only

²⁴

Braun, R. et al (2010) Recent development in Bio-energy Recovery through fermentation

beneficial for the environment as it helps mitigate climate change, but also for the energy sector and the community.

Applications for LFG include direct use in boilers, thermal uses in kilns (cement, pottery, bricks), sludge dryers, infrared heaters, blacksmithing forges, leachate evaporation and electricity generation to name a few. LFG is increasingly being used for heating of processes that create fuels such as biodiesel or ethanol, or directly applied as feedstock for alternative fuels such as compressed natural gas, liquefied natural gas or methanol. The projects that use cogeneration (CHP) to generate electricity and capture the thermal energy are more efficient and more attractive in this sense.

The process of capturing LFG involves partially covering the landfill and inserting collection systems with either vertical or horizontal trenches. Both systems of gas collection are effective, and the choice of design will depend on the site-specific conditions and the timing of installation. They can also be employed in combination and an example is the utilisation of a vertical well and a horizontal collector. As gas travels through the collection system, the condensate (water) formed needs to be accumulated and treated. The gas will be pulled from the collection wells into the collection header and sent to downstream treatment with the aid of a blower. Depending on the gas flow rate and distance to downstream processes, the blowers will vary in number, size or type. The excess gas will be flared in open or enclosed conditions to control LFG emissions during start up or downtime of the energy recovery system, or to control the excess gas, when the capacity for energy conversion is surpassed²⁵.

The LFG treatment of moisture, particulates and other impurities is necessary, but the type and the extent will depend of the sort of energy recovery used and the site-specific characteristics. Minimal treatment can be employed for boilers and most internal combustion systems, while other internal combustion systems, gas turbines and micro-turbine applications will require more sophisticated procedures with absorption beds, biological scrubbers and others, to remove substances such as siloxane and hydrogen sulphide.

One million tonnes of MSW in the USA produces around 12,233m³ per day of LFG and will continue to produce it for another 20 to 30 years after the MSW has been landfilled. LFG is considered a good source of renewable energy, and has a heating value of about 500 British thermal units (Btu) per standard cubic foot²⁶. Benefits of using this WtE process go beyond abatement of GHG emissions and offset the use of non-renewable resources, to include other economic advantages such as revenue for landfills, energy costs reduction for

²⁵ EPA (2014)

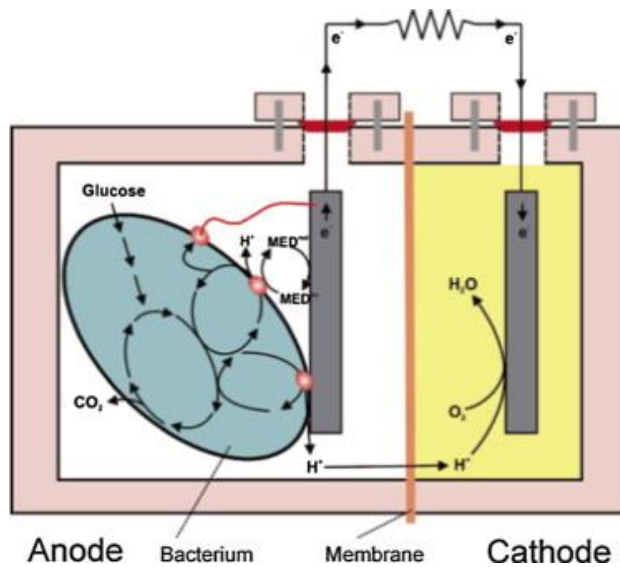
²⁶ EPA *ibid*

LFG energy users, sustainable management of landfills, local air quality improvement and job creation.

Microbial Fuel Cell (MFC)

MFCs are biochemical-catalysed systems in which electricity is produced by oxidising biodegradable organic matters in the presence of either bacteria or enzyme²⁷. Bacteria are more likely to be used in MFCs for electricity production, which also accomplish the biodegradation of organic matters and wastes. Good sources of microorganisms include marine sediment, soil, wastewater, fresh water sediment and activated sludge. MFCs consist of anodic and cathodic chambers separated by a proton exchange membrane. The anodic part is usually maintained in the absence of oxygen, while the cathodic can be exposed to air or submerged in aerobic solutions. Electrons flow from the anode to the cathode through an external circuit that usually contains a resistor, a battery to be charged or some other electrical device. Figure 5 below shows a typical two-chamber MFC²⁸.

FIGURE 5: ILLUSTRATION OF A TYPICAL TWO-CHAMBER MICROBIAL FUEL CELL



Source: Rahimnejada, M. *et al.* (2015)

The activity in a MFC consists of microbes that oxidise substrates in the anodic chamber, releasing CO₂ and producing electrons and protons in the process. The electrons are

²⁷ Rahimnejad *et al.* (2011)

²⁸ Reddy *et al.* (2010)

absorbed by the anode and transported to the cathode through an external connection. After crossing the proton exchange membrane, the protons enter the cathodic chamber where they combine with oxygen to form water. In this reaction, the substrate is broken down to CO₂ and water, with the derivative of electricity production.

This technology is suitable for small scale electricity generation in remote areas or in places where the use of conventional batteries is expensive or dangerous. An example is the use of MFCs to power sensor devices that monitor corrosion and pressure levels in deep-sea oil and gas pipelines. Their applications extend to bio-hydrogen production, waste water treatment (e.g. odour removal, desalination, and sulphides removal), biosensors (as sensor for pollutant analysis and process monitoring) and bioremediation.

This technology is considered to be still in its infancy and faces practical challenges such as low power and density. Limitations relate to the inefficiency of the cell to generate power to a sensor or a transmitter continuously. Solutions in this area include expanding the surface area of the electrodes or to use capacitors to store energy released by the MFC and used in short bursts when needed. Research in this field proposed a design of MFC that amplifies power generation by removing the proton exchange membrane, which creates internal cell resistance, as follows: single chamber, stacked and up flow MFC. Furthermore, MFCs cannot operate at low temperatures because microbial reactions are slow at low temperatures. Commercial application of this environmentally friendly WtE technology is not yet feasible due to a lack of manufacturing capacity to produce the reactor cathodes and high costs of electrode materials²⁹.

CHEMICAL CONVERSION

Esterification

The esterification process involves the reaction of a triglyceride (fat/oil) with alcohol in the presence of an alkaline catalyst such as sodium hydroxide. A triglyceride has a glycerine molecule as its base with three long fatty acids attached. The alcohol reacts with the fatty acids to form a mono-alkyl ester, or biodiesel, and crude glycerol, used in the cosmetic, pharmaceutical, food and painting industries. The alcohol used is usually either methanol, which produces methyl esters, or ethanol, with ethyl esters. The base applied for methyl ester is potassium or sodium hydroxide, but for ethyl ester the former base is more suitable. The esterification reaction is affected by the chemical structure of the alcohol, the acid and the acid catalyst. Biodiesel is used in the transportation sector and can be produced from oils and fats through three methods: base catalysed transesterification of oil; direct acid catalysed transesterification of oil and; conversion of the oil to its fatty acids and then to

²⁹ Logan et al. (2015)

biodiesel. Base catalysed transesterification is the most economical process to produce biodiesel³⁰.

EFFICIENCIES AND PHYSICAL CONSTRAINTS

The energy performance of WtE plants can be affected by a variety of factors. The unfavorable physical properties of the solid fuel entail a larger combustion chamber with long residence times for complete combustion. Besides, the unfavorable composition of the waste fuel implies low boiler efficiency due to high moisture content, significant auxiliary consumption due to high ash content, costly and sophisticated flue gas treatment system to effectively remove unwanted pollutants, presence of highly corrosive species in the combustion products, thus the maximum pressure and temperature adopted in the steam cycle are much below than those adopted in fossil fuel-fired plants³¹.

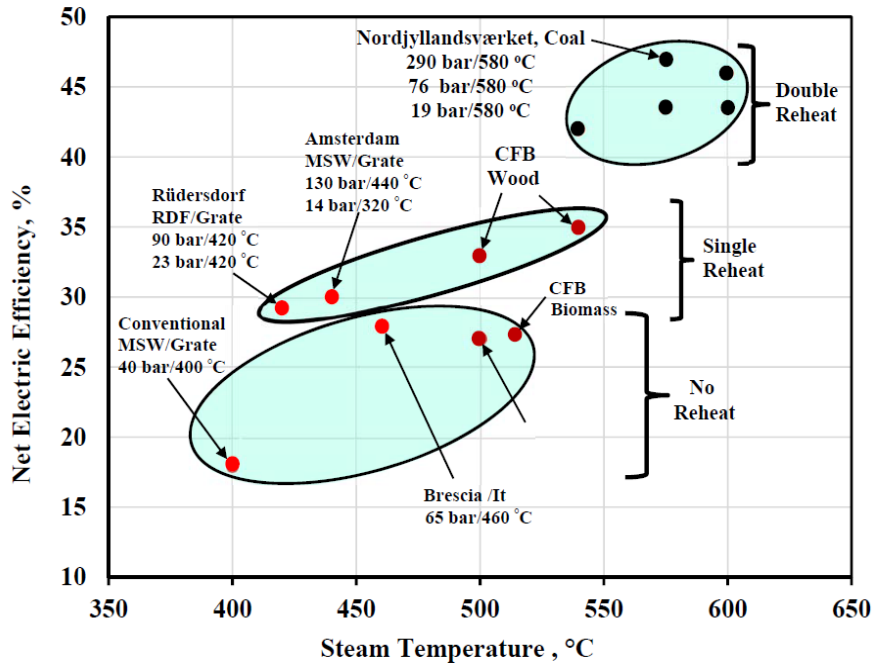
In addition, these facilities are of smaller scale and are forced to use relatively inefficient cycle configurations that reduce the productivity of the steam turbine. On average, the capital investment of WtE plants is approximately three times higher than the present coal-fired power plants³².

³⁰ <http://www.see.murdoch.edu.au/resources/info/Tech/waste/>

³¹ Consonni, Viganò & Eremed (2014)

³² Themelis and Reshadi (2009)

FIGURE 6: NET ELECTRIC EFFICIENCY OF WTE PLANTS COMPARED TO MODERN BIOMASS AND COAL FIRED POWER PLANTS



RDF – Refuse Derived Fuel CFB – Circulating Fluidised Bed It - Italy

Source: Hunsinger (2011) & Vainikka et.al (2013)

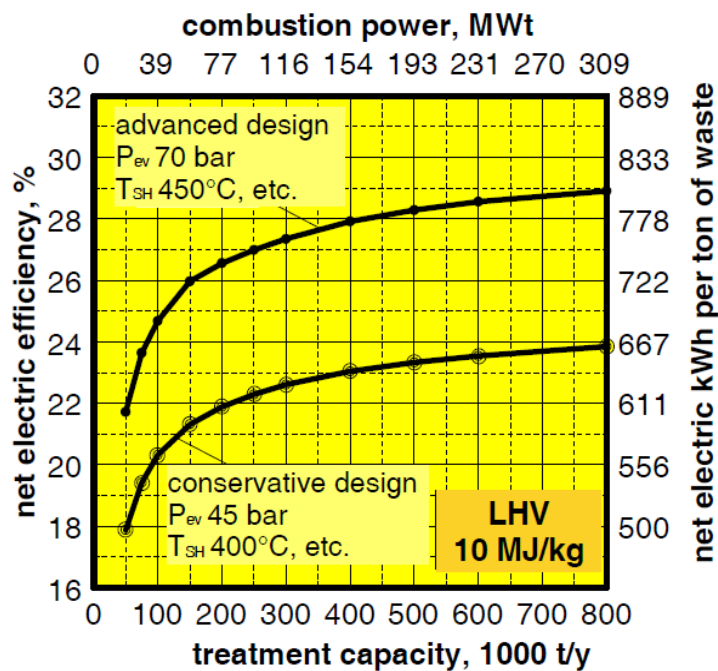
Compared to coal fired power plants, the energy performance of WtE plants is quite low as shown in Figure 6. This is because coal and waste fuel have different properties and characteristics such as quality of the fuel, size of the fuel particles, fuel composition, ash and moisture content and variable nature of the waste. Therefore, this affects the design of the combustion chamber, the amount of air and time required for complete combustion, stack losses and environmental concerns. Even though it is possible to find a double reheat coal fired plant with very high steam parameters up to 300 bar and 650°C, most WtE plants operate with steam parameters of around 40 bar/ 400°C due to corrosion problems.

The crucial parameters that increase the efficiency of WtE plants including the limitation of each factor are briefly described below. The efficiency of a plant can be boosted by finding ways to further increase the steam temperature and pressure while avoiding the corrosion problem of boiler tubes. Research in this area focuses on redesigning the boiler and adopting different steam cycle configurations, which includes external superheating by combining natural gas turbine or gas engines to a modern WtE plant³³ and steam

³³ Consonni, Viganò & Eremed (2014)

reheating. The WtE plant of Amsterdam is the first highly efficient waste fired plant with a net electric efficiency of around 30% with steam reheating concept and low steam condensation pressure, which aids plant efficiency³⁴. However, this process is affected by the water availability and ambient air conditions, depending of the type of condenser used. The efficiency of WtE plants can be further increased by up to 34% with an advanced combustion control system to reduce the excess air, a reduction of the boiler exit temperature to minimise stack losses and utilisation of CHP systems³⁵.

FIGURE 7: EFFECT OF STEAM PARAMETERS AND SCALE



Source: Consonni, Viganò and Bogale (2014³⁶)

EMERGING TECHNOLOGIES

Hydrothermal Carbonisation (HTC)

Hydrothermal Carbonisation is the chemical acceleration of natural geothermal processes using an acid catalyst. It is considered a highly efficient process which replicates the natural process of coal generation using a combination of heat and pressure to chemically transform bio-waste into a carbon dense material with similar or better properties as fossil fuel. The wet waste is heated in a ‘pressure cooker’ between 4 and 24 hours at relatively

34 Murer (2011)

35 Consonni, Viganò & Eremed (2014)

36 Ibid Consonni et al. (2014)

low temperatures of around 200°C. The feedstock is transformed into a coal-like product called ‘hydrochar’ (coalification) and is potentially ideal for carbon sequestration³⁷.

The feedstock needs pre-processing prior to carbonisation and any glass and metals should be removed. The input needs to have high moisture (>70%) in comparison with other typical thermal treatment feedstocks. The process requires an acid catalyst such as citric acid. While any organic material can be ‘coalified’ including lignocellulosic materials, it is best to use food waste owing to suitable moisture content³⁸.

This system emits the lowest amount of GHG of any biomass to fuel conversion process and the only by-product is toxin-free water. HTC is a highly efficient and environmentally sustainable method of converting biomass in solid fuel. Table 6 below shows a comparison to other biofuel production processes in terms of carbon efficiency.

TABLE 6: CARBON EFFICIENCY OF SEVERAL BIOFUEL PRODUCTION PROCESSES

Carbon Efficiency	Process
90%	Hydrothermal Carbonisation
70%	Alcoholic fermentation
50%	Anaerobic digestion / biogas
30%	Other biomass conversion processes (e.g. pyrolysis, gasification)
10%	Composting

Source: www.antanco.co.uk (2016)

Other advantages of this technology include scalability, fast and continuous operation, odour free and silent operation, hygenisation of products, available market for the ‘hydrochar’, attractive investment for private investors, thus reducing public debt³⁹.

³⁷ Stanley (2013)

³⁸ Stanley (2013)

³⁹ Hernandez (2015)

Dendro Liquid Energy (DLE)

DLE is a recent German innovation in biological treatment of waste, and presents high potential in the WtE field, being a close to 'zero-waste' technology. The reactor of DLE plants is able to process mixed waste from plastics to wood logs, producing clean fuels for electricity generation such as carbon monoxide and hydrogen. In comparison with anaerobic digestion, this technology is up to four times more efficient in terms of electric power generation, with additional benefits of no emissions discharge, effluence or nuisance problems at plant sites. The process leaves 4% to 8% inert residue that can be used as aggregate or sent to landfill.

This process system presents the following specific advantages:

- Small decentralised low-cost units
- There is no combustion involved, so no emissions abatement technology involved
- Works at moderate temperatures of 150 - 250°C, depending on the type of input material
- Accepts a wide variety of material, both wet and dry
- Energy conversion at 80% and high energy efficiency
- CO₂ neutral
- The resulted syngas is free of particulates and tar⁴⁰

⁴⁰ Ghougassian (2012)

2. ECONOMICS & MARKETS

HISTORIC AND CURRENT TRENDS

The global WtE market was valued at US\$25.32 billion in 2013, a growth of 5.5% on the previous year. WtE technologies based on thermal energy conversion lead the market, and accounted for 88.2% of total market revenue in 2013⁴¹.

Europe is the largest and most sophisticated market for WtE technologies, accounting for 47.6% of total market revenue in 2013. Increasing industrial waste, coupled with stringent EU-wide waste legislation have been the major drivers for the European market.

Switzerland, Germany, Sweden, Austria and Netherlands lead installation capacity within Europe. The Asia-Pacific market is dominated by Japan, which uses up to 60% of its solid waste for incineration. However, the fastest market growth has been witnessed in China, which has more than doubled its WtE capacity in the period 2011-2015⁴².

On the other hand, market growth in the developing economies of Sub-Saharan Africa has been largely inhibited by the large up-front costs for WtE, as well as a general lack of awareness of the benefits of WtE implementation. Low-cost landfilling remains the preferred option for the processing of waste in these parts of the world.

DRIVERS AND KEY DYNAMICS

The development of WtE market happened in contexts that created opportunities through several different drivers. These drivers include growing use of renewable energy resources, increasing amounts of waste generation globally, waste management regulations, taxes and subsidies, climate change policies to curb GHG emissions, technological advancements, access to talent, new financing opportunities, new global trends such as low fossil fuel prices, environmental degradation, circular economy, green business models, industrial symbiosis (companies that work in partnerships to share resources); and improved public perception of WtE⁴³.

Trends in Waste Generation

As modern society moves towards an increasing level of urbanisation, and with a growing population that demands higher consumption of goods and greater energy needs, the topic of waste management and energy recovery from waste becomes central for future scenarios of sustainable development.

^{41,3} Global News Wire (2015)

⁴² Yuanyuan (2015)

⁴³ Coolsweep

When it comes to waste generation as a product of society (with a particular focus on MSW), the specific characteristics of each region, country, and even city or conurbation of the world must be taken into account. These characteristics include:

- Population growth
- Rate of urbanisation
- Gross domestic product (GDP) and other economic development parameters
- Public habits, i.e. different consumption rates of different goods
- Local climate

A recent study conducted by the World Bank⁴⁴ shows the levels of waste generation per capita, for different regions of the world. As can be seen in Table 7, regions where the standards of living are higher and there is a greater consumption of goods (such as OECD countries) produce greater amounts of waste in kg/capita-day, while underdeveloped countries such as those in the South Asian Region (SAR) present lower waste generation levels per capita. Furthermore, within each single region, there can be large variations of waste production depending on local conditions and specific dynamics.

TABLE 7: WASTE GENERATION DATA IN 2012, BY REGION

Region	Total Urban Population (millions)	Total Urban MSW Generation (tonnes/day)	Urban MSW generation per capita (kg/day)
Africa	261	169 120	0.65
East Asia & Pacific	777	738 959	0.95
Eastern & Central Asia	227	254 389	1.12
Latin America & Caribbean	400	437 545	1.09
Middle East & North Africa	162	173 545	1.07

⁴⁴ Hoornweg&Bhada-Tata (2012)

OECD	729	1 566 286	2.15
South Asia	426	192 411	0.45
Total	2 982	3 532 255	1.19

Source: Hoornweg&Bhada-Tata (2012)

Figure 8 explicitly proves that economic development has a significant impact on the levels of waste generated in a certain territory. It shows a strong correlation between waste generation per capita and gross national income per capita (based on purchasing power parity).

FIGURE 8: WASTE GENERATION PER CAPITA (KG/DAY) TO GROSS NATIONAL INCOME (GNI) RATIO IN 2014 IN SELECTED COUNTRIES



Source: Navigant Research, World Bank (2014)

As a result of these waste generation rates, and taking into account projections for population growth and the increase in urbanisation, the World Bank estimates that global waste generation will nearly double by 2025 to over 6 million tonnes of waste per day. Table 8 justifies this prediction by showing the increase in waste generation per capita for each region. As can be noted from these results, OECD countries as of today produce approximately half of the world’s urban waste. However, it is estimated that by 2025 the influence of these countries on global waste generation will be strongly reduced. This is because of the efforts in terms of waste reduction and waste management in OECD countries, and a significant increase in waste generation per capita and overall waste

production for countries in developing regions of the world (e.g. in the East Asian and Pacific region). In addition, global waste generation rates are not expected to peak by the end of this century. While OECD countries will reach ‘peak waste’ by 2050, and East Asia and Pacific countries by 2075, waste will continue to grow in Sub-Saharan Africa. By 2100, global waste generation may hit 11 million tonnes per day⁴⁵.

TABLE 8: PROJECTED WASTE GENERATION DATA FOR 2025, BY REGION

Region	Total Urban Population (millions)	Total Urban MSW Generation (tonnes/day)	Urban MSW generation per capita (kg/day)
Africa	518	441 840	0.85
East Asia & Pacific	1 230	1 865 380	1.52
Eastern & Central Asia	240	354 811	1.48
Latin America & Caribbean	466	728 392	1.56
Middle East & North Africa	257	369 320	1.43
OECD	842	1 742 417	2.07
South Asia	734	567 545	0.77
Total	4 287	6 069 705	1.42

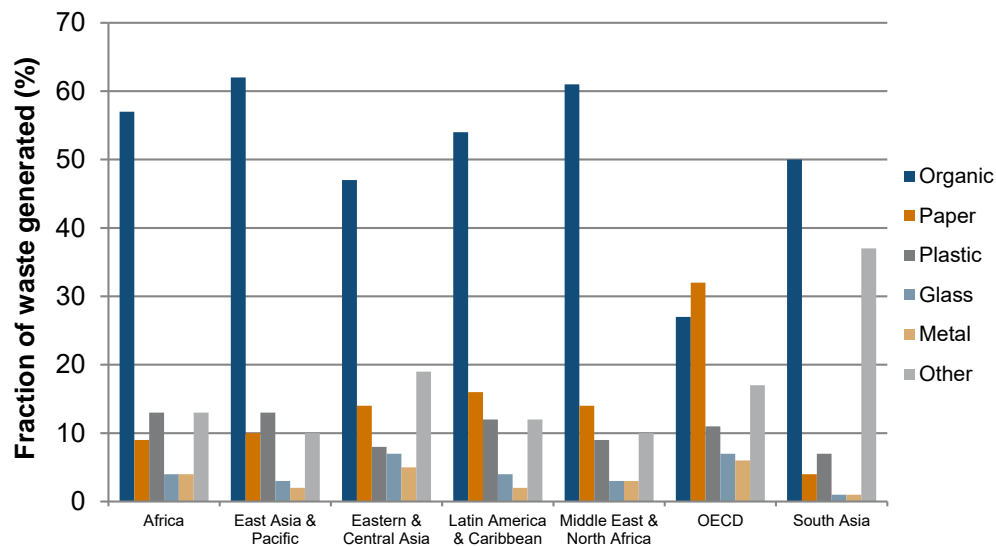
Source: Hoornweg & Bhada-Tata (2012)

Waste composition varies greatly between different areas, regions and countries of the world. It is influenced by many different factors such as culture, economic development, climate, and energy resources. Based on previous considerations, Figure 9 illustrates the different waste composition on a regional level. As can be seen, countries in the OECD

⁴⁵Hoornweg, Bhada-Tata & Kennedy (2013)

region strongly reflect the profile of the high income society, while poorer countries such as in East Asia and in the Pacific present large fractions of organic waste products.

FIGURE 9: COMPOSITION OF SOLID WASTE IN 2012, BY REGION



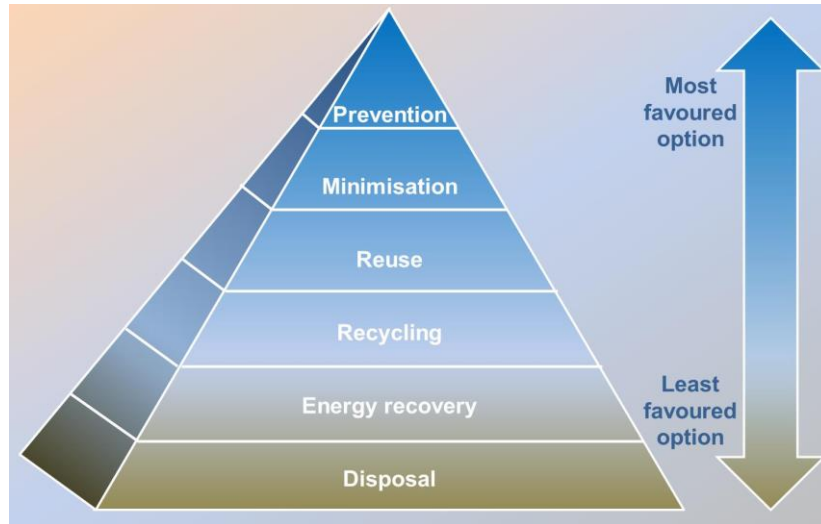
Source: Hoornweg&Bhada-Tata (2012)

Having considered differences across waste sectors for different regions of the world, similar observations can be made by focusing on the energy sector: increased economic and industrial development requires higher energy needs, most often in the form of electricity; different climates require different energy needs in the form of heating or cooling; growth in population and developing transport sectors will bring variations in the demand for fuels. Therefore, WtE technologies must be able to combine the specific needs of the waste sector with the demands of society in the energy sector in order to operate in the most efficient manner.

Overlap between Energy and Waste Management Sectors

Considering all these factors, which will surely contribute to an overall increase of waste generation, it is very important to manage these quantities of undesired materials. The waste management hierarchy, as shown in Figure 10, describes the preferred course of action for managing waste. Different versions of the hierarchy are adopted, but they all follow a step-wise process for waste where prevention, minimisation, and reuse (& recycling) of waste products are prioritised.

FIGURE 10: THE WASTE MANAGEMENT HIERARCHY

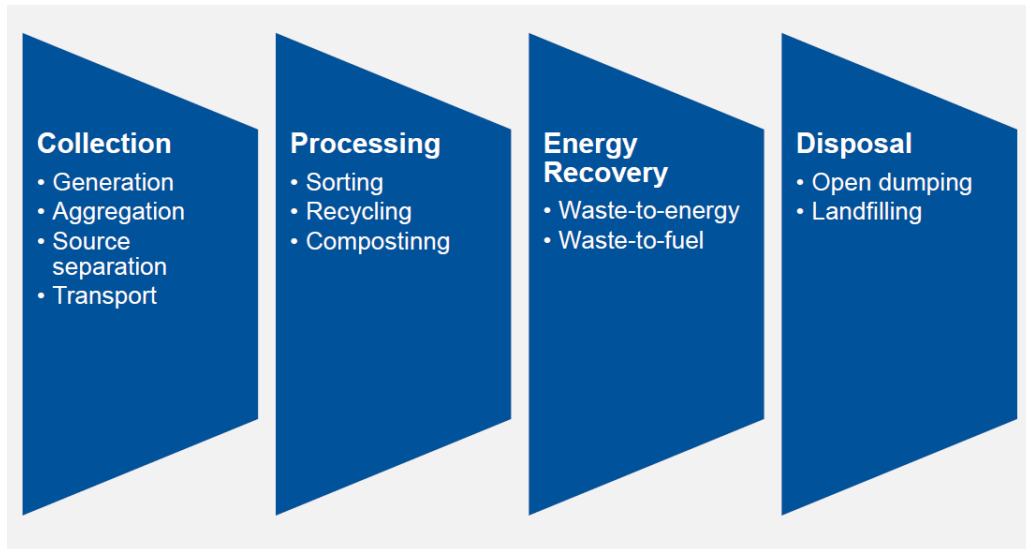


Source: Hughes (2013)

However, even by taking into account all these feasible solutions, there will always be a significant fraction of waste material that must be dealt with in a different way. WtE is a more convenient process than simple landfilling of waste, because of the beneficial side effect of producing useful energy in different forms. In this field, the waste sector is strictly connected to the energy sector. Waste materials, which originally have been used as specific products for societal needs, can be used for a second purpose: as a useful energy resource.

Sustainable waste management systems can then be developed based on the hierarchy, from waste collection to final disposal. However, in some contexts the waste hierarchy is not necessarily the most sustainable route for waste management, but adopting alternative process steps that use life cycle thinking which do not follow the hierarchy, can be a more sustainable solution. Figure 11 is an example of a waste management value chain that follows the waste management hierarchy.

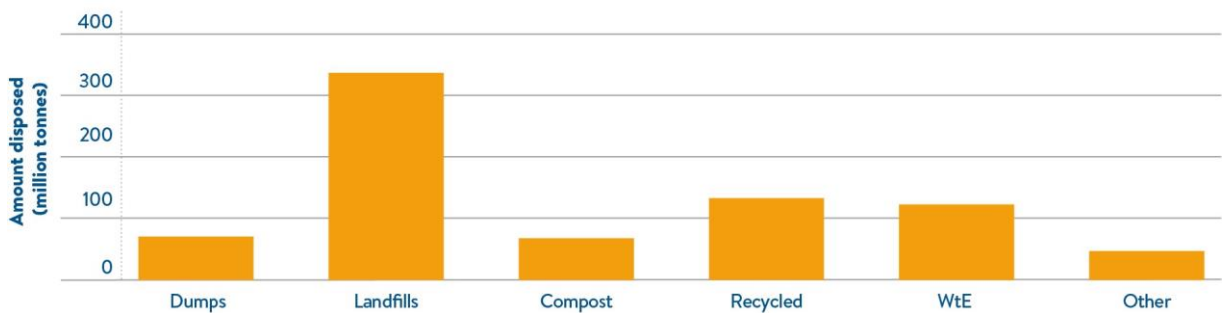
FIGURE 11: MANAGEMENT VALUE CHAIN FOR MSW



Source: Navigant Research (2014)

However, there remains a long way until a global sustainable waste management strategy is achieved. As of 2012, it is clear in Figure 12 that landfilling is by far the most utilised solution for waste disposal worldwide, despite being the least desirable waste management practice.

FIGURE 12: AMOUNT OF WASTE DISPOSED IN 2012, BY TECHNIQUE



Source: Hoornweg & Bhada-Tata (2012)

Depending on the income level and the development of each country, solutions like recycling and WtE are more or less developed. Of the estimated 122 million tonnes of waste that are used for WtE incineration – the most developed and established technology for energy recovery from waste – over 99% is treated in high-income level countries.

There is another aspect of the interaction between the waste management sector and the energy sector that is crucial for WtE plant operations. Because of the necessity to constantly deal with waste generation, WtE plants are typically required to operate at all times. In this way, the produced waste is always being managed and treated without any need for significant waste storage facilities, and thus the use of waste landfilling is minimised.

The potential of WtE implementation strongly depends on the specific economic, social and political conditions of the country where the implementation strategy must be carried out. The following classification for different countries is just one possible approach in order to analyse the various possible outcomes in terms of energy recovery from waste across the world.

TABLE 9: WTE STRATEGY IN HIGH INCOME COUNTRIES

High Income Countries		
Energy Sector	Waste Sector	WtE Strategy
Most competitive technologies implemented on both demand and supply side. Energy transmission and distribution infrastructure provides high quality services.	Practices based on sustainable waste hierarchy are implemented, with varying degrees of success. However, the undesired quantities of non-reducible and non-reusable materials remain significant.	Waste incineration with energy recovery (particularly CHP) is the preferred option. The technology is mature and well established on the market. Improvements in efficiency, generation flexibility and pollution control.
Greatest concerns related to environmental issues – improvements in efficiency of energy technologies, development in renewable energy technologies.	Hence, second-use energy recovery activities remain a feasible solution, despite environmental concerns linked on WtE technologies.	Other energy recovery solutions (gasification, pyrolysis, AD, bio-fermentation) can be locally implemented if system conditions yield a feasible economic outcome of each WtE project. Changing regulations can significantly impact technology deployment (e.g. rules on bio-residue sludge disposal).

TABLE 10: WtE STRATEGY IN MIDDLE INCOME COUNTRIES

Middle Income Countries		
Energy Sector	Waste Sector	WtE Strategy
There is a more diverse range of desirable energy vectors than in high income countries.	Inevitable increase of waste products (MSW, commercial waste, packaging); driven by industry, wealth and consumption.	Important to structure the WtE sector in relation to the needs and opportunities specific to that country.
Electricity is needed in areas where urbanisation is high, modern processes are developed, and a power grid is present.	Collection rates are variable, and there remains a sizeable informal waste sector.	Investments for implementation of WtE plants must be balanced by investments in the waste (and water) management sector.
Other required energy forms are domestic heating/cooling, process steam for industry, and synfuels for transportation (as seen in Brazil).	Collection, treatment and disposal of waste not highly supported by local and/or government authorities.	Regulatory framework around environment / emissions may not be present or effective. There needs to be an appropriate framework to drive WtE investments in a sustainable direction.

TABLE 11: WtE STRATEGY IN LOW INCOME COUNTRIES

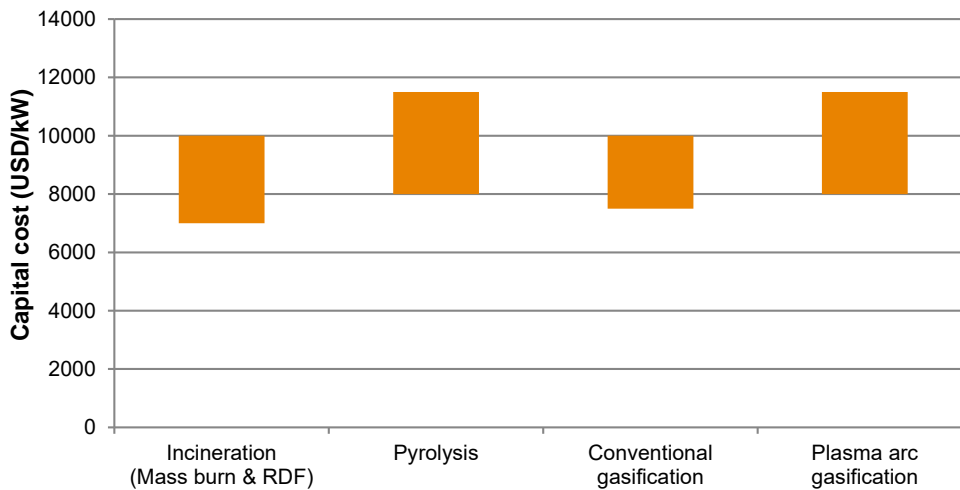
Low Income Countries		
Energy Sector	Waste Sector	WtE Strategy
Difficulty in implementing capital intensive T&D infrastructure for	Limited investments by governments and municipalities result in inefficient or non-existent	Severe limitations in the energy and waste sectors negate the potential for WtE

electricity and gas.	disposal of waste – not collected nor transported to treatment facilities / controlled landfill.	implementation.
At local level, difficulty in providing stand-alone, non-technological energy sources prevent people utilising energy as an everyday commodity.	Waste management is predominantly informal (waste picking). Recycling rates are high, but unregulated.	Local small scale WtE projects could provide improvements in terms of energy supply, waste management, pollution levels, job creation.

INVESTMENT COSTS

The capital investments for the construction and implementation of these technologies, and the costs needed to operate them for the entire lifetime of a chosen project can influence decisions when it comes to deciding the best WtE option. As of today, incineration of MSW still presents the most desirable economic conditions on the market, and is therefore the preferred option in most markets. Among the other thermal energy conversion technologies in the United States, capital costs for WtE incineration are slightly lower for the same plant output, as shown in Figure 13.

FIGURE 13: CAPITAL COSTS FOR THERMAL WTE POWER GENERATION TECHNOLOGIES IN THE UNITED STATES (15 MW OUTPUT)



Source: Stringfellow (2014)

Table 12 illustrates the differences in investment costs and main cost characteristics for WtE incineration across the world, depending on the economic conditions of different countries.

TABLE 12: INVESTMENT COSTS FOR WTE (INCINERATION)

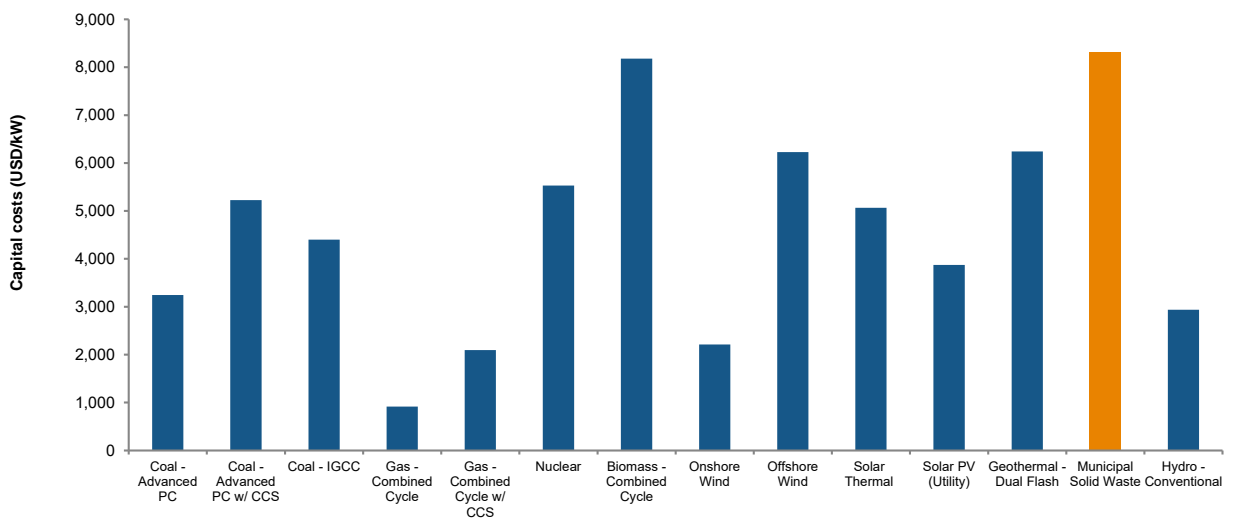
	Investment costs (US\$/yearly tonnage capacity)	Characteristics
Low-income countries	300 – 500	<ul style="list-style-type: none"> Low labour costs Low calorific value of waste Low need for structural protection of equipment
Middle-income countries	400 – 600	<ul style="list-style-type: none"> Some requirements for structural protection of plant Slightly higher calorific value of waste Higher labour cost
High-income countries (EU and	600 – 900	<ul style="list-style-type: none"> Stringent demands on equipment and safety

North America)		High architectural standard of buildings
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Source: ISWA (2013)

However, energy generation from waste remains a costly option, in comparison with other established power generation sources. Average capital costs for power generation from MSW remain much higher than for other sources in the United States, as seen in Figure 14, hence providing a barrier for the uptake of WtE across the country, particularly with the cheap availability of (shale) gas – MSW power generation capital costs are more than 8 times that of combined cycle gas plants.

FIGURE 14: CAPITAL COST ESTIMATES FOR UTILITY SCALE POWER GENERATION PLANTS IN THE UNITED STATES



Source: EIA (2013)

When it comes to the economics of various WtE technologies, the capital investment is generally high, but the costs differ according to the technology used and its size. Gasification technologies are usually more expensive than the usual grate combustion technologies. A gasification plant in the USA with a capacity of 750 tonnes per year would need roughly an investment cost of US\$550 per annual capacity tonne. Investment costs for the same technology and similar plant size can also vary significantly, due to location, site implementations and land availability. For example, a comparison between two grate combustion WtE facilities located in different cities in China showed a significant difference in capital investment. Accordingly, the WtE plant in the city of Foshan, with a capacity of 462,000 tonnes per year had an investment cost of US\$120 per annual capacity tonne, while the plant in Shanghai, with the capacity of 495,000 tonnes per year, had an

investment cost of US\$282 per annual capacity tonne. WtE technologies tend to have a lower investment cost in developing countries such as China even if they use Western technologies with CFB⁴⁶.

It is very difficult to generalise investment costs for each technology because there are regional differences in government incentives and market dynamics, and the amount of revenue gained depends on very localised conditions such as electricity prices, access to district heating network and recovery markets for recyclables (i.e. metals, paper, glass, plastic). In addition, investment costs of individual projects will vary depending on a range of factors including financing type, project developer, conditions in financial markets, maturity of technology, and risk and political factors⁴⁷.

ENERGY SECURITY

Issues linked to energy security differ from one country or region to the other, depending on the level of economic development and the availability and reliability of energy infrastructure. In regions such as Western Europe, growing concerns are linked to energy transmission and storage capacity limits, in relation to an increasing share of intermittent renewable energy generation units on the energy network. Considering the large fluctuations on the supply side, modern and efficient energy systems must be able to balance out these dynamic variations and transmit all the required energy to the demand side. If this is not achieved, then the population will be threatened by shortages of energy services. Also, due to the change of conditions within the energy sector (e.g. deregulation and privatisation of energy markets), the power flows in the existing network configuration do not necessarily follow original design criteria any more.

In less developed parts of the world, energy access remains a major challenge. As of 2013, 1.2 billion people still do not have access to electricity for lighting. Twice this population still relies on outdated stoves or open fires for cooking. It is estimated that more than 95% of people who cannot utilise modern energy services live in Least Developed Countries (LDCs) in sub-Saharan Africa and Asia⁴⁸. Energy systems at present are not sufficiently developed to ensure reliable supplies of energy to the populace. Many inhabitants dwell in remote villages and small towns, and are often not connected to an electricity grid or to possible district heating and/or cooling networks. 84% of all people who do not have access to modern energy services live in rural areas⁴⁹. Investment in a mature energy transmission system to cover the large distances between the energy generation centres and the end users has proven to be too costly for developing, but not yet thriving, economies. A realistic alternative to expanding the energy transmission and distribution infrastructure is the

⁴⁶ Themelis & Mussche (2013)

⁴⁷ Department of Energy & Climate Change (2012)

⁴⁸ IEA (2015) World Energy Outlook

⁴⁹ IEA

implementation, through both public and private sector investments, of mini-grids, stand-alone energy systems and other decentralised energy solutions which can be managed and operated locally.

At a global level, the influence of WtE on energy security may well be on a limited scale, especially in terms of power generation. While waste production is projected to increase, WtE suffers from limited levels of resource availability and hence power generation capacity, in comparison with the conventional energy resources. For example, with decreasing populations and increasing recycling rates, Sweden, Norway, Germany and the Netherlands currently do not generate enough waste to meet the demand of its WtE plants, and hence resort to import waste from neighbouring countries to keep the plants running. Developing countries with increasing energy needs will most likely rely on other types of energy for most of their generation capacity, limiting WtE to a minimal impact in this sense.

Furthermore, even in a theoretical case where waste could be seen as one of the main available energy resources of a country, the plants that will convert this resource into power are mostly characterised as base load units. This means that while available electricity capacity will increase, WtE plants will not be able to provide the necessary output flexibility required for grid balancing in regions such as Europe where the uptake of intermittent renewable power generation is a growing threat to energy security.

However, WtE could be seen as an interesting solution for energy security at a local level; a good example would be within the urban district heating and/or cooling market. Considering present and future trends both in population growth and in waste generation levels, and analysing the trends in waste recycling activities, the amount of available heat from waste treatment could be estimated and appropriately promoted.

WtE technologies would also gain traction as a reliable energy resource in remote, rural areas, and less developed countries where the energy system is not sufficiently developed. The investments necessary to build and correctly operate a WtE facility are significantly lower than those required to implement major energy transmission infrastructure to connect these areas to a main grid. Also, the fuel and primary energy source for these types of technologies is often already present on the local territory, thus fuel shipping costs can be avoided. This is the case in remote areas which are close to a reliable source of bio-waste. Forestry, agriculture and other processes which produce bio-waste can be the source of energy for local communities situated in proximity of these activities.

Depending on the needs of local communities in rural and decentralised areas, the required energy form can vary. Electricity may not always be as useful in regions of the world where electrical appliances are not commonly used. Production of biofuels, which is a privileged solution in specific developing countries, is often not important in these areas where

motorised transportation is often limited. An interesting example could be the use of anaerobic digestion facilities, which are able to treat waste streams with high organic fractions and produce biogas with relatively high energy content, the biogas then being used locally for cooking and/or heating. These types of WtE can be implemented as large scale plants, which present high capital costs but can treat large quantities of waste, or as small scale plants, which might be a more feasible option for small communities in rural areas.

3. SOCIO-ECONOMICS

ROLE OF GOVERNMENTS

Depending on the nature of a country's society and on its level of development, policy targets can and do differ greatly within and outside the economic and environmental spheres of concern. WtE implementation can be promoted or otherwise because of local policies and regulations, different public perception of the challenges related to these technologies or even possible phenomena of political entanglement, which often arise in the waste management environment.

Also, the waste treatment policies which are selected by the local governments of a specific region, country or city (e.g. separated waste collection, recycling centres, waste import/export, etc.) can strongly change the feasibility of WtE technology projects. One of the reasons for the diversity of policy approaches to waste-to-energy across all levels is the acceptance of waste as a renewable fuel. Generally, MSW is considered as a renewable source, because it cannot be depleted. The Intergovernmental Panel on Climate Change has also recognised the potential of WtE in greenhouse gas mitigation. WtE projects are eligible for offset under the Clean Development Mechanism (CDM) protocol, by displacing fossil-fuel electricity generation and limiting uncontrolled methane release from landfill. However, such as in the United States, Germany, France and Italy, MSW is not considered 100% renewable, since portions of MSW consist of non-renewable elements. Hence, only the biogenic proportion of waste (food, paper, wood, etc.) is considered renewable and this is reflected in the policies on energy extraction from waste.

Regulations and Targets

The following policy measures are granted to encourage the development of WtE:

- Government subsidies for WtE, for example, renewables certificates, feed-in tariffs and renewable heat incentives
- Zero-waste policies: WtE has gained traction in major markets thanks to policies disincentivising landfill, hence ensuring more waste is treated further up the waste hierarchy. EU legislation has placed a ban on the disposal of all recyclable waste by 2025. As of 2015, 18 countries in the EU implement bans on landfill in some form⁵⁰. Many countries also impose taxes on landfill, to make it less attractive for waste producers. In Sweden, where land for landfill disposal is relatively available and

⁵⁰ CEWEP, 2015

affordable (in the north of the country), WtE has nonetheless been a success (47% of all waste is converted to energy) as landfill fees are kept artificially high via taxation.

- Carbon taxes
- Renewables targets for WtE: These are usually made in conjunction with biomass. Table 13 shows policy targets related to waste-to-energy in countries where they exist.

TABLE 13: BIOMASS AND WASTE POLICY TARGETS IN SELECTED COUNTRIES

Country	Biomass and waste targets
China	30 GW by 2020
Germany	14% of heating by 2020
Indonesia	810 MW by 2025
Norway	14 TWh annual production by 2020
Philippines	267 MW by 2030
United States	Contained in state-level Renewable Portfolio Standards

Source: Navigant Research (2014)

Incentives

An incentive for WtE adoption that potentially cancels out the high capital investment costs comes from the several revenue streams that exist for WtE plant operators (other than the sale of energy). A direct comparison can also be made between WtE and landfilling activities in the waste management sector, regarding their operation. Capital costs and Operation & Maintenance costs are significantly higher in the case of WtE, but so are the revenues related to energy production. Also, additional costs related to environmental concerns may influence decision making.

Energy Production

If comparing any WtE technology with a traditional power plant which uses fossil fuels as an energy resource, the main benefit is given by the opposite pricing dynamics of the fuels. Waste is not a natural resource that can be utilised at a chosen rate, but it is a product of

human activity that is constantly generated and therefore must be always managed in a convenient way. Currently, because of its status of unwanted product of society, waste is not considered a positive resource but more like a problem.

When looking at the dynamics of the energy market, with particular attention to the power market, this translates into the necessity to prioritise energy generation from WtE plants. Therefore, in normal conditions, WtE plants have priority dispatch on the market, thus ensuring constant revenue from energy generation throughout the entire lifetime of the plant.

Tipping Fees

Because waste is an undesired product of society, all waste producers, from municipalities to private sectors, must spend part of their economic resources for its collection, management and disposal. Typically, if waste is used for energy recovery, each waste producer is obliged to pay a tipping fee (or gate fee) to the WtE facility in order to dispose of the waste.

If looking at this topic from the energy sector point of view, it is clear how the presence of tipping fees creates a strong benefit for a WtE production plant. The fuel utilised for energy production does not lead to additional costs for the energy producer, as is the case for fossil fuel based energy generators, but instead generates additional revenues. Tipping fees are usually measured in revenue per received tonne of waste, and vary greatly depending on the country or region in which they are implemented. Revenue from tipping fees is usually the largest stream of income for a WtE facility. Tipping fees represent up to 70% of income for WtE plants in the United Kingdom⁵¹.

If WtE tipping fees are too high, waste producers will seek alternative ways of disposing waste (e.g. illegal dumping). Also, overcapacity of WtE plants could lead to tipping fees being too low; however, tipping fees for WtE plants are usually based on a contract, and provide a guarantee for plant owners. Tipping fees may have to be subsidised for waste producers by central government / local authorities.

A comparison can be made between WtE and landfilling activities in the waste management sector. Tipping fee values for WtE and local landfilling can shift the final choice between these two options. Table 14 exemplifies the difference between WtE and landfill tipping fees in key markets.

⁵¹ Hicks & Rawlinson (2010)

TABLE 14: WtE VS LANDFILL TIPPING FEES IN SELECTED COUNTRIES (DECEMBER 2013 CURRENCY EXCHANGE RATES)

	Average WtE tipping fees (US\$/tonne)	Average landfill tipping fees (US\$/tonne)
United Kingdom	148	153
Sweden	84	193
United States	68	44

Source: SWANA (2011); WRAP (2013)

There is a correlation between high tipping fees for landfill and the uptake of WtE, and vice-versa. In the United States, where fees for landfill are relatively low, only 12% of all solid waste was converted to energy in 2011, while 54% went to landfill⁵². Shifting economic factors will also have an effect on landfill disposal fees. For example, the current low oil and gas prices make transportation of waste to landfill cheap, hence making landfilling waste a more attractive option for waste producers. On the other hand, the decrease in available landfill facilities (from 6,326 in 1990 to 1,908 in 2013⁵³) will push up the cost of sending waste to landfill.

Materials Recovery

Another possible income stream for (incineration) WtE operators is from the sale of materials recovered from the ash remaining after incineration. These include metals and glass, which have no heating value, but can be sold on the secondary (scrap) market. Recovered porcelain and tiles can be sifted to extract gravel, which is used in road construction. Materials recovery and other mechanical and biological treatment (MBT) processes can be integrated into the operations of WtE plants, producing extra value from the waste as well as a higher-grade fuel (SRF) for the plant. However, the current low commodity prices may make materials recovery unviable for WtE operators.

SOCIO-ECONOMIC IMPACTS

The overlap between the waste management and energy sectors touches several points linked to human society. The environmental implications of choosing specific WtE technologies can lead to social concerns and doubts on this type of solution. The need of

⁵² Williams (2011) Waste-to-energy success factors in Sweden and the United States

⁵³ United States Environmental Protection Agency (2015)

waste treatment facilities close to urbanised areas is often in contrast with the public opinion to keep (incineration) WtE plants far away from cities because of health related issues.

There are also concerns that adoption of WtE treatment encourage production of waste, discourage recycling and are not compatible with the policies that promote a 'zero-waste' economy. In contrast, the countries that recover energy from waste also have high recycling rates, so there is no real basis for this claim. Moreover, there is no substantial evidence behind the fear that more WtE facilities translate into more wasteful management of resources. Developed countries focus on reducing waste generation, but this problem will exacerbate in developing countries due to population growth, urbanisation and higher rates of consumption. WtE plants that operate in areas where the waste hierarchy is applied are more likely to have stronger set of 'zero waste' policies, where residual waste is treated according to the energy value and environmental impact. For all of these reasons, and for many more, it is important to consider the social and political orientation of a specific location in terms of waste management before implementing and operating Waste-to-Energy facilities.

SOCIO-ECONOMIC BENEFITS

Focusing on MSW, the concentrated production of waste in urban areas is directly linked to a high energy demand in the same location. Therefore, a WtE facility which can treat waste – thus removing the complications related to land use for landfilling – and at the same time provide energy (electricity and heat) for the local population is a highly efficient solution. Incineration plants with appropriate emission control systems are largely used in countries (i.e. in northern Europe) where land availability is scarce and population density is high.

On the other hand, other types of waste can be produced far away from where the energy demand is high. This is typically the case of bio-waste from forestry activities or agriculture. In this case, the distances from the waste production site and the urban centres can be significant. For these situations, it is important to find a WtE technology that can recover energy from the waste and transfer it to the final users without having to build large infrastructure to connect these two parts of the system. An interesting choice could be an anaerobic digestion process in order to produce biogas and/or biofuels, which can then be more easily transported to where they are needed or sold on the market.

WtE facilities bring additional benefits in terms of employment and educational opportunities. Typical employment for a waste incineration plant of 50,000 tonnes per annum capacity would be 2 to 6 workers per shift. For a 24-hour operation, a typical plant would work on a three shifts system. For example, the WtE industry in the United States employed around 5,350 people nationwide in 2014, working at 85 specific sites. There were

also additional 8,600 jobs created outside the sector. The jobs generated by the sector are usually well paid, stable and support the local economy⁵⁴.

Also, the plant staff will most likely receive vocational training. New WtE plants are more likely to engage with the communities as this is not only beneficial in the light of receiving project acceptance and support, but also with regards to community integration. Accordingly, they are often built with a visitors centre to enable local groups to see the facility and learn about how it operates⁵⁵.

WASTE-TO-ENERGY POTENTIAL IN ETHIOPIA

The 50 MW WtE incineration plant under construction in Addis Ababa is touted not only as a much-needed solution to the city's growing waste problem, but also as the first of many to be developed in the country. The US\$120 million project is expected to come online in early 2017, and will process 350,000 tonnes of waste a year. The power station will be Ethiopia's first baseload plant, providing 24-hour electricity for at least 330 days of the year, and will also be the first WtE facility in Sub-Saharan Africa⁵⁶. The Ethiopian Government has identified WtE as an important part of its strategy to reduce the country's emissions, and feasibility studies on WtE adoption have been undertaken in other cities, with developers looking to expand adoption to locations in Dire Dawa, Adama, and Mekelle.

However, the development of the project, and successful operation, face a number of challenges. Analysis shows the low calorific value of the incoming waste stream will lower the power output of the plant by as much as 44%. There is also a lack of local technical expertise required to operate the plant. While the plant is partly funded by the World Bank, low energy prices and the absence of supplementary income streams and incentives (e.g. tipping fees and carbon credits) mean the plant will struggle to recoup its costs over its operational lifetime.

The waste management system in Addis Ababa is also underdeveloped. Food and paper waste are rarely separated at source. The vast majority of MSW generated in Addis Ababa is collected informally. There are private companies that collect waste in the city for a fee of about ETB 10 (US\$ 0.47) per month, but very few citizens can afford this. These issues contribute to making WtE incineration not particularly viable in the city.

The hope is that the plant's operation would lead to the development of a viable waste management system in Addis Ababa. The Ethiopian Electric Power Corporation (EEPCo), who will run the plant, is collaborating with the city's

⁵⁴ Michaels (2014)

⁵⁵ Defra (2013)

⁵⁶ <http://www.eepco.gov.et/project.php?pid=27&pcatid=9>

administration to ensure that waste collection for the plant is streamlined. While the plant will employ 100 skilled personnel, it is estimated that thousands of jobs will be created with the newly created waste collection system. It would be of interest to monitor the development of the project and the plant's operation, especially in the first 5 years, to evaluate the project's success.

SAFETY

WtE technologies, in particular incineration, produce pollution and carry potential health safety risks. There is extensive literature comprising numerous studies that investigated several aspects of the linkage between the discharged pollutants from waste incinerators and health conditions such as cancer. Waste incinerators have been highly scrutinised by the public health agencies, NGO activists and the general public, which influenced the legislators to impose stricter limits on emissions. Older MSW incinerators posed higher health risks and some epidemiological studies found a positive correlation between groups of congenital anomalies of the population living in the vicinity of a waste combustion plant. However, many studies have inconclusive results or their assessment methods are contested or do not simply convince that incinerators cause public health impacts.

Government regulators assure the general public that MSW incinerators do not endanger public health safety because it is being warranted they adhere to the prescribed safety standards. Even so, concerns still exist and they refer to the undiscovered potential effects of the combustion by-products and how they interact with the living organisms, especially because the pollutants bio-accumulate and can cause long-term effects and over a wider geographical region. It is argued in this context that the Precautionary Principle found in national and international law, which stipulates that precautionary measures should be taken if there are uncertainties about an activity producing environmental and public health risks, should be applied as the safeness of the activity should be firstly demonstrated by the proponents, and the burden of proof should not fall onto the opponents⁵⁷.

The following air emissions are associated with incineration facilities: metals (mercury, lead and cadmium), organics (dioxins and furans), acid gases (sulphur dioxide and hydrogen chloride), particulates (dust and grit), nitrogen oxides and carbon monoxide. People can be exposed to these toxic emissions in a number of ways: inhalation of contaminated air, direct skin contact with the contaminated soil or dust, and ingestion of foods that were grown in an environment polluted with these substances. The ash resulted from waste combustion processing contains varying levels of toxic chemicals and is usually disposed of in landfills.

⁵⁷ Thomson & Anthony (2008)

Research shows that the metals and organic compounds from the landfilled ash can leach and potentially contaminate the soil and the ground water⁵⁸. Nonetheless, the incinerator bottom ash can be further processed and utilised as aggregate replacement in base road construction, bulk fill, concrete block manufacture or concrete grouting⁵⁹.

The safety levels of an incineration plant can be jeopardised if the concentration of these toxic chemicals is above the established limits, the environmental controls are not properly implemented, the height of the emissions stack is not appropriate, if it is located too close to urban/residential area and in unfavourable weather conditions. While it has been argued that siting a WtE plant close to the source of waste (urban areas) is desirable as it reduces waste transportation costs, but also is able to provide additional important benefits such as district heating if the infrastructure is in place; studies have shown that locating WtE plants close to urban areas is not actually very safe since the discharged pollutants will predominantly fall in the surrounding area of the plant. Accordingly, isolated areas or industrial sites seem to be safer options for minimising contamination⁶⁰.

Criticisms of waste combustion also relate to the actual effectiveness of modern emissions abatement procedures and the inconsistency of monitoring plant operation to the highest standards. Modern plants are equipped with air emissions control technologies that can effectively remove the substances of concern. The technologies available to control emissions range from fabric filters, electrostatic precipitators to scrubbers. The best air pollution control system includes dry scrubbing that neutralises acids followed by a baghouse that filters emissions of metals and organic compounds. These technologies are useful as long as the combustion plants are properly operated and emissions controlled, and in many modern facilities computer control systems are utilised to achieve this. The cost implications of using the newest technologies that improve safeness are not negligible. This is a significant adoption barrier faced by the industry in the developing countries, along with the lack of trained personnel to successfully handle such a complex and daunting process⁶¹.

Advanced thermal technologies are considered to be much safer in terms of emissions control and toxicity of dry residue. Gasification processes do not produce ash and the substances contained in the residue are environmentally benign, while the resulting syngas is a useful fuel that substitutes fossil fuels and reduces greenhouse gas emissions.

⁵⁸ UNEP

⁵⁹ WRAP (2012)

⁶⁰ UNEP ibid

⁶¹ UNEP ibid

4. ENVIRONMENTAL IMPACTS

The environmental impacts of MSW management have been studied extensively around the world. The studies focused on the environmental performance of several methods of MSW treatment such as recycling, landfilling, incineration and anaerobic digestion. Several research papers that looked the optimal combination of MSW management in cities (for example London - Al-Salem et al., 2014, Liège - Belboom et al., 2013, Rome - Cherubini et al., 2009, Macau - Song et al., 2013, Irkutsk - Tulokhonova and Ulanova, 2013 and Seoul - Yi et al., 2011), draw similar recommendations that landfilling has the severe environmental impacts and should be minimised, recycling should be encouraged and implemented as far as possible, and energy recovery from high calorific residual waste should be maximised⁶².

LAND USE

Before a WtE plant is built, an assessment of how much land is needed for operation will be conducted, as different technologies will have different land requirements. WtE plants allocate land for feedstock, waste reception, processing requirements, storage requirements and other ancillary equipment. In addition, more land could be used for depositing bottom ash and flue residues at the production site or in a landfill. The outputs of the process (heat, electricity or steam) could also require space for connecting to, for instance, heat users, electricity sub-station or local electricity distributor⁶³. Table 15 below exemplifies the land area required for the building footprint and for the entire site (including supporting site infrastructure) for several gasification plants in the United Kingdom.

TABLE 15: SIZE AND LAND TAKE FOR SELECTED GASIFICATION PLANTS IN THE UK

Gasification Plants	Capacity (tonnes per annum)	Buildings Area	Total Land take	Indicative Stack Height
Avonmouth, Bristol	100,000 tpa	14,850 m ²	65,000 m ²	25m
Peterborough	650,000 tpa	43,776 m ²	137,600 m ²	49m

⁶² Jeswani & Azapagic (2016)

⁶³ WRAP (2012)

Sheepbridge, Chesterfield	60,000 tpa	6,806.25 m ²	45,000 m ²	21m
Sinfin Lane, Derby	190,000 tpa	10,195 m ² (of which 3,403 m ² for ATT facility)	34,000 m ²	55m
Desborough, Northants	96,000 tpa	4,782 m ²	16,800 m ²	53m

Source: Defra (2013⁶⁴)

Finding a suitable location for a WtE plant is not always that easy and every project will take into consideration different factors. For example, some plants are located in proximity of the source of waste - an urban area, for economic reasons; while others are sited in land-use zones dedicated to medium or heavy industry, thus lowering the likelihood of pollution, noise, dust and odour in residential areas⁶⁵.

WtE plants reduce the volume of processed waste up to 90%, effectively preventing the expansion of landfills. The decline in available space for landfilling is an increasing issue in many countries around the world, making WtE technologies a solution to this pressing concern of increasing waste streams and reduced space for disposal. The land saved could successfully be used for housing, other economically productive activities or just left unutilised for nature conservation.

The environmental impact of WtE installations is not strictly proportional to treatment capacity, as shown by a 2009 study⁶⁶. The scale of the facility is not as significant in this respect as the qualitative aspects of the MSW.

WATER USE

MSW incinerators use water in boilers and for other processes such as cleansing, slag cooling, flue gas scrubbers and staff sanitary purposes. The water used for slag cooling does not necessarily have to be sanitised, so polluted river water or from other sources can be used. The water consumption for a state-of-the-art slag extractor is on average between 0.05 to 0.01 m³/tonne. Water is also required when flue gas scrubbers or semi-dry reactors are present, and it should contain a minimum solid content, so lime can be diluted in it and sprayed through nozzles into the flue gas stream. Water consumption will differ according

⁶⁴ Defra (2013) Advanced Thermal Treatment of Municipal Solid Waste

⁶⁵ World Bank (1999)

⁶⁶ Rada, et al. (2009)

to the technology utilised, so the semi-dry absorption process, which does not generate waste water, has an average of 0.1 m³/tonne, while the wet process will range from 0.25 to 0.4 m³/tonne, which produces between 0.07 to 0.15 m³ waste water per tonne.

The water discharged from the wet process usually contains high levels of chloride and soluble heavy metals; from which cadmium is the most problematic as it has emissions limits. The variation of elements found in discharged water will depend on the initial composition of the waste feed. In addition to the water discharged from the processes at the incineration plant, there will also be cleaning water and storm water released in the area, which will most likely be contaminated with waste residues and contain high levels of organic compounds⁶⁷. Any wash down waters or liquid within the waste is managed using a drainage system on site.

The enclosed nature of the new WtE facilities significantly reduces the impact on the water environment.

EMISSIONS

WtE can contribute to global climate change mitigation. The most effective utilisation of WtE processes can result in greenhouse gas emission reductions in three main ways. Firstly, residual waste that is sent to landfills to decompose will release significant amounts of CH₄ and CO₂, and WtE technologies can capture these gases for energy production and process the waste in a more efficient and environmentally friendly manner. Secondly, by using the energy generated by WtE plants there will be less demand for energy from fossil fuel plants, hence less production and subsequent GHG emissions. Thirdly, there is a possibility to recover ferrous and non-ferrous metals when processing waste for energy, reducing thus the demand for such primary materials and avoid emissions from extracting and treating raw materials⁶⁸. A state-of-the art WtE plant can produce carbon emission savings in the range of 100 to 350 kg CO₂ equivalent per tonne of waste processed depending on the waste composition, amount of heat and electricity supplied and country energy substitution mix. However, even greater savings (in the range of 200 to 800 kg CO₂ per tonne of waste) will be realised if WtE replaces landfilling⁶⁹.

The environmental impact of different WtE technologies is an important criterion when it comes to assessing the best WtE strategy, but most of all it is important to compare the sustainability of WtE with that of burning fossil fuels and also of waste landfilling. Both gas phase and solid phase emissions should be taken into account. A comparison between coal fired power plants and WtE plants is considered. These two energy generation technologies produce many similar regulated constituents, with comparable emission

⁶⁷ Bank ibid

⁶⁸ UNEP (2010)

⁶⁹ CEWEP (2012)

levels. Table 16 below compares the average emissions from MSW incineration and coal combustion in the United States.

TABLE 16: EMISSIONS FACTORS (G/KWH) FROM MSW INCINERATION AND COAL COMBUSTION IN THE UNITED STATES

	MSW Incineration	Coal combustion
Carbon dioxide (CO ₂)	1355.33	1020.13
Sulphur dioxide (SO ₂)	0.36	5.90
Nitrogen oxides (NO _x)	2.45	2.72

Source: Wilson, Williams, Liss, & Wilson (2013)

However, in order to complete this comparison, it must be kept in mind that there are considerable additional emissions for mining, cleaning and transporting coal to the power plant.

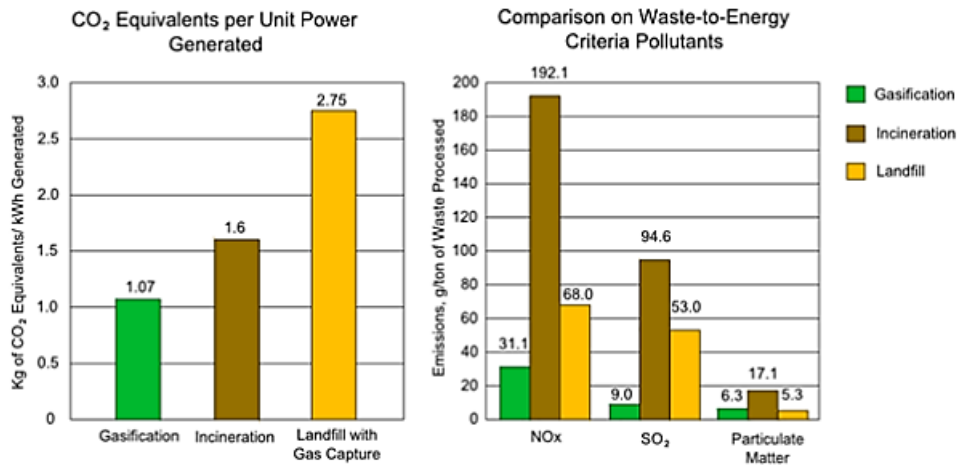
Similar considerations can be made as well for particulate emissions, which have been of great concern especially for incineration plants – i.e. dioxin and furan emission levels. To reduce particulate and gas phase emissions, both coal and incineration plants have adopted a series of process units for cleaning the flue gas stream, and this has led to a significant improvement in terms of environmental sustainability. Today, incineration plants are no longer significant sources of dioxins and furans. This is because of the implementation of governmental regulations on emission control strategies, which have led to a reduction of total annual incineration-related dioxin emissions from 10,000 grams in 1987 to 10 grams in 2013, a reduction of 99.9%⁷⁰.

As can be seen in Figure 15, emissions from WtE incineration and alternative WtE technologies (gasification and landfill with gas capture) are compared to each other. Gasification of waste produces reduced emissions per unit of generated power if compared to both incineration and landfilling. If focusing on the amount of pollutant emissions per unit

⁷⁰ United States Environmental Protection Agency

of treated waste, gasification is also the preferred option, while incineration is the most harmful.

FIGURE 15: COMPARISON OF CO₂, NO_x, SO₂ AND PARTICULATE EMISSIONS PER KWH GENERATED BY DIFFERENT WTE TECHNOLOGIES



Source: Riera & Wilson (2015)

As shown in Table 17, regarding particulates and gas phase emissions, incineration is often the most harmful technology in this field. This and other similar findings, along with a growing concern over harmful energy related emissions, have led to a fast development of alternative WtE technologies, which will likely influence the future market and change the way energy recovery from waste is done.

TABLE 17: COMPARISON OF PARTICULATE AND GAS PHASE EMISSIONS FOR DIFFERENT WTE TECHNOLOGIES

	Incineration	Pyrolysis	Plasma Arc Gasification	Aid Fed Gasification (PRM)	Anaerobic Digestion / Co-Gen	Anaerobic Digestion Gasification
Lifecycle CO ₂ /kWh	14-35				11	11-14
SO _x (mg/m ³)	1-40	35	26	1.2		
NO _x (mg/m ³)	40-100	77-139	150	26		

Particulates	1-20	5.75	12.8	0.018		
Ash (% of fuel mass)	5-10	in char	2-4	4-5		

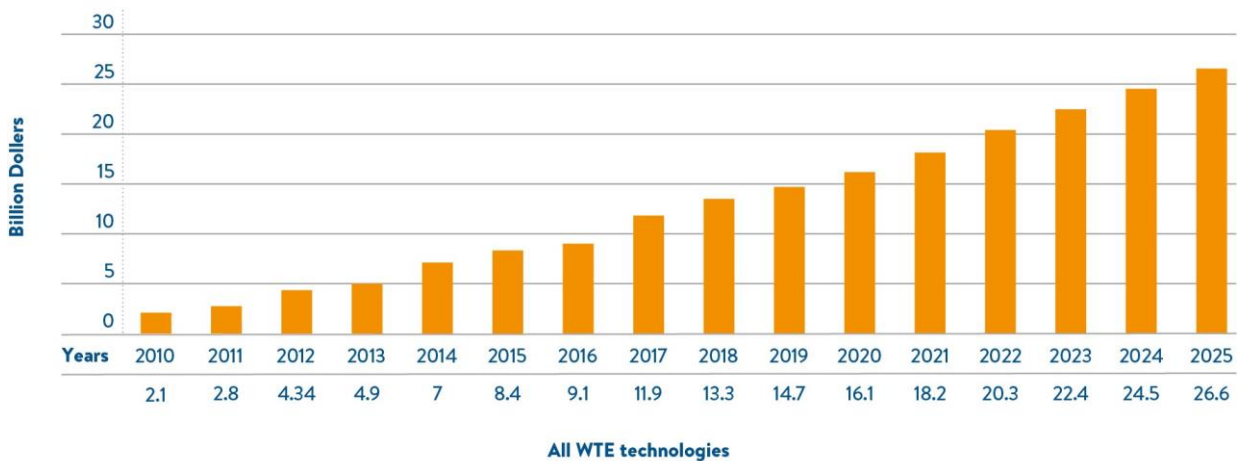
Source: Wilson, Williams, Liss, & Wilson (2013)

5. OUTLOOK

SHORT AND MEDIUM TERM

The global market is expected to maintain its steady growth to 2023, when it is estimated it would be worth US\$40 billion, growing at a CAGR of over 5.5% from 2016 to 2023.⁷¹ Figure 16 below shows that globally all WtE technologies will grow significantly even in conservative forecasts up to 2025.

FIGURE 16: GROWTH OF ALL WTE TECHNOLOGIES GLOBALLY WITH A CONSERVATIVE FORECAST UP TO 2025



Source: Ouda & Raza (2014)

Biological WtE technologies will experience faster growth at an average of 9.7% per annum, as new technologies (e.g. anaerobic digestion) become commercially viable and penetrate the market. From a regional perspective, the Asia-Pacific region will register the fastest growth over this period (CAGR of 7.5%), driven by increasing waste generation and government initiatives in China and India; and higher technology penetration in Japan. Growth in the Asia-Pacific region will also be characterised by the implementation of low cost technologies indigenously designed to specifically treat local waste, leading to a very competitive market.

⁷¹ <http://www.mynewsdesk.com/us/global-market-insights/pressreleases/waste-to-energy-wte-market-size-industry-outlook-potential-report-regional-analysis-2016-2023-1374171>

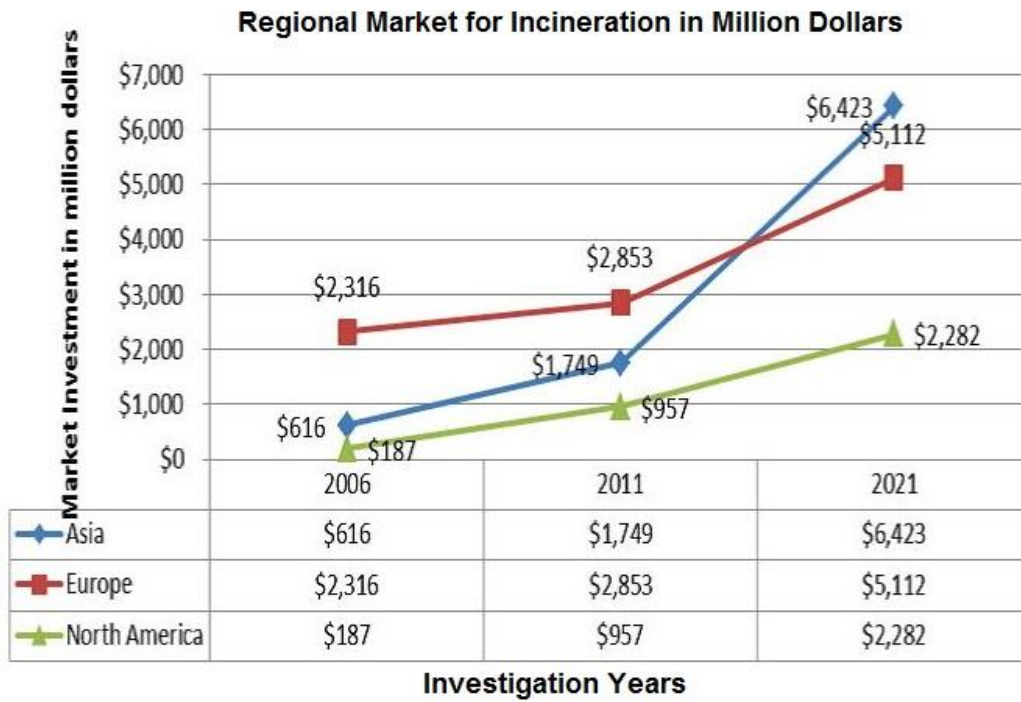
WtE market will continue to develop globally as governments will impose supportive regulation with subsidies and tax benefits. The need to increase the share of renewable energy and reduce GHG emissions, along with raising environmental consciousness to protect the environment from polluting and unsustainable practices such as landfilling will have a positive impact on WtE market development. In addition, as waste generation will grow, there will be enough space in the market for new entrants.

One of the biggest barriers to market development will be the high technology costs in comparison with landfilling, which is the most financially-effective way of waste disposal. The growth of the market and future technological advancements will most likely drive the costs down for WtE technologies, making them affordable in developing countries as well. Further research into increasing the energy efficiency of the plants, along with treating outputs from pollutants such as desulfurisation of flue gas, is expected to benefit the market growth. Bio-chemical treatments of waste are expected to contribute significantly to the market development, especially in developing countries⁷².

Incineration is the dominant WtE technology globally and this trend is likely to continue owing to relatively low technology costs, market maturity and high efficiency (of about 27%). Plus, incineration is suitable in both urban and rural areas and takes in all types of waste. Figure 17 below shows the incineration market trend in Asia, Europe and North America. It can be observed that Asia is going to continue investing heavily in waste combustion with energy recovery, followed by Europe and North America, which has a much slower ascendant trend. Other thermal technologies such as Gasification and Pyrolysis are more efficient, score better in environmental impacts but have still high capital costs, and fit best countries with available capital and limited land resources, like the case of Japan.

⁷² Hexa Research (2016)

FIGURE 17: MARKET INVESTMENT FOR INCINERATION IN ASIA, EUROPE AND NORTH AMERICA



Source: Ouda & Raza (2014)

Governments around the world will increasingly adopt better MSW management practices, which include treating residual waste with various WtE technologies as it is a viable option for disposal of MSW and energy generation. There are many factors that will influence the choice of technology and every region will have to properly assess its specific context to implement the most reasonable solution. The WtE sector is very complex, fragmented in terms of policy and regulation and has a huge untapped potential. Both international and regional orchestrated efforts are necessary for the WtE market to be able to spread, benefitting thus the waste management and energy sectors.

6. GLOBAL TABLE

TABLE 18: RENEWABLE MUNICIPAL WASTE⁷³ (MW) 2015 DATA

Country	Electrical Generating Capacity (MW) in 2015 IRENA (2016)	Electricity Generation (GWh) from RMW in 2014 IRENA (2016)	Municipal Solid Waste Generation Per Capita kg/year in 2014 Eurostat (2016)
Austria	539	285	565
Azerbaijan	37	174	-
Belgium	247	810	435
Canada	34	89	850*
Chinese Taipei	629	1 596	-
Czech Republic	45	88	310
Denmark	325	885	759
Estonia	210	-	357
Finland	-	441	482
France	872	1 824	511
Germany	1 888	6 069	618
Hungary	22	137	385

⁷³ Municipal Solid Waste is generally accepted as a renewable energy source.

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Country	Electrical Generating Capacity (MW) in 2015 IRENA (2016)	Electricity Generation (GWh) from RMW in 2014 IRENA (2016)	Municipal Solid Waste Generation Per Capita kg/year in 2014 Eurostat (2016)
Iceland	-	-	345
India	274	1 090	124*
Indonesia	7	32	190*
Ireland	17	68	586
Israel	6	14	774*
Italy	826	2 370	488
Japan	1 501	6 574	624*
Korea Rep	184	564	-
Latvia	-	-	281
Lithuania	10	29	433
Luxembourg	17	34	616
Malaysia	16	17	555
Martinique	4	23	-
Netherlands	649	1 909	527
Norway	77	176	423
Poland	-	-	272
Portugal	77	240	453

Country	Electrical Generating Capacity (MW) in 2015 IRENA (2016)	Electricity Generation (GWh) from RMW in 2014 IRENA (2016)	Municipal Solid Waste Generation Per Capita kg/year in 2014 Eurostat (2016)
Qatar	25	110	485*
Singapore	128	963	544*
Slovakia	11	22	321
Slovenia	-	-	414
Spain	251	686	435
Sweden	459	1 626	438
Switzerland	398	1 102	730
Thailand	75	201	624*
United Kingdom	781	1 422	482
United States of America (USA)	2 254	8 461	942*
Uruguay	1	-	40*
World	12 912	40 131	-

Source: IRENA Capacity Statistics 2016, IRENA Renewable Energy Statistics 2016, Eurostat Press Release of 22 March 2016

Note: Numbers are approximated, with for instance figures between 1 and 1.5 shown as 1, and between 1.5 and 2, shown as 2.

*Data collected from 2012 World Bank Report, Urban development - What a Waste: A global review of solid waste management.

Please note that an accurate comparison between countries in terms of waste generation cannot be easily realised, because waste data is registered differently and countries use different calculations for establishing the quantity of waste generated.

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REFERENCES

- Albrecht, H. (2015) *Management of Municipal Solid Waste and Industrial Materials*, Report of the Standing Committee on Environment and Sustainable Development, http://publications.gc.ca/collections/collection_2015/parl/x50-1/XC50-1-1-412-8-eng.pdf
- Alwaeli, M. (2015) 'An overview of municipal solid waste management in Poland. The Current Situation, Problems and Challenges', in *Environment Protection Engineering*, 4(41), p.180-193, DOI 10.5277/epe150414
- Antaco (2016) *Hydrothermal Carbonisation*, www.antaco.co.uk
- Asia Development Bank (2014) *Sector assessment (summary): water and other urban infrastructure and services*, Country Partnership Strategy: Azerbaijan, <http://www.adb.org/sites/default/files/linked-documents/cps-aze-2014-2018-ssa-03.pdf>
- Belgian Waste to Energy, <http://www.bw2e.be/fr>
- Blanco, M. M. (2014) *Life cycle model of waste to energy technologies in Spain and Portugal*, University of Cantabria, <http://repositorio.unican.es/xmlui/bitstream/handle/10902/6267/TesisMMB.pdf?sequence=1>
- Burgess, J. (2013) 'Sweden has Run out of Rubbish for Waste-to-Energy Industry', in *Oil Price*, September 19, <http://oilprice.com/Latest-Energy-News/World-News/Sweden-has-Run-out-of-Rubbish-for-Waste-to-Energy-Industry.html>
- Canadian Resource Recovery Council, *Poll shows Canadians overwhelming support energy from waste*, <http://www.resourcerecovery.ca/poll-shows-canadians-overwhelming-support-energy-from-waste/>
- Braun, R. *et al* (2010) *Recent development in Bio-energy Recovery through fermentation*, DOI 10.1007/978-3-642-04043-6_2, Springer
- Clean Energy Finance Corporation (2015) *The Australian bioenergy and energy from waste market*, <https://www.cleanenergyfinancecorp.com.au/media/107567/the-australian-bioenergy-and-energy-from-waste-market-cefc-market-report.pdf>
- Condair, n. d. *Humidification in the incineration plant Spittelau, Austria*, <http://www.condair.com/humidification-for-spittelau-in-vienna>
- Consonni, S., Viganò, F. & Eremed, W. B. (2014) *Ultimate energy performances of grate combustor WTE plants*, 5th International Conference on Engineering for Waste and Biomass Valorisation (WasteEng 2014), Rio de Janeiro, 25-28 August, [http://www.wtert.com.br/home2010/arquivo/noticias_eventos/2014-08-28_WastEng_Consonni_Final%20\[Compatibility%20Mode\].pdf](http://www.wtert.com.br/home2010/arquivo/noticias_eventos/2014-08-28_WastEng_Consonni_Final%20[Compatibility%20Mode].pdf).
- Consonni S., & Viganò F., (2012) 'Waste gasification vs. conventional Waste-to-Energy: a comparative evaluation of two commercial technologies', in *Waste Management*, 32(4), p. 653-66; doi: 10.1016/j.wasman.2011.12.019, <http://www.ncbi.nlm.nih.gov/pubmed/22285961>
- Coolsweep (2014) *Report – Global analysis of the waste-to-energy field*, <http://webcache.googleusercontent.com/search?q=cache:GKVMActKaT4J:www.energyclust>

er.it/files/79/Deliverable-1-2_-report-on-Global-analysis-of-WtE.pdf+&cd=1&hl=en&ct=clnk&gl=uk

Coolsweep, *In-depth analyses of the waste-to-energy field, D 1.4 Approved analytical reports for six European regions involved in the COOLSWEEP consortium*, <http://coolsweep.org/wp-content/uploads/2014/03/Deliverable-1.4-Approved-analytical-reports-for-six-European-regions-in-the-COOLSWEEP-consortium-.pdf>

Cuff, M. (2016) 'Oslo waste incinerator launches experiment to capture CO₂ from burning rubbish', in *Business Green*, January 27, <http://www.businessgreen.com/bg/news/2443343/oslo-waste-incinerator-launches-experiment-to-capture-co2-from-burning-rubbish>

Department of Energy & Climate Change (2012) *Electricity generation costs*, https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/65713/6883-electricity-generation-costs.pdf

Department for Environment, Food & Rural Affairs (2014) *Energy from waste – A guide to debate*, www.gov.uk/defra

Department for Environment, Food & Rural Affairs (2013) *Advanced Thermal Treatment of Municipal Solid Waste*, https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/221035/pb13888-thermal-treatment-waste.pdf

Department for Environment, Food & Rural Affairs (2013) *Incineration of Municipal Solid Waste*, https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/221036/pb13889-incineration-municipal-waste.pdf

Dutch Waste Management Association, *Waste-to-Energy in Netherlands*, <http://www.wastematters.eu/about-dwma/activities/waste-to-energy/activities-in-the-netherlands.html>

Ecoprog (2015) *Waste to Energy 2015/2016 – Technologies, plants, projects, players and backgrounds of the global thermal waste treatment business*, Extract 8th edition, http://www.ecoprog.com/fileadmin/user_upload/leseproben/ext_market_report_WtE_2015-20-2016_ecoprog.pdf

Electric Power & Light (2014) *Latin America turns to waste-to-energy for power generation*, September 25, <http://www.elp.com/articles/2014/09/latin-america-turns-to-waste-to-energy-for-power-generation.html>

Energy Information Administration (2016) *Waste-to-energy electricity generation concentrated in Florida and Northeast*, April 8, <http://www.eia.gov/todayinenergy/detail.cfm?id=25732>

Energy Information Administration (2013) *Updated Capital Cost Estimates for Utility Scale Electricity Generating Plants*, http://www.eia.gov/forecasts/capitalcost/pdf/updated_capcost.pdf

Eremed, W. B. (2015) *Increasing energy recovery of waste-to-energy plants*, PhD Thesis, Polytechnic of Milan.

Ethiopian Electric Power Corporation, *Koshe Waste-to-Energy*, <http://www.eepco.gov.et/project.php?pid=27&pcatid=9>

- Eunomia (2014) *Anaerobic Digestion market update – Addressing the feedstock famine*, <http://www.biogen.co.uk/upload/item/page30/file/Eunomia%20Anaerobic%20Digestion%20Report%20-%20June%202014%20FINAL.pdf>
- European Biogas Association (2015) *Spain: Report calls for more energy from waste capacity*, <http://european-biogas.eu/2015/10/15/spain-report-calls-for-more-energy-from-waste-capacity/>
- European Commission (2011) *Country Factsheet Latvia*, http://ec.europa.eu/environment/waste/framework/pdf/LV%20factsheet_FINAL.pdf
- European Environment Agency (2013) *Managing municipal solid waste – a review of achievements in 32 European countries*, www.eea.europa.eu
- European Environment Agency (2013) *Municipal waste management in Hungary*.
- Eurostat (2016) *Each person in the EU generated 475 kg of municipal waste in 2014*, March 22, <http://ec.europa.eu/eurostat/documents/2995521/7214320/8-22032016-AP-EN.pdf/eea3c8df-ce89-41e0-a958-5cc7290825c3>
- Eurostat (2012a) *Generation and treatment of municipal waste (1 000 t) by NUTS 2 regions*, http://epp.eurostat.ec.europa.eu/portal/page/portal/statistics/search_database
- Fortum (2015) *Fortum and Lietuvos Energija cooperate to build a waste-to-energy CHP plant in Lithuania*, October 15, <https://globenewswire.com/news-release/2015/10/15/776348/0/en/Fortum-and-Lietuvos-Energija-cooperate-to-build-a-waste-to-energy-CHP-plant-in-Lithuania.html>
- Gellenbeck, K. (2014) 'The role of the waste management sector in Germany's energy transition', in *Remondis Aktuell*, <http://www.remondis-aktuell.com/en/remondis-aktuell/032014/latest-news/the-role-of-the-waste-management-sector-in-germany-s-energy-transition/>
- Ghougassian, B. (2012) 'Waste to Energy Technologies', in *Arab Forum for Environment and Development*, November 26, <http://www.afedmag.com/english/ArticlesDetails.aspx?id=12>
- Global News Wire (2015) *Waste To Energy (WTE) Market Will Be Worth \$37.64 Billion By 2020: New Report By Grand View Research, Inc.*, February 2, <http://globenewswire.com/news-release/2015/02/02/701987/10118057/en/Waste-To-Energy-WTE-Market-Will-Be-Worth-37-64-Billion-By-2020-New-Report-By-Grand-View-Research-Inc.html>
- Goff, S., Norton, J., and Castaldi, M. (2013) 'Webinar: Turning trash into renewable energy treasure', *American Society of Mechanical Engineers*, <https://www.asme.org/engineering-topics/media/energy/webinar-turning-trash-into-renewable-energy>
- Green Investment Bank (2014) *The UK residual waste market*, <http://www.greeninvestmentbank.com/media/25376/gib-residual-waste-report-july-2014-final.pdf>
- Grosso, M., et al. (2011) 'A quantitative estimate of potential aluminium recovery from incineration bottom ashes', in *Resources, Conservation and Recycling*, 55(2), p. 1178-1184, doi:10.1016/j.resconrec.2011.08.001, <http://www.sciencedirect.com/science/article/pii/S0921344911001625>

- Hernandez, M. (2015) *Potentials of Hydrothermal Carbonisation Technology*, Brussels, September 24th, <http://www.eubren.com/M.Hernandez.pdf>
- Hexa Research (2016) *Waste to energy market analysis, market size, application analysis, regional outlook, competitive strategies and forecasts, 2014 to 2020*, <http://www.hexaresearch.com/research-report/waste-to-energy-industry/>
- Hicks, M. & Rawlinson, S. (2010) 'Cost model: Energy from waste', in *Building Magazine*, April 23, <http://www.building.co.uk/cost-model-energy-from-waste/3162156.article>
- Higman, C. & Burgt, M. (2011) *Gasification*, Gulf professional publishing.
- Hoornweg, D. Bhada-Tata, P. Kennedy, C. (2013) 'Environment: Waste production must peak this century', in *Nature*, October 30, <http://www.nature.com/news/environment-waste-production-must-peak-this-century-1.14032>
- Hoornweg, D. and Bhada-Tata, P. (2012) What a waste – a review of solid waste management. *World Bank Urban development series*, No. 15 Knowledge Papers, http://siteresources.worldbank.org/INTURBANDEVELOPMENT/Resources/336387-1334852610766/What_a_Waste2012_Final.pdf
- Hughes, J. (2013) *Small scale environmental solutions – a new market opportunity*, June 21, <http://www.pennog.com/small-scale-environmental-solutions-a-new-market-opportunity/>
- International Renewable Energy Agency (2016) *Renewable energy statistics*, http://www.irena.org/DocumentDownloads/Publications/IRENA_RE_Statistics_2016.pdf
- International Renewable Energy Agency (2016) *Renewable capacity statistics*, http://www.irena.org/DocumentDownloads/Publications/IRENA_RE_Capacity_Statistics_2016.pdf
- International Energy Agency (2015) *World Energy Outlook*, <http://www.worldenergyoutlook.org/resources/energydevelopment/energyaccessdatabase/>
- International Solid Waste Association (2013) *Guidelines: Waste-to-energy in low and middle income countries*, www.iswa.org
- Iona Capital (2016) *Anaerobic Digestion adoption*, <http://www.ionacapital.co.uk/page/95/Anaerobic-Digestion-Adoption.htm>
- Jeswani, H. K. & Azapagic, A. (2016) 'Assessing the environmental sustainability of energy recovery from municipal solid waste in the UK', in *Waste Management*, 50, pp. 346-363, doi:10.1016/j.wasman.2016.02.010, <http://www.sciencedirect.com/science/article/pii/S0956053X16300599>
- Karimova, A. (2016) 'Waste-to-Energy production exceeds 180 mln kWh in Azerbaijan', in *Azernews*, January 13, <http://www.azernews.az/business/91614.html>
- Kość, W. (2014) 'PGNiG Termika to build WtE plant in Warsaw', in *Ends Waste & Bioenergy*, May 20, <http://www.endswasteandbioenergy.com/article/1295124/pgnig-termika-build-wte-plant-warsaw>
- Lawrence, M. & Woods, E. (2014) *Smart Waste – Advanced Collection, Processing, Energy Recovery, and Disposal Technologies for the Municipal Solid Waste Value Chain: Global*

- Market Analysis and Forecasts*, Navigant Research,
http://www.ibm.com/smarterplanet/global/files/us__en_us__cities__14_navigant_research.pdf
- Lokuge, C. (2016) 'What is holding back waste-to-energy developments in Australia?', in *Sustainability Matters*, April 12,
<http://www.sustainabilitymatters.net.au/content/waste/article/what-is-holding-back-waste-to-energy-developments-in-australia--910997839>
- Logan, B. E. *et al.* (2015) 'Assessment of Microbial Fuel Cell Configurations and Power Densities', in *Environmental Science & Technology Letters*, 2, pp. 206-2014, DOI: 10.1021/acs.estlett.5b00180, <http://pubs.acs.org/doi/pdf/10.1021/acs.estlett.5b00180>
- McMahon, A. (2016) 'Ireland's population one of the most rural in European Union', in *The Irish Times*, June 1, <http://www.irishtimes.com/news/health/ireland-s-population-one-of-most-rural-in-european-union-1.2667855>
- Messenger, B. (2016) 'Covanta secures feedstock contract for 58MW Dublin Waste to Energy plant', in *Waste Management World*, February 12, <https://waste-management-world.com/a/covanta-secures-feedstock-contract-for-58mw-dublin-waste-to-energy-plant>
- Messenger, B. (2016) 'Indian Waste to Energy conference – potential for 6GW capacity', in *Waste Management World*, February 26, <https://waste-management-world.com/a/indian-waste-to-energy-conference-potential-for-6-gw-capacity>
- Messenger, B. (2016) 'World's biggest Waste to Energy plant to be built in China', in *Waste Management World*, February 5, <https://waste-management-world.com/a/video-worlds-biggest-waste-to-energy-plant-to-be-built-in-china>
- Michaels, T. (2014) *The 2014 ERC directory of Waste-to-Energy facilities*,
http://energyrecoverycouncil.org/wp-content/uploads/2016/01/ERC_2014_Directory.pdf
- Murdoch University, *Waste to Energy technologies*,
<http://www.see.murdoch.edu.au/resources/info/Tech/waste/>
- Murer M. J. (2011) 'High efficient waste-to-energy in Amsterdam: getting ready for the next steps', in *Waste Management & Research: ISWA* DOI: 10.1177/0734242X11413334
- My News Desk (2015) *Waste to Energy market size, industry outlook potential report, regional analysis 2016-2023*, Press release April 15,
<http://www.mynewsdesk.com/us/pressreleases/waste-to-energy-wte-market-size-industry-outlook-potential-report-regional-analysis-2016-2023-1374171>
- Ouda, O. K. M. & Raza, S. A. (2014) *Waste-to-Energy: Solution for Municipal Solid Waste challenges – Global Perspective*, 2014 International Symposium on Technology Management and Emerging Technologies, May 27-29,
<http://www.pmu.edu.sa/kcfinder/upload/files/Indonisa-Conference-Omar%20Ouda.pdf>
- Rada, E. C. *et al.* (2009) 'Trends in the management of residual municipal solid waste', in *Environmental Technology*, 30(7), p. 651-661.

- Rahimnejad, M., Ghoreyshi, A. A., Najafpour, G. and Jafary, T. (2011) 'Power generation from organic substrate in batch and continuous flow microbial fuel cell operations', in *Applied Energy*, 88, pp. 3999–4004, DOI: 10.1016/j.apenergy.2011.04.017
- Rahimnejad, M. et al. (2015) 'Microbial fuel cell as new technology for bioelectricity generation: A review', in *Alexandria Engineering Journal*, 54(3), pp. 245-756, doi:10.1016/j.aej.2015.03.031, <http://www.sciencedirect.com/science/article/pii/S1110016815000484>
- Reddy, L. V. et al. (2010) *Microbial Fuel Cells (MFCs) - a novel source of energy for new millennium*, <http://www.formatex.info/microbiology2/956-964.pdf>
- Riera, L. & Wilson, B. W. (2015) *Municipal Solid Waste as Renewable Resource*, Presented at the 4th Global Economic Leaders' Summit, Changchun China, August 30 - September 1, http://www.eprenewable.com/uploads/files/67_MSW-as-Resource-China_Final.pdf
- Scheffl, C. *Sustainable management of solid wastes: legal ban on landfills for hazardous and for organic wastes in Austria*, http://www.iswa.org/uploads/tx_iswaknowledgebase/Scheffl.pdf
- Stanley, B. (2013) 'Summary of waste conversion technologies', in *Environmental Research & Education Foundation*, http://www.newmoa.org/events/docs/112_109/EREF_MSW_Conversion_Techs_Aug2013.pdf
- Stringfellow, T. (2014) 'An independent engineering evaluation of Waste-to-Energy technologies', January 13, in *Renewable Energy World*, <http://www.renewableenergyworld.com/articles/2014/01/an-independent-engineering-evaluation-of-waste-to-energy-technologies.html>
- Swiss Business Hub, APAX Consulting Group (2015) *Market Report: Waste Management in Poland*, http://www.s-ge.com/sites/default/files/private_files/BBK_Waste_management_report_Poland_0.pdf
- The Confederation of European Waste-to-Energy Plants (2015) *Industry barometer Waste-to-Energy 2015*, http://www.cewep.eu/news/m_1438
- The Confederation of European Waste-to-Energy Plants (2012) *The outlook for the Energy from Waste industry across Europe*, April 25, <http://www.ecolateral.org/EFWFactsEurope2012.pdf>
- The Official Information Portal on Anaerobic Digestion, <http://www.biogas-info.co.uk/about/>
- The Solid Waste Association of North America (2011) *Integrated Solid Waste Management System*.
- The Waste and Resources Action Programme (2016) *Anaerobic digestion – the process*, <http://www.wrap.org.uk/content/anaerobic-digestion-process>
- The Waste and Resources Action Programme (2013) 'Comparing the cost of alternative waste treatment options', in *Gate Fees Report 2013*.
- The Waste and Resources Action Programme (2012) *Energy from Waste development guidance*, http://www.wrap.org.uk/sites/files/wrap/O_And_EFW_Guidance_FULL.pdf

- Themelis, N. J. & Mussche, C. (2013) *Municipal Solid Waste management and Waste-to-Energy in The United States, China and Japan*, 2nd International Academic Symposium on Enhanced Landfill Mining, October 14-16, http://elfm.eu/Uploads/ELFM/FILE_73D907E9-8225-4B93-91F8-10F71F59B793.PDF
- Themelis, N. J., and Reshadi, S. (2009) 'Potential for Reducing the Capital Costs of WTE Facilities', in *American Society of Mechanical Engineering*, pp. 245-251, doi:10.1115/NAWTEC17-2366
- Thomson, J. & Anthony, H. (2008) *The health effects of waste incinerators*, 4th Report of the British Society for Ecological Medicine, http://www.bsem.org.uk/uploads/IncineratorReport_v3.pdf
- Tighe, C. (2016) 'Teesside investor drops £300m renewables project', in *Financial Times*, April 5, <http://www.ft.com/cms/s/0/226c0e34-fb47-11e5-8f41-df5bda8beb40.html#axzz4AKBRb4QF>
- Umberto, A. (2011) 'Process and technological aspects of municipal solid waste gasification – A review', in *Waste Management*, 32, p. 625-639, doi:10.1016/j.wasman.2011.09.025, http://www00.unibg.it/dati/corsi/39048/52292-review_Arena.pdf
- United Nations Environment Programme, *Sound practices – Incineration*, http://www.unep.or.jp/ietc/ESTdir/Pub/MSW/sp/SP5/SP5_4.asp
- United Nations Environment Programme (2010) *Waste and Climate Change – Global trends and strategy framework*, <http://www.unep.or.jp/ietc/Publications/spc/Waste&ClimateChange/Waste&ClimateChange.pdf>
- United States Environmental Protection Agency (2015) *Inventory of U.S. Greenhouse Gas Emissions and sinks: 1990-2013*, <https://www3.epa.gov/climatechange/Downloads/ghgemissions/US-GHG-Inventory-2015-Chapter-7-Waste.pdf>
- U.S. Environmental Protection Agency (2014) 'Landfill Gas Energy Basics', in *LFG Energy Project Development Handbook*, https://www3.epa.gov/lmop/documents/pdfs/pdh_chapter1.pdf
- Uutiset (2014) *Finland's biggest waste-to-energy plant opens in Vantaa*, September 17, http://yle.fi/uutiset/finlands_biggest_waste-to-energy_plant_opens_in_vantaa/7476864
- Vainikka, P. *et al.* (2013) 'Trace elements found in the fuel and in-furnace fine particles collected from 80MW BFB combusting solid recovered fuel', in *Fuel Processing Technology*, 105, pp. 202-211, doi:10.1016/j.fuproc.2011.06.023
- Vorotnikov, V. (2015) 'Baku to the future', in *Recycling Waste World*, October 30, <http://www.recyclingwasteworld.co.uk/in-depth-article/baku-to-the-future/109004/>
- Walsh, L. (2015) 'Fire at Slovakia's largest EfW plant', in *Ends Waste & Bioenergy*, February 27, <http://www.endswasteandbioenergy.com/article/1336066/fire-slovakias-largest-efw-plant>

- Waste Management World (2014) *Successful Tests at Struggling Plasma Gasification Waste to Energy Project in France*, June 25, <https://waste-management-world.com/a/successful-tests-at-struggling-plasma-gasification-waste-to-energy-project-in-france>
- Wien Energie, *Spittelau waste incineration plant*, <http://www.wienenergie.at/eportal3/ep/channelView.do?pageTypeld=72164&channelld=51715>
- Williams, M. (2011) *Waste-to-Energy success factors in Sweden and The United States*, <http://www.acore.org/wp-content/uploads/2012/04/WTE-in-Sweden-and-the-US-Matt-Williams..pdf>
- Wilson, B., Williams, N., Liss, B. & Wilson, B. (2013) *Comparative Assessment of Commercial Technologies for Conversion of Solid Waste to Energy*, EnviroPower Renewable, Inc..
- The International Bank for Reconstruction and Development (1999) *Municipal Solid Waste Incineration*, http://www.worldbank.org/urban/solid_wm/erm/CWG%20folder/Waste%20Incineration.pdf
- The World Bank (2012) *Urban Development Series*, <http://siteresources.worldbank.org/INTURBANDEVELOPMENT/Resources/336387-1334852610766/AnnexJ.pdf>
- Yolin, C. (2015) *Waste management and recycling in Japan. Opportunities for European Companies*, EU-Japan Centre for Industrial Cooperation, http://www.eu-japan.eu/sites/default/files/publications/docs/waste_management_recycling_japan.pdf
- Yuanyuan, B. (2015) 'Chinese Waste-to-energy market experiences rapid growth during last five years', in *Renewable Energy World*, April 28, <http://www.renewableenergyworld.com/articles/2015/04/chinese-waste-to-energy-market-experiences-rapid-growth-during-last-five-years.html>
- Zhejiang University (2015) *Energy from waste: Opportunities and challenges*

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KEY FINDINGS

1. Global installed capacity for solar-powered electricity has seen an exponential growth, reaching around 227 GW_e at the end of 2015. It produced 1% of all electricity used globally.
2. Germany has led PV capacity installations over last decade and continues as a leader followed by China, Japan, Italy and the United States.
3. Major solar installation has been in regions with relatively less solar resources (Europe and China) while potential in high resource regions (Africa and Middle East) remains untapped.
4. Government policies have contributed to the development of the most mature solar markets (Europe, United States and Australia).
5. Costs for solar power are falling rapidly – “grid parity” has been achieved in many countries, while new markets for the solar industry are opening in emerging and developing nations. Policy and regulatory incentives, oversupply of installation components, and advancements in technology are driving down the reduction in cost.
6. Government incentives for the solar energy sector are being gradually scaled back in mature solar markets. There is now a need for a new electricity market design and for novel methods of financing solar projects in the absence of government support.
7. Technology is constantly improving, and new technologies such as Perovskite¹ cells are approaching commercialisation. Advancements are also opening solar energy to new applications.
 - While there has been continuous improvement in the conversion efficiency of PV cells, concentrated photovoltaics (CPV) may hold the key in enabling rapid increases in solar energy efficiency, with recent progress reaching 46% for solar cells.
8. Expansion of solar capacity could be further hindered by existing electricity infrastructure, particularly in countries with young solar markets.
9. In order to prevent environmental damage from solar PV, there is a need for strict and consistent regulation on processes over the entire life-cycle of infrastructure. Disposal and recycling must be considered as more modules reach the end of their lifespan.

¹ Perovskite cells include perovskite (crystal) structured compounds that are simple to manufacture and are expected to be relatively inexpensive to produce. They have experienced a steep rate of efficiency improvement in laboratories over the past few years.

INTRODUCTION

Focus Area & Rationale

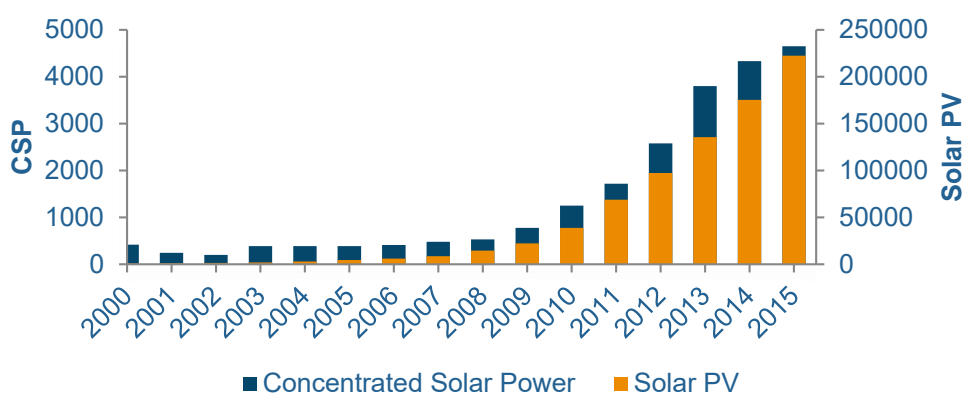
Investments in solar PV capacities are now rapidly growing in both grid connected and off-grid mode. Solar generation has been a reliable source for supplying electricity in regions without access to the grid for long. However, the penetration of solar energy as a grid connected power source has increased significantly only in the last decade. Thus the overall share in net energy generation still remains low at only 1% (2015) globally and is bound to only increase in future.

Costs of energy production are continually falling, technology is improving and a diverse and growing range of applications are open to the solar energy sector. Hence, solar energy is going to be a competitive energy or power source in future with huge investments being drawn into this segment. Competitiveness can be a challenge where energy storage is required to address the demand, as energy storage technologies are a little behind in learning curve, and commercial acceptability is yet to be achieved. Though, there are many locations where grid peak is experienced during solar generation hours (day time), so broadly, solar power is currently very competitive.

GLOBAL TRENDS

PV is mainstream technology. Global installed capacity for solar-powered electricity reached around 227 GW_e at the end of 2015², while total capacity for solar heating and cooling in operation in 2014 was estimated at 406 GW_{th}³. Photovoltaic (PV) has been the mainstream solar power technology as shown in Figure 1 below.

FIGURE 1: GLOBAL INSTALLED SOLAR POWER CAPACITY, 2000-2015 (MW)



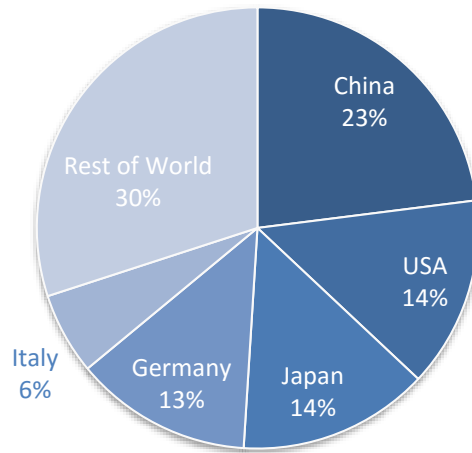
² IRENA, 2016

³ IEA solar heating and cooling programme (2015)

Source: IRENA (2015)

China is a leader in PV installations, followed by the USA, Japan, Germany and Italy as shown in Figure 2 below.

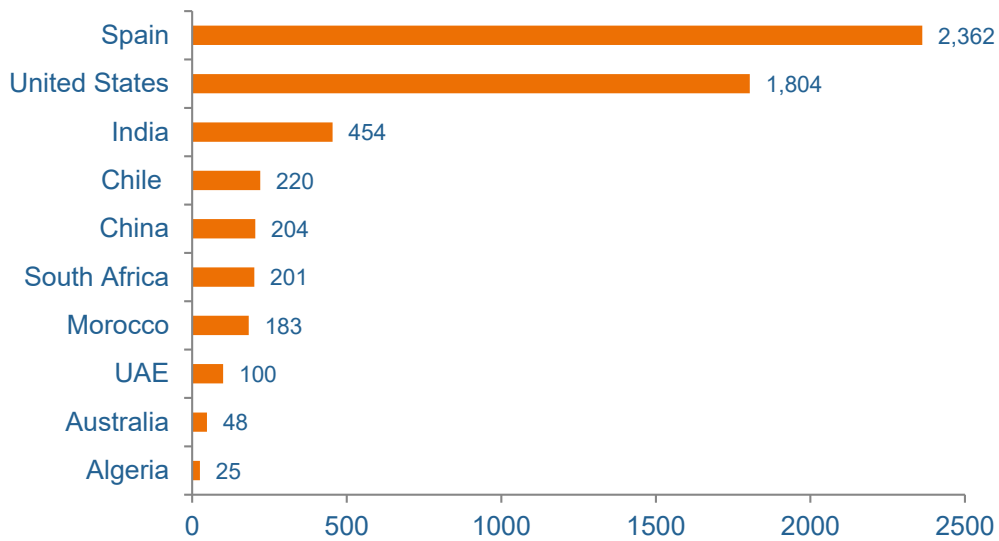
FIGURE 2: CUMULATIVE GLOBAL PV INSTALLATIONS 2016



Source: IHS (2016)

Concentrated Solar Power (CSP) remains with very limited capacity (4 GW today and 70 to 256 GW in 2040 according to the IEA scenarios), i.e. less than 3% of global capacity. As shown in Figure 3, Spain is the leader in CSP deployment with 2,362 MW installed capacity in 2016, followed by USA with 1,804 MW, India 454 MW and all other countries have a small contribution to the total capacity installed across the globe. According to the Climate Investment Fund, the largest CSP project in the world until January 2016 is Noor in Morocco and global operational power stands at 4,705 MW.

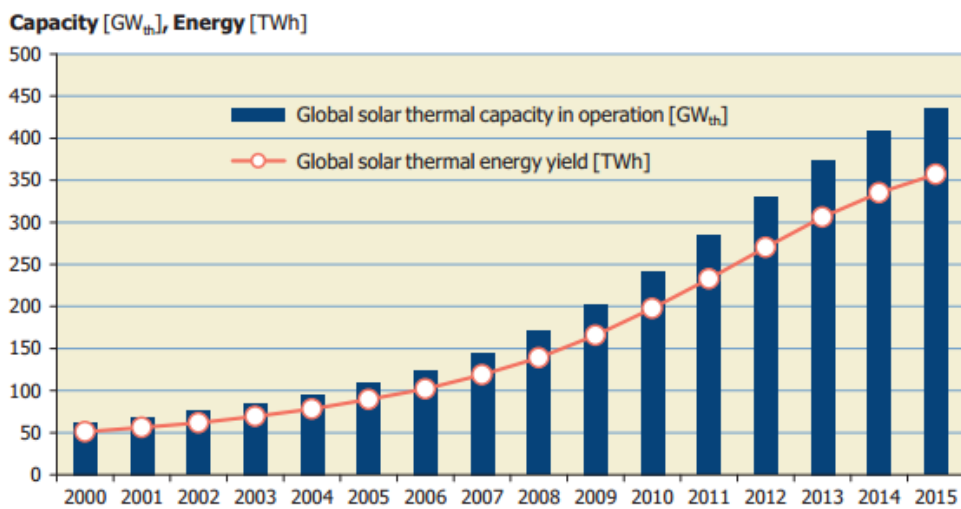
FIGURE 3: CSP INSTALLED CAPACITY IN MAJOR COUNTRIES UP TO 2016 (IN MW)



Source: Statista (2016)

Trend in global solar heating/cooling capacity in operation is shown in Figure 4. It can be seen below that solar thermal energy yield has been increasing continuously.

FIGURE 4: GLOBAL INSTALLED SOLAR HEATING / COOLING CAPACITY, 2000-2015

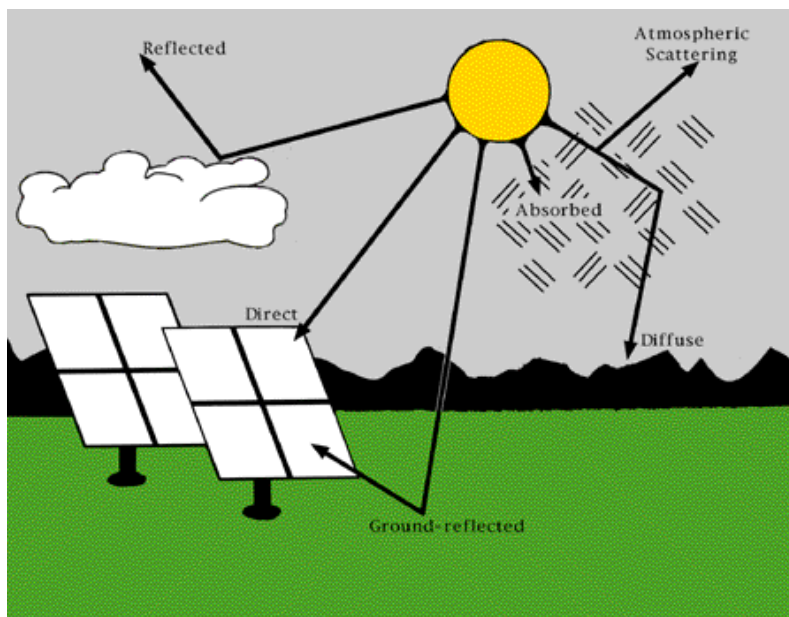


Source: IEA-SHC (2016)

RESOURCE POTENTIAL

One of the most important factors in solar energy technologies' applications is the amount of solar energy incident at a location. The amount of solar energy incident per unit area per unit time is referred to as irradiance (measured in kWh/m² per day or kWh/m² per year) and is the most suitable criteria in the assessment of the solar resource at a geographical location. Solar radiation consists of a direct (direct beam radiation) and a diffuse component. For the purposes of different types of applications, solar radiation data is given as Global Horizontal Irradiance (GHI) and Direct Normal Irradiance (DNI). The various components of solar radiation are illustrated on Figure 5.

FIGURE 5: ILLUSTRATION OF SOLAR RADIATION



Source: http://rredc.nrel.gov/solar/glossary/gloss_g.html

Some of the solar radiation entering the earth's atmosphere is absorbed and scattered. Direct beam radiation comes in a direct line from the sun. Diffuse radiation is scattered out of the direct beam by molecules, aerosols, and clouds. The sum of the direct beam, diffuse, and ground and surroundings reflected radiation arriving at the surface is called total or global solar radiation.

GHI is the total amount of solar energy incident on a horizontal surface. DNI is the amount of radiation incident on a surface that is always kept perpendicular (normal) to the direct

solar beam. Part of the solar radiation that arrives on a horizontal surface, called diffuse horizontal irradiance (DHI), is due to scattering of sunlight in the atmosphere and reaches the horizontal surface from all directions of the sky. These three quantities are related via the expression $GHI = DNI \cos Z + DHI$, where Z is the sun zenith angle. GHI is the important parameter for photovoltaic applications (PV), while DNI is the most important parameter for CSP plants and Concentrating Photovoltaic (CPV) plants. The amount of GHI and DNI vary due to variation in geographical location and due to local climate effects. Table 1 provides ranges of the solar resource data for the WEC geographical regions.

It is to be noted that all solar technologies can use trackers to increase the overall output. Trackers are mechanical parts that facilitate solar modules to track sun. Tracking could be for over a day only or can also include seasonal tracking.

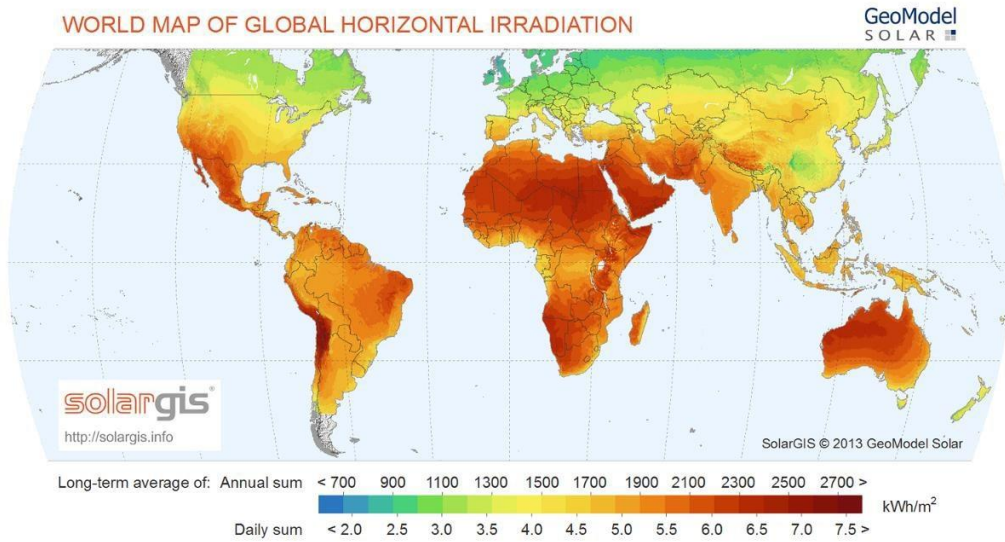
TABLE 1: ANNUAL GLOBAL HORIZONTAL IRRADIANCE (GHI) AND DIRECT NORMAL IRRADIANCE (DNI) FOR WEC GEO-REGIONS

WEC Geo region	GHI range (kWh/ m ² per year)	DNI range (kWh/m ² per year)
Africa	1600 – more than 2700; Lowest: Congo Basin Highest: Sahara & Namib Deserts	900 – 3200; Lowest: Congo Basin Highest: Southern Namibia & North-western South Africa
Middle East & North Africa	1700 – more than 2700; Lowest: Caspian region of Iran Highest: Saudi Arabia & Sahara region of North Africa	1100 – 2800; Lowest: Caspian region of Iran Highest: North-western Saudi Arabia & Sahara region of North Africa
Latin America & Caribbean	1000 – more than 2700; Lowest: Patagonia region of Argentina & Southern Chile Highest: Atacama region of Chile	800 – 3800; Lowest: Patagonia region of Southern Chile Highest: Atacama region of Chile
North America	Less than 700 – more than 2600; Lowest: Arctic region of Canada & United States	700 – 3100; Lowest: Arctic region of Canada & United States Highest: Mojave & Sonoran

	Highest: Sierra Madre region of Mexico	Deserts of United States & Mexico
Europe	Less than 700 – 2100; Lowest: Arctic region of Russia & Scandinavia Highest: Southern Spain	500 – 2300; Lowest: Arctic region of Russia & Scandinavia Highest: Southern Spain
South & Central Asia	1400 – 2400; Lowest: Northern India & Pakistan Highest: Afghanistan & Southern Pakistan	1100 – 2500; Lowest: Northern India & Pakistan Highest: Afghanistan
East Asia	1000 – 2300; Lowest: Eastern foot of Tibetan Plateau Highest: Tibetan Plateau of South-western China	500 – 2600; Lowest: Eastern China Highest: Tibetan Plateau of South-western China & Mongolian steppes
South East Asia & Pacific	900 – 2600; Lowest: Southern New Zealand Highest: Great Sandi Desert of Australia	900 – 3200; Lowest: Indonesia Highest: Western Australia

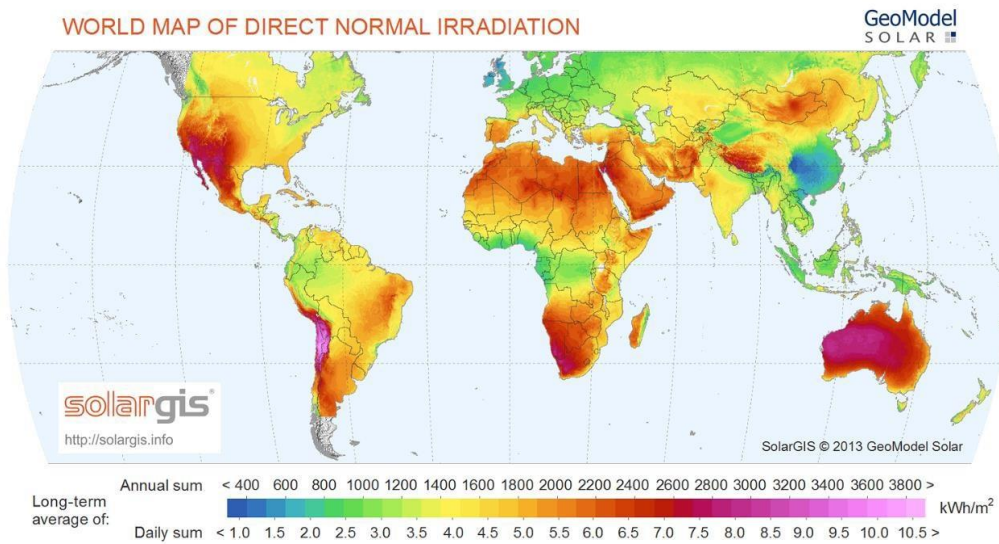
Source: SolarGIS and Meteornorm

FIGURE 6: GLOBAL DISTRIBUTION OF GLOBAL HORIZONTAL IRRADIANCE (GHI)



Source: SolarGIS

FIGURE 7: GLOBAL DISTRIBUTION OF DIRECT NORMAL IRRADIANCE (DNI)



Source: SolarGIS

1. TECHNOLOGIES

CURRENT TECHNOLOGIES

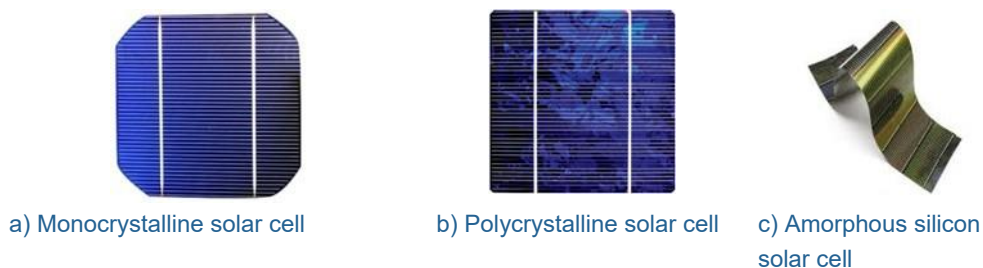
Solar Photovoltaic (PV) Technologies

One of the key solar energy technologies is solar PV, where a semi-conductor material is used to convert sunlight to electricity directly. There are various photovoltaic technologies developed to date, few are commercialised and others still remain at research level.

The solar PV market is currently dominated by crystalline silicon (c-Si) technology, of which two types are used. The first is monocrystalline, produced by slicing wafers (up to 150 mm diameter and 200 microns thick) from a high-purity single crystal boule. The second is polycrystalline, made by sawing a cast block of silicon first into bars, and then into wafers. The main trend in crystalline silicon cell manufacturing involves a move toward polycrystalline technology. However, it may be noted that PV manufacturers are reducing the price for producing monocrystalline, which might get close to the current price for polycrystalline and be much more competitive in the future.

Aside from crystalline silicon cells, other PV cell technologies including amorphous silicon (a-Si), thin-film and organic cells are commercially available. Amorphous silicon solar cells require only 1% of the material (the silicon) needed for the production of crystalline silicon cells. It can be grown in any shape or size, and can be produced in an economical way. Amorphous silicon cells were the first type of solar cells to be used in the application of consumer products such as watches, calculators and other non-critical outdoor applications; and given their low cost, they have been adopted by other larger scale applications.

FIGURE 8: DIFFERENT TYPES OF SOLAR CELLS



Source:<http://www.sustainabilityoutlook.in/>

Thin-film modules are constructed by depositing extremely thin layers of photosensitive materials onto a low-cost backing such as glass, stainless steel or plastic. Thin-film manufacturing processes result in lower production costs compared to the more material-intensive crystalline technology. A price advantage which is counterbalanced by lower efficiency rates of conversion of the different types of thin-film modules (depending on the active material used), cadmium telluride (CdTe), and copper-indium/gallium-diselenide/disulphide (CIS/CIGS) have reached commercial viability to certain extent.

In case of organic solar cells, there are several different technologies, including dye-sensitized solar cells, antenna cells, molecular organic solar cells and completely polymeric devices. The dye cell is closest to market introduction, while the other possible organic solar cell concepts are still being researched.

Solar Thermal Technologies

Solar thermal technologies extract heat energy transferred by solar radiation. The heat could be used for heating and cooling applications, or to drive a heat engine, in turn run a generator and produce electricity. Solar thermal collectors make use of a working fluid for energy transfer, such as water, oil, salts, air, and carbon dioxide. Concentrating solar collectors use mirrors to focus the sun's energy on a tube containing fluid. The mirrors follow the sun, heating the fluid to very high temperatures. Absorption chillers operate by using this solar-heated fluid, to drive the refrigeration process. Using solar energy with absorption chillers reduces site-generated greenhouse gases as well as the emissions created when fossil fuels are burned to create electricity.

In case of solar PV systems, the solar energy is directly converted into electrical energy limiting PV to work only in daylight unless it is integrated with battery system for storage. However, solar thermal technologies, with a medium for thermal storage, can operate through the day, making it attractive for large-scale energy production. Heat can be stored during the daytime and excess daytime heat can potentially be stored and converted to electricity when required. Work is in progress towards development of such thermal plants, which will improve storage capacities to optimise the economics and the dispatch-ability of solar electricity.

Low Temperature Solar Thermal Systems

This type includes unglazed (flat plate) solar collectors and evacuated tube collectors. The operation of the system is reliant on the 'greenhouse effect'. Incident (high energy, short wavelength) solar radiation passes through the transparent or translucent surface of the solar collector. The metal or plastic surface and glazed panels reduce the heat radiated back out, resulting in lower heat loss by the convection of heat from the hot absorbing surface. These types of systems are used for low temperature (up to 180°C), for example

TVP solar, applications such as water and space heating, and swimming pools; where the loss of heat will not be as significant as with higher temperature panels. Figure 9 shows a typical picture of these types of solar thermal systems.

FIGURE 9: LOW-TEMPERATURE SOLAR THERMAL SYSTEMS



a) Flat plate collectors



b) Evacuated tube collectors
(inset: tube used)

Source: <http://solartribune.com/>; <http://www.setnrgh2o.com/>

High Temperature Solar Thermal Systems

High temperature solar thermal systems are based on two methods of solar thermal collection – line focus collection and point focus collection. Line focus collectors track the sun in one axis and focus solar radiation on a line receiver. Line focus collectors have concentration factors of 60-80, producing medium to high temperature heat (100-550°C). They are comparatively economical and technically easier to operate. Point focus techniques track the sun along two axes and concentrate incident sunlight at a point receiver, generating much higher temperatures of up to 800°C⁴. The high temperature heat from these systems is used for industrial purposes, or in electricity generation (i.e. concentrated solar power). Concentrating solar thermal power generators use mirrors to concentrate solar radiation. The heat generated can be transferred directly or via a working fluid to create superheated steam, and then to a turbine to generate electricity.

There are mainly four different types of high temperature solar thermal systems as described below. Figure 10 depicts the various technologies.

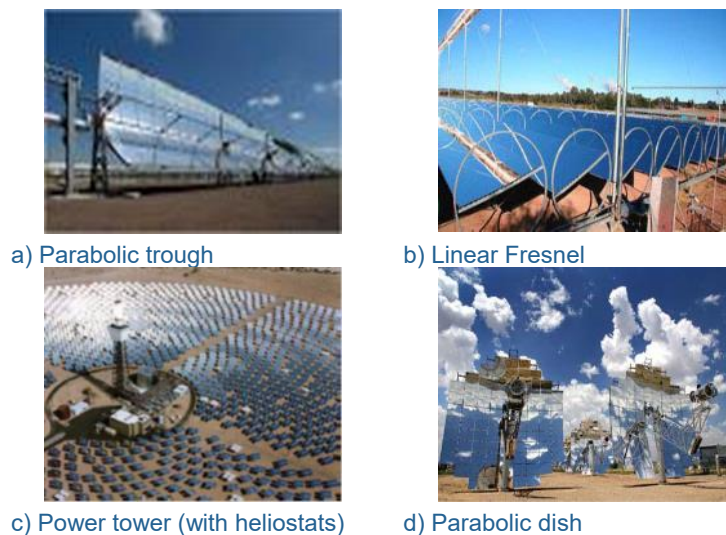
- **Parabolic trough collector (PTC):** Consists of parallel rows of parabolic mirrors (reflectors) curved to focus the sun's rays. Each reflector focuses radiation to a single tube, with a selective coating, fixed to the mirror structure. The coating allows pipes to

⁴ IRENA 2013, Concentrating solar power technology brief

absorb high levels of solar radiation while emitting very little infra-red radiation. In almost all parabolic trough systems, synthetic oil is used as the heat transfer fluid (HTF) to generate superheated steam.

- **Linear Fresnel reflector:** The reflectors are similar to parabolic trough reflectors, but are flat (or slightly curved) and configured to reflect sunlight onto a receiver tube suspended above the mirrors. The compact linear Fresnel reflector (CLFR) uses two parallel receivers for each row of mirrors and thus needs less land than parabolic troughs per unit output energy. However, due to less efficiency of such type of reflectors it is costly to enhance the storage capacity.
- **Central receiver (solar tower):** These achieve high temperatures by concentrating the sunlight on a central receiving system. It uses several hundreds of thousands of reflectors, also known as heliostats, to focus and concentrate the sunlight on the fixed receiver. Due to usage of high numbers of reflectors and high level of concentration, very high temperature heat is generated.
- **Parabolic dish:** Solar radiation is concentrated to a focal point at centre of the dish. Most dishes have an independent engine/generator (such as a Stirling machine or a micro-turbine) at their focal points. This design eliminates the need for a heat transfer fluid and for cooling water. Each dish produces electricity independently, with capacities limited to tens of kW or less.

FIGURE 10: DIFFERENT TYPES OF HIGH TEMPERATURE SOLAR THERMAL SYSTEMS



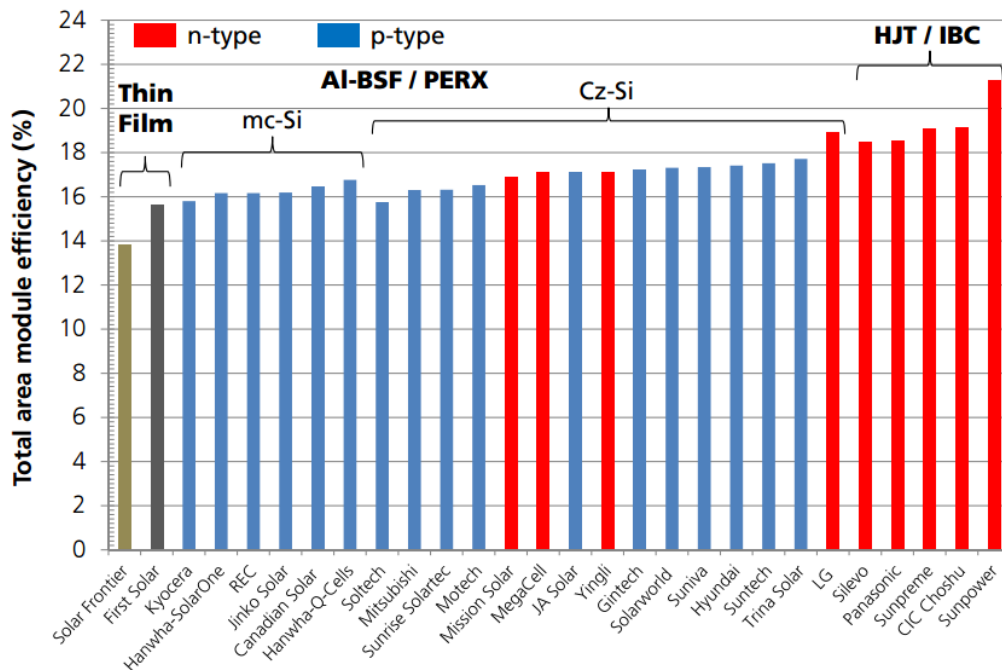
Source: High Temperature Solar Thermal Technology Roadmap; www.wyldgroup.com.au

EFFICIENCIES AND PHYSICAL CONSTRAINTS

Photovoltaic (PV)

The major concern about photovoltaic technologies is the efficiency, life and performance with time. Commercial PV modules convert less than 20% of the solar energy incident on them to electricity. The efficiencies of PV panels also have a temperature coefficient, and generally degrade with rising temperature. Figure 11 shows the reported efficiencies of current best-performing commercial PV modules. Monocrystalline solar panels have the highest efficiency rates, typically 17-21%.

FIGURE 11: CURRENT EFFICIENCIES OF COMMERCIAL PV MODULES



Source: Fraunhofer ISE (2015)

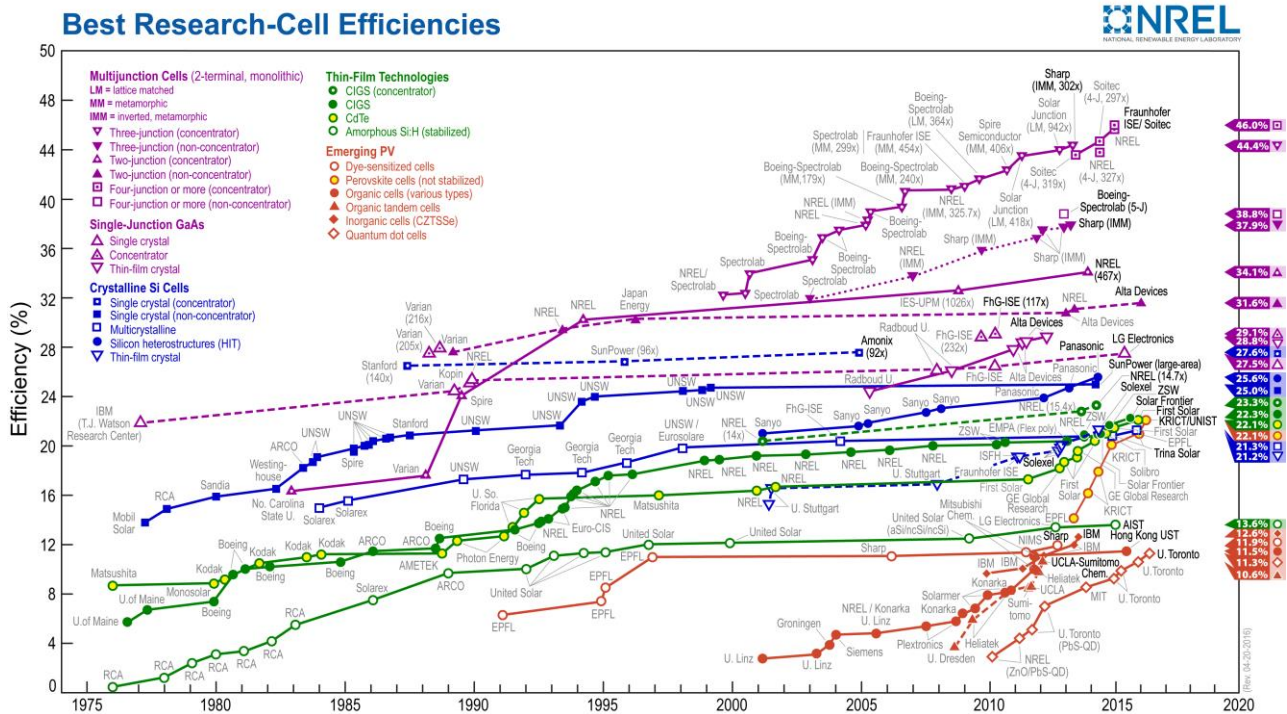
Monocrystalline solar panels are the most efficient commercially available modules, and have the longest life. They are also the most expensive to produce, since four sides of the silicon ingots are cut off to make high-purity silicon wafers. A significant amount of the original silicon ends up as waste.

On the other hand, polycrystalline and thin-film solar modules are economical with little less efficiency (14-16% for polycrystalline, 13-15% for thin-film). From a financial standpoint, a solar panel that is made of polycrystalline silicon (and in some cases thin-film) can be a better choice for several applications. The process used to make polycrystalline silicon is

simpler and hence economical since amount of waste silicon is less compared to monocrystalline. Mass production costs of thin-film modules are lower than for crystalline silicon modules, and also have a higher heat tolerance.

At research level, efficiencies of the best-performing solar PV cells are fast approaching 50%, utilising new technologies including multi-junction cell configurations and concentrated photovoltaics. Figure 12 shows the trend in maximum achieved efficiencies of different solar PV cell technologies, from 1975 to the present day.

FIGURE 12: BEST RESEARCH SOLAR CELL EFFICIENCIES OBTAINED TO DATE



Source: NREL (2015), http://www.nrel.gov/ncpv/images/efficiency_chart.jpg

Solar Thermal

The variation in CSP technologies comes in terms of their optical design, shape of receiver, nature of the transfer fluid and capability to store heat. On the other hand, tower technology ranks second only to parabolic dishes with respect to concentration ratio and theoretical efficiency, and offers the largest prospects for future cost reductions. Broadly, the efficiency of such types of systems varies between 70-80%.

With regards to solar heating, the efficiencies of solar collectors can be improved by making them spectrally selective. A spectrally selective surface has maximum absorption for short wavelength solar radiation (0.3 – 2.5 μ m) and minimum emission for long wavelength thermal radiation (3.0 – 30.0 μ m).

TECHNOLOGICAL ADVANCEMENTS

New materials and manufacturing methods for solar PV

In the coming years, the solar photovoltaic industry will be focused on developing high stability photovoltaic devices and manufacturing methods that enable commercial-scale PV module technology with the following characteristics:

- Very low capital intensity (< EUR 0.25 per W_p per year within 2025)
- High conversion efficiency (> 20% within 2025)
- Excellent environmental profile, reducing the production of harmful materials
- Long module lifetime (> 35 years) and low degradation (< 0.3%/year)

With the solar PV industry currently heavily dependent on silicon, research has gone into the development of solar cells from new materials. In addition to thin-film and organic solar cells, compounds such as perovskite are being used in developing the next generation of solar PV cells. Efficiencies of perovskite cells have jumped from 3.8% in 2011 to over 20% by 2014. While perovskite solar cell technology is yet to be consolidated for commercial modules, cells can be very cheap as they are made from relatively abundant elements such as ammonia, iodine and lead. However, there are severe doubts in terms of environment safeguarding over the use of lead. Moreover, perovskite⁵ cells are unstable and deteriorate significantly when exposed to the environment. Therefore, the replacement of lead with a more environment friendly element and the improvement of stability will be important objectives for the researchers in this field.

Recently promising approaches combining perovskites and silicon based solar PV cells have been proposed to raise the conversion efficiency above the theoretical limit of the conventional solar cell⁶. High bandgap perovskite PV cells capture blue and green light and are transparent to red and infrared light which can be efficiently absorbed by silicon cells. Developing a tandem solar cell with correct matching of the top perovskite and bottom silicon cell is expected to increase the conversion efficiency of the solar cells well beyond 25%, while keeping manufacturing costs low.

⁶ Mailoa *et al.*, (2015)

Many other new materials and promising methods of fabrication are under development. Among new materials, graphene could be a successful implementation of future low cost solar cells, with the possibility of developing high efficiency solar cells on flexible plastic substrates. However, so far, despite the promising characteristics of the material, it has been difficult to obtain solar cells with adequate efficiencies and stability. New methods include fabricating large area thin-film PV cells from high efficiency III-V compounds such as Indium Phosphide (InP), by using low cost vapour-liquid-solid (VLS) growth of thin-films on metal foils⁷.

Nevertheless, it is worthwhile to point out that efficiencies of silicon solar cells also continue to improve. This has been mainly achieved by developing new cell architectures that minimise light shadowing, such as back contact cells, or by implementing new contact and hetero-junction schemes. Today, due to very tough competition to the economy of scale and partly to global production overcapacity, silicon based solar cells with efficiencies of 20% are available at much lower prices than a few years ago. As matter of fact, manufacturing costs of higher efficiency silicon PV modules are quite competitive with those of thin-film PV modules, and it is highly likely that the Si based technology will continue to dominate the market in the next five years. This will be especially true if new fabrication techniques are able to process crystalline silicon wafers with highly reduced thickness (below 50µm), thus strongly reducing manufacturing costs.

In such a timeframe, it will be vital to develop innovative, high efficiency solar cells with improved thermal stability (low temperature degradation ratio), longer PV module lifetime and the characteristics of capturing grazing angle and diffused light. Bifacial solar cells will also be an interesting development because of the possibility of raising the energy gain by capturing the light from the rear side of the solar cell.

Concentrated PV

While there has been continuous improvement in the efficiencies of PV cells, concentrated photovoltaics (CPV) may hold the key in enabling rapid increases in solar energy efficiency. CPV involves the use of optics to concentrate incident solar energy on PV cells, hence reducing the area of high-efficiency cell required. Concentrating optics used include Fresnel lenses and mirrors. CPV also employs tracking systems to ensure maximum solar incidence on the panels at all times. CPV technology is best served in areas with DNI exceeding 2000 kWh/m² per year. There are two classes of CPV, based on the level of concentration used, as shown in Table 2.

⁷ Kapadia, R. *et al.*, 2013

TABLE 2: DESCRIPTION OF CONCENTRATED PV CLASSES

Class	Concentration ratio	Tracking type	PV cell used
High concentration PV (HCPV)	300-1000	Two-axis	III-V multi-junction cells
Low concentration PV (LCPV)	<100	One or two-axis	c-Si or other cells

Source: Fraunhofer ISE, NREL (2015)

As the bulk of the cost of solar PV comes from the manufacturing of the semiconductor cells, CPV could drive further reductions in cost in the long term. The technology is already cost-competitive with concentrated solar power in certain sunny areas. Recent progress in CPV has seen record efficiencies reach 46% for solar cells and 36.7% for modules in laboratory conditions. CPV has also moved into the commercial space, as a provider of utility-scale electricity. Efficiencies for commercially available CPV modules currently exceed 30%⁸. In addition to higher efficiencies, CPV technologies have lower temperature coefficients than flat-plate PV and could theoretically be scaled up to the GW range.

The CPV market is still very young and small in size, limited to locations with favourable conditions such as China, United States, South Africa, Italy and Spain. The global market since the mid-2000s has also been marked by specialist companies going out of business and scrapped projects. Global CPV capacity in 2014 stood at 330 MW_p. The world's largest CPV plant at Golmud, China has a capacity of 80 MW_p, and came online in 2013⁹.

Solar Fuels

There has been much research on the development of 'solar fuels' – where fuel is created from sunlight, water and air (with the aid of a catalyst). This is described as 'artificial photosynthesis', as it is akin to the natural process evident in plant life. The most common practice of artificial photosynthesis involves the use of sunlight to split water molecules to create hydrogen fuel. Current solar-to-fuel efficiencies are on average about 7%; this compares favourably to natural photosynthesis, which has an efficiency of 0.5-2.0%. However, researchers from Germany and the United States have achieved efficiencies of 14%¹⁰. In addition, newer research into solar fuels has identified another method of artificial

⁸Fraunhofer ISE, NREL (2015) – Current status of concentrator photovoltaic (CPV) technology

⁹ <http://cpvconsortium.org/projects>

¹⁰ May *et al.* (2015)

photosynthesis, where solar energy breaks carbon dioxide into synthesis gas (which comprises of carbon monoxide and hydrogen), which in turn can be used to create hydrocarbons. Efficiencies of this method are estimated at 18%. Hythane, a blend of hydrogen and methane, can also be created at an efficiency of 20%¹¹.

New Applications

With advancements in solar technology, the range of potential applications of solar power widens further. The combination of perovskite and graphene to produce semi-transparent panels could lead to high-efficiency solar windows. Utility-scale solar is already providing water desalination services in the Middle East, and in Oman solar energy is utilised to recover oil from the country's reserves, as the case study below shows.

Solar panels are being built and deployed in ingenious manners, on freshwater dams and lakes, in order to save land and in some cases water. For example, the 13.7 MW Yamakura solar power station in Japan will employ 51,000 solar modules built on the freshwater dam, which will save agricultural land and reduce water evaporation. A similar concept is being developed in India at a much smaller scale. The project consists of covering a 750 metre stretch water canal (from the total 85,000 km) in the province of Gujarat with solar panels that will generate 1 MW of electricity. The project has great potential for expansion given the long size of the canal, so if only 10% would be covered with solar panels the generating capabilities would be around 2,200 MW. Using the canals to produce this much energy would save 11,000 acres of land and would eliminate the loss of millions of litres of water per year.

SOLAR-POWERED OIL PRODUCTION

Oil companies are increasingly producing heavy oil, which accounts for 70% of today's remaining reserves. Heavy oil is abundant, but difficult to extract. The leading method of producing heavy oil is steam injection, a type of thermal enhanced oil recovery (EOR) that injects steam into a reservoir to heat the oil making it easier to pump to the surface. Steam injection can boost well productivity by up to 300%, but is an energy intensive process.

To produce the steam for EOR, oil companies burn an enormous amount of gas—a valuable resource that is in short supply in many oil-producing regions. Solar-powered EOR replaces burning natural gas with concentrated solar power. Solar energy can provide a significant amount of an oilfield's steam needs, significantly reducing the amount of gas consumed. To maintain steam injection around the clock, solar steam is injected during the day, and steam produced by burning natural gas is injected at night. Enclosed trough technology is built to meet the unique needs of the oil industry. Curved

¹¹ Singh *et al.* (2015)

mirrors inside a glasshouse track the sun, focusing heat onto a pipe containing water. The concentrated sunlight boils the water to generate steam. The glasshouse protects the mirrors from wind, dust and sand. It has an automated washing machine to maintain performance in harsh desert environments.

Solar energy produces steam with zero emissions; the gas saved can be exported or redirected to higher value uses such as power generation or industrial development. As a result, solar-powered EOR can boost the local economy and help create jobs too.

Petroleum Development Oman (PDO), Oman's largest producer of oil and gas, partnered with solar steam generator company GlassPoint to develop the Middle East's first Solar-powered EOR system. The 7MW_{th} pilot began producing steam in December 2012 and continues to operate successfully, producing an average of 50 tons of emissions-free steam per day. The solar steam is fed directly to PDO's existing steam distribution network. The pilot has achieved above 98% uptime, maintaining regular operations even during severe dust and sand storms. The success of the pilot is now paving the way for larger solar EOR projects in Oman and the rest of the Gulf region. In July 2015, PDO and GlassPoint signed an agreement for a 6000 t/d facility (equivalent to just over 1 GW_{th}) in the south of Oman. The project named Miraah ("mirror" in Arabic) is expected to save 5.6 trillion Btu of gas and 300,000 tons of CO₂ emissions per year. First steam is expected in 2017.

Figure 13: PICTURE OF THE SOLAR-POWERED EOR PROJECT IN OMAN



COMPACT SOLAR POWERED WATER TREATMENT STATIONS IN INDIA

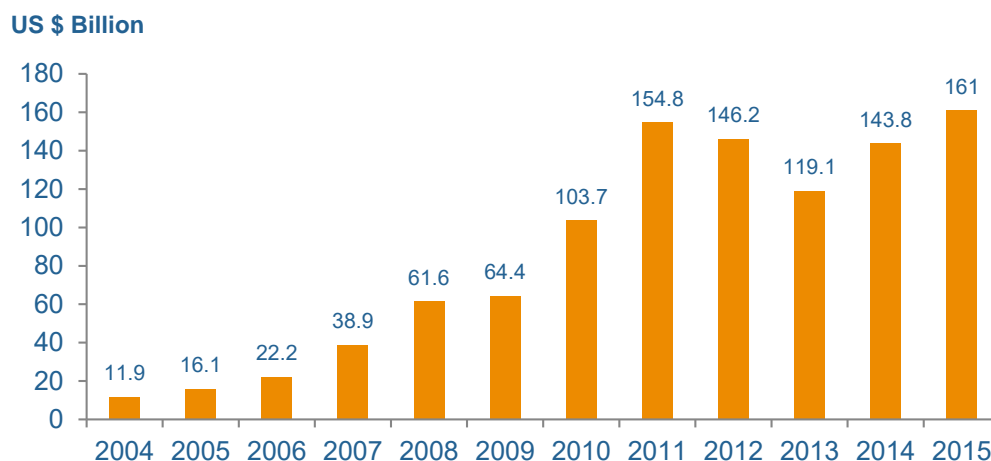
In a rural village (of Andhra Pradesh state of India) with no access to clean water and irregular power supply, SunSource Energy Pvt Ltd. in association with an NGO named as SANA installed a solar system to purify waste water and make it potable. Local

governance body of the village (Panchayat) with the co-operation was made a partner in the model, and representatives of the Panchayat were trained for the up keeping of the water station, the solar panels and water distribution. The water station converts 1.8 million litres of contaminated water into WHO standard potable drinking water for the local villagers. This project has won the Google Impact Award for 2013 and SunSource Energy Pvt. Ltd is looking for other such villages in rural parts of India and nearby countries where solar energy can bring change to lives of rural people.

2. ECONOMICS & MARKETS

Recent global investments in the clean energy sector have exceeded those in conventional or fossil fuel based power generation technologies. This has been driven by an availability of a variety of solar technologies catering to different needs (power generation, lighting, heating etc.) and recent efficiency advancements achieved in those technologies. Figure 14 below shows trend in solar power investments over the last decade. It can be seen that overall there has been increasing trend which has resulted into huge capacity addition in this technology.

FIGURE 14: YEARLY NEW INVESTMENTS IN SOLAR POWER (US \$ BILLION)



Source: UNEP, Bloomberg New Energy Finance (2016)

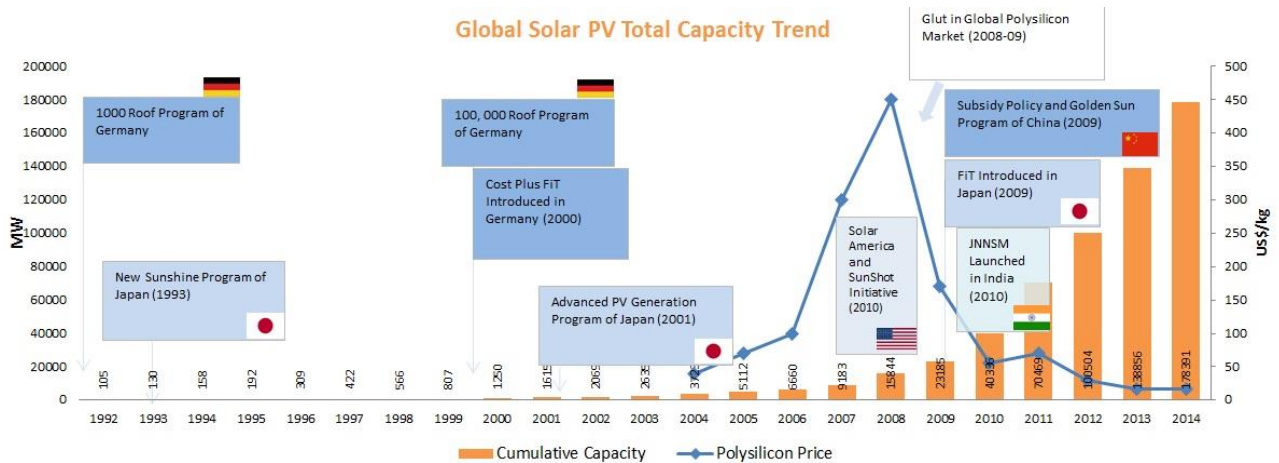
This section will cover the trend in solar markets across the globe, identifying key drivers that have ensured good returns for investors while contributing towards larger policy objectives of governments – energy security, energy poverty & access and adaptation to climate change strategies.

SOLAR PV

Historic and Current Trends

According to the International Energy Agency, solar PV installed capacity had reached around 227 GW by end of calendar year 2015¹². Capacity has increased tenfold since 2008, producing more than 1.3% of all the electricity demand globally. In addition to several policy, regulatory and market initiatives that have been taken by many governments across the globe, the cost economics of polysilicon has also been a key driver of this evolution in solar PV. As can be seen in Figure 15, the price of polysilicon is indirectly proportional to capacity additions in solar PV (after 2008).

FIGURE 15: GLOBAL TREND IN TOTAL PV CAPACITY AND PRICE OF POLYSILICON



Source: Author's compilation of IRENA, IEA, EPIA, JETRO data

Historically, solar PV was not considered to be a mainstream energy source, and was characterised by very low cell efficiencies and high prices of polysilicon. Most of the polysilicon produced before 2005 was used by the IT industry and hence, there was a supply constraint. Policy targets to combat climate change and addition of significant capacity of solar PV by many developed countries such as Germany, the United States and Japan pushed investments in polysilicon gradually and by 2008-09 there was a glut in polysilicon market. This resulted in drastic fall in polysilicon prices and hence overall solar PV prices, attracting huge investments in the sector. In fact, the glut in market was so big that many big industry players had to shut down their polysilicon manufacturing facilities,

¹² IEA-PVPS (2015)

due to disappearing profit margins and struggles to be cost-competitive with Chinese output.

It is also very important to mention that improvement in cell efficiencies lately has also played a vital role in qualifying solar PV as an important source of energy.

Cost of Technology

The solar PV sector is so dynamic that today’s cost of generation may become tomorrow’s benchmark. Prices for the offtake of solar PV electricity have reduced dramatically in the last decade; and with the availability of economic financing and policy / fiscal pushes, it is expected to drop further in the future. Cost of major equipment does not vary much across the globe; however, it is the financial engineering that is defining these prices in current scenarios. Since the terms of financing and solar resources vary across countries, so does the yield or output of energy and returns from solar PV projects. Hence, the focus of this section will be on the cost of the PV equipment.

A complete solar PV system is a consolidated package of various elements. These elements are diverse and are integrated through substantial effort by various players across a very large supply chain consisting of different major components including the solar modules and the balance of system (BoS) – inverter, mounting structures, electrical infrastructure and (in some cases) energy storage.

The capital cost of a PV system is composed of the PV module cost and the BoS cost. The cost of the PV module – the interconnected array of PV cells – is primarily determined by raw material (polysilicon) costs; while the BoS cost includes items such as the cost of the structural system, the electrical system costs, and the soft costs of system development (e.g. customer acquisition, permitting, labour costs for installation). The cost of the battery or other storage system, if any, in the case of off-grid applications also needs to be added. The detailed breakdown of solar PV cost components is shown in Table 3.

TABLE 3: BREAKDOWN OF SOLAR PV COST COMPONENTS

Component	Costs
Semiconductor	Capital & equipment cost + raw materials (e.g. silicon, saw slurry, saw wire) + utilities + maintenance & labour + manufacturer margin
Cells	Capital & equipment + raw materials (metallization, dopants) + utilities + maintenance & labour + manufacturer margin
Modules	Capital & equipment + raw materials (glass, ethylene vinyl acetate (EVA), metal frame, junction box) + utilities + maintenance & labour

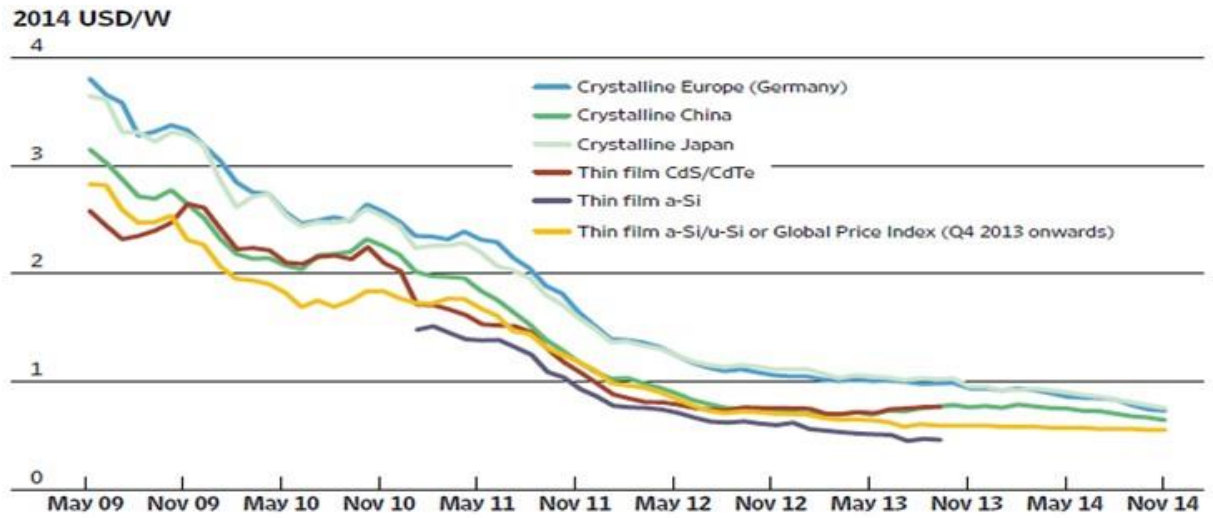
	+ margin + shipping + retailer margin
Inverter	Capital & equipment + raw materials (magnetics, board, enclosures) + power electronics + utilities + maintenance & labour + manufacturer margin
Balance of system / Installation	Mounting + hardware + wiring + design + installation

Source: IRENA (2015)

As solar PV module prices have declined, the importance of the BoS cost is increasing, particularly the soft costs. This has important ramifications for policy-makers, as price declines for solar PV modules will now be more modest in absolute terms and will no longer be a major driver of cost reductions for solar PV systems in the future. Policy-makers must now turn their attention to driving down BoS costs. This will bring a new set of challenges, as a much more diverse range of cost drivers have an important role in the BoS, from permitting procedures and costs, to installation labour, to customer acquisition costs.

Between 2007 and 2014, PV module prices declined by around 79%; the biggest yearly reduction was seen in 2011, of around 40% from 2010. Within this period of declining prices, there was a slight increase in Chinese module price in year 2013 due to exchange fluctuations and trade disputes. In 2014, the downward trend was restored to a range between 7% for thin-film modules and 22% for German modules. In 2013-14 higher cost module manufacturers in Germany and China experienced more reduction than average Chinese modules. The slowdown in the rate of price reductions in 2013 and 2014 was driven by solar PV module manufacturers consolidating margins and, in many cases, trying to return to positive margins after a period of manufacturing overcapacity and severe competitive pressures in the industry. Locally, the cost of PV modules is influenced by taxation (import duties), performance of modules, market conditions etc. Variation among countries could be significant and this is shown in Figure 16. The prices of modules in Germany and Japan in comparison to China have always been higher. Furthermore, it is important to mention that within a country the prices of modules of different sizes will vary. This is because both manufacturing cost and margins can be better controlled for larger module sizes.

FIGURE 16: TREND IN SOLAR PV MODULE PRICES, BY MARKET



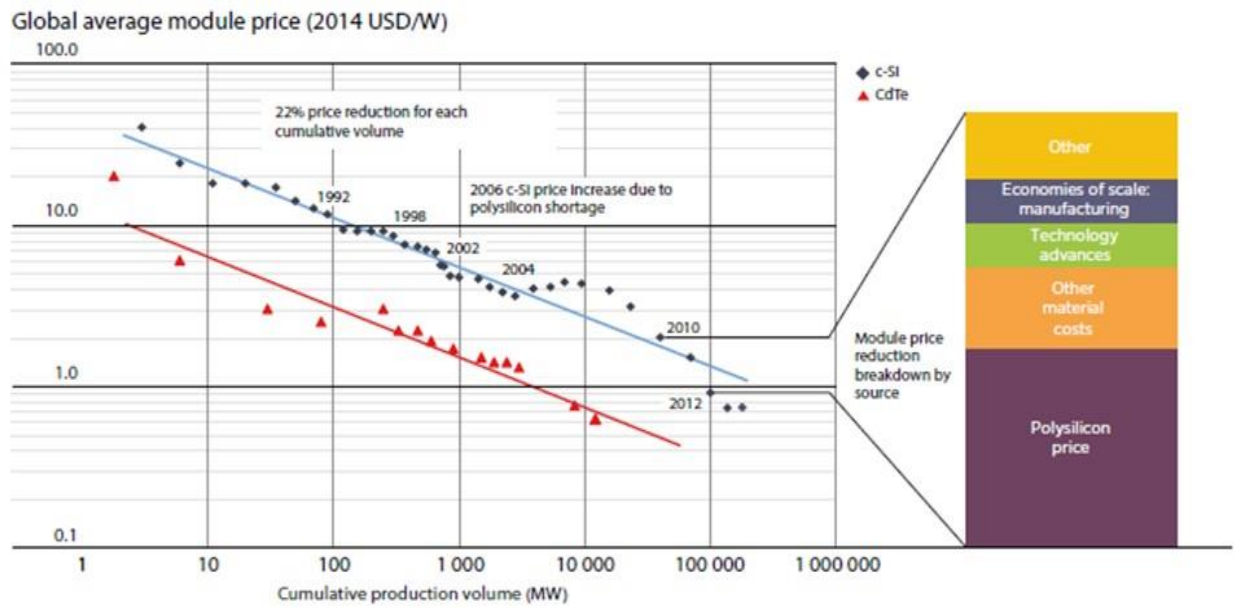
Source: IRENA (2015)

Figure 17 shows that prices of solar PV modules have significantly overshot the expected learning curve. This was the result of significant overcapacity in module manufacturing and the cut-throat competition that saw many module transactions occur at cash cost, or in some cases even lower, as financially stressed manufacturers tried to maintain cash flows. In 2013, despite record solar PV installations of around 39 GW, global PV manufacturing capacity, including c-Si and thin-film, exceeded 63 GW¹³. An additional 10 GW of new module production capacity may have been added in 2014¹⁴. The competitive pressures in the solar PV module manufacturing industry are therefore likely to remain intense, although – unlike in recent years – profitability for the major manufacturers has improved and is now on a more sustainable footing.

¹³ IRENA (2014)

¹⁴ GTM Research (2014)

FIGURE 17: LEARNING CURVE RATES FOR SOLAR PV

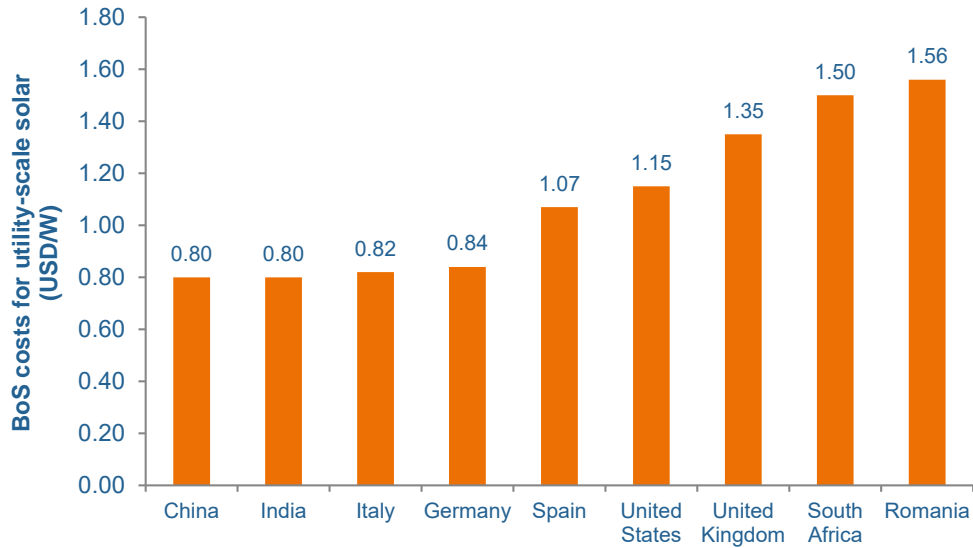


Source: IRENA (2015)

There has been a pause in reductions in average module selling prices in 2014; however current prices are still significantly below the learning curve. They are also now so low that continued cost reductions, based on learning rates of 18% to 22%, will not yield large absolute cost reductions, as in the past. This means, in most countries, that BoS costs and in particular the soft costs, will provide the largest opportunity for future cost reductions in absolute terms and represent the next great challenge for the solar PV industry.

BoS costs are lagging behind the trend for overall PV module prices. BoS costs fell by 39-64% between 2007 and 2014. Local market conditions and the regulatory environment can have a significant impact on the BoS costs, and wide variations typically exist within a country and between countries. Figure 18 shows the range of BoS costs for utility-scale solar in selected markets. These variations reflect the maturity of markets and supply chains, but also in many cases the efficiency of support mechanisms since solar system pricing is often value-based to some extent and influenced by the support levels in place. However, it has been observed that there is a marginal increase in BoS cost for small scale or residential systems across the globe.

FIGURE 18: TYPICAL BOS COST FOR UTILITY-SCALE SOLAR (USD/W) ACROSS VARIOUS ECONOMIES IN 2014

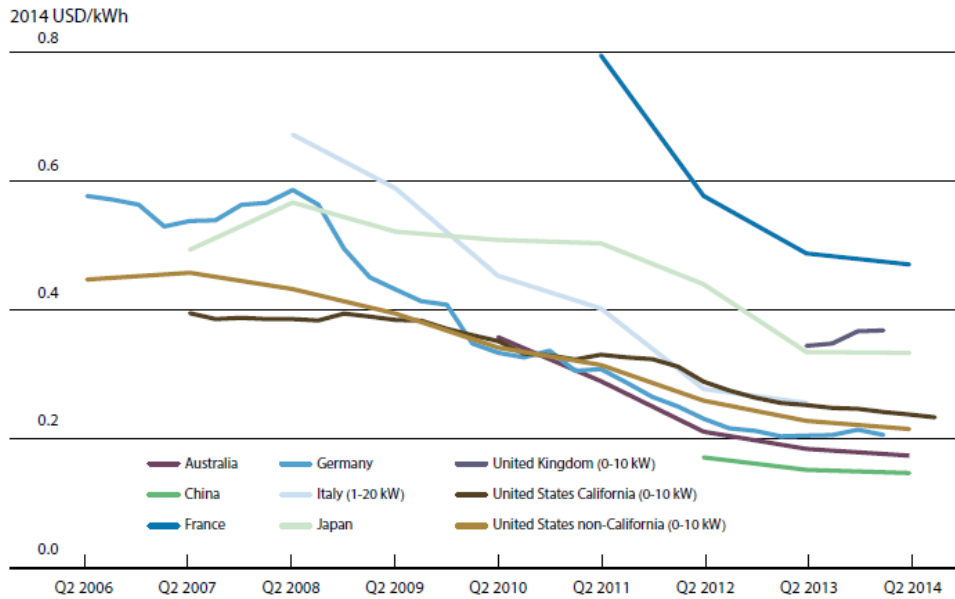


Source: IRENA (2014); MIT (2014)

Levelised Cost of Electricity (LCOE)

The global average utility-scale LCOE of solar PV is estimated to have declined by around 50% between 2010 and 2014, from around US\$0.32 per kWh to US\$0.16 per kWh in 2014. The estimated global average LCOE of utility-scale solar PV declined by 14% between 2010 and 2011, 34% between 2011 and 2012 and by a further 8% between 2012 and 2013. The LCOE changed little between 2013 and 2014, despite continued modest declines in installed costs in virtually every major market.

FIGURE 19: TRENDS IN LCOE FOR SOLAR PV IN KEY MARKETS



Source: IRENA Renewable Cost Database; BSW, 2014; CPUC, 2014; GSE, 2014; LBNL, 2014; and Photon Consulting, 2014.

Source: IRENA (2015)

The average LCOE of residential PV systems without battery storage was estimated to be US\$0.38-0.67 per kWh in 2008 for the data presented in Figure 19. But this declined to US\$0.14-0.47 per kWh in 2014. LCOE of electricity for residential systems declined by around 42% between 2008 and 2014 for small systems (0-4 kW) in California and by 44% for the larger 4-10 kW systems; in other parts of the United States the decline was 52% and 54%, respectively, for these residential systems. The LCOE of French residential systems is estimated to have declined by 61% between 2008 and 2014, while the LCOE of Japanese residential systems fell by 42%. The estimated LCOE of residential systems in Italy fell by 59% between 2008 and 2013 for systems of 1-3 kW in size, while they fell by 66% for larger systems of 3-20 kW in size, for an average decline of around 63%. Between 2010 and 2014, the average LCOE of residential systems in Australia declined by 52%. A shorter time series is available for China, which has very competitive LCOE levels.

LCOE is well-adapted to areas where demand and sunshine are simultaneous, for instance places with peak demand at noon due to high rate of air conditioning such as California; but in places where peak demand is in the evening in winter, and with around 1000 hours sunshine per year, such as Germany, electricity storage or back up by the grid is required: cost for the customer must take into account these additional costs in order to give the right market signal.

It is worthwhile to mention that LCOEs vary across the countries due to variation in factors such as capital cost of equipment, labour cost of system installation, cost of capital (debt and equity), solar insolation etc.

CONCENTRATED SOLAR POWER (CSP)

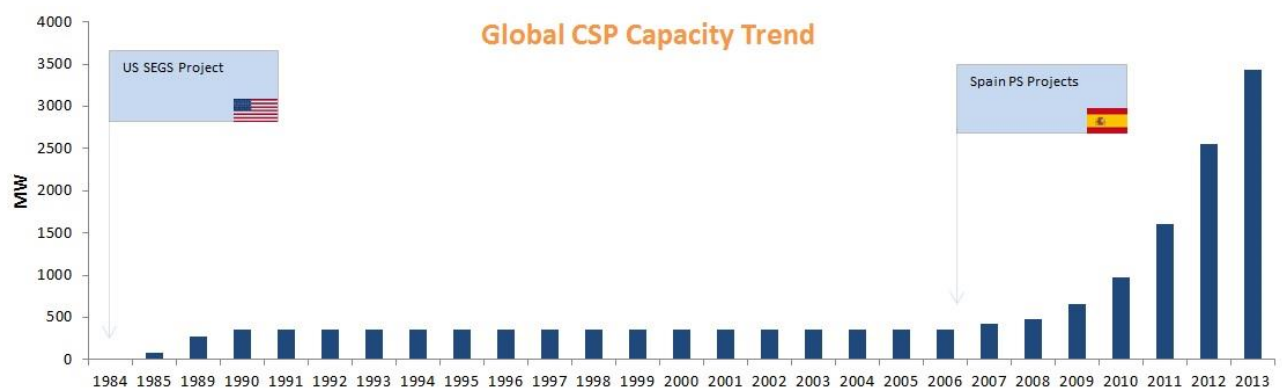
Historic and Current Trends

Although research and demonstration started in CSP much earlier than PV, the growth in this industry has been much slower than that in PV industry. This is because of complexities in both project implementation and operation. In addition to solar energy conversion components (consisting of mirrors, lenses, concentrators and heat medium), a conventional power block (turbines and generators) of thermal plants, a solar block is also required for CSP operation. The design of system along with implementation of these plants requires substantial skill sets as the system needs to have storage facility to maintain grid reliability.

The commercial deployment of CSP plants started in 1984 in the United States with the Solar Energy Generating Systems (SEGS) project. The last SEGS plant was completed in 1990. From 1991 to 2005, no CSP plants were built anywhere in the world. Global installed CSP capacity has increased nearly tenfold since 2004 and grew at an average of 50% per year between 2009-10 and 2013-14. In 2013, worldwide installed capacity increased by 36% to more than 3.4 GW. Spain and the United States remain the global leaders, while the numbers of countries with installed CSP are growing. There is a notable trend towards developing countries and regions with high solar radiation.

Moreover, water needs for CSP is a key challenge in inter-tropical regions, and should be addressed in every project before making decisions.

FIGURE 20: TREND IN GLOBAL CSP CAPACITY



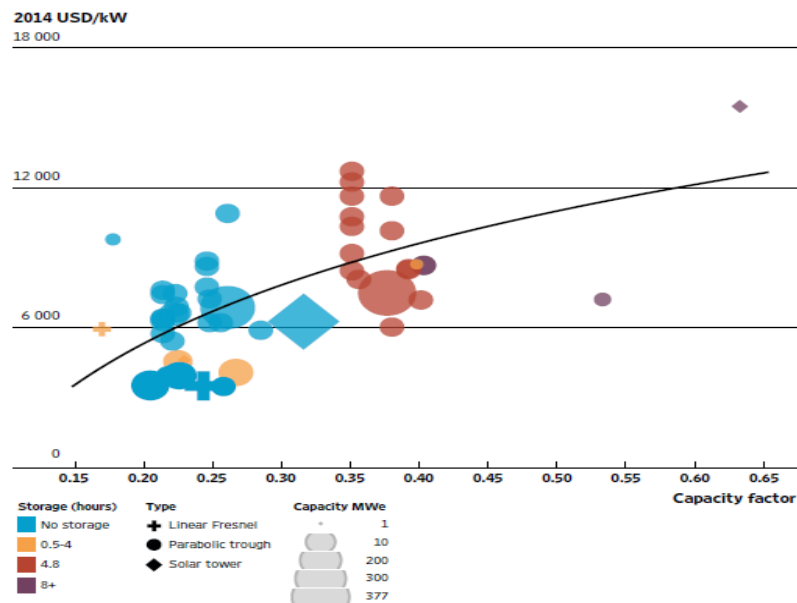
Source: Author's compilation of REN 21, IRENA, CSP-World.com

Cost of Technology and LCOE

The current CSP market is dominated by parabolic trough collector (PTC) technologies, both in terms of number of projects and total installed capacity (around 85% of capacity). PTC technology's share of total installed capacity will decline slowly in the near future, as around one-third of the capacity of plants currently under construction is either solar tower projects or linear Fresnel systems¹⁵.

The current investment costs for PTC plants without storage in the OECD countries are typically between US\$4,600-8,000 per kW. PTC plants without storage in non-OECD countries have been able to achieve a lower cost structure, with capital costs between US\$3,500-7,300 per kW.

FIGURE 21: INSTALLED COSTS AND CAPACITY FACTORS OF CSP PROJECTS BY THEIR QUANTITY OF STORAGE



Source: IRENA (2015)

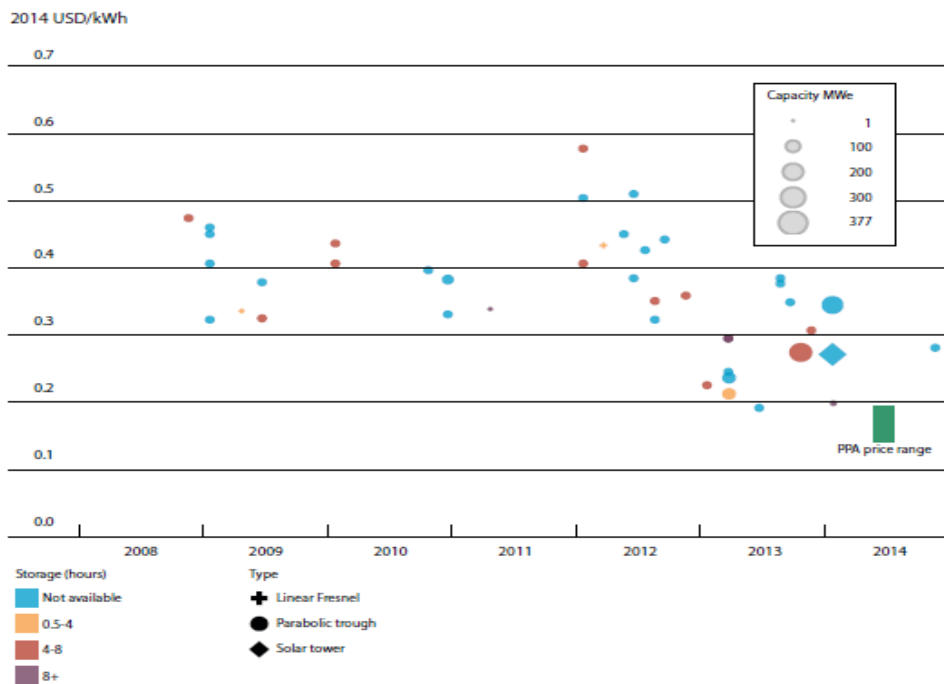
CSP plants with thermal energy storage tend to have higher investment costs, but they allow higher capacity factors, dispatch-ability and typically lower LCOEs than plants without storage (particularly for molten salt solar towers). They also have the ability to shift generation to when the sun is not shining and/or the ability to maximise generation at peak demand times. There are a small number of PTC, linear Fresnel and solar tower projects

¹⁵SolarPACES, 2014

around the world with modest storage capacity of between 0.5 and 4 hours. These plants have estimated installed capital costs of between US\$3,400-6,700 per kW.

The costs of PTC and solar tower plants with thermal energy storage of between 4 and 8 hours are typically between US\$6,800-12,800 per kW for projects with available data. This cost range is wider than the bottom-up engineering estimates obtained from the available literature of between US\$6,400-10,000 per kW.

FIGURE 22: LCOE OF CSP PROJECTS 2008-2014



Source: IRENA (2015)

The evolution of the LCOE between 2008 and 2014 is presented in Figure 22 above. There was little change in the LCOE range for CSP projects between 2008 and 2012, although the range widened and grew somewhat with the burst in growth in 2012. Between 2012 and 2014, the LCOE of the projects generally trended downwards. The LCOE for recent parabolic trough plants without storage is in the range of US\$0.19-0.38 per kWh. Adding storage narrows this range to US\$0.20 to US\$0.36 per kWh. The fact that recent power purchase agreement (PPA) prices, where no direct subsidies are supplied, have been between US\$0.14-0.19 per kWh suggests that government guarantees and development financing have been able to reduce financing costs for some CSP plants to below a 7.5% weighted average cost of capital (WACC).

RISKS

Technology Advancements Risk

Reduction in solar prices is good news from the beneficiary's point of view. However, substantial and swift reduction is a major risk for investors. This is because energy generation cost of a system implemented later than earlier ones will always be lower. If the time difference between implementation of new and earlier systems is very small, then the beneficiary may become inclined towards dismantling the earlier system and installation of a newer one. This will pose a huge risk for investors of projects implemented earlier. Another risk for investors is the retroactive reduction of FiT, which should be avoided as much as possible for maintaining investors' confidence.

Furthermore, it is advisable to perform an assessment of the future cost and be ready to adapt to the change appropriately (e.g. in case of the beneficiary wishing to dishonour the agreement) and negotiate a price that is acceptable to both the parties. For instance, a system providing power at US\$0.10 per kWh in current scenario may be asked to supply power at US\$0.05 per kWh after just 3 years of operations. In this case, the developer / investor may dismantle PV modules and install newer high efficiency and cheaper modules and sell off the obsolete PV modules for rural electrification and other needs. The developer may then negotiate and strike a deal at US\$0.07 per kWh.

Regulatory Risk

Investment in solar energy is also at risk from swift changes from policy and regulation, particularly in light of steeply falling costs of implementation and rising deployment. As these trends were difficult to predict, policymakers have been forced to modify or prematurely phase out initiatives supporting solar in a bid to save costs. Retroactive policies were responsible for the boom-and-bust cycles in solar development witnessed in Spain (2008-09) and Italy (2010-12). Retroactive policies are usually as a result of a poor design of the initial policy structure, through a lack of foresight on the potential changes to the market and the inability of the measures to respond quickly and adequately to arising problems. For example, the feed-in tariff implemented in Spain was adjudged to be too generous to investors and project developers, and retroactive efforts to check this put off investment, causing the solar PV market to crash. In Italy, excessively long transition periods between policy schemes caused a boom in installations just before the new scheme came into effect.

Regional Conflicts

Over the last few years, China has emerged as one of the biggest exporters of solar PV modules across the world; hampering sales of domestic module manufacturers in Europe, United States and other countries like India. A series of trade disputes in these countries were designed and pursued to protect domestic firms but it is generally argued that the disputes come at a cost of slowing down the growth of solar energy.

The European Commission pursued both anti-dumping and anti-subsidy investigations against PV modules imported from China. It first adopted provisional import duties in December 2013, before moving to a settlement that established a price floor of EUR 0.56 (US\$0.61) per watt and a total annual import limit of 2,000 GW. The EC extended the implementation of the measures beyond the end of 2015, pending a review which may last until early 2017¹⁶.

In the United States, two cases unfolded – in 2011-12 and 2013-14 respectively – both leading to unilateral tariffs on solar PV. Following anti-dumping and anti-subsidy investigations, the U.S. Department of Commerce (DoC) set preliminary unilateral tariffs on Chinese module imports in May 2012. The ruling left the possibility open that Chinese manufacturers import modules assembled in China with cells from Taiwan, leading to a second case. In May 2014, the DoC expanded the scope and the level of duties.

Similarly, India's Domestic Content Regulation (DCR) of utilising domestic modules/cells for a pre-specified scheme/capacity was also challenged by the United States and other countries. This was done by the Indian government to safeguard the small domestic PV industry in the country. Since the power purchase from these schemes (DCR) is done by public/government agencies, the Indian government, under the government procurement clause of WTO, continues to practice these schemes.

Despite these regional conflicts and trade disputes, the import of Chinese modules has been increasing because of their cost competitiveness and very large capacity installations across the world.

FUTURE OUTLOOK

Investment in Mature Markets

Thanks to spectacular growth of the global solar industry within the last decade, solar power projects are entering a new phase of existence, particularly in established markets such as the United States, Australia and parts of Europe. The wide consensus is that national governments will gradually scale back on the investment and incentives that have contributed to the proliferation of solar capacity. This presents a new challenge to solar project developers, on how they can continually secure the financing required to maintain capacity additions in a future devoid of capital subsidies and tax credits. There is a need for pure market-led financial structures for solar energy development to maintain growth in mature solar markets, as well as foster development in emerging markets. The following case study describes recent efforts to meet this challenge.

¹⁶ Fuhs (2015)

NEW FINANCING MODELS FOR SOLAR ENERGY

Developers in the United States are leading the way in devising novel methods of financing projects for solar and other renewable energy technologies. A very popular financing vehicle is the 'YieldCo', which is designed for investments in all power generation sources, but has seen exponential increases in solar portfolios since 2013. A YieldCo is created by a parent company and bundles the company's renewable and/or conventional generation assets in order to generate predictable cash flows, which are distributed amongst the company's shareholders. This arrangement is designed to produce low-risk returns (currently around 3-7%) that will grow over time. The capital raised can then be ploughed back into the company to finance future projects.

In 2014, SunEdison created a YieldCo, TerraForm Power, with a portfolio existing solely of solar PV systems exceeding 1 GW capacity. By 2015, the three biggest PV manufacturers in the United States had all established YieldCos. It is expected that the renewables YieldCo market will grow from USD 30 billion to USD 1 trillion within the decade, exceeding similar instruments that exist for oil and gas investment, and further driving down the cost of finance for renewable energy projects¹⁷. However, towards the end of 2015, the YieldCo market began to face challenges. Stocks declined by 24% on average between April and September 2015, caused by perceived saturation within the market, and fears over a rise in interest rates in the United States.

At the distributed level, solar crowdfunding platforms such as Mosaic and Sunfunder are providing individuals and communities access to capital for solar projects, free of third-party ownership. Crowdfunding does face some limitations to growth, including barriers to entry for would-be investors and risks that the project owner will default on the loan. In Europe, green bonds are the new financing vehicle of choice, but are spread over wider range of asset class – from solar and renewables to transport and other social projects.

SOLAR DEVELOPMENT IN CHILE

With an investment around US\$270 million, Enel Green Power Chile Ltda has recently commissioned the largest solar PV project in the entire Latin America with a generating capacity of more than 400 GWh of electricity on annual bases, capable of powering around 198,000 households and reducing more than 198,000 tonnes of

¹⁷ Deutsche Bank, 2015

carbon dioxide emissions. The project that is connected to the grid, a 160 MW is located in the municipality of María Elena in the Antofagasta Region, the northern part of the country. Power generated from this project will be delivered to Chile's Northern Region Transmission Network.

Figure 23 : PICTURE OF THE CHILEAN SOLAR PV PROJECT



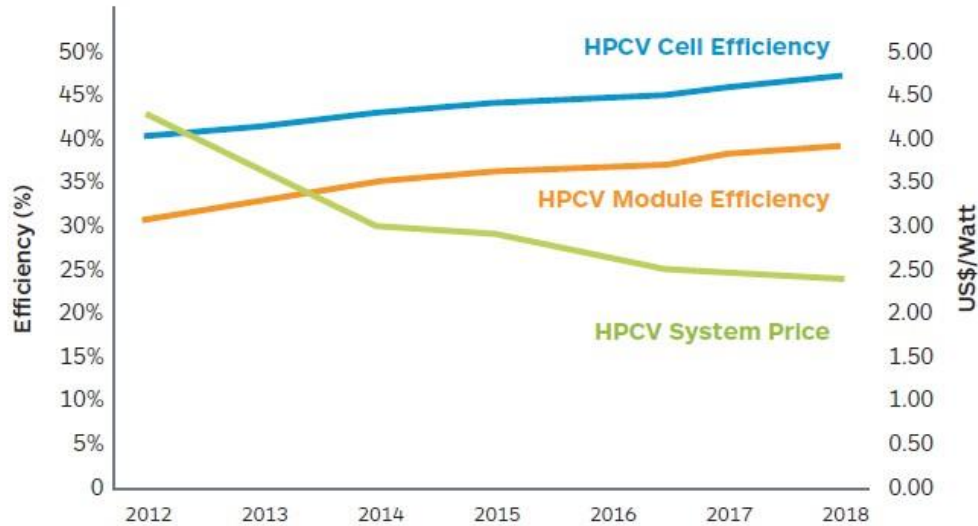
Concentrated PV (CPV) to See Accelerated Growth

On the backdrop of increasing efficiency and reduction in cost, concentrated photovoltaic (CPV) will see accelerated growth from current levels. It is estimated that the growth rate of both High Concentration Photovoltaic (HCPV) and Low Concentration Photovoltaic (LCPV) will be in double digits every year through to 2020¹⁸. This is because the efficiency of HCPV cells is estimated to reach 50% from the current level of 42%. The cost of a HCPV module is expected to drop from US\$3.00 per W currently to under US\$2.50 per W by 2018.

As far as c-Si technologies are expected to reach the physical limits in efficiency, RD&D is key for the future: as soon as the end of the next decade, a new step in PV and CPV deployment might rely on new materials.

¹⁸ IHS (2014), Top solar power industry trends for 2015

FIGURE 24: FORECAST EFFICIENCY DEVELOPMENT AND SYSTEM PRICE OF HCPV



Source: IHS (2014)

CSP to See Decent Growth and Cost Reduction

It has been estimated that, in an ambitious scenario, concentrated solar power could account for up to 25% of the world’s energy needs by 2050. Investment in the technology worldwide would increase from EUR 2 billion (US\$2.15 billion) in 2015 to EUR 92.5 billion (US\$99.23 billion) in 2050¹⁹. In any case, the CSP sector is expected to expand globally, with new markets being developed. Spain, currently the largest market for CSP, has more than 50 government-approved projects in the works. It also exports its technology, further increasing the technology’s stake in global energy system. Morocco and South Africa are expected to be fastest growing markets for CSP in the coming years, aided by “pro-renewables” energy policy and irradiation levels very suitable for the technology. LCOE could be lowered to US\$0.10 per kWh from a current low of US\$0.14 per kWh, with the development of half a dozen projects in the region²⁰. China and India are also keen to enter the CSP market, which will help reduce the costs of collector tubes, mirrors, and storage infrastructure even further. Growth will also be enhanced by the use of CSP in the oil and gas sector for thermal enhanced oil recovery (a 1 GWth solar EOR plant is under construction in Oman).

¹⁹SolarPACES

²⁰Acwa Power (2015)

3. SOCIO-ECONOMICS

GOVERNMENT POLICIES

As described in the previous section, solar energy is becoming increasingly affordable, thanks to the dramatic fall in component prices and the cost of installation and operation, both at utility and distributed level. Nonetheless, with the relatively high upfront costs characteristic of solar and other renewable energies, there remains the need for governments to monitor and guide the uptake of solar energy applications in many parts of the world, by utilising a wide range of policy instruments currently available. Policy frameworks must be well designed to minimise capital costs of implementation for developers and regulatory risk for investors.

Countries are increasingly recognising the potential of solar energy to provide sustainable energy, and this is reflected in the growth in the number of targets and support policies enacted by governments. By 2015, 164 countries had renewable energy targets in place²¹; around 45 of them had targets specific to solar energy – across power generation and heating & cooling²². Developing and emerging economies have led the expansion in policy targets in recent years.

The world's most established solar markets have all benefited or are currently benefitting from both supply-side and demand-side drivers. For utility-scale solar, subsidies such as feed-in tariffs (FiTs) and feed-in premiums (FiPs) have been particularly successful in Europe, Australia and the United States. In the United States, utilities sign long-term power purchase agreements (PPAs) with developers, securing income streams for the power plant. Some governments also provide investment or production tax credits to boost solar development. For distributed systems, FiTs and net metering have been successful measures. Table 4 shows the range of policy measures driving solar PV and CSP development in these markets.

FiT is a regulatory instrument that guarantees an investor a buy back price at which the power purchaser (distribution utility in most cases) will buy power that is being fed to the grid directly. This tariff or buy back price is calculated considering the overall investments in the renewable/solar project along with regulated return on the investment. FiT is always prescribed for a fixed tenor.

It is to be noted that buy back price available to excess energy fed to the grid (after meeting self-consumption) under net-metering mechanism is generally not called FiT because there

²¹ Kenning (2015)

²² REN21 (2016) Renewables 2016 Global Status Report

is no direct feed into the grid, and certainty over quantum of energy being fed to grid is also not there under this mechanism.

TABLE 4: KEY DRIVERS FOR GROWTH IN MAJOR SOLAR PV MARKETS

Country	Policy / Regulatory Target	Supply Side Drivers	Demand Side Drivers	Fiscal Incentives	Remarks
Germany	Yes	Feed-in tariff; Competitive bidding	Mandatory interconnection	Capital subsidy	Grid parity achieved, capital subsidy now provided for energy storage.
China	Yes	Feed-in tariff; Competitive bidding		Capital subsidy	
Japan	Yes	Feed-in tariff	Net metering	Capital subsidy	Shifted from net to gross metering in 2009.
Italy	Yes	Feed-in tariff			
United States	Yes	Investment tax credit (ITC)	Renewable Portfolio Standards (RPS); Net metering	Capital subsidy; Tax credits	A few states have gross metering in place
France	Yes	Feed-in tariff			
Spain	Yes	Feed-in tariff		Capital subsidy	New projects not eligible for FIT from 2012, additional 6% on participating

					projects.
United Kingdom	Yes	Feed-in tariff	Net metering; Renewable Obligation (RO)	Capital subsidy	
Australia	Yes	Feed-in tariff	Net metering	Capital subsidy	
India	Yes	Feed-in tariff; Competitive bidding	Renewable Portfolio Obligation (RPO); Renewable Energy Credits (REC)	Capital subsidy; Viability gap funding; Accelerated depreciation; Tax holidays; Priority Sector Lending; Concessional Duties	Competitive bidding on tariff is preferred instrument rather than FIT.

Source: Author's Analysis

TABLE 5: KEY DRIVERS FOR GROWTH IN MAJOR CSP MARKETS

Country	Policy / Regulator y Target	Supply Side Drivers	Demand Side Drivers	Fiscal Incentives	Remarks
Spain	Yes	Feed-in tariff		Capital subsidy	New projects not eligible for FIT from 2012, additional 6% on participating projects.
United States	Yes	Production & investment tax	Renewable Portfolio	Demonstratio	DoE loan guarantee

		credits	Standards (RPS)	in projects	program played important role
Australia	Yes		Large-scale generation (LGC) certificates		CSP not eligible to feed-in incentives in most states.
Morocco	Yes	Competitive bidding	Peak and non-peak tariff		
South Africa	Yes	Competitive bidding and Feed-in-Tariff	Preferential procurement		

As costs for solar (PV in particular) have fallen dramatically in these markets, the described measures are gradually being scaled back by policymakers, hence increasing the exposure of solar to price signals experienced by more established sources of electricity on the (liberalised) electricity market. For example, in Germany, the target for annual solar PV capacity additions is set to 2.4-2.6 GW; in the event this ‘corridor’ is exceeded, then the feed-in tariff available to solar PV investors in new installations, which was designed to automatically decrease with increasing capacity, will be adjusted downward further and more frequently than initially planned. In addition, the government has placed a national capacity ceiling for solar PV of 52 GW, and all support for solar new PV in excess of market revenue will be scrapped once capacity reaches the ceiling²³. The UK cut its feed-in tariffs for rooftop solar PV by 65% in January 2016, and caps will be placed on government spending on new capacity up to 2019²⁴.

In emerging solar markets such as India, South Africa, the Middle East and North Africa, auctions (in conjunction with ambitious solar capacity targets) are an increasingly common means of ensuring solar power development. Tariffs based on reverse bidding have led to highly competitive markets with some of the lowest tariffs in the world, and an explosion in capacity developments over the last few years. Agreed long-term contract prices for tendered solar PV projects have dropped as low as US\$0.06 per kWh in the UAE and

²³ The Brattle Group (2014) Solar Energy Support in Germany

²⁴ Defra (2015)

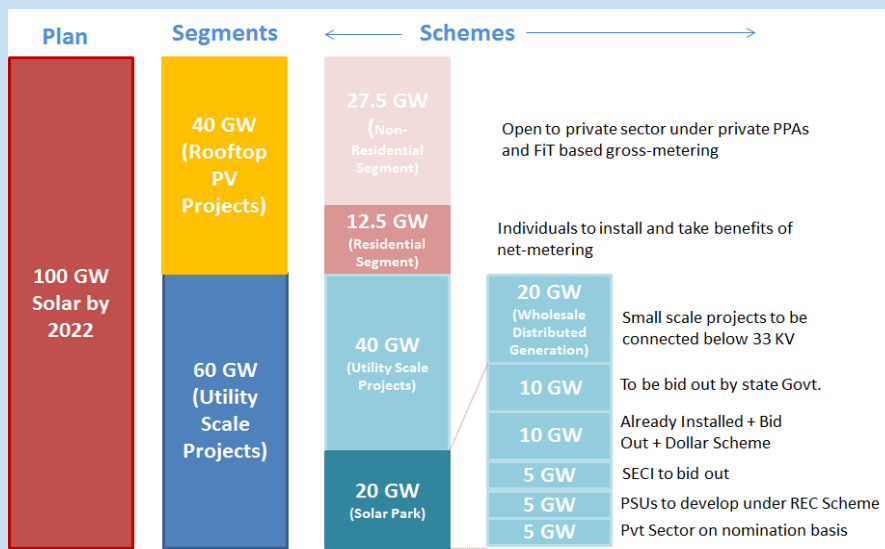
Jordan²⁵ in early 2015, and in Peru the lowest was under US\$0.048 per kWh and Mexico the average was US\$0.045 per kWh in early 2016²⁶; and US\$0.12 per kWh for CSP in South Africa²⁷.

The following case studies detail the ambitious government-led programmes, and realised benefits, regarding solar power development in India and South Africa, two of the fastest-growing solar markets in the world.

INDIA SOLAR PLAN

India has set an ambitious target of reaching 100 GW of solar capacity by 2022, up from around 5.2 GW by January 2016. According to the 18th Electricity Power Survey (EPS) from Indian government, the country's peak demand will exceed 285 GW by the end of 2022. This will correspond to about 8% of power demand being generated by solar systems across the country in 2022.

The country's solar plan has envisaged that both central level institutions, such as the National Thermal Power Corporation (NTPC) and the Solar Energy Corporation of India (SECI), and state governments (through State Nodal Agencies) will co-operate to achieve the target. The solar scale up plan of India was designed by Ministry of New and Renewable Energy (MNRE) in association with PwC India. The breakdown of 100 GW under different segments and schemes is as follows:



There are many incentives provided to solar power development culminating from

²⁵ IEA (2015)

²⁶ Ren21 (2016) Global Status Report

²⁷ CSP Today (2015)

both central and state level policy. Central government incentives include:

- Capital subsidy equivalent to 30% of the project cost for non-commercial rooftop PV systems.
- Income tax holidays and accelerated depreciation for commercial projects
- Concessional custom duties on solar equipment
- Limited financial support for solar park projects

State government incentives include:

- Exemption from electricity duty in some states.
- Exemption from scheduling and forecasting requirements
- Concessional excise duties on solar equipment

India's growing solar industry has already benefitted from some recent innovative schemes. The Jawaharlal Nehru National Solar Mission (JNNSM) phase 1 introduced a bundling scheme to bring the cost of solar power down in 2010-11. As per the scheme, solar power was bundled by unallocated quota of thermal power in the country and sold to distribution licensees at a "selling" price of INR 5.50 (US\$0.08) per kWh. This scheme garnered interest amongst the solar project developers because they could sell solar power at its wholesale price, while the off-takers bought the power at the selling price. In the second phase of the mission, viability gap funding (VGF) was provided by the National Clean Energy Fund (NCEF), to ensure that selling price of solar remained constant. Recently bid price has gone as low as INR 4.34 (US\$0.06) per kWh. This is one of the lowest solar buy back price across the world.

As proof of the level of progress made, the JNNSM had set a target of 20 GW by 2022. This target has been revised 5 times now and hence the above mentioned schemes must be supplemented with more innovative schemes. Bringing economical dollar currency financing backed by dollar based PPAs is one such scheme that will be implemented soon.

(Exchange rate 1 US\$= INR 65)

REAPING THE BENEFITS OF SOLAR IN SOUTH AFRICA

The success of South Africa's Renewable Energy Independent Power Producers Procurement Programme (REIPPPP) has been largely underpinned by its competitive bidding process. While price is the primary factor, bids are also evaluated on factors

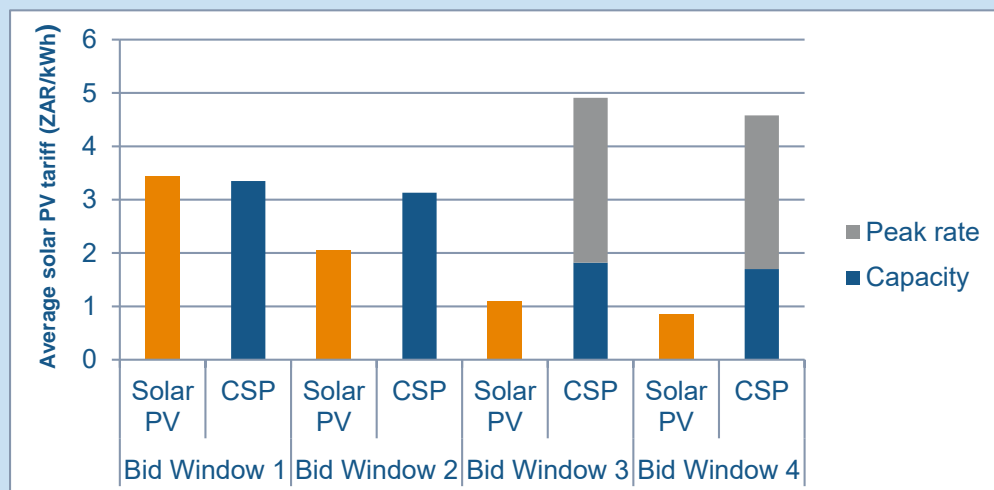
such as job creation, local content, enterprise development and socioeconomic development. The REIPPPP has been immensely successful; not only in generating huge investment in renewable energy in South Africa (private sector investment in excess of US\$19.6 billion over the length of the programme to date, of which 28% is foreign investment²⁸), but also in having significantly driven down the cost of renewables, especially that of solar photovoltaics.

The REIPPPP was launched in 2011, with the first bidding window was concluded with 632 MW of solar PV procured at an average tariff of ZAR 3.44 (US\$0.24) per kWh; and 150 MW of CSP at an average tariff of ZAR 3.35 (US\$0.23) per kWh²⁹.

Since bid window one, South Africa has seen a significant drop in Solar PV tariffs, with the average rates at the end of 2015 at ZAR 0.85 (US\$0.06) per kWh - 75% lower than the first bid window.

The massive drop in the solar PV tariff and the fact that a typical PV power plant takes only two years on average to build are contributing factors to the government's acknowledgement of the value of solar power and its recent announcement of an expedited round with 1800 MW up for procurement³⁰. The government has also recognised the value of CSP with storage (and the potential for dispatch-ability) and offers a 270% tariff increase for CSP systems generating power in peak demand periods.

Figure 25: SOLAR POWER TARIFFS IN SOUTH AFRICA (ZAR/kWh)



Even with the relatively high tariffs paid in bid window 1, South Africa experienced a net financial gain from renewables, with the first round of solar PV and wind power

²⁸ South African Department of Energy (2015)

²⁹ Eberhard (2014)

³⁰ South African Department of Energy (2015)

creating an extra ZAR 800 million (US\$55.9 million) in financial benefits to the country. The reasons for this are twofold. Firstly, there is a financial saving gained through replacing the electricity that would otherwise have been generated from diesel. In addition to this, there is an economic saving which results from the mitigation of unserved energy. South Africa's power grid is currently under severe constraints, with the national power utility resorting to load shedding (controlled black outs) in order to protect the grid from a total black out. Renewable sources have been able to provide power during these times, reducing the amount of unserved energy.

The growth in the solar market has also led to changes in policy and market design affecting other energy sources. For example, in some European markets (United Kingdom, Germany, France, Italy, Belgium) and parts of the United States, the rapid growth of solar and wind-powered electricity on the grid and the inherent variability of their output, has contributed towards the establishment of, or desire to establish, variant Capacity Remuneration Mechanisms (CRMs) in these markets, where conventional generators are paid to ensure security of electricity supply and stability of the grid. The incentive for capacity payments is two-fold. Firstly, they are designed to ensure that sufficient capacity is available at all times. Also, the extra income would help alleviate the struggle of existing conventional plants to cover their operational costs; which has been experienced in Germany, where the penetration of renewables has significantly reduced the number of operating hours of conventional generators and driven down wholesale electricity prices. On the other hand, critics claim that CRMs will have negative effects on free competition and the potential integration of multiple energy markets³¹.

SOCIO-ECONOMIC IMPACTS

Job and Wealth Creation

The solar industry has continued to show an expansion in employment creation, despite a decline in overall solar energy investment. In 2014, nearly 3.3 million people worldwide were employed (directly and indirectly) by the solar energy sector, with the solar PV sector accounting for 2.5 million jobs³². The vast majority of jobs are in Asia, especially as the manufacturing of solar equipment and the major demand centres for solar energy move eastwards. On the other hand, solar PV employment has decreased in Europe. Job growth has been particularly strong in the operations and maintenance (O&M) sector, needed to support the burgeoning secondary solar PV market. The solar heating and cooling sector employed over three-quarters of a million people globally in 2014, with the significant markets in China, India and Brazil. This is however a decline from previous years, driven by a slowing down in solar water heater installations in China.

³¹Zgajewski (2015)

³²IRENA (2015) Renewable energy and jobs: Annual review 2015. *Please note that this is gross number of job creation, net may be lower as solar energy is subsidized in many countries.*

TABLE 6: TOP SOLAR ENERGY EMPLOYMENT (THOUSANDS) IN 2014, BY COUNTRY

Country	Solar PV	CSP	Solar heating & cooling	Total
China	1 641	0	600	2 241
Japan	210	0	0	210
India	125	0	75	200
United States	164	5	5	174
Bangladesh	115	0	0	115
Germany	56	1	11	69

Source: IRENA (2015)

Rooftop PV – Addressing the Energy-Food Nexus

The energy-food nexus is being discussed in many countries across the world in present scenario. Our world is facing the pressure of continuously increasing food demand (due to rise in population and increase in average income), supplemented by lower agriculture yield. Land requirement is increasingly a premium in many countries of the world. Solar PV technology, through rooftop PV segment, provides a very huge social benefit by not utilising land but spare rooftops.

It is normally argued that most of the land banks utilised for solar plant installations are generally non-fertile; however, this argument ignores the possibility of innovations in agriculture technologies that could find out ways to utilise non-fertile land for production of some crops. A solar plant has a life of around 25 years which is too long a horizon for ignoring innovations in agriculture technologies.

Share of rooftop PV systems across the globe is not known, as in many countries differentiation between rooftop PV and utility scale PV is not recorded. However, if major countries are considered (as shown in Table 7) it can be said that easily above 200,000 acres of land saving has been accrued to date due to rooftop PV segment.

TABLE 7: APPROXIMATE LAND SAVINGS IN MAJOR ROOFTOP PV MARKETS

Country	Solar PV installed capacity (GW)	Share of rooftop PV (%)	Rooftop PV installed capacity (GW)	Land savings (acres)
Germany	~38	~60	~22.8	114,000
Japan	~24	~35	~8.4	42,000
United States	~20	~40	~8.0	40,000
Australia	~4	~80	~3.2	16,000
Total				212,000

Source: Author's Analysis

Effects on the Local Economy

It should be noted that the figures for solar sector employment represent gross effects of the industry to the economy. Net effects of the solar industry would be less, especially given that the sector remains heavily subsidised by governments. In the case of Germany where the cost of subsidies for solar (and other green) energy is passed onto consumers in higher electricity bills, the public would have less disposable income to demand other goods and services, hence having a negative impact (such as job losses) on other local industries, both within and outside the energy space.

UNDP PREPARES A DETAILED PV STATUS REPORT FOR LEBANON

The decentralised rooftop solar PV market in Lebanon has more than doubled between 2014 and 2015. Actual numbers indicate that the market is expected to have a much bigger increase between 2015 and the current year 2016. According to a full market survey completed by the DREG (Decentralized Renewable Energy Generation) project based on the LCEC NEEREA numbers and a detailed market survey, the solar PV market is even more promising in the next five years. The DREG project, a joint project between UNDP Lebanon and the Ministry of Energy and Water, has finalised the full study in that regard. The results of the study will be presented during a full session of

the International Beirut Energy Forum 2016.

4. ENVIRONMENTAL IMPACTS

While the clear benefit of solar energy compared to other energy sources is the low level of greenhouse gas (GHG) emissions, the implementation of solar energy technologies may result in significant environmental trade-offs. The environmental impacts of solar energy can differ greatly, according to technology and capacity. Adverse environmental impacts must be taken into consideration while developing strategies for the installation of solar energy systems.

LAND USE

Utility-scale solar generation comes with a sizeable land requirement, depending on factors such as the technology adopted, the topography of the available site and solar intensity at the site. A study by NREL on solar power plants in the United States found a wide range of total land use requirements across the different technologies. The average total land footprint of solar generation capacity was estimated at 8.9 acres (36,017 square metres) per MW, and average land area directly used at 7.3 acres (29,542 square metres) per MW³³. The configuration of utility-scale plants also makes it difficult to share this land for other uses such as agriculture. It is also important to note that utility scale solar infrastructure theoretically have lifetimes of 30-60 years³⁴.

Concerns have also been raised over the effects of utility-scale generation on soil quality. Research in China has shown that land use change (clearing of vegetation, digging of foundations, construction traffic) for solar thermal construction has led to soil erosion in near environment, particularly in regions with sandy soils and a dry climate. Results also showed that solar thermal installations lowered soil temperatures by 0.5-4.0°C in the summer, and raised soil temperatures by the similar margins in the winter³⁵. The negative impacts of utility-scale solar can be minimised, somehow, by siting plants in brownfield locations.

Small-scale PV and solar heating installations have minimal land impact, where they are actively integrated into buildings and structures they serve.

WATER USAGE

As with other forms of thermal electricity generation, solar thermal plants have a sizable water footprint to produce electricity. While some of the water requirement is to raise steam

³³ http://www.solarindustrymag.com/issues/SI1309/DEPT_New%20%26%20Noteworthy.html

³⁴ Hernandez *et al.* (2013)

³⁵ European Commission (2015)

for the plant's steam cycle, 85-95% of the withdrawn water is for cooling purposes. Hence, the cooling technology adopted at the plant is a major determinant of the amount of water withdrawn by the plant. While most of the water requirement is not consumed and will be returned to the point of withdrawal, the quality of the returned water will differ from that drawn from the reservoir, and may be a cause for concern.

Water demand of solar thermal plants with (once-through) wet cooling is estimated at up to 3573 litres/MWh of electricity, higher than figures for coal (3123 litres/MWh) and nuclear (3055 litres/MWh) generation plants with the same cooling system; but also for combined-cycle gas turbines, which have the lowest water withdrawal and consumption rates among thermal power plants, at 570-1100 litres/MWh using a wet cooling tower³⁶. This is down to lower average operating efficiencies of solar thermal plants compared to coal and nuclear power plants, and additional requirements such as the washing of mirrors (approximately 20 litres/MWh)³⁷. On the other hand, solar thermal plants with a dry cooling system could reduce its water requirements to less than 10% of that with a wet cooling system. However, the water savings come with significant trade-offs – these plants have higher capital costs, and consume up to 1.5% more power than wet cooled plants³⁸. In addition, dry-cooled technology becomes less effective at ambient temperatures above 38°C.

Solar PV does not use water for electricity generation, and its water requirement, estimated at 118 litres/MWh, comes from the manufacturing of the PV cells and maintenance of modules.

HAZARDOUS MATERIALS

A wide range of potentially harmful materials are produced in the manufacturing process of solar PV cells. The materials produced in silicon PV manufacturing are similar to those found in the electronics industry. They include silane gas, which is potentially explosive with several incidents reported every year; and waste silicon dust (known as kerf), which can cause breathing difficulties for industry workers. Harmful chemicals such as hydrochloric acid, sulphuric acid, nitric acid, 1,1,1-trichloroethane and acetone are used in cleaning and purifying the silicon substrate. Sulphur hexafluoride (SF₆), used to clean the reactors used in silicon production, has a Global Warming Potential over 16,000 times more than that of CO₂³⁹. Strict regulations to limit fugitive emissions of SF₆ are imperative so as to preserve the global warming reduction potential from solar power.

Thin-film PV cells contain some very hazardous materials including gallium, indium, and arsenic. Cadmium, which is used in cadmium-telluride (CdTe) cells, is extremely toxic, but forms a very stable compound with tellurium and hence is not banned as a hazardous substance. In addition, the cadmium content in one CdTe module is 2500 times less than

³⁶ IEA (2012)

³⁷ Martin (2014)

³⁸ World Nuclear (2015)

³⁹ UNFCCC (2015)

found in one nickel-cadmium (NiCd) battery, and 360 times less than that emitted by an average coal-fired power station per kWh of electricity generated⁴⁰.

In the case of a leakage, the heat transfer fluid (HTF) used in CSP systems (synthetic oils in particular) also pose a risk to soil, ground and surface water, air and humans. Research shows that HTF leakage from parabolic trough and parabolic dish technologies are potentially more harmful than from solar tower systems⁴¹.

LIFE-CYCLE EMISSIONS

The majority of emissions from solar energy systems occur at the upstream stage of the life-cycle (manufacturing, transportation and installation). Materials use contributes a high fraction of life-cycle emissions, reaching up to 50% of total emissions for tower CSP. Between 50-80% of greenhouse gas emissions arise during the production of the module⁴². Emission levels depend on the type of technology and the source of energy used in manufacturing. Silicon PV in particular has a very energy-intensive manufacturing process. For instance, studies have shown that the carbon footprint of a solar panel manufactured in China is twice that of a panel made in Europe, due to the coal-powered energy used in the process. Nonetheless, as there are no GHG emissions evident during electricity generation, emissions from solar energy are much lower than those from fossil-fuelled generation.

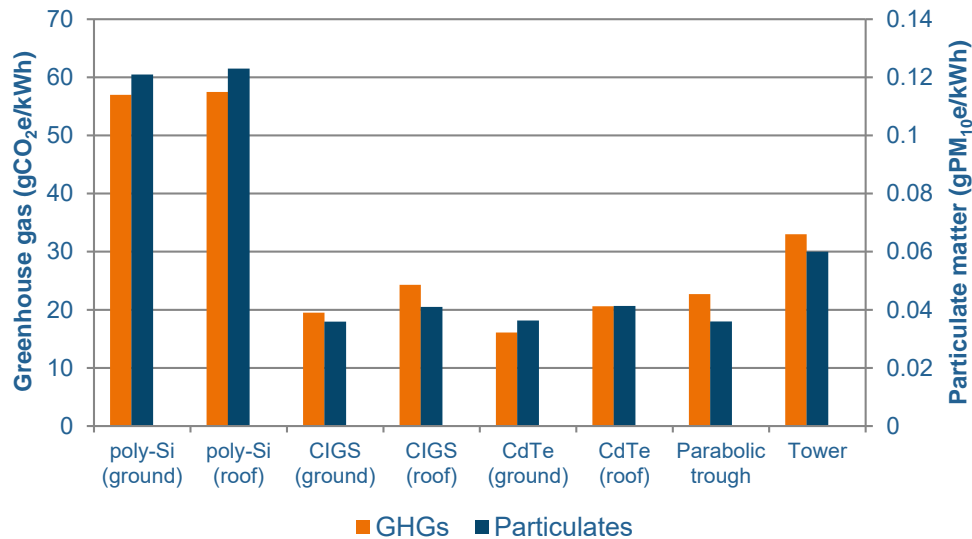
Figure 26 shows the average life-cycle emissions from different solar technologies, using the following indicators: greenhouse gases, particulate matter, and eco-toxicity. Emission factors from both ground- and roof-mounted polysilicon PV are significantly higher than those from other solar technologies.

⁴⁰ CAT Information Service

⁴¹ Fabrizi (2012)

⁴² Weisser, IEA

FIGURE 26: LIFE-CYCLE EMISSIONS FROM SOLAR ENERGY, BY TECHNOLOGY



Source: Hertwich *et al.* (2014)

Concerns are also growing over solar panels once they reach the end of their lifetime. The disposal of panels could cause leakage of dangerous materials into the surrounding ecosystem. Recycling of old panels is not common as it is not economically attractive to do so yet. Costs of recycling modules in the United States may be as high as US\$400 per tonne⁴³. However, it is hoped that better sustainability standards regulating the solar industry and the opportunity to recover rare elements from old devices will drive recycling in the future. From 2015, a German law on electrical and electronic equipment requiring manufacturers to take back their products once they reach the end of their lives was extended to PV systems, hence incentivising the recycling of modules. The law also stipulates that the products, once sold in Germany, must be recycled in the country, preventing them from being shipped to less developed countries.

OTHER IMPACTS

Solar energy systems, especially at utility scale, can also affect the biodiversity of the local environment, both within and outside of their land footprint. Landscape fragmentation can harm vulnerable vegetation, and create barriers to the movement of species. The mortality of resident bird species from the operation of utility scale solar plants has been documented in the United States. The causes of death identified include collision with infrastructure and

⁴³ Friedrichs, Solar Industry Magazine

burning by heliostats⁴⁴. Research has also shown that utility-scale solar can affect land-atmosphere interactions, such as albedo (the ratio of how much radiative energy is reflected back to the atmosphere) and local wind dynamics.

⁴⁴ McCrary et al. (1986)

5. OUTLOOK

CHALLENGES

Low oil prices

The current trend of relatively low international crude oil prices is having a profound effect on the adoption of solar energy, and renewables as a whole. The effect is double-edged – for example, crude oil exporting nations such as Mexico have seen a drop in government receipts from oil exports, which in turn have led to slower importation of renewable energy infrastructure; for majority oil importers, while oil is not in direct competition with renewables, the trend of coal and (to a lesser extent) natural gas prices to follow crude oil may slow the uptake of solar energy for electricity generation, as conventional generation becomes very cost-effective to operate.

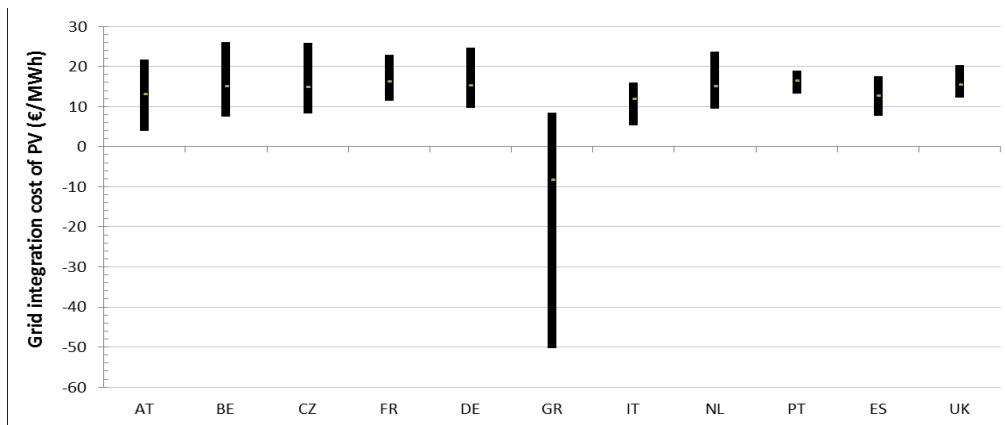
Grid integration issues

With growing levels of grid penetration of solar in the electricity grid (especially in Europe), integrating solar powered electricity in the future will be a major sticking point. As solar plants rely on the availability of sunlight, they cannot operate constantly, which means that (conventional) back-up supply is required to cover the electricity demand un-met by the absence of solar power, and ensure the grid remains balanced. A suite of auxiliary technologies, including flexible conventional generating plants, transmission interconnections and grid-scale energy storage are required to aid solar grid integration at high penetration levels. In Germany, where solar capacity and rates of solar installations are the highest in the world, grid balancing with high penetration of solar power on the system is currently manageable, thanks to its sizeable backup conventional generation capacity and its interconnection capacity with neighbouring countries. However, it is worthy of note that in Germany new solar capacity is not substituting existing conventional capacity, hence leaving the electricity network increasingly under-utilised (which has a cost implication), and calls into question solar power's contribution towards energy security. Issues are also arising at the distribution network level. In Hawaii, which leads the United States in solar installations per electricity customer, high penetration levels of solar PV on the distribution network are causing concerns of overvoltage on the network, putting electrical appliances and heavy equipment at risk of damage. This has caused the local utility to enact policy measures with a more stringent approval of rooftop solar installations, and potentially charging owners for the required network upgrades.

It is thus important that at least policy makers are aware of likely grid integration cost of solar energy. It is also strongly required to establish aggregators as innovative solutions for control of distributed renewable energy (DRE) and of demand response (DR) units in

providing its flexibility⁴⁵. Figure 27 below shows the grid integration cost of a few European countries. All the countries assessed have cost except for Greece. In Greece, the cost is even negative indicating the benefit that PV can bring in reducing/releasing the distribution network capacity in the country. This is due to the strong correlation between peak demand and output of PV.

FIGURE 27: RANGE OF GRID INTEGRATION COST OF PV IN EUROPE



(AT- Austria, BE- Belgium, CZ- Czech Republic, FR-France, DE- Germany, GR- Greece, IT- Italy, NL- Netherland, PT-Portugal, ES- Spain, UK- United Kingdom)

Source: Pudjianto *et al.* (2013)

Materials consumption

The expansion of the solar PV industry and commercialisation of next-generation PV technologies will add a strain on the sourcing of the specialist materials required to their manufacture. While the vast majority of solar PV cells are based on silicon, which is readily abundant in sand; thin-film cells rely on less abundant materials which face constraints to their production, as is shown in Table 8. Chromium is also of strategic importance to the solar industry, as black chromium plating is used to absorb solar energy; while the reflectivity of silver makes it high in demand in silicon cells and new-age flexible solar cells.

⁴⁵ INCREASE (June 2016), Emerging Frameworks for aggregators in the EU, Policy Brief No. 1

TABLE 8: CONSTRAINTS AND RISKS TO MATERIALS CONSUMED BY SOLAR PV

Element	R/P ratio (years)	Production constraint	Level of risk to solar industry
Cadmium	30	Environmental	High
Chromium	>16	Geopolitical & commercial	High
Gallium	N/A	Commercial	High
Germanium	N/A	Commercial	High
Indium	N/A	Commercial	Medium
Silver	23	-	Low
Tellurium	N/A	Commercial	High

Source: BP Zepf (2014)

Production constraints of these elements may be down to environmental concerns and respective legislation banning their use (as in the case of cadmium), competition between different applications for their use (e.g. gallium and germanium are also heavily used in the LED industry), limited reserves, or the high concentration of global reserves within one or a few sovereign states (e.g. majority of global chromium is situated in South Africa and Kazakhstan)⁴⁶.

Financing and barriers to investment

In many parts of the world, solar energy still requires government support to keep it competitive with conventional sources of energy. In the future, when government support for solar will be scaled back; the industry must come up with innovative mechanisms to secure financing required for the continual growth of the sector. This could be trickier in developing and emerging markets, where government legislation can inadvertently block new financing models. For example, crowdfunding is currently outlawed in India, thus

⁴⁶ University of Augsburg (2011)

making solar crowdfunding schemes that are so popular in the United States impossible to implement. In addition, traditional barriers to private sector investment, such as public sector control, bureaucracy and corruption; can hinder the growth of solar in these regions. A new market design is also necessary to foster solar investment.

Grid capacity constraints

Expansion of solar capacity could also be hindered by existing electricity infrastructure, particularly in countries with young solar markets. Here, a lack of additional grid capacity and an infrastructure maintenance culture will limit the uptake of utility-scale solar. Power loop flows are symptomatic of inadequate grid access in Germany, where a lack of grid capacity connecting the north and south of the country forces power flows from solar and wind generation to be diverted to neighbouring Poland⁴⁷. Inadequate grid infrastructure is a major limiting factor to the growth of the solar market in Chile, with installations forecast to decline by 40% from 2016 due to grid saturation⁴⁸.

Technical expertise

It has already been intimated that solar energy can play a major role in extending energy access to communities in the developing world. However, it is clear that these countries suffer from a lack of technical expertise to implement these facilities. In Mexico, a shortage in the indigenous human resource is a key barrier to fulfilling the high potential for solar development in the country. It is important that the effective transfer of technical skills is ensured in these regions, and the more advanced economies can play a role in effecting this. For example, in 2015, investors from China co-launched a technology and transfer and training centre in Kenya, to promote the assembly of solar lighting systems⁴⁹. The ultimate aim of schemes like this is to develop an indigenous solar industry in these countries.

Climate change

The changing climate will also have a profound effect on the availability and operation performance of solar energy technologies. Solar thermal power in particular is at risk, especially with an expected decrease in water availability in the future. Concentrated solar plants are best situated in arid and semi-arid regions, where solar insolation is high but water stresses already exist. Increased deposition of dust in these regions on mirrors and PV panels will also lead to negative performance of plants. The warming climate will be of concern for solar PV systems as output deteriorates with rising temperatures; but could be more favourable for solar thermal plants as higher ambient temperatures may aid operating efficiencies^{50,51}. As a result, the geographical distribution of solar technologies is expected to change over time.

⁴⁷ Platts (2012)

⁴⁸ IHS (2014)

⁴⁹ African Review (2015)

⁵⁰ Hernandez *et al.* (2013)

⁵¹ Lovegrove and Stein (2012)

OPPORTUNITIES

Business opportunity of solar PV waste

Solar PV panel waste after active life is arising as a new environmental challenge that needs to be addressed. However, at the same time management of panel waste is an opportunity that could be as big as US\$15 billion by 2050 according to IEA/IRENA. It is estimated that globally 4500 GW or around 78 million tonnes worth of panels will be required to be managed by 2050⁵².

Responsive policy actions are needed to address the challenges of waste management with enabling framework being adapted to needs and circumstances of each region or country. China, US, Japan, India and Germany (in the decreasing order) are going to produce largest share of PV panel waste by 2050. However, at present only EU has adopted PV-specific waste regulations.

It is important for this to be seen from an opportunity point of view because end of life management could become a significant component of the PV value chain by 2050. It is estimated that wasted 4500 GW worth of panels can be recycled to around 630 GW new panels, if recycling frameworks will be designed and adhered to.

Off-grid electricity

The growth of solar power could be boosted by the expansion of off-grid electricity systems. About 1.3 billion people globally do not have access to electricity⁵³. Individual off-grid systems have the potential to improve rates of energy access in the developing world, by providing simple energy services (e.g. lighting, heating) to remote communities and other areas where grid connection is unavailable or unreliable.

TABLE 9: NATIONAL AND RURAL ELECTRIFICATION RATES

Country	Population without electricity (millions)	National electrification rate (%)	Rural electrification rate (%)
India	304	75	67
Nigeria	93	45	35

⁵² Under early loss scenario meaning panels life to be less than expected. In regular loss scenario it was little less at 60 million tonnes

⁵³ IEA (2014)

Ethiopia	70	23	10
Bangladesh	62	60	48
Congo (Dem. Rep.)	60	9	1
Indonesia	60	76	59
Pakistan	56	69	57
Tanzania	36	24	7
Myanmar	36	32	18
Kenya	35	20	7

Source: IEA World Energy Outlook (2014)

Solar power has contributed to providing energy access to millions of people globally over the last decade. Numerous schemes, particularly in Asia have leveraged the potential of small-scale solar applications to lift millions of citizens out of poverty. For example, the government-backed Solar Home System (SHS) scheme in Bangladesh has been hugely successful, installing 3.6 million solar power units in the country by early 2015, and benefitting 20 million citizens. The scheme has not only expanded electricity access in rural parts of the country, but has also led to the creation of an indigenous solar industry which employed up to 115,000 people in 2014⁵⁴. The following case study exemplifies the effects of a simple yet effective scheme leveraging solar power.

LIGHTING A MILLION LIVES (LAML) PROJECT – PAKISTAN

Pakistan is in the depths of a major energy crisis. The current average power shortfall in the country is 5000 MW, increasing to 6500 MW during peak periods. Over 50 million citizens do not have access to electricity, with the grid failing to reach about half of rural villages.

⁵⁴ IRENA (2015) Renewable energy and jobs: Annual review 2015

In an effort to tackle this crisis, the Buksh Foundation launched the Lighting a Million Lives (LaML) project in 2009. The project's aim is to replace kerosene-based lighting with cleaner, more efficient and reliable solar lighting devices in poor un-electrified villages of Pakistan. The foundation has partnered with The Energy and Research Institute (TERI) in India to expand on its project of Lighting a Billion Lives, currently running in South Africa, Uganda and Bangladesh. LaML aims to "light a million lives", equivalent to 4000 villages, by the end of 2017.

LaML is the first impact project in the developmental sector in Pakistan that aims to provide turnkey solutions to stimulate change, and empower people and organizations from the grassroots level. The project involves the implementation of a Solar Charging Station with 50 solar lanterns for locals as sources of low-cost, clean energy. The charging stations are operated by a young female entrepreneur (Roshna Bibi, or "Light Lady"), who is trained by the Buksh Foundation, along with the development of a male technical entrepreneur and engaging the entire community towards ownership of the project. Certified by the UN Foundation, International Finance Corporation, World Energy Council, and Forbes Magazine, LaML has proven to be a successful model of change in Pakistan. The project has electrified over 150 villages with a total impact on 45,000 lives, especially underprivileged groups such as women and children, with the support of partner organizations and companies.

Based on the Buksh Foundation's impact assessment, an average of USD 3 per month is spent on kerosene oil in each of the 7500 households reached so far; the solar lanterns eliminate this additional expenditure, saving these people USD 22,500 per month. In the first three years of operation, LaML saved impoverished families across Pakistan a total of USD 7.5 million in energy expenditure. In addition, the reduction of 6.27 kilograms of CO₂ produced by one household using kerosene oil has resulted in the mitigation of 51.836 tonnes of CO₂ emissions in LaML villages since 2009, helping to overcome diseases caused by the toxic paraffin-based energy sources⁵⁵.

Even in more developed markets, off-grid solar is becoming more attractive. In some countries / regions such as Australia, California and parts of India; solar energy has reached 'socket parity', where off-grid solar is cheaper over its lifetime than consuming electricity from the grid. It should be pointed out, however, that in these areas grid connection provides insurance of a constant supply of electricity for customers, in the event that the off-grid systems break down.

Stand-alone solar PV systems could be aggregated to create mini-grids for groups of customers (e.g. communities). Mini-grid systems provide more security of supply from solar

⁵⁵ Chilcott, (2006) Health Protection Agency

energy thanks to the diversity of energy demand from customers. Mini-grid systems could also ensure that the relatively high capital costs of implementing stand-alone systems are shared among customers.

Heating for industry

While the use of solar thermal technologies for domestic heating is a mature market in some parts of the world (particularly in the Mediterranean countries), the potential for the use of solar for industrial heat is yet to be realised on a commercial, global scale. Industry consumes a third of all primary energy, and of that, 40% is for process heat at temperatures less than 400°C⁵⁶. Based on the temperature requirements, parabolic trough / dish technology is best placed to provide solar industrial process heat (SIPH). The food, automotive, oil & chemicals, pharmaceuticals, paper and textile industries all stand to gain from the use of SIPH. Awareness of SIPH can be assured through developing policy frameworks in favour of the technology, and enabling assimilation of the technology into industrial processes.

Solar PV and energy storage

Installations in renewable energy sources and their interconnection with grid are evolving the entire power system across the globe. The traditional and relatively simple system of one-directional flow from large-scale conventional generators through transmission and distribution lines to consumers is now changing to an increasingly complex mix of small, distributed generators and consumers at all points in the electricity grid. Moreover, the intermittency of renewable energy is posing grid balancing problems and hence the storage of renewable energy is required from a technical point of view. In fact, from an economic point of view storage also makes complete sense as prices of PV are falling in contrast to increasing cost of fossil fuels and hence retail electricity tariffs.

Germany and Japan accounted for almost 70% of the residential PV energy storage systems in 2014 and will continue to gain leadership positions. FiT for solar is lower than retail tariff in Germany and hence self-consumption of PV energy is encouraged in the country by capital subsidy for batteries. In Japan, frequent blackouts after closure of nuclear plants made way for penetration of storage systems and the now wide variance between peak and off-peak prices provides incentives to store energy. On the other hand, the United States will see penetration in the commercial segment because of peak demand charges that make a significant proportion of electricity bills of consumers. The potential savings combined with incentives offered by the Self-Generation Incentive Program (in California) and tax credits, can make solar and energy storage an extremely attractive proposition to commercial-rate payers in the country. Regulatory restriction of the renewable ramp rate in many states will also push storage of PV energy. It is estimated that around 1 GW of storage installations will be achieved by 2016 across the world, with most installations coming in the aforementioned countries.

⁵⁶ Industrial Solar – Solar Process Heat

6. GLOBAL TABLE

TABLE 10: SOLAR ENERGY GLOBAL DATA

Country	Solar Photovoltaic (PV) Generating Capacity (MW) in 2015 IRENA (2016)	Concentrated Solar Power (CSP) (MW) in 2015 IRENA (2016)	Total Solar Generating Capacity (MW) in 2015 IRENA (2016)	Total Solar Electricity Consumption (GWh) in 2015 BP (2016)	Total Solar Electricity Generation in 2014 (GWh) IRENA (2016)	Share of Solar PV in Total Installed Power Generating Capacity in 2015 (%) BP (2016)
Afghanistan	1	-	1	-	1	-
Albania	1	-	1	-	1	-
Algeria	274	25	299	79	194	-
Angola	12	-	12	-	19	-
Antigua and Barbuda	3	-	3	-	1	-
Argentina	8	-	8	-	16	-
Armenia	1	-	1	-	-	-
Aruba	5	-	5	-	7	-
Australia	5 031	3	5 034	6 073	4 858	2.2%
Austria	900	-	900	956	785	0.4%
Azerbaijan	3	-	3	-	1	-
Bahamas	1	-	1	-	2	-

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Bahrain	5	-	5	-	9	-
Bangladesh	167	-	167	230	212	-
Barbados	9	-	9	-	10	-
Belgium	3 200	-	3 200	3 162	2 883	1.4%
Belize	1	-	1	-	6	-
Benin	1	-	1	-	2	-
Bolivia	7	-	7	-	-	-
Bosnia and Herzegovina	11	-	11	-	5	-
Botswana	2	-	2	-	2	-
Brazil	21	-	21	-	61	-
Brunei Darism	1	-	1	-	2	-
Bulgaria	1 040	-	1 040	1 401	1 252	0.4%
Burkina Faso	7	-	7	-	10	-
Burundi	2	-	2	-	3	-
Cabo Verde	10	-	10	-	14	-
Cambodia	6	-	6	-	3	-
Cameroon	2	-	2	-	2	-
Canada	2 236	-	2 236	2 589	1 756	1.1%
Chile	848	-	848	1 380	489	0.4%

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China	43 050	12	43 062	39 200	25 007	18.9%
Chinese Taipei	800	-	800	875	552	0.4%
Cook Islands	1	-	1	-	2	-
Costa Rica	1	-	1	-	2	-
Croatia	44	-	44	-	35	-
Cuba	8	-	8	-	29	-
Curacao	8	-	8	-	12	-
Cyprus	85	-	85	-	84	-
Czech Republic	2 075	-	2 075	2 262	2 123	9.5%
Denmark	791	-	791	604	596	0.3%
Dominican Republic	16	-	16	-	20	-
Ecuador	26	-	26	-	16	-
Egypt	25	20	45	70	40	-
El Salvador	2	-	2	-	2	-
Fiji	2	-	2	-	1	-
Finland	11	-	11	-	8	-
France	6 549	-	6 549	7 332	5 909	2.8%
Fr Guiana	39	-	39	-	51	-

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French Polynesia	22	-	22	-	5	-
FYR Macedonia	16	-	16	-	14	-
Germany	39 634	2	39 636	38 432	36 056	17.2%
Ghana	2	-	2	-	4	-
Greece	2 596	-	2 596	3 503	3 792	1.1%
Guadeloupe	67	-	67	-	103	-
Guatemala	80	-	80	-	7	-
Guyana	2	-	2	-	3	-
Honduras	455	-	455	-	-	-
Hungary	96	-	96	107	56	-
India	4 964	204	5 167	6 600	4 910	0.4%
Indonesia	12	-	12	-	11	-
Iran	-	17	17	104	19	-
Ireland	1	-	1	-	1	-
Israel	766	6	772	1 048	770	2.2%
Italy	18 910	6	18 916	25 205	22 319	8.2%
Jamaica	6	-	6	-	7	-
Japan	33 300	-	33 300	30 915	26 534	15.4%
Jordan	26	-	26	-	14	-

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Kazakhstan	55	-	55	-	1	-
Kenya	24	-	24	-	30	-
Kiribati	2	-	2	-	2	-
Korea Rep	3 173	-	3 173	3 818	2 729	1.5%
Lao PDR	1	-	1	-	-	-
Latvia	2	-	2	-	-	-
Lebanon	4	-	4	-	7	-
Libya	5	-	5	-	8	-
Lithuania	71	-	71	73	73	-
Luxembourg	120	-	120	-	95	-
Madagascar	5	-	5	-	4	-
Malawi	1	-	1	-	6	-
Malaysia	184	-	184	125	160	0.1%
Maldives	4	-	4	-	2	-
Mali	6	-	6	-	8	-
Malta	60	-	60	-	68	-
Marshall Islands	1	-	1	-	1	-
Martinique	62	-	62	-	84	-
Mauritania	18	-	18	-	25	-

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Mauritius	18	-	18	-	25	-
Mayotte	13	-	13	-	4	-
Mexico	234	-	234	346	221	0.1%
Micronesia	1	-	1	-	1	-
Moldova Rep	3	-	3	-	1	-
Mongolia	5	-	5	-	1	-
Morocco	18	23	41	-	61	-
Mozambique	7	-	7	-	11	-
Namibia	21	-	21	-	26	-
Nepal	32	-	32	-	48	-
Netherlands	1 288	-	1 288	866	785	0.6%
New Caledon	8	-	8	-	13	-
New Zealand	33	-	33	-	16	-
Nicaragua	1	-	1	-	1	-
Niger	6	-	6	-	8	-
Nigeria	17	-	17	-	22	-
Norway	14	-	14	-	11	-
Pakistan	210	-	210	1,172	241	-
Palau	1	-	1	-	1	-

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Panama	14	-	14	-	1	-
Peru	96	-	96	230	199	-
Philippines	132	-	132	128	7	-
Poland	71	-	71	57	7	-
Portugal	451	-	451	789	627	2.2%
Puerto Rico	88	-	88		48	-
Qatar	3	-	3	56	5	-
Reunion	180	-	180	-	236	-
Romania	1 301	-	1 301	1 987	1 616	0.6%
Russian Federation	407	-	407	54	7	-
Rwanda	9	-	9	-	13	-
St Kitts and Nevis	1	-	1	-	2	-
St. Lucia	1	-	1	-	-	-
St. Vincent and The Grenadines	1	-	1	-	1	-
Samoa	3	-	3	-	5	-
Saudi Arabia	25	-	25	-	43	-
Senegal	8	-	8	-	13	-
Serbia	6	-	6	10	6	0.08%

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Singapore	57	-	57	51	40	-
Slovakia	533	-	533	550	597	0.3%
Slovenia	240	-	240	-	257	-
Solomon Islands	1	-	1	-	2	-
Somalia	1	-	1	-	1	-
South Africa	1 361	150	1 511	1 927	1 098	0.5%
Spain	4 832	2 300	7 132	13 874	13 673	2.4%
Sri Lanka	16	-	16	-	18	-
Suriname	5	-	5	-	8	-
Sweden	85	-	85	80	47	0.1%
Switzerland	1 376	-	1 376	1 122	842	0.6%
Tanzania	14	-	14	-	16	-
Thailand	1 600	5	1 605	2 423	1 564	0.6%
Togo	1	-	1	-	1	-
Tokelau	1	-	1	-	1	-
Tonga	4	-	4	-	5	-
Trinidad Tobago	3	-	3	-	4	-
Tunisia	15	-	15	-	22	-
Turkey	249	-	249	250	17	0.1%

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Tuvalu	1	-	1	-	-	-
Uganda	20	-	20	-	31	-
Ukraine	432	-	432	402	483	-
United Arab Emirates	33	100	133	327	300	-
United Kingdom	9 077	-	9 077	7 556	4 050	3.9%
United States of America (USA)	25 540	1 777	27 317	39 000	24 603	11.1%
US Virgin Islands	4	-	4	-	-	-
Uruguay	68	-	68	-	3	-
Venezuela	3	-	3	-	5	-
Zambia	2	-	2	-	3	-
Zimbabwe	4	-	4	-	7	-
Total World	222 360	4 650	227 010	253 000	223 948	-

Source: International Renewable Energy Agency IRENA, 2016 Statistics; BP Statistical Review of World Energy 2016 workbook

Note: Numbers are approximated, with for instance figures between 1 and 1.5 shown as 1, and between 1.5 and 2, shown as 2.

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REFERENCES

- African Review (2015) *Kenya and China launch solar technology transfer and training institute*, April 27, <http://www.africanreview.com/energy-a-power/renewables/kenya-and-china-launch-solar-technology-transfer-and-training-institute>
- Boyd, J. (2016) 'Japan building world's largest floating solar power plant', in *IEEE Spectrum*, January 25, <http://spectrum.ieee.org/energywise/energy/renewables/japan-building-worlds-largest-floating-solar-power-plant>
- BP Global (2016) *Statistical Review of World Energy 2016 Workbook*, <http://www.bp.com/en/global/corporate/energy-economics/statistical-review-of-world-energy.html>
- CAT Information Service, *What is the environmental impact of photovoltaic (PV) solar panels?*, <http://info.cat.org.uk/questions/pv/what-environmental-impact-photovoltaic-pv-solar-panels>
- Chilcott, R. P. Health Protection Agency (2006) 'Compendium of Chemical Hazards: Kerosene', *World Health Organization*.
- Critchley, A. (2015) 'Mexico's solar market still faces obstacles after energy market reforms', in *Green Tech Media*, August 26, <http://www.greentechmedia.com/articles/read/Mexicos-Solar-Market-Still-Faces-Obstacles-After-Energy-Market-Reforms>
- CSP Today (2015) *Getting access to cheaper financing is key to remaining competitive in 2015*, March 13, <http://social.csptoday.com/markets/getting-access-cheaper-financing-key-remaining-competitive-2015>
- Department of Energy & Climate Change (2015) *Changes to renewable subsidies*, 17 December, <https://www.gov.uk/government/news/changes-to-renewables-subsidies>
- Deutsche Bank (2015) *Deutsche Bank's 2015 solar outlook: accelerating investment and cost competitiveness*, January 13.
- Eberhard, A. (2014) *South Africa's energy IPP procurement programme: Success factors and lessons*, <http://www.gsb.uct.ac.za/files/ppiafreport.pdf>
- European Commission (2015) *The impacts of large-scale Concentrated Solar Power on the local environment*, http://ec.europa.eu/environment/integration/research/newsalert/pdf/environmental_impact_of_large_scale_concentrated_solar_power_400na2_en.pdf
- Fabrizi (2012) *Environmental impact of CSP technologies*, https://www.esmap.org/sites/esmap.org/files/ESMAP_IFC_RE_CSP_Training_World%20Bank%20Fabrizi.pdf
- Fraunhofer Institute for Solar Energy Systems (2016) *Photovoltaics Report*, June 6, <https://www.ise.fraunhofer.de/de/downloads/pdf-files/aktuelles/photovoltaics-report-in-englischer-sprache.pdf>
- Fraunhofer Institute for Solar Energy Systems (2016) *Recent facts about Photovoltaics in Germany*, April 22, <https://www.ise.fraunhofer.de/en/publications/veroeffentlichungen-pdf-dateien-en/studien-und-konzeptpapiere/recent-facts-about-photovoltaics-in-germany.pdf>

- Fraunhofer Institute for Solar Energy Systems, NREL (2015) *Current status of concentrator photovoltaic (CPV) technology*, <http://www.nrel.gov/docs/fy16osti/65130.pdf>
- Friedrichs, O., *German PV Recycling law likely to set a global standard*, http://www.solarindustrymag.com/online/issues/SI1411/FEAT_02_German-PV-Recycling-Law-Likely-To-Set-A-Global-Standard.html
- Fuhs, M. (2015) 'EU Commission: solar dumping duties and minimum price to remain', in *PV Magazine*, December 06, http://www.pv-magazine.com/news/details/beitrag/eu-commission--solar-dumping-duties-and-minimum-price-to-remain_100022307/#axzz3xbGNvJl6
- Hernandez, R. R. *et al.* (2013) 'Environmental impacts of utility-scale solar energy', in *Renewable and Sustainable Energy Reviews*, 29, pp. 766-779, doi:10.1016/j.rser.2013.08.041
- Hertwich, E. G. *et al.* (2014) 'Integrated life-cycle assessment of electricity-supply scenarios confirms global environmental benefit of low-carbon technologies', in *PNAS*, 112 (20), pp. 6277-6282, doi: 10.1073/pnas.1312753111
- Industrial Solar – *Solar Process Heat*, <http://www.industrial-solar.de/CMS/en/solutions/solare-prozesswaerme/>
- Information Handling Services, IHS (2016) *As European Solar Installations Slow, China, US and Japan Lead Global Installed PV Capacity in 2016, IHS Says*, February 29, <http://press.ihs.com/press-release/european-solar-installations-slow-china-us-and-japan-lead-global-installed-pv-capacity>
- Information Handling Services, IHS (2014) *Top solar power industry trends for 2015*, https://www.ihs.com/pdf/Top-Solar-Power-Industry-Trends-for-2015_213963110915583632.pdf
- International Energy Agency Photovoltaic Power Systems Programme IEA-PVSP (2016) *A snapshot of global Photovoltaic markets*, <http://www.iea-pvps.org/>
- International Energy Agency Solar Heating and Cooling Programme (IEA-SHC) (2016) *Solar Heat Worldwide: markets and contribution to the energy supply 2014*, <https://www.iea-shc.org/data/sites/1/publications/Solar-Heat-Worldwide-2016.pdf>
- International Energy Agency IEA (2015) *IEA Solar Heating and Cooling Programme*, <https://www.iea-shc.org/>
- IRENA and IEA (2016) *End-of-life management: Solar Photovoltaic Panels*, http://www.irena.org/DocumentDownloads/Publications/IRENA_IEAPVPS_End-of-Life_Solar_PV_Panels_2016.pdf
- International Renewable Energy Agency IRENA (2016) *Renewable Energy Capacity Statistics*, http://www.irena.org/DocumentDownloads/Publications/IRENA_RE_Capacity_Statistics_2016.pdf
- International Renewable Energy Agency IRENA (2015) *Remap 2030. Renewable Energy Prospects: United Arab Emirates*, http://www.irena.org/remap/irena_remap_uae_report_2015.pdf

- International Renewable Energy Agency IRENA (2015) *Renewable energy and jobs: Annual review 2015*,
http://www.irena.org/DocumentDownloads/Publications/IRENA_RE_Jobs_Annual_Review_2015.pdf
- International Renewable Energy Agency IRENA (2015) *Renewable Power Generation Costs in 2014*,
http://www.irena.org/documentdownloads/publications/irena_re_power_costs_2014_report.pdf
- International Energy Agency IEA (2015) *Medium-term renewable energy market report*,
<https://www.iea.org/Textbase/npsum/MTrenew2015sum.pdf>
- International Energy Agency IEA (2014) *Technology Roadmap – Solar Photovoltaic Energy*,
https://www.iea.org/publications/freepublications/publication/TechnologyRoadmapSolarPhotovoltaicEnergy_2014edition.pdf
- International Energy Agency IEA (2014) *World Energy Outlook*, www.iea.org
- International Energy Agency (2012) 'Water for energy: is energy becoming a thirstier resource?', Excerpt from the *World Energy Outlook 2012*,
http://www.worldenergyoutlook.org/media/weowebiste/2012/WEO_2012_Water_Excerpt.pdf
- International Renewable Energy Agency IRENA (2016) *Renewable Capacity Statistics*,
http://www.irena.org/DocumentDownloads/Publications/IRENA_RE_Capacity_Statistics_2016.pdf
- International Renewable Energy Agency IRENA (2013) Concentrating solar power technology brief
- Jittapong, K. (2015) 'Thailand ignites solar power investment in Southeast Asia', in *Reuters*, July 12, <http://www.reuters.com/article/thailand-solar-idUSL3N0ZM2JB20150712>
- Kapadia, R. *et al.* (2013) 'A direct thin-film path towards low-cost large-area III-V photovoltaics', in *Scientific Reports*, 3: 227, DOI: 10.1038/srep02275
- Kenning, T. (2015) *IRENA: Number of countries with renewable energy targets quadrupled in a decade*, June 10, http://www.pv-tech.org/news/irena_number_of_countries_with_renewable_energy_targets_quadrupled_in_a_dec
- Lovegrove, K. and Stein, W. (2012) *Concentrating solar power technology: Principles, developments and applications*. Elsevier.
- Martin, A. D. (2014) *Understanding the water requirements of the power sector: the complexities and challenges of determining water use by different power generation technologies*,
<http://water.worldbank.org/sites/water.worldbank.org/files/publication/World-Bank-Presentation-Anna-Delgado-UNWater-Thirsty-Energy-2014.pdf>
- May, M.M. *et al.* (2015) 'Efficient direct solar-to-hydrogen conversion by in situ interface transformation of a tandem structure', in *Nature*, doi: 10.1038/ncomms9286, www.nature.com/articles/ncomms9286

- Mailoa, J. P. *et al.* (2015) 'A 2-terminal perovskite/silicon multijunction solar cell enabled by a silicon tunnel junction', in *Applied Physics Letters*, 106, 121105, doi: 10.1063/1.4914179
- McCrary, M. D. *et al.* (1986) 'Avian Mortality at a Solar Energy Power Plant', in *Journal of Field Ornithology*, 57(2), pp. 135-141, <http://www.jstor.org/stable/4513113>
- Platts (2012) *German power loop flows threaten EU's internal market: regulators*, February 1, <http://www.platts.com/latest-news/electric-power/brussels/german-power-loop-flows-threaten-eus-internal-8878410>
- Pudjianto, D. *et al.* (2013) *Grid integration cost of photovoltaic power generation – Direct cost analysis related to grid impacts of photovoltaics*, http://www.pvparity.eu/fileadmin/PVPARITY_docs/public/PV_PARITY_D44_Grid_integration_cost_of_PV_-_Final_300913.pdf
- Renewable Energy Policy for the 21st Century REN21 (2016) *Renewable 2016 – Global Status Report*, <http://www.ren21.net/gsr-online/chapter02.php>
- Renewable Energy Policy for the 21st Century REN21 (2015) *Renewables 2015 – Global status Report*, http://www.ren21.net/wp-content/uploads/2015/07/REN12-GSR2015_Onlinebook_low1.pdf
- Renewable Energy Policy for the 21st Century REN21 (2014) *Renewables 2014 – Global status Report*
- Sentanta Energy&Water, *Solar Hot Water – Residential Info*, <http://www.setnrgh2o.com/>
- Singh *et al.* (2015) 'Thermodynamic and achievable efficiencies for solar-driven electrochemical reduction of carbon dioxide to transportation fuels', in *PNAS*, <http://www.pnas.org/content/112/45/E6111.full.pdf>
- Solargis (2016) *Maps of Global horizontal irradiation (GHI)*, www.solargis.info
- Solargis (2016) *Maps of Direct normal irradiation (DNI)*, www.solargis.info
- Solarpaces (2014) *Concentrating solar power projects*.
- South African Department of Energy (2015) *State of Renewable energy in South Africa*, <http://www.energy.gov.za/files/media/Pub/State-of-Renewable-Energy-in-South-Africa.pdf>
- Statista (2016) *Leading countries in installed concentrated solar power (CSP) as of 2014 (in MW)*, <http://www.statista.com/statistics/494169/global-installed-concentrated-solar-power-csp-capacity-by-key-country/>
- The Brattle Group (2014) *Solar Energy Support in Germany*, http://www.brattle.com/system/publications/pdfs/000/005/060/original/Solar_Energy_Support_in_Germany_-_A_Closer_Look.pdf?1406753962
- United Nations Environment Programme and Bloomberg New Energy Finance (2016) *Global trends in renewable energy investment*, http://fs-unep-centre.org/sites/default/files/publications/globaltrendsinrenewableenergyinvestment2016lower_0.pdf
- University of Augsburg BP (2011) *Materials critical to the energy industry*.

- U.S. Department of Energy (2015) *The quadrennial technology review. An assessment of energy technologies and research opportunities*, http://energy.gov/sites/prod/files/2015/09/f26/Quadrennial-Technology-Review-2015_0.pdf
- U.S. Energy Information Administration EIA (2016) Solar, natural gas, wind make up most of 2016 generation additions, <http://www.eia.gov/todayinenergy/detail.cfm?id=25172>
- Weisser, D. A guide to life-cycle greenhouse gas (GHG) emissions from electric supply technologies, https://www.iaea.org/OurWork/ST/NE/Pess/assets/GHG_manuscript_preprint_versionDanielWeisser.pdf
- World Nuclear (2015) Cooling Power Plants, <http://www.world-nuclear.org/information-library/current-and-future-generation/cooling-power-plants.aspx>
- Wyld Group (2008) High temperature Solar Thermal Technology Roadmap, https://www.coag.gov.au/sites/default/files/HTSolar_thermal_roadmap.pdf
- Zepf V., Reller A., Rennie C., Ashfield M. & Simmons J., BP (2014): Materials critical to the energy industry. An introduction. 2nd edition.
- Zgajewski, T. (2015) The rise of capacity markets: Are they inevitable in the European Union?, <http://www.egmontinstitute.be/wp-content/uploads/2015/10/ep80.pdf>

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**World Energy
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KEY FINDINGS

1. Geothermal energy contributes a tiny proportion of the world's primary energy consumption. Even in electricity generation, geothermal produces less than 1% of the world's output.
2. There were 315 MW of new geothermal power capacity installed in 2015, raising the total capacity to 13.2 GW.
3. Turkey accounted for half of the new global capacity additions, followed by the United States, Mexico, Kenya, Japan and Germany.
4. In terms of direct use of geothermal heat, the countries with the largest utilisation that accounted for roughly 70% of direct geothermal in 2015 are China, Turkey, Iceland, Japan, Hungary, USA and New Zealand.
5. In 2015, total power output totalled 75 TWh, the same number being also valid for total heat output from geothermal energy (excluding ground heat pumps).
6. World geothermal heat use (direct & storage) reached 563 PJ in 2014.
7. Global investment in 2015 was US\$2 billion, a 23% setback from 2014. During the period 2010-2014, around US\$20 billion were invested in geothermal energy by 49 countries for both direct use and electric power.
8. The pace of geothermal development has been conditioned by legal frameworks and particularly by conservation legislation. However, the pace of development might accelerate due to climate change concerns and increasing need to decarbonise the energy sector.
9. Geothermal energy currently finds itself burdened by a higher installed costs and longer development periods relative to solar and wind. As a result, in many countries, geothermal energy projects have been and are reliant on government incentives to compete against both natural gas and other renewable generation.

INTRODUCTION

Geothermal energy refers to the use of heat energy or thermal properties within the earth. The earth's heat engine is driven by cooling of the crust and heating of the lower crust and mantle by thermal decay of radioactive isotopes. So, the deeper beneath the surface, the hotter the temperature is. Over most of the earth, the rate of temperature increase with depth is too low to provide sufficient energy to undertake useful work. However, some parts of the crust have abnormally high heat flow and these can provide heat energy at depths that can be economically exploited.

This review summarises the current use of geothermal energy around the world and prospects for further growth in the near future. With international concerns regarding air quality, water quality, and greenhouse gas emissions, policy analysts and planners are increasingly recognising the potential of geothermal energy to displace fossil fuels and help meet clean air and decarbonisation obligations.

RESOURCE POTENTIAL

The earth's natural heat reserves are immense. EPRI (1978) estimated the stored thermal energy down to 3 km within continental crust to be roughly 43×10^6 EJ. This is considerably greater than the world's total primary energy consumption of 560 EJ in 2012¹. Estimates by Bertani (2003), Stefansson (2005) and Tester et al (2005) of the accessible electrical potential range from 35 to 200 GW. This is 16 times the current installed generation capacity.

Although geothermal resources emit low levels of greenhouse gases, international energy agencies classify geothermal energy as renewable because energy is continuously restored by the upwards flow of heat from the earth's interior. While in detail, the rate of heat extraction may, for a period, exceed the rate of recovery, direct experience (Larderello geothermal field has operated continually since 1946) and reservoir modelling demonstrates that some geothermal systems can supply power for over a century without fatally disrupting the heat flow that sustains them.

TYPES OF GEOTHERMAL RESOURCES

Over most of the earth, the heat flow rising from the mantle through the crust is insufficient to create reservoirs of extractible heat close enough to the surface to be economic. The average geothermal gradient is 30°C per km². In thick crust, the gradient can be as low as 16°C/km³. In thin crust, the regional gradient can exceed 90°C/km⁴. Geothermal resources are therefore anomalous features arising from localised high heat flows from shallow

¹ EIA

² Grant and Bixley (2011)

³ Lund and Zoback (1998)

⁴ Saemundsson (2007)

intrusive bodies combined with the ability of surrounding rocks to transmit fluids (permeability).

Geothermal resources provide both heat and heat storage over a wide spectrum of conditions. While these resources are complex and diverse, they can be classified based on their temperature and heat flow mechanisms.

Temperature is the most fundamental measure of energy available for work. While differing in detail, the industry recognises three grades of extractive geothermal energy: **high temperature** (> 180°C), **intermediate temperature** (101 to 180°C) and **low temperature** (30 to 100°C).

Geothermal resources can be further classified based on the mechanisms that control the movement and concentration of heat as well as their common geologic settings. The two main heating mechanisms, convection and conduction really comprise end members in a heat transfer spectrum. Elements of each are present in many geothermal resources.

Convective hydrothermal systems represent zones where the Earth's heat rises towards the surface predominately by the convective circulation of buoyant, naturally occurring liquids or steam. The heat source driving convection is the presence of magma within the crust or high heat flow from the mantle surging through thinned crust.

Most of the world's high temperature geothermal fields are convective hydrothermal systems with a magmatic heat source. These igneous systems include the vapour (steam) dominated fields such as Kamojang (IDA) and Larderello (ITA) as well as the liquid dominated reservoirs prevalent in New Zealand, Iceland, Kenya, the Philippines, and Japan. Typically, these systems contain high temperatures.

Hydrothermal convection may also occur within tensional faults associated with high rates of crustal extension (fault-hosted systems). These resources have predominately intermediate temperatures and comprise the geothermal systems of the Basin-and-Range (USA) and Western Anatolia (TUR).

Conductive geothermal systems arise where relatively high heat flow and insulation combine to create anomalously hot rock. In some cases, the normal conductive heat flow is boosted by radioactive decay and trapped by insulating sedimentary layers (Hot Crystalline Rock). In other configurations (Hot Aquifers), conductive heat may be transferred to circulating ground water creating artesian warm springs such as Bath (GBR) or regional aquifers such as the Malm Limestone (DEU). In rapidly subsiding sedimentary basins, over-pressured mudstones caused by rapid sedimentation may create thermal blankets that trap conductive heat in strata (Geopressured Aquifers) such as the East Java (Porong) sub-basin.

The vast majority of conductive geothermal resources have low to intermediate temperatures. However, deep exploration wells at Habanero (AUS) and Luttligeest (NLD) have encountered temperatures and fluids exceeding 200°C at 4,000 metres depth. While these resources are not yet economic, they do illustrate the vast potential of deep resources.

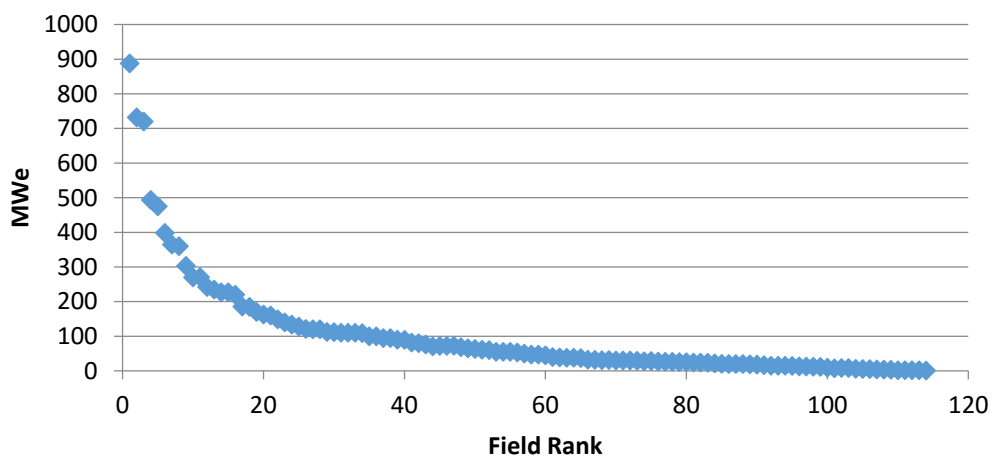
Over the past 30 years, the geothermal industry has attempted to both improve the productivity of conventional geothermal fields and exploit new (unconventional) resources by developing techniques that improve the permeability of hot rocks. For convenience, this report will refer to such endeavours as engineered geothermal systems (EGS). Although much of the work to date has focused on recovering heat from impermeable hot rock, the techniques can be applied to conventional fields as well.

SIZE DISTRIBUTION OF DEVELOPED GEOTHERMAL RESOURCES

Like many mineral resources, the distribution of convective geothermal resources resembles a log-normal distribution (Figure 1). The largest 12 fields (10% of the population) contain 46% of the total installed generation capacity. The presence of large fields played a pivotal role in stimulating the development of national geothermal industries in Italy, New Zealand, USA, the Philippines, and now Kenya due to the availability of economies of scale.

Fault-hosted systems are rarer (25% of all convection systems) and smaller than igneous systems (mean size of 39 MWe vs 103 MWe). However, these fields may be geographically clustered (as in the Carson Sink, Basin and Range Province, western USA) and therefore provide the economies of scale necessary for building a geothermal industry.

FIGURE 1 : CONVECTIVE GEOTHERMAL SYSTEMS - FIELD SIZE DISTRIBUTION



Source: IGA Power Plant Database, Bertani (2015), Daiz A. R. et al (2015), Contact Energy Ltd

In terms of power generation, conductive systems comprise just 3% of the total power generation capacity. The low to intermediate temperatures typical of these resources make them less favourable for power generation but economical for direct use.

Geographically, 72% of installed generation capacity resides along tectonic plate boundaries or *hot spot* features of the Pacific Rim. All of these are igneous convective resources. In contrast, only 20% of total installed generation capacity resides in convection fields situated along spreading centres and convergent margins within the Atlantic Basin.

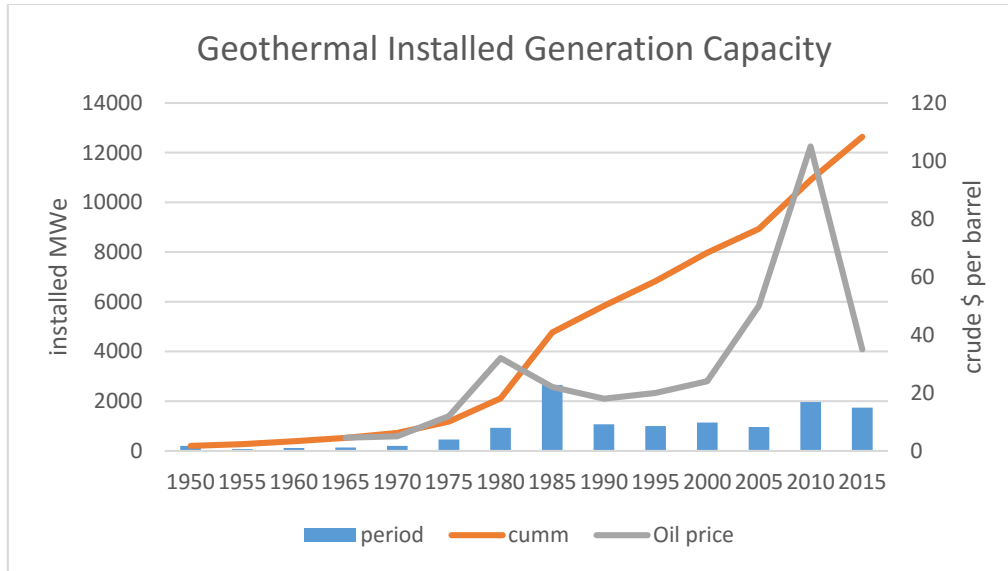
A disproportional percentage of installed generation capacity resides on island nations or regions (43%). Virtually all these resources occupy positions either at the junction of tectonic plates (such as Iceland) or within a “hot spot” (as per Hawaii).

The small size of the overall population of geothermal resources reflects their recent creation. Geologically, geothermal systems are ephemeral phenomena. Virtually all high temperature fields are no older the Quaternary (2 million years old). Convection resources display a cycle of birth, maturity and death as the sustaining heat flux waxes and wanes.

HISTORY OF GEOTHERMAL USE

While geothermal hot springs and associated mineral by-products have been used since antiquity, the first industrial use of geothermal resources did not occur until the early 1900s where electricity was first generated at Larderello, Italy. Due to the abundance of available hydro generation, geothermal development remained dormant until after the Second World War when economic expansion and fewer remaining hydro development sites presented an economic opportunity.

FIGURE 2: GEOTHERMAL GENERATION CAPACITY GROWTH



Source: IGA

Growth of the total installed geothermal generation capacity has followed the oil price cycle (Figure 2). Prior to international commitments to reduce greenhouse gas emissions (Kyoto commitments in 2005) geothermal energy was an important substitute for natural gas and oil for power generation particularly for those countries or regions that lacked indigenous fossil fuel reserves such as Iceland, the Azores, the Philippines, Japan, Central America, and New Zealand.

Today, over half (54%) of total installed generation capacity resides in countries that are net energy importers. This reflects government policies to preserve foreign currency reserves, promote energy security, and (in some instances) has provided electricity at a lower price than imported fuels.

The pace of geothermal development has been conditioned by legal frameworks and particularly by conservation legislation. Using geothermal energy requires the extraction of water. Water resources in Civil, Common and derivative law have different ownership, access, and use rights compared to minerals. Because geothermal resources contain elements of both water and minerals, many countries seeking to exploit geothermal energy have had to enact new legislative frameworks to facilitate use rights. Establishing functional legal frameworks remains a challenge for countries seeking to develop their first geothermal projects to this day.

In addition, the amenity and cultural values are commonly associated with surface geothermal features (hot springs, geysers, fumaroles, mud pots, etc.). This has often resulted in legal protection of the surface features before technology permitted exploitation of the underlying geothermal resource for electricity generation. The protection of geothermal springs was particularly prevalent in Common Law countries. In Australia and New Zealand, provincial and colonial governments enacted provisions bringing hot springs under the Crown's protection in the 1860's. In Canada, hot springs were vested to the Canadian Government in 1885. The United States established a system of national parks and monuments in 1872 bringing many geothermal features (notably those at Yellowstone) under the protection of the Federal Government.

Today, many countries struggle to balance the protection of surface features with development. An example would be the fluctuating status of El Tatio in Chile. Once gazetted for development, the field is now protected as a tourist attraction. Development has been further complicated by the increasing recognition of aboriginal rights around water and geothermal resources. Obtaining access to geothermal resources will usually require extensive negotiations, recognising cultural aspects and the rights of indigenous peoples, with appropriate compensation for the potential impacts of development, together with any land that may be alienated.

Geothermal energy currently finds itself burdened by a higher installed costs and longer development periods relative to solar and wind. This results, in part, from a commodities boom driving up the cost of materials, access to land, and drilling costs from 2004 through 2014. The generous investment subsidies provided by many countries allowed these high costs to be passed onto the consumers. As a result, in many countries, geothermal energy projects have been and are reliant on government incentives to compete against both natural gas and other renewable generation.

So, while the cost of geothermal development rose, new technology facilitated a fall in the capacity cost for solar and wind. This cost gap has consequential economic and policy implications that will influence the deployment of geothermal energy in the future.

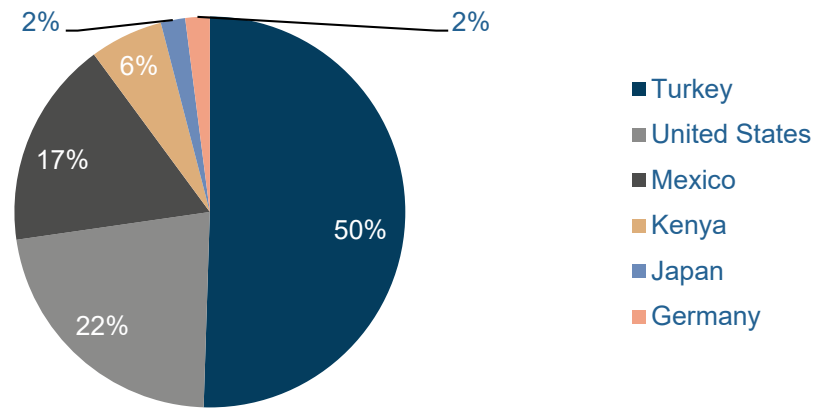
GLOBAL STATUS IN 2015

Contribution to World Energy Supply

Geothermal energy contributes a tiny proportion of the world's primary energy consumption. Even in electricity generation, geothermal produces less than 1% of the world's output. However, for individual countries, such as the Philippines, which lacks indigenous fossil fuels, geothermal energy contributes materially to the nation's energy supply and wellbeing. There were 315 MW of new geothermal power capacity installed in 2015, raising the total capacity to 13.2 GW. More specifically, new additions came from 11 binary power plants totalling 129 MW and 8 single-flash plants totalling 186 MW. Turkey accounted for half of the new global capacity additions, followed by the United States, Mexico, Kenya, Japan and

Germany. Figure 3 below illustrates the share by country of global geothermal capacity additions in 2015.

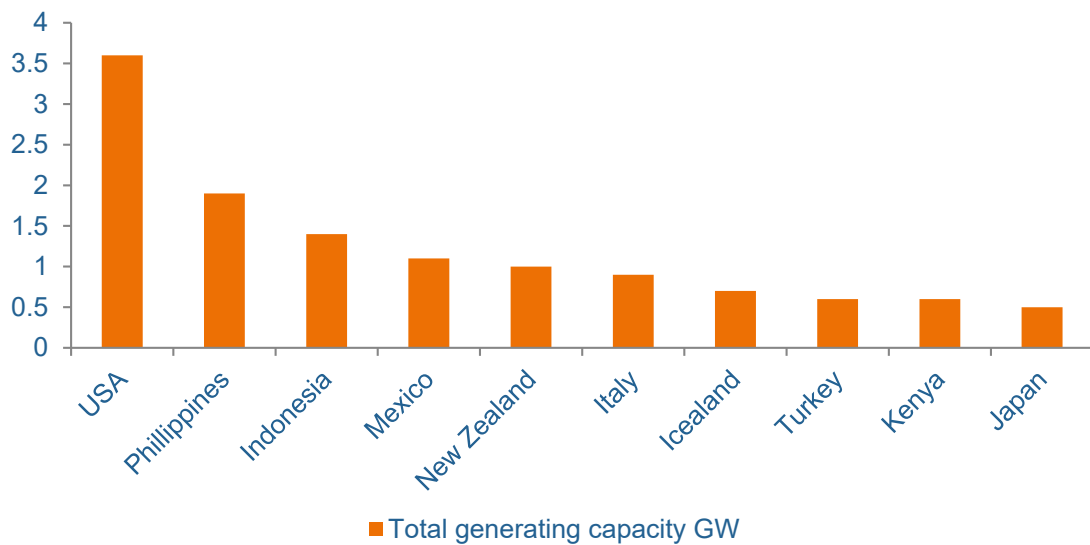
FIGURE 3: GEOTHERMAL GLOBAL CAPACITY ADDITIONS IN 2015, BY COUNTRY



Source: Ren21 (2016) Global Status Report

Figure 4 below shows the top countries with the largest amounts of geothermal power generating capacity at the end of 2015.

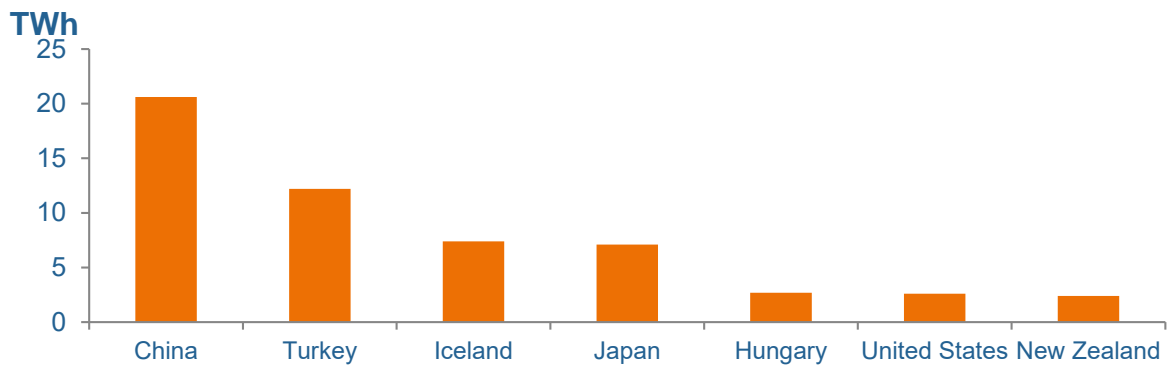
FIGURE 4: TOP COUNTRIES PER GEOTHERMAL GENERATING CAPACITY AT END-2015 (GW)



Source: Ren21 (2016) Global status report

In terms of direct use of geothermal heat, the countries with the largest utilisation that accounted for roughly 70% of direct geothermal in 2015 are China, Turkey, Iceland, Japan, Hungary, USA and New Zealand, as shown in Figure 5 below.

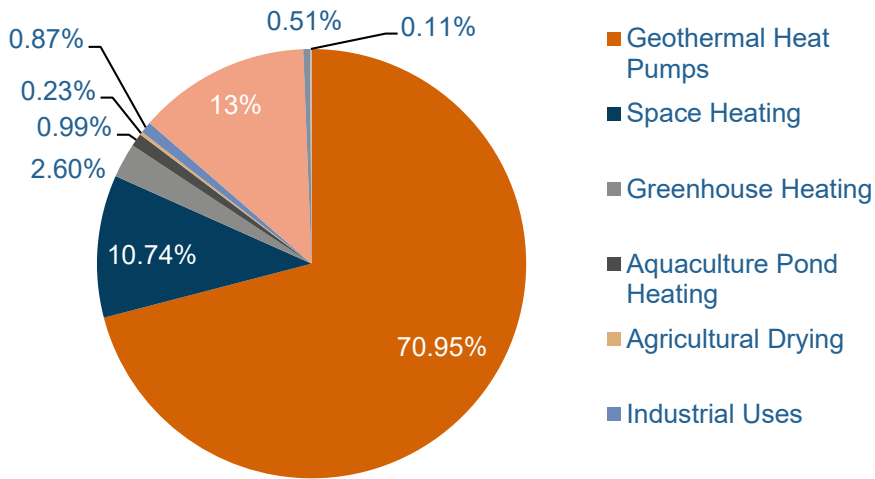
FIGURE 5: TOP COUNTRIES THAT UTILISE THE MOST DIRECT GEOTHERMAL HEAT IN 2015



Source: Ren21 (2016)

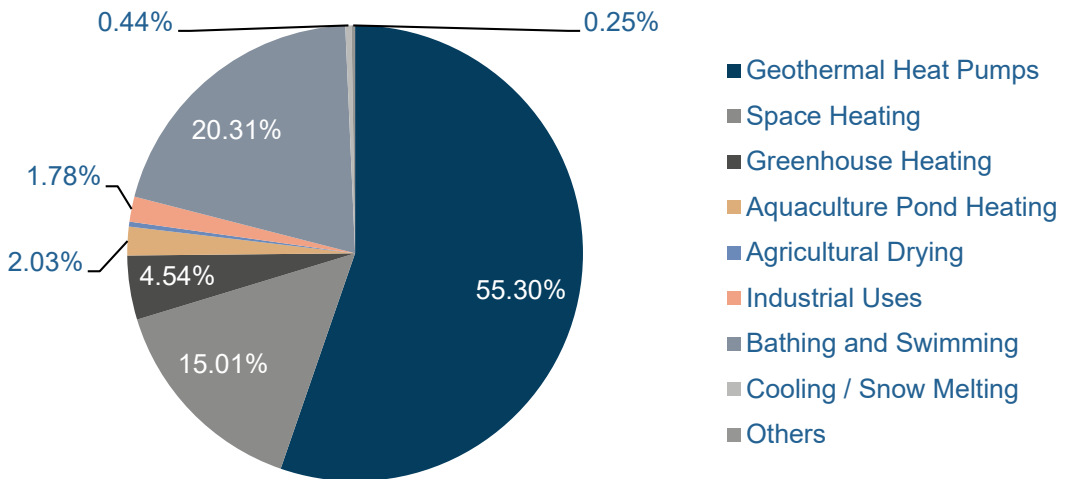
Moreover, global direct use of geothermal energy can be further divided into categories of energy utilisation. Some of the categories include: geothermal heat pumps, space heating, greenhouse heating, aquaculture pond heating, agricultural drying, industrial uses, bathing and swimming, cooling/snow melting and others. Figures 6 and 7 below show the installed capacity of geothermal direct utilisation (MWt) and worldwide utilisation (TJ/year) by the aforementioned categories.

FIGURE 6: GEOTHERMAL DIRECT APPLICATIONS WORLDWIDE IN 2015, DISTRIBUTED BY PERCENTAGE OF TOTAL INSTALLED CAPACITY (MWT)



Source: Lund and Boyd (2015)

FIGURE 7: GEOTHERMAL DIRECT APPLICATIONS WORLDWIDE IN 2015, DISTRIBUTED BY PERCENTAGE OF TOTAL ENERGY USED (TJ/YEAR)

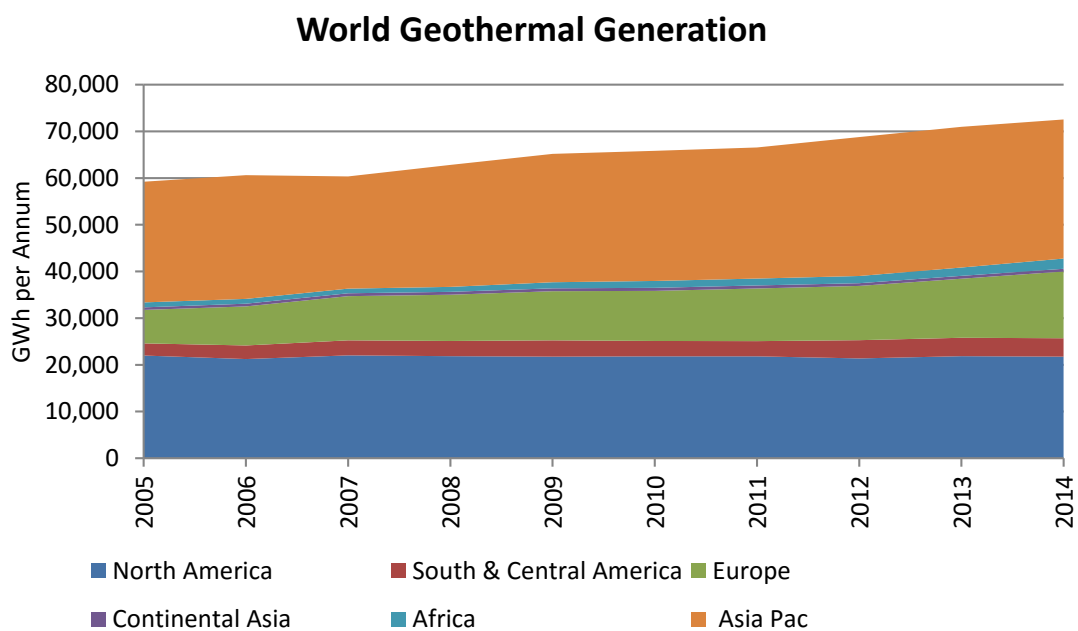


Source: Lund and Boyd (2015)

Distribution

World electricity generation in 2014 totalled 73.3 TWh, spread among 24 countries⁵. In 2015, total power output totalled 75 TWh, the same number being also valid for total heat output from geothermal energy (excluding ground heat pumps)⁶. The Asia Pacific region (40%) generated the most electricity followed by North America (30%). Despite the high capacity growth among developing nations in recent years, OECD countries still account for over 63% of the output.

FIGURE 8: WORLD GEOTHERMAL GENERATION BY REGION



Sources: EIA, IEA, DOE Philippines, company annual reports, Contact Energy Ltd.

World geothermal heat use (direct & storage) reached in 2014 563 PJ⁷. Roughly 40% represents direct use; the balance comprises energy used from heat pumps. China dominates heat usage with over half of the world's consumption. Europe is the second largest user with 30% of world consumption. Direct heat use is geographically concentrated in regions above 35° latitude due to heating requirements during winter.

⁵ Bertani (2015)

⁶ Ren21 (2016)

⁷ Lund and Boyd (2015)

Total Potential

As noted in the Introduction, the Earth’s interior supplies an enormous quantity of heat to the crust. Various studies suggest the electrical potential of geothermal resources is 10 to 100 times the current generation. Direct use potential has similar multiples to current use. While estimating geothermal energy potential is difficult, the industry consensus is that growth will not be resource constrained over the next half century.

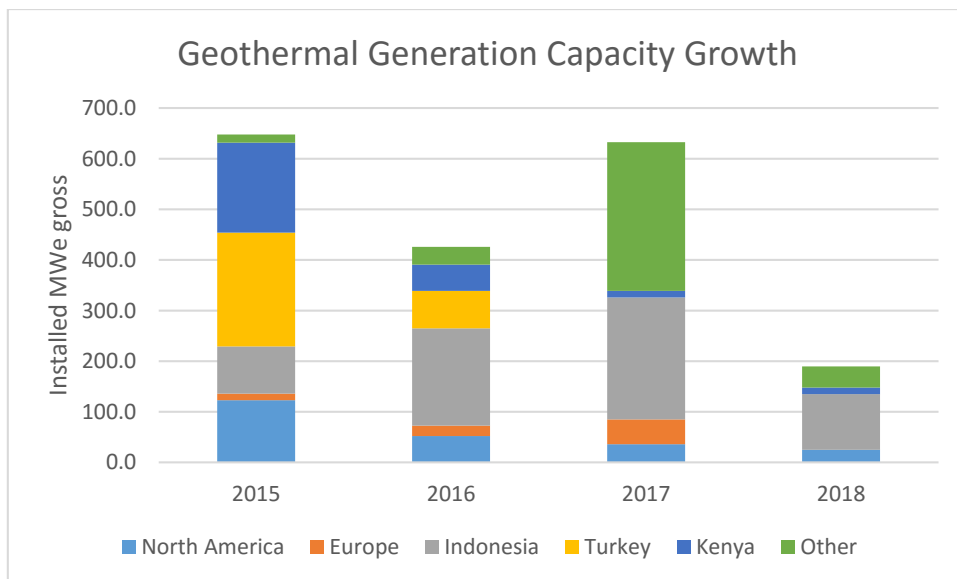
Growth and Growth Factors

Over the past decade, world geothermal generation capacity grew at a rate of 3 to 4% per year, roughly in line with the rate of world economic growth. Most of this growth took place in Kenya (392 MWe), the USA (352 MWe), New Zealand (400 MWe), and Turkey (306 MWe); together accounting for 60% of world capacity growth.

Economic growth coupled with high fossil fuel prices has driven much of the recent capacity investment. New development is increasingly focused in non OECD countries with rising electricity consumption. In contrast, the OECD economies are experiencing falling energy usage relative to GDP, lower economic growth, and the recent collapse in fossil fuel prices. So, geothermal development must displace existing capacity in some way to be viable.

Looking forward, committed projects will add almost 2,000 MWe (a 16% capacity increase) between January 2015 and December 2018 (Figure 9). Most of this new capacity will be installed in Indonesia (636 MWe), Turkey (298 MWe) and Kenya (255 MWe). Geothermal generation will expand to Iran, Croatia, Chile, and Honduras.

FIGURE 9: GEOTHERMAL GENERATION CAPACITY GROWTH – FROM COMMITTED PROJECTS



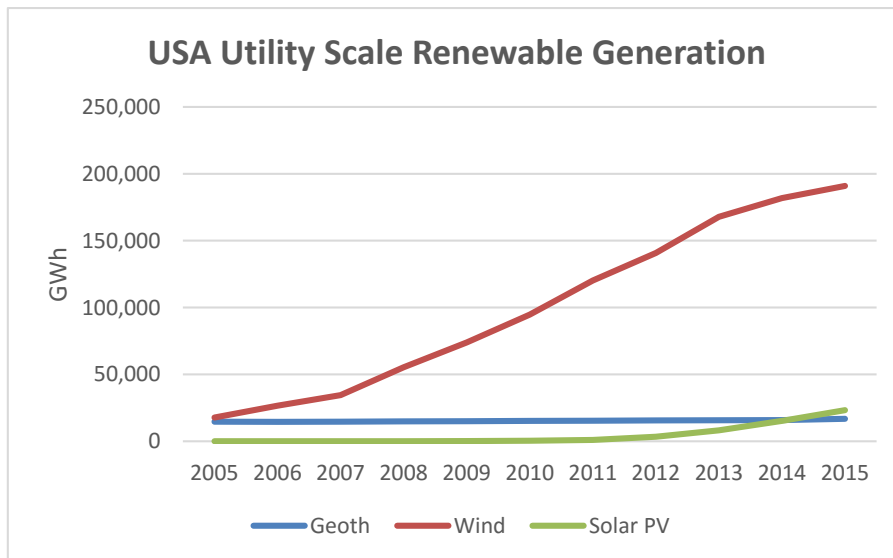
Source: Contact Energy Ltd.

While statistics for direct use are less systematic, the surveys completed by the International Geothermal Association suggest overall direct heat use grew at 7.8% annually between 2004 and 2014. Heat pump installations account for most of this growth. New district heating schemes in Europe accounts for balance of the rest.

The main drivers for investment are clean air regulations and decarbonisation incentives. Energy security coupled with the high cost or absence of natural gas may also stimulate investment for northern European countries. Growth, particularly for district heating from deep wells will be reliant on price supports. This dependence on subsidies makes investments vulnerable to regulatory shifts. Recently both Spain and Germany have reduced price supports for renewables such as solar, eliminating the economic returns for some existing schemes.

Geothermal energy growth has lagged behind the explosive growth in wind and solar generation. Starting from practically nothing, solar and wind generation in the USA overtook geothermal output in a decade (Figure 7). This result reflects both the limited distribution of geothermal resources and the deteriorating cost position relative to solar and wind. The future of the geothermal industry, may well depend on how well geothermal technology can drive down the costs of capacity.

FIGURE 10: USA SOLAR, WIND AND GEOTHERMAL GENERATION



Source: EIA

1. TECHNOLOGIES

Geothermal energy is used in power generation, for direct heating, and for storage-retrieval (ground-source heat pumps). The technologies employed are well proven, some of them ancient. However, the industry's inability to evolve standard designs and incorporate new technologies has harmed its cost competitiveness.

POWER GENERATION TECHNOLOGY AND PERFORMANCE

Geothermal power generation is valued for its high reliability, independence from short term weather fluctuations, and long operating life. Individual plants, such as Wairakei (NZL), the Geysers (USA), Larderello (ITA), Bulalo (PHL) and Oita (JPN) have reliably generated electricity for over 40 to 50 years. Geothermal generation typically has low operating costs (making them easy to dispatch) but suffers from high up front capital costs and associated resource risks.

Geothermal operators generate electricity by either using the steam extracted from geothermal fields directly in a turbine or by using hot pressurised fluid to vaporise a low boiling point fluid for use in a binary turbine. Steam turbines are typically used in high temperature resources while binary plants are used in intermediate temperature systems. In both these generation systems, pressurised vapour passes through a turbine and is subsequently condensed. The passage of vapour spins the turbine which turns a generator to produce electricity.

The efficiency of the conversion from heat to electrical energy depends, in part, on the condensation process. Most steam turbine systems use water (once-through or in a closed loop) to quench the steam, producing a partial vacuum. The colder the water, the better the quench; the lower the vacuum pressure, the higher the generation. In contrast, binary turbine systems commonly use air driven by fans to cool and condense the vapour. The principle remains the same: the colder the air, the greater the output from the plant.

Like other Rankin cycle plants, the condensing process affects the electrical output. This affect is significant because the temperature and pressure of the steam or fluids feeding the turbines is significantly lower than for fossil-fuelled thermal plants. So, geothermal generation will vary with the ambient air temperature during day and season. Nameplate plant output may vary by 5% to 20% throughout the year depending on the ambient temperature. In some small scale applications, such as the Azores, this variation may have important consequences for system supply. In continental environments where the summer cooling load is large, the lower effective capacity of air cooled geothermal plant reduces its value to system supply (and consequently lowers the power price).

Over the last decade, geothermal steam plant designers/manufacturers have made modest improvements to the efficiency of their units by increasing turbine sizes (up to 138 MW) and raising the inlet steam pressure (up to 20 bar.a.). Similarly, the largest binary units have more than doubled in size from 7 to 24 MWe. Importantly, this increase in scale has moderated the installed unit cost of capacity.

Binary plant manufacturers have also improved thermal efficiencies through employing radial turbines, using different working fluids such as ammonia, and employing supercritical pressure systems. However, these improvements remain in the developmental stage. In some cases, the increase in efficiency has been offset by a decline in availability. For example, despite extensive development investments, only four small Kalina cycle plants have been built at Husavik (ISL), Unterhaching and Bruchsal (DEU) and Matsunoyama Onsen Hot Spring (JPN).

Depending on fluid temperature and separation pressure, some binary plants, like Ngawha and Ngatamariki (NZL), have boosted performance by utilising both flashed steam and separated fluid in the binary process. This configuration also improves the ability to minimise fluid loss (pressure decline) from the reservoir.

Recently, operators have experimented with hybrid plants that combine geothermal and other renewable technologies. At Stillwater (USA), Enel Green Power increased the performance of its 48 MWe binary plant by employing a thermal-solar trough to increase the enthalpy of the secondary loop working fluid. Similarly, at Cornia 2, Enel uses a biomass boiler to increase the inlet steam temperature from 160° C to 370° C and the capacity by 5 MWe.

In financial terms, geothermal plant performance depends on the factors controlling output (revenue): plant life, availability, and the reliability of geothermal supply.

Annual plant availability in individual years can reach as high as 97% as at Hellisheidi (ICL) but typically range from 90% to 94%. Occasionally, plant availabilities slip to 85% for several years due to extended refurbishments as at Cerro Prieto (MEX).

Maintaining geothermal energy supply to the generating plant is one of the major operating risks of a geothermal project. Annual plant capacity factors typically range from over 95% at Wyang Windu (IDN) to 36% at Momotobabo (NIC), with the median lying between 80% and 90%. However, the difference between maintaining an 88% vs 92% capacity factor is highly material to the project meeting its financial objectives.

There is a common tendency for geothermal energy supply to decline over the life of a project. This may be caused by falling temperatures and/or pressures in the geothermal reservoir as well as a reduction in the water saturation (in some dry steam resources). A good example is Coso Field (USA) where annual production over the past decade has declined at 5% per year due mainly to “dry out”. In contrast, some fields such as Kizildere

(TUR) or Beowawe (USA) have managed falling temperatures and pressures for more than 20 years without sustained output declines.

Employing generating technology also affects capital costs. The highly variable conditions of geothermal resources have hindered the employment of standard turbines. Every design is optimised to a particular resource and changes to temperature and pressure over time. This keeps costs high. United Technologies attempted to produce and market standard binary units (*Purecycle*) but the additional capital costs in the cooling cycle (to make up for the lower conversion efficiency) devoured any cost savings rendered from standardisation.

To decrease construction time, binary OEMs have moved to container-sized, scalable modular designs for power plant components. The size of these modular binary units has increased over time, greatly improving economies of scale.

Another important factor influencing geothermal power's economic performance is the ancillary electrical load required to run the supporting systems around a geothermal plant. For favourably located, high grade resources, ancillary factors can be as low as 3.5% such as Reykjanes (ISL); in hot dry climates with pumped, moderate temperature reservoirs, the parasitic load may reach 20% of capacity as reported at Blue Mountain (USA). Most fields have ancillary loads ranging between 5 and 10%.

Geothermal output can also vary markedly with the composition of the reservoir fluids. The amount of work available is a function of the heat available for conversion. The amount of heat extracted from geothermal fluid depends on the mineralisation level. All things being equal, the higher the mineralisation the lower the amount of heat available. So, geothermal fields characterised by briny fluids are more difficult to economically exploit than similar fields containing relatively fresh reservoir fluid (typically with silica or carbonate scaling).

STEAMFIELD TECHNOLOGY

Roughly half the capital costs of a geothermal energy system derive from supplying hot fluid or steam from the geothermal field. In addition, the steamfield tends to consume most of the ongoing capital expenditure to sustain operations.

The steamfield typically comprises a steam/fluid supply system and a re-injection system to dispose geothermal fluid after heat extraction. The supply system contains production wells, separation vessels, conveyance pipe-work, conditioning vessels (to regulate the properties of steam/fluid) and controls. Reinjection systems commonly contain fluid conveyance pipe-work, pumps, mineral scale inhibitors, injection wells, and associated controls.

The technologies for steam flashing, conditioning, and conveyance are over 50 years old. Still, steam quality remains an issue at many steam turbine plants where long-established design rules are not followed – or replaced by modern steam-washing technology. Poor

steam quality can erode or corrode turbines blades. This lowers turbine performance, increases outage time, and lifts maintenance costs.

Production wells are typically 1 to 3 km deep and produce high to intermediate temperature two-phase fluids or steam. While oil and gas wells have reached over 9,000 m, there are only a small number of geothermal wells producing from zones deeper than 4,500 m. Production flow rates are highly variable; meaning that tight wells may produce energy sufficient for only 1 MWe while exceptional wells can produce more than 25 MWe. Typical high temperature production wells attain 5 to 12 MWe.

Injection wells display variable performance, because they tend to be drilled into the periphery of geothermal resources where permeability is low. The field operator's objective is to position wells so that the injected fluid provides some degree of pressure support but does not re-enter and cool the high temperature reservoir. Consequently, the number of production wells relative to rejection wells varies from 1:1 at Berlin (SVL) to 6 or 7 to 1 at Svartsengi (ISL). At steam dominated fields like Kamojang (IDN) the ratio may be 10 to 1 at commissioning. For intermediate temperature resources, the number of injection wells may even exceed the number of production wells as at San Emidio (USA).

Most production well-flows decline with time, with rates varying from 3-10% per year, depending on changes in reservoir pressure and temperature and formation of scale in the wellbore. To sustain production, field operators typically must perform workovers and drill makeup production and injection wells. As a result, on-going drilling costs partly determine the field's economic returns. Drilling costs are high relative to oil and gas wells because the number of casing strings is higher, the drilling rate-of-penetration is lower, and the cost of mobilising and operating a rig in remote locations is higher than for established oil and gas provinces. In addition, drilling services are commonly denominated in US dollars and the resulting exchange rate can significantly add to drilling costs.

To remain competitive, the geothermal industry has tried to improve drilling performance through employing more automated rigs, drilling multiple wells from pads, employing larger diameter completions, and completing multiple legs from one well. More recently, the industry is experimenting with percussion drilling and water jet technology. The results to date are mixed.

ADVANCES IN RESERVOIR TECHNOLOGY

Another way to increase system yield (other than drilling new wells) is to improve the performance of existing wells by reservoir stimulation and conditioning. Over the last decade, the industry has completed hydrologic stimulation trials at Habanero (AUS), Desert Peak, Newberry, and Raft River (USA) and Soultz (FRA). While the results have been encouraging, the technology needs further development before it can be deployed in producing geothermal fields economically.

Similarly, individual field operators have experimented with improving permeability using chemical stimulation as at Alasehir (TUR), thermal cracking, and deflagration. The results have proved interesting but to date not economically compelling.

Conjointly with the development of stimulation methods, field operators have adapted coiled tube and wireline techniques to replace the role of drilling rigs. In some cases, this has significantly lowered the cost of well conditioning (work-overs) to clean out mineral scale or repair casing damage. Remote island locations, such as Hawaii or Guadeloupe are particularly vulnerable to the costs of importing drilling rigs for well conditioning.

National regulators are increasingly concerned with well integrity, particularly after the Lusi blowout in Indonesia and potable water contamination concerns in the USA. Service companies can now provide wireline-based, high temperature casing condition monitoring tools to help field operators manage well integrity risks.

As the number of mature geothermal fields has risen with time, reservoir modelling has become an indispensable tool for production planning and reservoir management. The standard simulation code is TOUGH-2, developed by Lawrence Berkeley National laboratories in California. Other research groups such as the University of Auckland Geothermal Institute have incrementally improved code output and interfaces. Other analytical software for specialist analysis like well bore simulation (TETRAD with Petrosim interface) has also emerged along with visual packages for geoscience modelling (Leapfrog). Such tools have increased the field management and exploration capabilities.

DIRECT USE TECHNOLOGIES

People have been using geothermal springs for heating, cooking, and bathing for thousands of years. The development of drilling techniques in the 20th century facilitated the utilisation of underground geothermal resources for an array of direct uses. In practice, well depths vary from a few hundred metres to over 4 km deep. While drilling technology has improved, the basic technology of heat conveyance and use dates back to the 19th century.

Direct-use applications use reservoir temperatures between 40°C and 180°C in the form of heated (liquid) water, or low pressure saturated steam. The uses vary greatly in energy intensity from timber drying to spa pools and greenhouse heating.

Geothermal fluids contain dissolved minerals that make them inappropriate for many process uses. So, applications commonly employ a heat exchanger to separate the geothermal cycle from a clean water/steam process cycle.

The geothermal cycle comprises a circulating loop of geothermal fluid from the production well(s) through a heat exchanger or steam generator, and back to an injection well(s). The process cycle circulates air or water through the heat exchanger to the application and back again. In the case of clean steam, the process cycle condenses the steam before re-cycling the condensate back to the clean steam generator.

Most geothermal direct applications use low temperature fluids for low intensity heating. Facility investments are modest; consequently, substantially more money and effort has been directed into technical improvements for electricity production.

Designing system controls to match variable heat process loads or narrow heat specifications with geothermal well operating characteristics can be difficult. While modern sensors and control systems allow some load fluctuation, the primary system commonly needs a mechanism to shed heat in the event of a forced outage or sudden change in heat load.

GROUND SOURCE GEOEXCHANGE TECHNOLOGY

The term 'geoexchange' is a term used to describe heat exchange processes using stable temperatures present at shallow depths below the ground surface. These stable temperatures result from solar radiation rather than radiogenic decay within the earth. Thus, geoexchange resources are distinct from true 'geothermal' resources.

The earth's surface temperature varies with the season; in high latitudes, the difference between summer and winter can exceed 40° C. However, a few metres below the earth's surface, the ground remains at a relatively constant temperature within the range of 7°C to 21°C.

Several technologies use these heat sink and transfer properties of the shallow subsurface to provide heating and cooling for residential and commercial scale buildings. Such applications mainly transfer existing heat (rather than produce heat); in some applications the subsurface is used to store heat.

The most common underground thermal application is ground-sourced heat pumps (GHP). These installations provide both cooling and heating and comprise three main components.

- **A Ground Loop:** an underground, closed network of pipes that collect and dispose heat; such loops reside besides the building they service.
- **A Heat Pump:** a device using vapour-compression refrigeration technology to move heat. In heating mode, the heat pump transfers heat collected in the ground loop and delivers it to the building; in cooling mode, the process is reversed and heat in the building is removed and disposed in the ground loop.
- **Distribution System:** this duct network distributes heat to or removes heat from the building or application.

Sorption chilling is another, similar technology using the thermal properties of the shallow subsurface for cooling (only). A sorption chiller uses the vaporisation and condensation of a working fluid, like a heat pump, but achieves condensation via a chemical process rather than mechanical compression.

Ground-sourced heat pumps can be combined with other technologies, such as solar heating, to create hybrid systems for greater performance. It is possible to integrate these components with solar PV, batteries, and water use through home energy management systems (HEMS) that facilitate automated smart homes and buildings.

GHPs can be installed almost anywhere but are more practical in higher latitude locations. The installation cost is generally higher than conventional central heating systems, or air-sourced heat pumps. The working life is 25 years for the indoor components and 50 years for the ground loop.

According to the IGA⁸, world GHP capacity has been growing at a rate of 12.5% per annum over the past decade. This is widely expected to continue as the economies in Western Europe, North America and China decarbonise.

⁸ Lund and Boyd (2015)

2. ECONOMICS & MARKETS

OWNER-OPERATORS

Electricity market reforms have reshaped the market structure of geothermal energy profoundly since the mid-1990s.

- National utilities with substantial geothermal operations such as Enel Green Power, the Philippines National Oil Company and Electricity Corporation of NZL have been privatised, transferring much of the world's geothermal capacity into private ownership.
- The integrated oil companies, who pioneered geothermal development in the USA, the Philippines, and Indonesia, have almost entirely exited the industry (the last remaining company, Chevron, has announced its intention to sell all its geothermal assets).
- The common ownership split between the resource and the power station was largely removed by privatisation. However, this model has re-emerged as developing nations attempt to attract foreign investors by taking on the resource risk.

Over 70% of geothermal electrical generation is controlled by just 20 operators (Table 1). Interestingly, several of the top operators such as Calpine, Chevron, BH Energy (formally Cal Energy), and CFE have essentially just maintained their existing assets since 2010. The operators most active in developing new capacity have been Ormat, Mighty River Power, and Pertamina Geothermal Energy. In addition, new entrants like GEODESA (MEX) and Zorlu Enerji (TUR) are developing a significant quantity of the new capacity.

To manage risk, joint venture partnerships or consortiums have returned to favour. PT Supreme (IDN), Maibarara (PHL), Sarulla Operations Ltd. (IDN), and Tawau Green Energy (MAL) are all recently founded and are now operating, constructing and developing projects.

New entrants also include passive investors such as Energy Capital Partners (USA) who have purchased interests solely in operating geothermal projects as part of a wider renewable energy portfolio.

TABLE 1: LARGEST GEOTHERMAL PLANT/FIELD OPERATORS

Operator	Country	Class	Capacity (MWe)
Energy Development Corporation (EDC)	PHL	IPP	1,159
ENEL Green Power	ITA	IPP	1031
Comision Federal de Electricidad (CFE)	MEX	Nat Utility	839
Calpine Corporation	USA	IPP	725
Ormat Industries	ISR	IPP	697
Perusahaan Listrik Negara (PLN)	IDN	Nat Utility	562
Kenya Electricity Generating Company	KEN	Nat Generator	474
Mighty River Power	NZL	Nat Generator	466
Chevron Corporation	USA	Oil & Gas - IPP	435
Aboitiz Power	PHL	Public Utility	430
Contact Energy	NZL	IPP	423
Reykjavik Energy	ISL	Nat Utility	409
Pertamina Geothermal Energy (PGE)	IDN	Nat Generator	402
Berkshire Hathaway Energy	USA	IPP	317
Star Energy	IDN	IPP	230
La Geo	SLV	Nat Generator	191
HS Orka	ISL	Public Utility	170
ICE	CRI	Nat Utility	162
Kyushu Electric Power	JPN	Public Utility	122

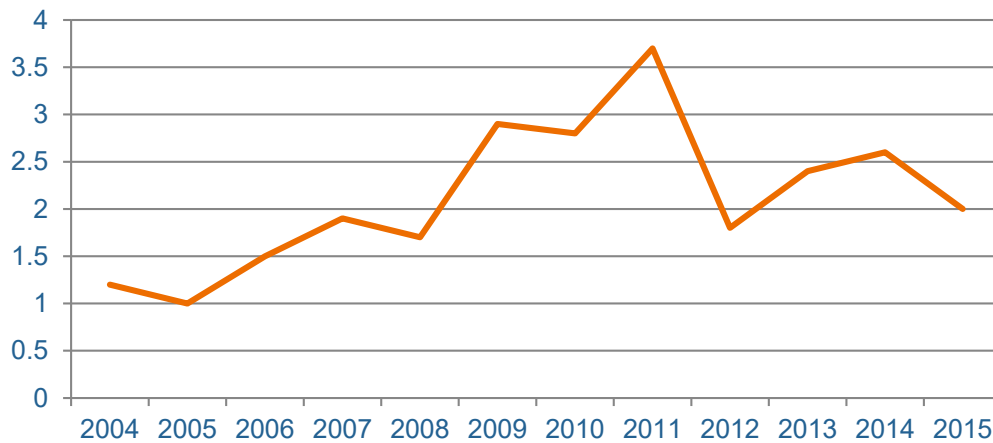
Gurmat	TUR	IPP	112
Total			9,356

In contrast, the owners of direct-use facilities tend to be small enterprises (greenhouses, hotel/baths), municipalities (district heating), or individual homes. There are a few large scale district heating utilities in Iceland, France, Turkey and China. There are also a handful of large industrial users of steam such as Norske Skog (NZL) and Mitsubishi Materials (JPN).

INVESTMENT

Global investment in 2015 was US\$2 billion, a 23% setback from 2014⁹. During the period 2010-2014, around US\$20 billion were invested in geothermal energy by 49 countries for both direct use and electric power. Figure 11 illustrates the trajectory of yearly new investment in geothermal energy from 2004 to 2015.

FIGURE 11: YEARLY NEW INVESTMENT IN GEOTHERMAL ENERGY, 2004-2015 (USD BILLION)



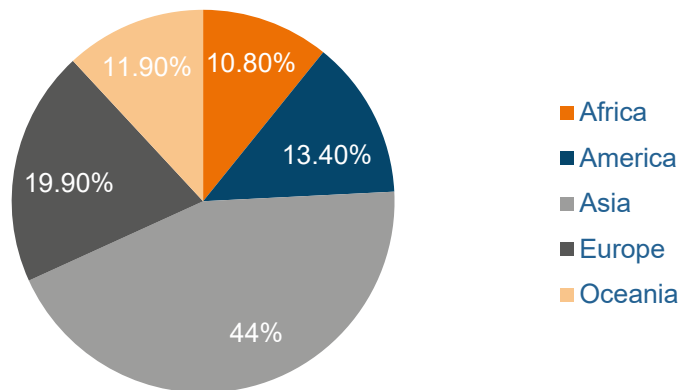
Source: Bloomberg New Energy Finance, UNEP (2016)

The countries with the highest investments include: Turkey, Kenya, China, Thailand, USA, Switzerland, New Zealand, Australia, Italy and South Korea. Investments by category

⁹ BNEF (2016)

include: 28.3% for electricity utilisation in 16 countries, 21.8% for direct use in 32 countries, 25.6% for field development and production drilling in 32 countries, and 24.4% for R&D which includes surface exploration and exploratory drilling in 48 countries. In addition, regional investments have been identified as follows: 10.8% in Africa by 2 countries (US\$2,160 billion), 13.4% in the Americas by 9 countries (US\$ 2,669 billion), 44% in Asia by 9 countries (US\$8,765 billion), 19.9% in Europe by 27 countries (US\$3,953 billion) and 11.9% in Oceania by 2 countries (US\$2,375 bln) (Figure 12).

FIGURE 12: GLOBAL INVESTMENT FROM 2010-2014 BY REGION, IN PERCENTAGE

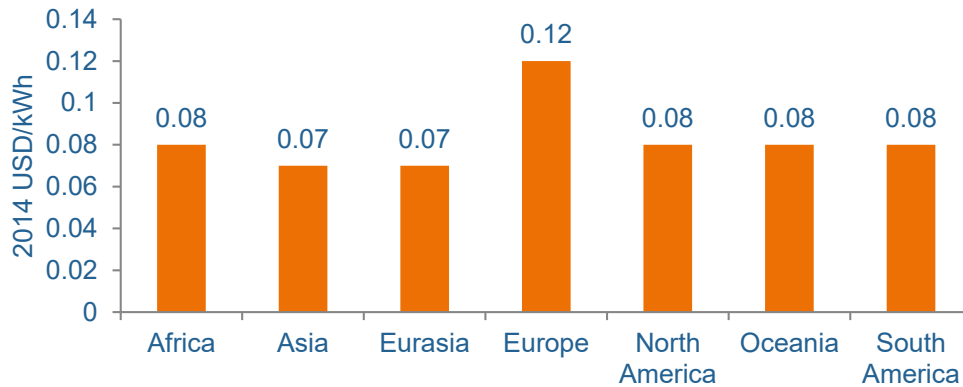


Source: Lund & Boyd (2015)

COMPARATIVE COST ECONOMICS

A number of international energy consultancies (Bloomberg, Lazard) and agencies (IEA, EIA) have assessed the levelised cost of geothermal generation plant compared with its rivals. While in detail these costs differ depending on the present value of the currency used, capacity factors assumed, and the countries of origin, the relative ranking remains consistent. Figure 13 presents the average levelised cost of electricity (LCOE) for geothermal in 2014 by region.

FIGURE 13: AVERAGE LEVELISED COST OF ELECTRICITY FOR GEOTHERMAL IN 2014, BY REGION



Source: IRENA (2016)

Geothermal generation is generally ranked as costlier than either gas-fired, combined cycle or coal-fired steam plants (conventional or fluidised bed) (see Table 2). In addition, in some applications utility scale solar PV and wind have materially lower levelised costs and can be located closer to the load centres. The perceived lower project risk for solar PV means that projects will proceed with internal rates of return (IRRs) as low as 5%.

TABLE 2: INDICATIVE LEVELISED COSTS FOR GENERATION PLANT (USD/MWH, 2014 BASIS)

Plant/Fuel Type	Low	Median	High
Solar PV rooftop	150	190	265
Solar PV utility	60	90	150
Wind onshore	40	87	150
Geothermal	85	96	200
Gas Combined Cycle	65	80	125
Coal Steam (conventional)	65	85	150

Note: cost figures do not include carbon charges

In practice, geothermal developers report a very wide range of installed capacity costs (Table 3). Since company reports do not include associated scopes of work, it is unclear whether the costs reported include all the components. Notwithstanding these uncertainties, the figures suggest greenfield developments will range from US\$4,500 to US\$5,100 per kW. These installed costs are consistent with recent power purchase agreements (PPA) tariff awards in Indonesia that are in the US\$95/MWh to US\$110/MWh range.

TABLE 3: REPORTED PROJECT CAPITAL COSTS

Project	Country	Capacity MW	Year	US\$ per kw
Ngatamariki	NZL	82	2013	4,487
Neal Hot Springs	USA	22	2012	4,827
Wyang Windu II	IDN	120	2009	2,200
San Jacinto I	NIC	36	2009	5,117
Thermo	USA	11	2009	8,810
Bagnore 4	ITA	40	2014	4,060

Note: Wyang Windu II was a brownfield development on an existing field

Sources: Mighty River Power, US Geothermal, Star Energy, Ram Power, Racer Technologies, and Enel annual reports

3. SOCIO-ECONOMICS

GOVERNMENT INCENTIVES

A survey of practices completed by the WEC shows that geothermal energy does not enjoy the incentives available to other renewable energy projects like solar and wind. The survey also shows that incentives vary depending on whether the primary objective is to grow electricity supply or reduce greenhouse emissions.

Renewable portfolio standards (RPS) are the most common mechanism to displace fossil fuel and nuclear energy with renewable energy¹⁰. These renewable energy consumption targets vary widely. The European standards have specific targets for electricity, heating/cooling and transport. In North America, the individual states/provinces targets vary from none at all to the full suite of energy sectors. Central and South America tend to target electricity generation only. The Asia Pacific Region also preferentially targets electricity generation. Because RPS standards are broad and indirect, it is difficult to assess what, if any, impact they have in promoting geothermal energy.

Feed-in tariffs are the most common direct incentive for geothermal investment. Countries in Europe such as Germany, Austria, and Turkey use this mechanism to reduce greenhouse emissions. Feed-in tariffs range from US cents 10.4 per kWh (TUR) to 23 per kWh (DEU). While prices represent a significant premium over wholesale power prices, they are subject to change as with the recent removal of solar price supports in Spain and Germany.

In contrast, countries such as Indonesia and Kenya rely on feed-in tariffs to stimulate capacity investment by removing price risk and providing a premium to cover resource and country risks. These tariffs, commonly issued under competitive tenders, are embedded into 30 year PPAs with a national utility and so have far less risk and higher bankability than the European renewable tariffs.

It is worth noting that tax exclusions on import duties and value added levies are also important mechanisms to attract geothermal investment in many developing countries.

In North America, the preferred direct incentives include tax credits, government guaranteed debt, and in a few cases, direct government grants (for EGS). The main advantage seems to be that wholesale power prices are not distorted. However, the increased incentives for solar and wind have disadvantaged geothermal development.

¹⁰ IRENA (2015)

Cap and trade schemes (emission trading systems) have been trialled in Europe, Canada, China, Korea, California, and New Zealand. To date, traded carbon prices have been too low (US\$10 to \$15 per tonne) to provide any real advantage to geothermal energy relative to natural gas.

Within the OECD, renewable energy policies also seek to advance geothermal energy use through direct funding of research and development. To date government funding has focused on technology related to geothermal resources principally EGS demonstration projects such as Soultz (FRA) and Desert Peak (USA). Equipment manufacturers have focused on improving the reliability and efficiency of electricity generating and balance-of-plant equipment. Many of the large operators spend relatively little on research but focus on incremental improvements to their existing operations.

LAND ACCESS AND USE

Geothermal developments, particularly for power stations, require a substantial land area. Access to the resource depends on firm land rights. In many countries seeking to expand geothermal generation, occupiers of the land may lack formal titles, the right to land having originated from continued occupation for long periods (in some cases hundreds, if not thousands of years). Geothermal developers must work through the legal processes to formalise land rights and suitable compensation for access. In practice, these necessary social/political frameworks may delay projects for several years. This is a material risk for countries looking to attract independent power producers to invest in geothermal generation.

In countries having an established geothermal industry, rival claims on water and land for other uses can restrict geothermal energy use or development. In particular, local infrastructure claims on land beside or overlying geothermal resources are difficult for operators to defend. National guidelines to protect geothermal resources for extraction and conservation may be required to prevent the erosion of beneficial use.

UTILITY PARADIGM SHIFT

The emergence of new energy and systems technologies is altering the scope and economics of the traditional electric utility. The centralised, unidirectional flow from generation to local use via a transmission/distribution system is giving way to network platforms supporting local generation, balancing, pricing, storage, consumption and associated services.

Both the technology pull and policy push towards local electricity networks favours the adaptation of smaller-scale, local geoexchange technologies relative to the central generating role of geothermal electricity generation. While long the poor cousin to electric generation, ground sourced heat pumps may be entering a golden age.

Similarly, growth in district heating systems has propelled interest in “smart” thermal grids. These systems integrate deep geothermal heat extraction and other local energy sources with the storage and cooling capabilities of geoexchange systems.

The social and political economy is changing the energy technology and application preferences of communities and customers. So future geothermal use will depend on how geothermal energy conforms to these new imperatives.

GEOTHERMAL PROJECT IN INDIA

Geothermal resources are present in 7 provinces in India, however there is no geothermal power plant yet, but only a number of projects. One of the projects is the result of a recent collaboration between India and Norway in the north-western Himalayas. Two pilot demonstration projects investigating the utilisation of low and medium temperature geothermal resources for heating purposes, successfully improved the livelihood of the local population. The area has a very short supply of electricity of about 3 hours per day, and temperatures drop in the winter season to below 20°C. In addition, natural resources such as wood are in short supply and people rely on fossil fuels like coal for heating their homes.

The researchers assessed the resource potential and heat load for heating up a hotel and restaurant, and successfully managed to install heating systems that keep the indoor temperature at about 20°C. Due to the shortage of electricity available, solar panels have been installed to make possible the continuous operation of the heat pumps. These kinds of projects play a key role in improving the life expectancy and overall standard of living of people living in areas characterised by fuel-poverty, relative isolation and geothermal resource potential¹¹.

At the country level, India announced plans to develop 10,000 MW of geothermal energy by 2030 in partnership with countries that are top producers of geothermal power generation: USA, Philippines, Mexico and New Zealand. There are already some sites in the country where geothermal energy is explored, namely Cambay Graben in Gujarat, Puga and Chhumathang in Jammu and Kashmir, Tattapani in Chhattisgarh, Manikaran in Himachal Pradesh, Ratnagiri in Maharashtra and Rajgir in Bihar. The plan is part of the government’s pledge to increase the share of renewable power to 350 GW by 2030¹².

¹¹ Richter (2016) Geothermal project successful in providing heat to community in the Himalaya

¹² Richter (2016) India sets ambitious target for geothermal development by 2030

4. ENVIRONMENTAL IMPACTS

Geothermal extraction results in a number of discharges and impacts on the environment. These include gas discharges to air, chemicals to land and water, noise, and the potential for induced seismicity.

Geothermal fluids contain dissolved gasses, commonly carbon dioxide and nitrogen with trace amounts of ammonia and hydrogen sulphide. In Table 4 below it is presented the typical composition of geothermal gas. When two-phase geothermal fluid is separated into steam and water, or cooled in a heat exchanger, these gases emerge from the solution and are commonly vented to the atmosphere without adverse effects. However, hydrogen sulphide is a hazardous substance and many countries now regulate the management of H₂S discharges. The USA and Italy have both mandated the installation of scrubbers to remove hydrogen sulphide from air discharges. Other countries place strict limits on H₂S levels in air emissions.

TABLE 4: TYPICAL COMPOSITION OF GEOTHERMAL GAS (WEIGHT % DRY GAS)

	CO ₂	H ₂ S	H ₂	CH ₄	NH ₃	N ₂	AR
Median	95.4	3.0	0.012	0.15	0.29	0.84	0.02
Maximum	99.8	21.2	2.2	1.7	1.8	3.0	0.04
Minimum	75.7	0.1	0.001	0.0045	0.005	0.17	0.004

Source: ESMAP (2016)

The level of potential adverse environmental effects varies with the intensity of gas emissions. Low and moderate temperature fluids have significantly lower concentrations of dissolved gases than the high temperature, resources. Some of the district heating systems using low grade fluids from sedimentary basins are able to extract and inject geothermal fluids without any venting of gases.

Primary or separated geothermal fluids also contain dissolved cations of potential environmental concern such as mercury, arsenic, antimony, and boron. These may also precipitate out as scale, commonly in the form of silica or metal silicates but stibnite, cinnabar, or (rarely) orpiment may also occur. The cleaning of pipes or heat exchangers commonly results in material quantities of precipitate. Some regulators now require that operators dispose such mineral scale as a hazardous substance.

Similarly, geothermal fluids, once the heat has been removed, are usually reinjected back into geothermal reservoir below the potable water level. This avoids potential contamination of potable water supplies. In a few locations, geothermal fluid is disposed into evaporation ponds or discharged to the ocean or rivers but these practices are waning. In recent years, community concerns regarding the integrity of geothermal, oil and gas wells have induced mandatory casing inspections, and plug and abandonment practices to avoid accidental contamination of shallow potable aquifers.

If geothermal power plants are operated close to settlements, they will impact the local community. The most common complaints are noise, odour, rights to fresh groundwater, and sometimes ground subsidence. Many jurisdictions now have strict noise and odour limits on operating geothermal power stations. In arid regions like the Altiplano or the western USA, geothermal operators must compete with other interests for the use of groundwater for drilling and occasionally injection for reservoir pressure stabilisation. This rivalry can provoke litigation and community opposition to geothermal development.

It is well known that depleting shallow aquifers can result in ground subsidence. There are well documented cases of ground subsidence (Steamboat Springs, USA, and Wairakei-Tauhara, NZL). Such subsidence has the potential to damage surface facilities and regulatory authorities may require surface monitoring to manage and avoid these effects.

Over the last 30 years, nearly all geothermal developments have included reinjection of the used process fluids. Such injection has the potential to induce seismic activity. There are emerging community concerns regarding induced seismicity. Several geothermal fields such as Coso (USA), Rotokawa (NZL), Wairakei (NZL), and Reykjanes (ISL) display micro seismicity that is likely induced by production and injection. In addition, engineered geothermal systems (EGS) purposely induce micro earthquakes to increase permeability. Oil and gas operations demonstrate a correlation between the high pressure injection of fluids into known fault zones and seismic activity. To date, there are few, if any, examples of material damage caused by induced seismicity from geothermal operations. However, the disposal of fluids in sedimentary basins as a result of oil and gas extraction (USA) triggers noticeable seismic swarms. In Europe, the threat of induced seismicity has halted operations at the Basel (CHE) Enhanced Geothermal System plant. Several countries (USA, NZL, DEU) require seismic monitoring to better understand underground processes and to provide the opportunity to manage seismic effects.

In summary, geothermal operations have widely varying impacts on the environment. Many countries regulate practices to manage these effects as geothermal activities increasing take place close to population centres. The result is that geothermal energy development faces increasing environmental costs relative to its rival renewable energy sources.

GREENHOUSE GAS EMISSIONS FROM GEOTHERMAL POWER PLANTS

Power production from intermediate to high temperature geothermal resources does result in the emission of some greenhouse gases (GHG), although the quantity emitted is much lower in comparison with traditional fossil fuelled power generation units. This is mainly because GHGs are naturally present in the geothermal fluid, and thus their emission in the atmosphere occurs without any drilling or power production taking place. The non-condensable gas (NCG) present in the geothermal fluid is mainly composed of carbon dioxide (CO₂), around 95% and methane (CH₄), up to 1.5% in rare cases. The way in which these kinds of emissions are regarded and reflected in national regulatory frameworks varies among the countries of the world. Accordingly, some countries do not count geothermal emissions as anthropogenic, while others require annual monitoring and reporting if a specific emission limit is surpassed. The expansion of geothermal industry and increased exploitation of resources can result in higher than usual amount of emissions, especially when the reservoir has a higher concentration of GHGs¹³.

The global average estimate for operational GHG emissions in 2001 was 122 g CO₂/kWh. Other countries reported emissions in line with the global average, for example the United States (106 g CO₂/ kWh in 2002) and New Zealand (123 g CO₂/kWh in 2012). Extremes can be found in Iceland with as low as 34 g CO₂/kWh and Italy with as high as 330 g CO₂/kWh. Excessive emissions have been registered in South West Turkey to range between 900 g to 1,300 g CO₂/kWh, higher values than for fossil-fuelled power plants which can go up to 1,030 g CO₂/kWh for a circulating fluidised bed coal plant and 580 g CO₂/kWh for open-cycle gas plant. However, the circumstances (high temperature geothermal reservoirs located in carbonate rich rocks) that favour such high level of emissions are rare¹⁴.

Geothermal CO₂ can be effectively captured and utilised in a number of ways, but it is not a common practice worldwide. NCG from geothermal power plants is captured in Turkey at Kizildere, Dora I and II, and Gumusköy. The CO₂ captured is commercialised for dry ice production and for the production of carbonated beverages, but also for enhancing photosynthesis in greenhouses, production of paint and fertiliser, fuel synthesis and enhanced oil recovery. Moreover, the gas can also be reinjected back into the system, and two examples where this is practiced is at the Puna plant in Hawaii and Hellisheidi power plant in Southwest Iceland. The economic feasibility of CO₂ capture from NCG depends on

¹³ ESMAP (2016)

¹⁴ Ibid

factors such as the composition of the gas, total gas flow, the gas to liquid ratio and size of demand relative to the volume produced. The opportunities or constraints of NCG capture and utilisation are defined by market conditions as well as technology¹⁵.

SUSTAINABILITY

As a policy matter, governments and international energy agencies generally classify geothermal energy as “renewable” because the heat withdrawn may be replaced over time by the natural heat flux. Usually the rate of heat withdrawal is at least an order of magnitude greater than the rate of replacement.

Operating a field sustainably can present challenges to the operator. The time required to rejuvenate a geothermal system will depend on its particular characteristics including the enthalpy, rate of pressure decline, extraction rate, and re-injection strategy. The pressure decline in the reservoir due to fluid extraction may induce an influx of cold water into the geothermal reservoir, where suitable permeability exists. For example, at Momotombo (NIC), where production is reduced to preserve the convective forces in the reservoir or at Wairakei (NZL) or Tiwi (PHL) where influx of cool fluids prematurely cooled significant parts of the resource to the extent that production could not be sustained.

ENEL’S STILLWATER SOLAR-GEOTHERMAL HYBRID PLANT

Enel Green Power commissioned in 2011 the 33 MW Stillwater geothermal power station in Nevada, USA. The plant operated from the beginning with 26 MW of PV capacity, translating into 89,000 solar panels covering 240 acres. However, the utility company decided to add in 2014 17 MW of Concentrated Solar Power (CSP) capacity, making the plant the first in the world to integrate these three renewable technologies. The hybrid power plant combines the continuous generating capacity of binary-cycle, medium-enthalpy geothermal power with solar thermodynamic. One important benefit of combining CSP with geothermal is the possibility to increase the capacity factor of the plant without increasing the nominal power. The CSP system in binary geothermal plants can heat the working fluid to a higher temperature to produce more output.

Other important advantages of CSP integration includes the life extension of geothermal reservoir, as it reduces the need to drill additional production wells or relocate injection wells; offsetting the parasitic load, especially useful in dry climates where water is scarce, as it reduces the costs of buying and treating water and reduces the rate of reservoir depletion due to evaporation loss; and also reheating of the spent brine in binary power plants, which allows the brine to be recycled back into the power plant and re-injected into the reservoir at higher temperature.

¹⁵ ESMAP (2016)

Hybrid systems that are properly designed as such from the planning phase can increase the performance of geothermal reservoirs, thus can help enhance the overall sustainability of the project¹⁶.

¹⁶ Hashem (2016)

5. OUTLOOK

The World Energy Council notes that energy sustainability relies on three pillars: energy security, energy equity (access and affordability), and environmental sustainability. The future of geothermal energy investment growth will depend on how well this technology and the associated regulatory framework can blend with these objectives.

Historically, harnessing geothermal energy has enhanced national energy security, particularly for island nations/regions. The rural locations of many high grade geothermal resources have also improved public access to electricity. However, the biggest challenge going forward will be providing affordable energy.

The short and medium term outlook is quite different for OECD and developing countries.

For OECD countries with established geothermal industries, decreasing intensity of electricity use and the lower cost of alternatives is suppressing greenfield development and encouraging brownfield development, repowering, and refurbishments. For these countries, geothermal energy output will grow at a rate less than national economic growth.

Most of the growth in geothermal electricity generation will take place in developing economies such as Kenya and Indonesia where energy demand is rising, geothermal resources are plentiful, and development bank capital can be employed to facilitate construction.

However, to survive in the 21st century, the geothermal industry needs to innovate. The existing steamfield and drilling costs structure is simply not sustainable. Cost and health & safety pressures will continue to drive the de-manning of plant and drilling operations, incentivising innovation in controls, instrumentation, process modelling, and condition monitoring.

Over the last decade, the geothermal industry's centre-of-gravity has pivoted away from the USA towards Europe and Asia. Already many of the largest geothermal operators reside in the Asia-Pacific region. Other centres of geothermal excellence are emerging in Kenya, Mexico (with privatisation) and Turkey. Europe and China dominate growth in direct use and district heating technology. Financing will continue to be dominated by the Multilateral Development Banks. Expertise will steadily migrate towards countries with large geothermal operators.

New, non-geothermal technology will continue to drive the use of geothermal in unexpected directions. The application of smart networks, electrical storage, electric vehicles, and energy management technology will shape new roles for geothermal power and energy.

The high grade, easily accessible geothermal resources have mostly been developed. The average size of projects will continue to decline and utilise lower grade resources, particularly in Europe and the USA.

THE INFLUENCE OF COP21 TO GEOTHERMAL DEVELOPMENT

The climate change conference from Paris at the end of 2015 managed to bring together 161 countries of the world to sign a global agreement to mitigate climate change. These countries submitted Intended Nationally Determined Contributions (INDC) pledges to cut carbon emissions, and one way of achieving this goal is by increasing the share of renewables in the energy mix. Geothermal energy is included in the INDC pledges of several countries, and the Table 4 below lists the countries that have made climate mitigation commitments in which geothermal power is explicitly mentioned.

TABLE 5: COUNTRY INDC COMMITMENTS THAT MENTION GEOTHERMAL POWER

Country	Geothermal information in pledge
Bolivia	Pledges to increase renewables including geothermal power.
Costa Rica	To achieve and maintain a 100% renewable energy mix by 2030 with geothermal power as part of the portfolio.
Canada	Pledges investments to encourage the generation of electricity from renewable energy sources such as wind, low-impact hydro, biomass, photovoltaic and geothermal energy.
China	Plans to proactively develop geothermal energy.
Djibouti	Pledges to develop renewable energy including geothermal power
Dominica	Made commitments to reduce emissions in energy sector using geothermal power.
Eritrea	Pledges to develop geothermal as part of its commitment.
Ethiopia	Pledges to develop geothermal as part of its commitment.
Fiji	Pledges to develop geothermal as part of its commitment.

Grenada	Pledges to build 15 MW of geothermal power in the near-term.
Kenya	Expansion in geothermal and other renewables as part of its emissions mitigation strategy.
Papua New Guinea	Pledges to develop geothermal as part of its commitment.
St Lucia	35% Renewable Energy Target by 2025 and 50% by 2030 based on a mix of geothermal, wind and solar energy sources.
St Vincent and Grenadines	The largest contributor to reducing emissions will be the installation of a geothermal electricity generation facility, which when operational will provide over 50% of the country's electricity needs.
Solomon Islands	Geothermal listed as mitigation opportunity.
Uganda	Geothermal listed as mitigation opportunity.
Vanuatu	Pledges to build 8 MWs of geothermal by 2030.
St. Kitts and Nevis	Commitment to geothermal as part of its INDCs.

Source: Geothermal Energy Association (2016)

These INDC commitments will have a positive influence on geothermal development, so much so that it is estimated that capacity will double by 2030. In addition, Global Geothermal Alliance pledged to increase fourfold the global geothermal capacity to around 65 GW by 2030.

It is important to note that the realisation of the pledges will require substantial financial investment, with an estimated public investment increase 7 to 10 fold, from US\$7.4 billion currently to US\$56-73 billion. Developing countries are facing a number of difficulties in geothermal development related not only to lack of sufficient public funding and insurance, but also to challenging private investment markets, modest experience with geothermal and project risk mitigation barriers. However, there are some international efforts to mitigate geothermal project risk in developing countries such as US\$31.2 million drilling programme at Lake Assal, Djibouti and US\$115 million resource exploration and drilling at Casita-San

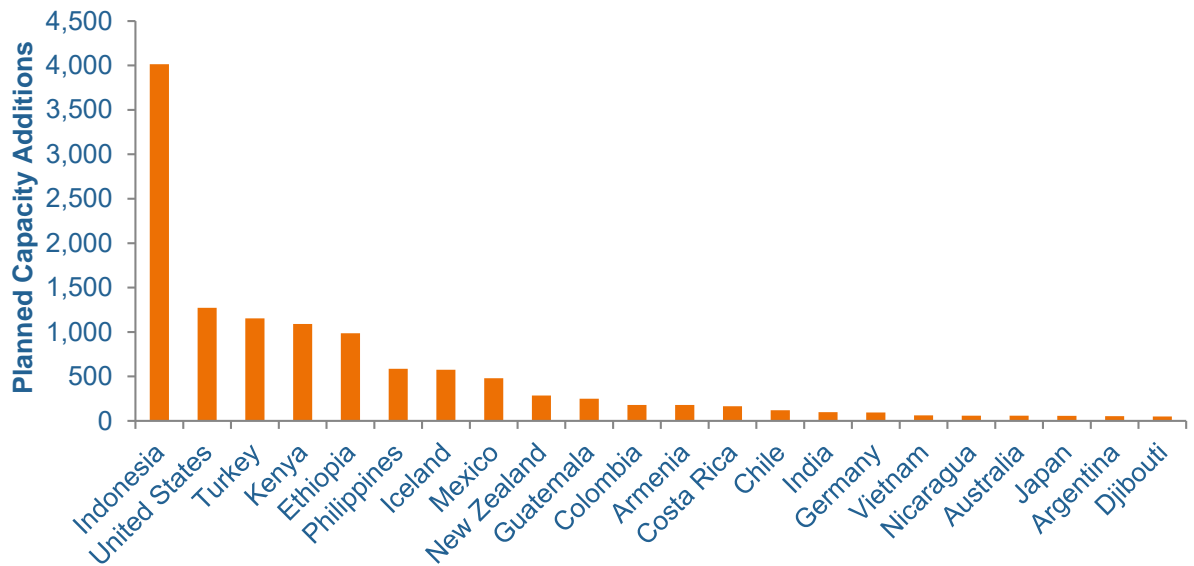
Cristobal, Nicaragua. The World Bank’s Geothermal Development Plan endeavours to supply US\$500 million to help tackle these issues and more¹⁷.

GLOBAL MARKET

According to a GEA (2016) report, the global market for geothermal energy is forecasted to reach 18.4 GW by 2021. In a conservative forecast, where only projects under construction and with definite completion dates have been taken into account, the increase is projected to be around 14.8 GW. The industry has seen a steady growth within the past few years, and it is believed that this trend will not only most likely continue, but maybe accelerate due to climate change concerns and an increasing need to decarbonise the energy sector¹⁸.

Figure 14 below shows planned capacity additions updated in 2015.

FIGURE 14: CAPACITY UNDER DEVELOPMENT BY COUNTRY (MW)



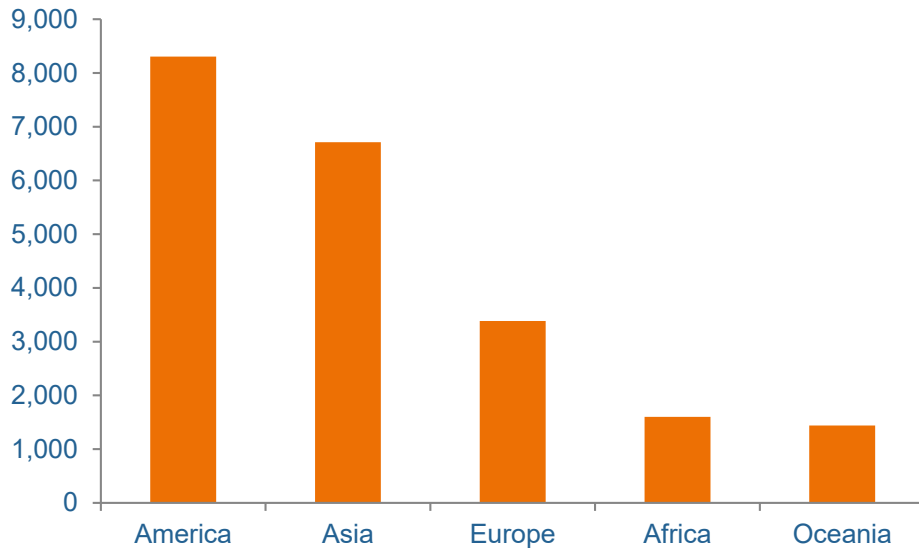
Source: GEA (2016)

Furthermore, some projections go even further than that to see the power capacity growth to around 21 GW by 2020. The Figure below presents a breakdown of total projected capacity by region in 2020.

¹⁷ Geothermal Energy Association (2016)

¹⁸ Ibid

FIGURE 15: PROJECTED INSTALLED GEOTHERMAL POWER CAPACITY WORLDWIDE IN 2020, BY REGION (MW)



Source: Statista (216)

Lastly, Table 6 below lists the countries that have specific targets for geothermal power installed capacity and/or generation up to year 2030.

TABLE 6: COUNTRIES WITH SPECIFIC TARGETS FOR GEOTHERMAL INSTALLED CAPACITY AND/OR GENERATION

Country	Geothermal Target
Algeria	15 MW by 2030
Argentina	30 MW by 2016
Armenia	50 MW by 2020; 100 MW by 2025
Chinese Taipei	10 MW by 2020; 150 MW by 2025; 200 MW by 2030
Ethiopia	75 MW by 2015; 450 MW by 2018; 1 GW by 2030
Grenada	15 MW (no date)

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Indonesia	12.6 GW by 2025
Italy	6,759 GWh/year generation from 920 MW capacity by 2020
Kenya	1.9 GW by 2016; 5 GW by 2030
Korea, Dem. Republic	2,046 GWh/year by 2030
Philippines	1.5 GW added 2010–2030
Portugal	29 MW by 2020
Rwanda	310 MW by 2017
Solomon Islands	20–40 MW (no date)
Spain	50 MW by 2020
Thailand	1 MW by 2021
Turkey	1 GW by 2023
Uganda	45 MW by 2017

Source: REN21 (2016)

6. GLOBAL TABLE

TABLE 7: GEOTHERMAL ENERGY GLOBAL TABLE

Country	Total Electricity Generating Capacity (MW) in 2015	Total Electricity Generation (GWh) in 2014	Geothermal Direct-use Installed Capacity (MWt) in 2014	Geothermal Direct-use Energy Utilisation (GWh) in 2014
Albania	-	-	16.23	29.89
Algeria	-	-	54.64	472.25
Argentina	-	-	163.60	277.81
Armenia	-	-	1.50	6.25
Australia	2.1***	0.5*	16.09	53.99
Austria	1.4***	2.2*	903.40	1 816.26
Belarus	-	-	4.73	31.54
Belgium	-	-	206.08	24.01
Bosnia & Herzegovina	-	-	23.92	70.10
Brazil	-	-	360.10	1 839.70
Bulgaria	-	-	93.11	340.14
Canada	-	-	1 466.78	3 226.65
Caribbean Is	-	-	0.10	0.77

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Country	Total Electricity Generating Capacity (MW) in 2015	Total Electricity Generation (GWh) in 2014	Geothermal Direct-use Installed Capacity (MWt) in 2014	Geothermal Direct-use Energy Utilisation (GWh) in 2014
Chile	-	-	19.91	51.70
China	27	145	17 870.00	48 434.99
Colombia	-	-	18.00	80.50
Costa Rica	202	1 538	1.00	5.83
Croatia	-	-	79.94	190.15
Czech Rep	-	-	-	-
Denmark	-	-	353.00	1 043.14
Ecuador	-	-	5.16	28.45
Egypt	-	-	6.80	24.45
El Salvador	204	1 558	3.36	15.56
Estonia	-	-	63.00	98.90
Ethiopia	7	17	2.20	11.56
Finland	-	-	1 560.00	5 000.40
France	16*	115*	2 346.90	4 407.85
Georgia	-	-	73.42	193.12
Germany	38	98	2 848.60	5 425.80
Greece	-	-	221.88	368.49

Country	Total Electricity Generating Capacity (MW) in 2015	Total Electricity Generation (GWh) in 2014	Geothermal Direct-use Installed Capacity (MWt) in 2014	Geothermal Direct-use Energy Utilisation (GWh) in 2014
Greenland	-	-	1.00	5.83
Guadeloupe	15	75	-	-
Guatemala	49	247	2.31	15.68
Honduras	-	-	1.93	12.50
Hungary	-	-	905.58	2 852.47
Iceland	665	5 238	2 040.00	7 422
India	-	-	986.00	1 195.10
Indonesia	1 404	10 038	2.30	11.83
Iran	-	-	81.50	306.45
Ireland	-	-	265.54	344.62
Israel	-	-	82.40	609.22
Italy	824	5 916	1 014.00	2411.90
Japan	533	2 602	2 186.17	7 258.94
Jordan	-	-	153.30	427.81
Kenya	607	3 178	22.40	50.73
Korea (South)	-	-	835.80	745.24
Latvia	-	-	1.63	8.84

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Country	Total Electricity Generating Capacity (MW) in 2015	Total Electricity Generation (GWh) in 2014	Geothermal Direct-use Installed Capacity (MWt) in 2014	Geothermal Direct-use Energy Utilisation (GWh) in 2014
Lithuania	-	-	94.60	198.04
Macedonia	-	-	48.68	166.99
Madagascar	-	-	2.81	21.00
Mexico	1 069	6 000	155.82	1 158.70
Mongolia	-	-	20.16	94.58
Morocco	-	-	5.00	13.89
Nepal	-	-	3.32	22.53
Netherlands	-	-	790.00	1 785.14
New Zealand	979	7 258	487.45	2 394.91
Nicaragua	155	662	-	-
Norway	-	-	1 300.00	2 294.63
Pakistan	-	-	0.54	0.68
Papua New Guinea	53	400	0.10	0.28
Peru	-	-	3.00	16.95
Philippines	1 930	10 308	3.30	11.00
Poland	-	-	488.84	761.89
Portugal	25	205	35.20	132.84

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Country	Total Electricity Generating Capacity (MW) in 2015	Total Electricity Generation (GWh) in 2014	Geothermal Direct-use Installed Capacity (MWt) in 2014	Geothermal Direct-use Energy Utilisation (GWh) in 2014
Romania	0.1*	0.4*	245.13	529.30
Russia Fed	78	455	308.20	1 706.66
Saudi Arabia	-	-	44.00	42.47
Serbia	-	-	115.64	500.73
Slovakia	-	-	149.40	686.05
Slovenia	-	-	152.75	315.93
South Africa	-	-	2.30	10.28
Spain	-	-	64.13	95.80
Sweden	-	-	5 600.00	14 423.38
Switzerland	-	-	1 733.08	3 288.26
Tajikistan	-	-	2.93	15.39
Thailand	0.3*	1.2*	128.51	328.14
Tunisia	-	-	43.80	101.12
Turkey	624	2 364	2 886.30	12 536.00
Ukraine	-	-	10.90	33.00
UK	-	-	283.76	529.63
USA	3 567	16 800**	17 415.91	21 074.52

Country	Total Electricity Generating Capacity (MW) in 2015	Total Electricity Generation (GWh) in 2014	Geothermal Direct-use Installed Capacity (MWt) in 2014	Geothermal Direct-use Energy Utilisation (GWh) in 2014
Venezuela	-	-	0.70	3.89
Vietnam	-	-	31.20	25.65
Yemen	-	-	1.00	4.17

Source: IRENA (2016) Renewable Energy Statistics; Lund and Boyd (2015) Direct utilisation of geothermal energy 2015 worldwide review.

*Data taken from Bertani (2015) Geothermal power generation in the world 2015-2014 update report.

** Data taken from REN21 (2016) Global Status Report.

***Data taken from BP Statistical Review of World Energy 2016 workbook

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REFERENCES

- Axelsson, G. et al (2005) *Sustainable Management of geothermal Resources and Utilisation for 100 – 300 Years*, in Proceedings World Geothermal Congress 2005, Antalya Turkey.
- Bertani (2015) *Geothermal Power Generation in the World 2010-2014 Update Report*, in World Geothermal Congress 2015, Melbourne Australia.
- Bertani (2003) *What is Geothermal Potential?* IGA News, 53, 1-3. <http://iga.igg.cnr.it>.
- British Petroleum (2015) *World Energy Statistics 2015*, British Petroleum, London, UK.
- Carey, B. et al. (2015) *New Zealand country update*, Proceedings World Geothermal Congress 2015, <https://pangea.stanford.edu/ERE/db/WGC/papers/WGC/2015/01052.pdf>
- Delony, J. (2016) '2016 Outlook: Future of Geothermal Industry Becoming Clearer', in *Renewable Energy World*, January 27, <http://www.renewableenergyworld.com/articles/2016/01/2016-outlook-future-of-geothermal-industry-becoming-clearer.html>
- Energy Information Administration EIA (2015) *Indonesia has significant potential to increase geothermal electricity production*, October 19, <http://www.eia.gov/todayinenergy/detail.cfm?id=23392>
- EPRI (1978) *Geothermal Energy Prospects for the Next 50 Years*; special report ER-611-SR, February 1978.
- Energy Sector Management Assistance Program (ESMAP) (2016) *Greenhouse gases from geothermal power production*, <http://documents.worldbank.org/curated/en/550871468184785413/pdf/106570-ESM-P130625-PUBLIC.pdf>
- Fonda, A. D., Marasigan, M. C. and Lazaro, V. S. (2015) *Geothermal development in the Philippines: The country update*, Proceedings World Geothermal Congress 2015, <https://pangea.stanford.edu/ERE/db/WGC/papers/WGC/2015/01053.pdf>
- Frankfurt School-UNEP Collaborating Centre for Climate & Sustainable Energy Finance and Bloomberg New Energy Finance (2016) *Global trends in renewable energy investment*, <http://fs-unep-centre.org/publications/global-trends-renewable-energy-investment-2016>
- Geothermal Energy Association (2016) *2016 Annual US & Global geothermal power production report*, <http://geo-energy.org/reports/2016/2016%20Annual%20US%20Global%20Geothermal%20Power%20Production.pdf>
- Goldstein, B. et al (2014) *Chapter 4 Geothermal Energy*, in *Renewable Energy Resources and Climate Change Mitigation*, Cambridge University press, United Kingdom.
- Grant M.A., and Bixley P.F., (2011) *Geothermal Reservoir Engineering* Second Edition, Elsevier, New York

- Gutiérrez-Negrín, L. C. A. *et al* (2015) *Present situation and perspectives of geothermal in Mexico*, Proceedings World Geothermal Congress 2015, file:///C:/Users/radu/Downloads/Mexico%20country%20update%202015.pdf
- Hance, C.N. (2005) *Factors Affecting Costs of geothermal Power Development*, Geothermal Energy Association, for the US Department of energy, Washington DC, USA.
- Hashem, H. (2014) 'World's first commercial CSP-geothermal hybrid underway', in *CSP Today*, 16 May, <http://social.csptoday.com/technology/world%E2%80%99s-first-commercial-csp-geothermal-hybrid-underway>
- IRENA (2015) *Renewable Energy Target Setting*; www.irena.org.
- Lund and Boyd (2015) *Direct Utilisation of Geothermal Energy 2015 Worldwide Review*; in: World Geothermal Congress 2015, Melbourne Australia.
- Lund B. and Zoback M.D. (1998) *Orientation and magnitude of in situ stress to 6.5 km depth in the Baltic Shield*, international Journal of Rock mechanics and Mining Sciences vol. 36 pages 969-190.
- Mines, G., *et al* (2015) *Geothermal Plant Capacity Factors*, in Proceedings Fortieth Stamford Geothermal Workshop, Stamford, CA, USA.
- Omenda, P. and Simiyu, S. (2015) *Country update report for Kenya 2010-2014*, Proceedings World Geothermal Congress 2015, <https://pangea.stanford.edu/ERE/db/WGC/papers/WGC/2015/01019.pdf>
- Ragnarsson, Á. (2015) *Geothermal development in Iceland 2010-2014*, Proceedings World Geothermal Congress 2015, <https://www.geothermal-energy.org/pdf/IGAstandard/WGC/2015/01077.pdf>
- Razzano, F. and Cei, M. (2015) *Geothermal power generation in Italy 2010-2014 update report*, Proceedings World Geothermal Congress 2015, <https://pangea.stanford.edu/ERE/db/WGC/papers/WGC/2015/01075.pdf>
- REN21 (2016) *Renewables 2016: Global status report*, http://www.ren21.net/wp-content/uploads/2016/06/GSR_2016_Full_Report_REN21.pdf
- Richter, A. (2016) 'Geothermal project successful in providing heat to community in the Himalaya', in *Think Geoenergy*, 29 June, <http://www.thinkgeoenergy.com/geothermal-project-successful-in-providing-heat-to-community-in-the-himalaya/>
- Richter (2016) 'India sets ambitious target for geothermal development by 2030', in *Think Geoenergy*, 9 June, <http://www.thinkgeoenergy.com/india-sets-ambitious-target-for-geothermal-development-by-2030/>
- Saemundsson K., (2007) *Geology and Gradient Wells*, in short Course on Surface Exploration for Geothermal Resources, UNU-GTP and KenGen, Lake Naivasha, Kenya.
- Santilano, A. *et al* (2015) *Convective, Intrusive Geothermal Plays: What About Tectonics?* Geothermal Energy Science, Vol 3 pages 51-59.
- Sanyal, S.K. *et al* (2007) *Is EGS Commercially feasible?* In: Transactions of the Geothermal Resources Council, Vol 31 pp 313-322.

- Sigfussion B. and Uihlein A., (2015) 2014 JRC Geothermal Energy Status Report, JRC report, European Commission.
- Statista (2016) *Global geothermal capacity installations forecast by region 2020*, <http://www.statista.com/statistics/495576/geothermal-installed-capacity-worldwide-by-region-forecast/>
- Stefansson (2005) *World Geothermal Assessment*; in: proceedings World Geothermal Congress 2005, Antalya, Turkey.
- Tester, J.W. et al (2005) *Sustainable Energy – Choosing Among Options*, MIT Press, Cambridge, MA, USA (ISBN 0-262-20153-4)
- Weber, J. et al (2015) *Geothermal energy use in Germany*, Proceedings World Geothermal Congress 2015, <https://pangea.stanford.edu/ERE/db/WGC/papers/WGC/2015/01045.pdf>
- Weber, J. et al (2014) *Trends in Geothermal Applications 2013*, International Energy Agency, <http://iea-gia.org>.
- Williams, C. F. et al (2011) *Updating the Classification of Geothermal Resources*, in Proceedings thirty-sixth Stamford Geothermal Workshop, Stamford, CA, USA.
- Yasukawa, K. and Sasada, M. (2015) *Country update of Japan: renewed opportunities*, Proceedings World Geothermal Congress 2015, <https://pangea.stanford.edu/ERE/db/WGC/papers/WGC/2015/01042.pdf>

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**World Energy
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KEY FINDINGS

1. World wind power generation capacity has reached 435 GW at the end of 2015, around 7% of total global power generation capacity. A record of 64 GW was added in 2015. The global growth rate of 17.2% was higher than in 2014 (16.4%).
2. With current policy plans, global wind capacity could rise from 435 GW in 2015 to 977 GW in 2030 (905 GW onshore and 72 GW offshore wind).
3. The global wind power leaders as at end-2015 are China, United States, Germany, India and Spain.
4. The total investments in the global wind sector reached a record level of USD 109.6 billion over the course of 2015.
5. For onshore wind, China has the lowest weighted average LCOE with a range between 50 USD/MW – 72 USD MW, while the highest weighted average LCOE are found in Africa, Oceania and Middle East with 95USD/MW, 97USD/MW and 99 USD/MW.
6. LCOE for offshore wind has continued to decrease owing to a wide range of innovations.
7. Floating foundations could be game changers in opening up significant new markets with deeper waters.
8. Direct subsidies for new wind generation are falling as the costs of wind power are today on par or below those of fossil and nuclear power generation.
9. There is ongoing research and development to modify the fundamental design of wind turbines, in order to bypass some of the limitations and environmental concerns of conventional HAWTs and VAWTs.
10. Wind deployment continues to be dominated by onshore wind, supported by continual cost reductions.

INTRODUCTION

World wind power generation capacity has reached 435 GW at the end of 2015, around 7% of total global power generation capacity. A record of 64 GW was added in 2015. The global growth rate of 17.2% was higher than in 2014 (16.4%).

China has once more underpinned its role as the global wind power leader, adding 33 GW of new capacity. This represents a market share of 51.8%. The US market saw good performance with 8.6 GW of added capacity, the strongest growth since 2012. Germany, in anticipation of changes in legislation, installed 4.9 GW. Brazil was the fourth largest market for new turbines with a market volume of 2.8 GW. India saw 2.3 GW of new installations by November 2015.

Global wind power generation amounted to 950 TWh in 2015, nearly 4% of total global power generation. Some countries have reached much higher percentages. Denmark produced 42% of its electricity from wind turbines in 2015 year, the highest figure yet recorded worldwide. In Germany wind power contributed a new record of 13% of the country's power demand in 2015.

The wind power market can be divided into large wind onshore (422 GW, around 210,000 machines), small wind onshore (less than 1 GW installed end 2015, more than 800,000 machines), and offshore (around 12 GW installed end 2015, around 4,000 machines). Large onshore and offshore wind turbines are typically arranged in a wind park. The largest wind parks exceed 1 GW in size, such as Gansu Wind Farm in China, Muppandal Wind Park in India or Alta Wind Energy Center in USA.

TABLE 1: TOP WIND POWER CAPACITY BY COUNTRY, END-2015

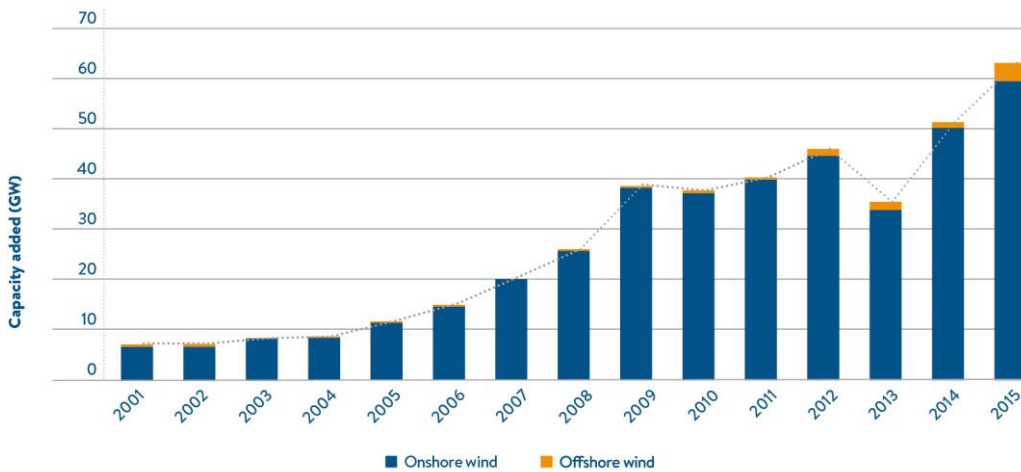
Country	Total Capacity (MW)	Added Capacity in 2015 (MW)
China	148 000	32 970
United States	74 347	8 598
Germany	45 192	4 919
India*	24 759	2 294
Spain	22 987	0

United Kingdom	13 614	1 174
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* By November 2015

Source: WWEA (2016)

FIGURE 1: ANNUAL NET GLOBAL WIND CAPACITY ADDITIONS, 2001-2015



Source: IRENA, GWEC

Onshore wind is one of the cheapest renewable sources in Australia, Brazil (besides hydro), Germany, Mexico, New Zealand (besides hydro and geothermal), South Africa and Turkey. Global weighed-average installed costs of onshore wind have significantly decreased from US\$4,766 per kW in 1983 to US\$1,623 per kW in 2014, meaning this a decline in the costs of two-thirds¹.

The average cost per kW of onshore wind has declined by 7% and levelised cost of electricity by 12%, for each doubling of installed cumulative over the period 1983 to 2014.² The global weighted average LCOE of onshore wind could decline by between 20% and 30% by 2025, depending on at least two major factors: technology incremental progress and the cost of capital. Costs are considerably higher for offshore wind because of the additional cost for foundations and connection of the offshore wind parks to the grid. The

¹ IRENA (2016) The Power of Change: Cost reduction potentials for solar and wind power technologies. Abu Dhabi.

² IRENA ibid

weighted average cost per unit of capacity was US\$4,650 per kW in 2015, with generation cost in excess of US\$15 cents per kWh. However, offshore wind is still in its infancy compared to onshore wind, with total installed capacity having reached 12 GW at the end of 2015. The next generation of advanced large offshore wind turbines, reduced costs for foundations and more efficient project development practices could reduce the LCOE of offshore wind from US\$19.6 cents per kWh in 2015 to roughly 12 cents per kWh in 2030.³

Wind power benefits from government support schemes. The type of support varies by country. Feed in tariffs, feed in renewable portfolio standards in combination with auctions, and production tax credits are among the support schemes that are deployed. Apart from the financial support wind power is usually granted preferential access and additional cost for grid management caused by wind variability are usually not borne by the wind generators. Direct subsidies for new wind generation are falling as the cost of wind power is today on par or below those of fossil and nuclear power generation.

SUBSIDY-FREE WIND ENERGY IN NEW ZEALAND

New Zealand has been one of the success stories for wind energy in recent times. Installed wind power capacity has grown nearly four-fold in the last ten years, and about 5% of total electricity generation in the country now comes from wind energy⁴. But what makes New Zealand's wind development relatively unique is that wind and other forms of clean energy (such as geothermal and hydro) have been developed in the absence of government subsidies – therefore developers will only build a wind farm if it can produce electricity at a cost competitive with other forms of electricity generation.

The country's rich wind resource and moderate wholesale electricity prices are the key factors for the success of the local wind industry. A 2011 report concluded that existing wind farms in the country were developed with a long-run marginal cost range of NZD 78-105 per MWh⁵. The lower end of this range compares well with other sources of electricity – forward wholesale electricity prices in the country are between (approximately) USD 53.2-60.3 (NZD 75-85) per MWh⁶, with central long-run projections significantly higher⁷. In addition, thanks to New Zealand's significant hydropower capacity capable of balancing variable supply, the associated costs of integrating further wind generation into the country's network are likely to be lower than many other countries.

New Zealand has a pipeline worth 2500 MW of new wind power projects, and developers aim to increase wind's contribution to annual electricity generation to

³ IRENA (forthcoming), Off-shore wind technology: an innovation outlook

⁴ New Zealand Wind Energy Association

⁵ Deloitte (2011)

⁶ ASX n.d.

⁷ MBIE n.d.

20% by 2030 (this is within the context of current renewable output at around 80% of total generation, and the New Zealand Government's aspirational target to increase renewable penetration to 90% by 2025).

An important issue for managing power systems that integrate large amounts of wind energy is the variability of the power output. The output grows with rising wind speed and it is constant above the rated wind speed. Wind turbines do not produce during periods of low wind speed and they may also stop producing at very high wind speeds. Wind speeds can change significantly on a timescale of minutes. The output of wind turbines is therefore variable. One way to achieve a higher share of wind generation in a grid system is to operate wind turbines or wind farms using integrated transmission systems and power output prediction systems, including weather forecasting. The development of standards and certifications can help to improve the performance of small wind systems, especially in developing countries⁸.

⁸ IEA-ETSAP and IRENA (2016), Wind power technology brief E07

1. TECHNOLOGIES

WIND TURBINES

A wind turbine's blades convert kinetic energy from the movement of air into rotational energy; a generator then converts this rotational energy to electricity. The wind power that is available is proportional to the dimensions of the rotor and to the cubing of the wind speed. Theoretically, when the wind speed is doubled, the wind power increases by a factor of eight (the mechanical power's formula is detailed in the section on Wind Turbine Operation).

Wind turbines have got progressively bigger, and more powerful. The size of wind turbines has continued to increase, and the average nominal rating of new grid-connected onshore turbines rose from 0.05 megawatts (MW) in 1985⁹ to 2.0 MW in 2014¹⁰. The largest commercially available turbines to date have a nominal rating of 8.0 MW and, a rotor diameter of 164 metres.

The three major elements of wind generation are the turbine type (vertical/horizontal-axis), installation characteristic (onshore/offshore) and grid connectivity (connected/stand-alone). Most large wind turbines are up-wind horizontal-axis turbines with three blades. Most small wind turbines (SWT) are also horizontal-axis. Innovative designs for vertical-axis turbines are being applied in urban environments, particularly in China. With aerodynamic energy loss of 50-60% at the blade and rotor, mechanical loss of 4% at the gear, and a further 6% electromechanical loss at the generator, overall generation efficiency is typically 30-40%. The majority of today's turbines are designed and built to commercial (i.e. utility) scale; the average turbine rated at 2-3 MW capacity.

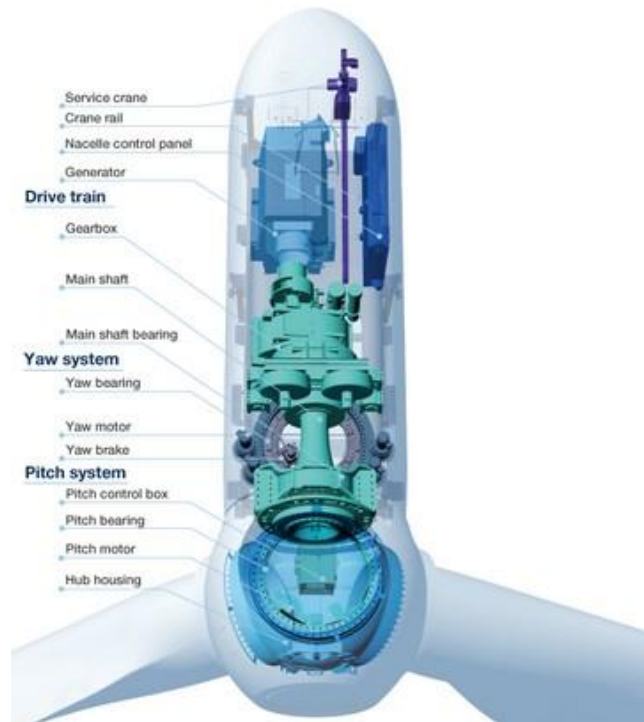
There is a wide range of small-scale turbines from 'micro SWTs' rated at less than 1 kW, to 'midi SWTs' reaching 100 kW. SWTs are commonly used as stand-alone electricity systems and frequently applied in isolated locations where the main grid is not accessible. Hybrid wind-diesel systems can improve the stability of power supply in small and off-grid areas, while reducing the costs for fuel and fuel transport by utilising the existing diesel-based generating infrastructure. However, small wind presents lower load factors and higher capital cost per kW than bigger wind farms, as well as high planning costs per installed unit. Major challenges of small wind include the assessment of the wind resource and the reduction of turbulence's negative effects on the wind resource at the tower's height. High towers reduce the negative impacts of turbulence in the wind resource caused by obstacles in the surroundings, but they increase the costs of small wind turbines. The

⁹ EWEA (2011)

¹⁰ Broehl, Labastida and Hamilton (2015)

rapidly declining costs of competing technologies, such as solar, also poses challenges to small wind deployment. Innovation opportunities emerge with these challenges to increase the efficiency and reduce the costs of small wind technology¹¹.

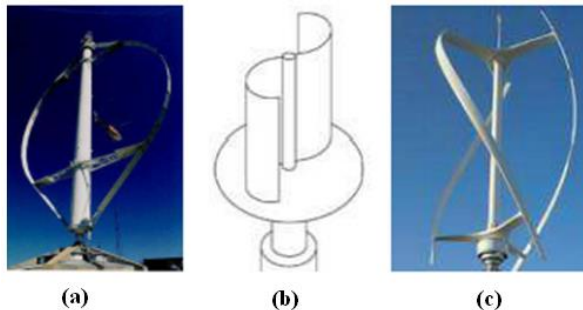
FIGURE 2: POWERTRAIN OF A WIND TURBINE



Source: Hitachi

Horizontal-axis wind turbine (HAWT) technology is the most usual kind of turbine which often has three blades, but could also have two. There are also vertical-axis wind turbines (VAWT), which can be grouped as shown in Figure 3: Darrieus (a), Savonius (b) and propeller-blade (c) turbines.

¹¹ IEA-ETSAP and IRENA (2016)

FIGURE 3: VERTICAL-AXIS WIND TURBINES

Types of Wind Turbines

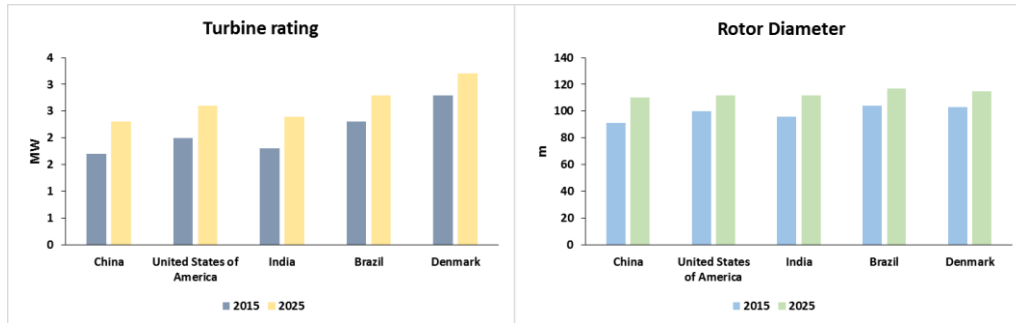
As the power available from the wind increases with the cube its wind speed, all wind turbines need to limit the power output in very high wind speeds. There are two principal means of accomplishing this, with pitch control on the blades or with fixed, stall-controlled blades. Pitch-controlled blades are rotated as wind speeds increase so as to limit the power output and, once the 'rated power' is reached; a reasonably steady output can be achieved, subject to the control system response. Stall-controlled rotors have fixed blades which gradually stall as the wind speed increases, thus limiting the power by passive means. These dispense with the necessity for a pitch control mechanism, but it is rarely possible to achieve constant power as wind speeds rise. Once peak output is reached the power tends to fall off with increasing wind speed, and so the energy capture may be less than that of a pitch-controlled machine. In the early days of the industry, the merits of the two designs were finely balanced and roughly equal numbers of each type were being built. Since the turn of the century, however, pitch-controlled machines have become much more popular. This is due to advances in pitch control, which allow larger and lighter machines compared to stall technology. Another reason is the lower efficiencies attained with stall systems when the wind speed is too high and the rotational speed is therefore decreased¹².

Initially, conventional wind turbines operated at a fixed (rated) speed when producing power, by starting from a parked position and accelerating due to the wind until it reaches the rated speed. At this point, a connection to the electricity grid is made, and the rotor speed is maintained using either pitch or stall control. Now, variable-speed operation, where the rotor is continuously matched with wind speed, is becoming more common. This means that the rotor can operate at wind speeds below and above rated speed, hence

¹² ¹² IEA-ETSAP and IRENA (2016)

increasing energy capture, and operation at high wind speeds relieves loading on the rotor blades and reduces the variability of power output. In addition, direct drive turbine systems are becoming increasingly popular, as they eliminate the requirement for a gearbox.

FIGURE 4: HISTORICAL AND PROJECTED TURBINE RATING AND ROTOR DIAMETER IN SELECTED MARKETS



Source: IRENA (forthcoming), MAKE CONSULTING (2015), and the Danish Energy Agency (2016).

Wind Turbine Operation

In 1920, the German Physician Albert Betz proved the formula for wind’s mechanical power as follows:

$$P = C_p \frac{1}{2} \rho S V_0^3$$

In this formula, P is the mechanical power obtained directly from the wind. C_p is a characteristic of a wind turbine in the fact that it determines the ratio of the wind energy converted into useful electrical energy by the turbine. This coefficient is theoretically limited to 16/27 or 0.593 at the maximal value of P . ρ is the specific mass of air, depending slowly on the temperature. S is the circular surface swept by the blades and V_0 is the wind speed at that position.

Capacity Factors

Recent trends in wind power development have seen turbines grow in height and rotor diameter faster than in total power capacity, leading to a decrease in specific power output (ratio of capacity to area swept by the rotor blades) of more recent turbines. This trend has pushed up capacity factors for wind turbines generating at similar wind speeds – on average, capacity factors have improved by up to 15 percentage points from 2003 to 2013

for wind turbines generating at moderate wind speeds (8 m/s)¹³. Capacity factors are also dependent on the wind resource at a specific site. In the UK, historic capacity factors stand at 26% for onshore wind and 35% for offshore wind¹⁴. Meanwhile, in resource-rich Denmark, aggregated lifetime capacity factor from its offshore wind farms is at 41%, and in instances can exceed 50% at certain sites¹⁵. The trend has also allowed for the development of rotors designed for low wind speeds (< 7 m/s), making more wind resource sites accessible for power generation.

The reliability of a wind turbine in generating power is indicated by the availability of the turbine, which is the proportion of time the turbine is ready for operation. Onshore turbines typically have availabilities of 98%, while offshore turbine availabilities are slightly lower (95-98%) but are improving due to better operation and maintenance.

WIND RESOURCE ESTIMATION AND FORECASTING

When planning the development of a wind farm at a site, it is of utmost importance to understand, as accurately as possible, the wind resource available at that site. This will inform developers in making financial decisions, such as profitability and investment requirements.

Local on-site measurement gives the most reliable estimation of the available wind resource at the site, using a meteorological mast containing measurement instruments such as a wind vane and an anemometer. The size of the proposed wind farm and the complexity of the site's terrain will determine the number of masts required to give reliable estimations of the local resource. One mast is usually sufficient for small farms. It is advisable to measure the wind speed at or close to the hub height of the proposed turbines. As taller masts are costlier to operate, measuring wind speeds at lower heights and theoretically scaling up the hub height resource is a cost-effective option, though it creates uncertainties in the resource estimate. Remote sensing using SODAR and LIDAR are also increasing in their cost effectiveness in measuring the wind at height in suitable terrain

Wind resource data from a nearby or other suitable reference station is also used to augment the on-site data, if available, hence improving data reliability. Computer models, mostly based on computational fluid dynamics (CFD), to process recorded meteorological data are widely used for resource estimation on a broader scale. Through modelling, other factors affecting wind power output can be estimated, such as wake effect, turbine performance and environmental factors.

In addition, a useful tool called WAsP Climate Analyst has been developed for wind and site data analysis. WAsP is the industry-standard software package for siting of wind turbines and wind farms. Many companies use WAsP worldwide for all steps from wind

¹³ Data from IEA (2013), Wind speeds at 50m height.

¹⁴ Renewable UK, n.d.

¹⁵ Andrew (2016)

resource and energy yield assessments, to wind conditions and site suitability characterisation; from single turbines in complex terrain to large wind farms offshore. The Global Wind Atlas provides global datasets describing wind climate including the effects of high resolution topography. The data is for aggregation analysis for energy integration modelling, energy planners and policy makers. ¹⁶

Due to the increase in wind energy penetration to the global energy mix, and the liberalised nature of many electricity markets today, there is also the growing need to accurately forecast expected wind power generation in the short term (i.e. days ahead of schedule), in order to manage the variability of wind energy. Transmission system operators require forecasting to ensure electricity supply and demand remain balanced at all times, power traders use forecasting to trade wind generation on electricity futures markets, and site operators utilise forecasting for scheduling their operations and maintenance. Table 2 shows the classification of wind forecasting timescales employed and their applications. According to the European Wind Energy Association, “to integrate wind energy successfully into an electricity system at penetration levels of more than 10%, accurate wind energy predictions are needed”¹⁷.

TABLE 2: TIMESCALE CLASSIFICATION FOR WIND FORECASTING

Time-scale	Range	Applications
Ultra-short-term	Few minutes to 1 hour ahead	<ul style="list-style-type: none"> • Electricity market clearing • Real-time grid operations • Regulation actions
Short-term	1 hour to several hours ahead	<ul style="list-style-type: none"> • Economic load dispatch planning • Load reasonable decisions • Operational security in electricity market
Medium-term	Several hours to 1 week ahead	<ul style="list-style-type: none"> • Unit commitment decisions • Reserve requirement decisions • Generator online/offline decisions
Long-term	1 week to 1 year	<ul style="list-style-type: none"> • Maintenance planning

¹⁶ http://www.wasp.dk/DataandTools#wind-atlas__global-wind-atlas

¹⁷ Wind energy – the facts (2010)

	ahead (or more)	<ul style="list-style-type: none"> • Operation management • Optimal operating cost • Feasibility study for wind farm design
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Source: Chang, W.-Y. (2014)

Numerical weather prediction (NWP) models are the foundation for many wind power forecasting systems. These models are often operated by government agencies or scientific institutions, and forecast the evolution of weather systems. However, NWP methods model forecasts at a regional or global scale, and lack the resolution required for wind farm-specific forecasts. Therefore, statistical techniques, such as lag regression models and Model Output Statistics, are used to improve resolution, and correct biases and error patterns in data output. NWP-based models provide forecasts for lead times ranging from three hours to 10 days; for shorter timescales, pure statistical methods that learn from existing data on wind speed at the specific location are used¹⁸.

The Portfolio Effect – Aggregation of Wind Farms

The intermittency and variability of the wind resource, and hence of wind turbine output, pose challenges to the integration of wind power generation to the existing electricity network. Intermittent generation will be evident at site level, but due to geographical diversity will reduce when generation is considered over larger areas (such as country or regional level). Hence, the intermittency of wind generation can be reduced significantly if the power outputs of wind farms over a specific area are aggregated together.

The 'portfolio effect' helps the accuracy of wind forecasting by reducing the mean absolute error of forecasts from singular wind farm sites. Forecasting wind generation output is commonly used for parts of Germany and Denmark, where wind generation is high and there is strong interconnectivity between farms. However, interconnection infrastructure and grid connection codes must be in place in the regions where this is done. Interconnection allows exports of wind energy, as well as other sources of variable energy, at generation peaks. In addition, larger interconnected systems are less vulnerable to frequency issues. Thus, interconnection requirements for turbines and other generation assets may be specified in international standards, such as for example IEEE 1547, Standard for Interconnecting Distributed Resources with Electric Power Systems. Grid connection codes provide requirements for connections of wind, as well as solar plants, to national electricity

¹⁸ Kirk-Davidoff (2012)

grids. This helps to maintain stability and reliability in the system, while ensuring the operability of both, generation assets owners and grid operators¹⁹.

TECHNOLOGICAL ADVANCEMENTS

Wind energy technology is a very mature technology – today’s turbines already extract nearly 50% of the energy conveyed in the wind (theoretical maximum of under 60%), and operate at very high rates of availability. Nonetheless, wind energy remains an evolving sector as it tries to adapt to changing energy demands and market conditions.

Cost reduction is largely but not solely driven by technological development. However, there remains great potential to reduce costs significantly in onshore and offshore wind technology.²⁰ Other drivers for design improvements include suitability for different sites and climates, grid compatibility, noise reduction, aerodynamic performance, and visual impact. Current developments in the wind energy industry are described below:

- Turbines are continuously increasing in size, with longer rotor blades up to 80m long. This trend in design has enabled turbines to operate at higher capacity factors, and also exploit low wind speed sites. However, research has gone into devising the optimum turbine size for onshore and offshore applications, both in terms of performance and cost. Scaling up turbines to 10-20 MW and reducing mechanical stress at the tips of longer blades are targeted by R&D centres. There is major development in rotor blade design to withstand the increased stresses, from making the blades out of stronger fibreglass composite structures to curved designs of the blades.
- In addition to harvesting energy in low wind speed sites, there is also a move towards extracting energy in specific environments and climates. Cold climate areas (regions where turbines are exposed to icing and/or temperatures below operational limits) are characterised by good wind resources and low populations, and the wind energy market in these regions are growing. At least 52 GW of wind energy projects have been deployed in icy climates around the world, and an additional 30 GW of capacity is expected to come online by 2017²¹. The cost of wind energy in cold climates is higher than in moderate climates, due to higher investment costs of turbines with anti- and de-icing capabilities, steel that remains ductile in low temperatures and special foundations for permafrost, or from lower energy yields caused by icing of the rotor blades.
- Direct-drive eliminates the gearbox, and could be crucial in removing the limiting size and weight of future turbines of 10 MW and beyond. Hybrid drive systems have simpler and more reliable gearing than conventional solutions with three stages of

¹⁹ IRENA (2016), Scaling up Variable Renewable Power: The Role of Grid Codes

²⁰ IRENA (2016), The Power of Change: Cost reduction potentials for solar and wind power technologies.

²¹ Windpower Monthly, Optimising wind farms in cold climates

gearing, while having a similar generator size. They contribute to a more compact arrangement within the turbine's nacelle. Hydraulic drivetrain designs also have the potential to replace the gearbox.

- Remote electronic controls are continually being incorporated into turbine design. In addition to pitch control and variable speed operation, individual turbines and whole farms may perform wind measurements remotely, using turbine-mounted technology such as lidar (LIght Detection and Ranging) and sodar (SOnic Detection and Ranging). The real-time data realised from remote sensing will optimise wind production as turbines constantly pitch themselves to the incoming wind.

FIGURE 5: VORTEX BLADELESS TURBINE AND BUOYANT AIRBORNE TURBINE



Source: Vortex Bladeless, Altaeros Energies

- There is ongoing research and development to modify the fundamental design of wind turbines, in order to bypass some of the limitations and environmental concerns of conventional HAWTs and VAWTs. A Spanish startup, Vortex Bladeless, has designed a turbine without rotor blades. It harnesses wind energy through vorticity which causes the structure to oscillate. As the design has no gears or bearings, it claims to reduce

the total cost and carbon footprint of wind generation both by up to 40%²². However, these turbines are likely to be constrained by the amount of power they can produce and will struggle to operate at high altitudes where wind is more turbulent. The next generation of wind turbines may well be airborne. Different configurations have been touted, including Google's Makani Project, which is a kite-type device tethered to the ground that flies in an orbit similar to the tip of a conventional HAWT. Another concept is the Buoyant Airborne Turbine (BAT) by Altaeros Energies, which consists of a conventional HAWT suspended and held afloat in a helium filled shell. Airborne wind solutions are emerging designs yet to reach commercial viability due to challenges related to cable loading, the impact of lightning and storms and the interferences with aircrafts and radars.

OFFSHORE WIND TECHNOLOGY PROSPECTS

It is expected that the most significant technology innovations for off-shore wind applications will be the introduction of next generation turbines, with larger rotors, and a range of innovations in foundations. The largest offshore wind turbine (in terms of rotor diameter) that has been deployed on a commercial-scale wind farm before the end of 2015 was the 6 MW Siemens SWT-6.0-154 turbine, which has a 154m diameter rotor. Ongoing developments in blade and drive train technology will enable even larger turbines with higher capacity ratings. An area where there has been increased research to larger rotor diameters is in modular blade technology. This technology permits different materials to be incorporated into blade components. Modular blades may facilitate the transportation of blades and their assembly closer to the wind farm site in contrast to conventional blades. Companies such as Blade Dynamics and previously Modular Wind have taken research in modular blades to the practical demonstration stage with demonstration blades being tested with a length of 78m. Larger turbines might lower the LCOE due to higher yields from greater efficiency and reliability. It is expected that the commercialisation of 10 MW turbines may take place in the early 2020s, while 15 MW turbines might be commercialised in the 2030s.

Concerning drive train technology, several significant innovations are under development. In addition to the demonstration of direct drive and mid-speed drive trains, which have the potential to increase reliability by reducing the number of critical components, such innovations include research and development on continuously variable drive trains and superconducting generators.

Continuously variable drive trains provide a variable ratio of input to output speed between the rotor and a synchronous generator by using hydraulic or mechanical devices. This technology avoids the need for a power converter as the control of the generator speed and thus the output frequency is controlled by the variable transmission. An example of this technology is the hydraulic system developed through in-house private sector research by MHI-owned Artemis Intelligent Power which received UK government funding.

²² <http://www.vortexbladeless.com/home.php>

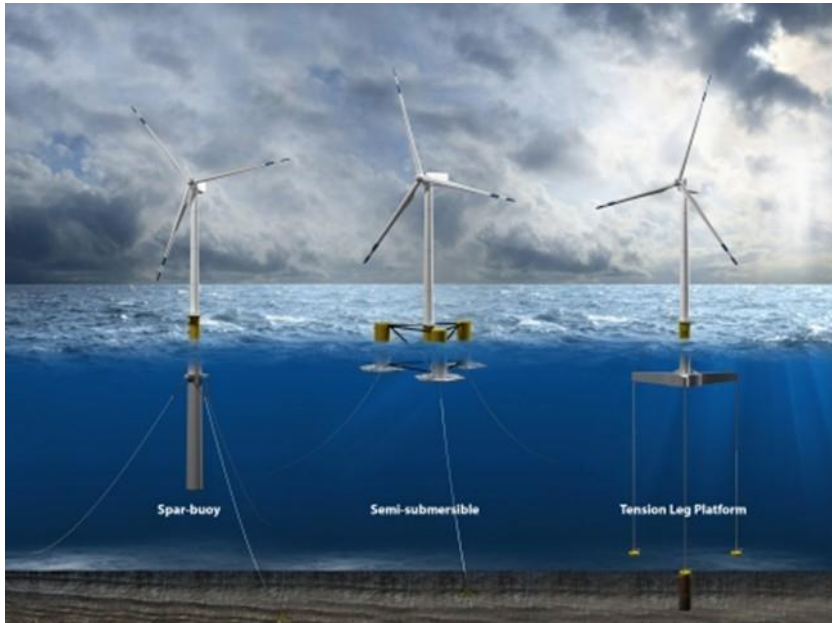
Superconducting generators use machine conductors with zero electrical resistance when cooled below their critical temperature. Since the conductors have no losses, there is no heat to dissipate and the conductors can carry very high currents on thin sections. This reduces the size and mass of the generator, and allows a much lower top head mass. With no losses on the rotor, the machine efficiency is improved, giving a higher annual energy yield. A megawatt-scale High-Temperature Superconducting generator was made for demonstration in the UK in 2011.

Floating Foundations

Currently deployed foundations for off-shore wind turbines, as monopiles, restrain their application to water depths greater than 50 m. This constrains the access to sites with higher wind resource and, potentially, large markets as Japan and the US with limited shallow water sites. While the wind sector moves into deeper water sites, it is likely that developers may still be using a mix of known designs as piled jackets, suction buckets and gravity base foundations. However, floating foundations could offer improvements to open up new markets in deeper waters. A number of designs of floating foundations would ease the installation and reduce its costs by avoiding the use of heavy-lift vessels.

Floating foundations are buoyant structures maintained in position by mooring systems. The technologies in development at present are: i) the spar buoy, as the Hywind concept developed by Statoil, ii) the tension-leg platform, as Glosten's PelaStar, and iii) the semi-submersible, as the one developed by Principle Power and the damped floater being developed by Ideol. Demonstration is an important ongoing stage for floating concepts and several full-scale prototype floating wind turbines have been deployed. The first was a spar buoy in Norway in 2009, followed by a semi-submersible installation in Portugal in 2011 and three installations in Japan (spar and semi-submersible) between 2011 and 2015. No tension-leg platform has been deployed for a wind application; the first, designed by Gicon is anticipated in Germany in 2016.

FIGURE 6: DIFFERENT DESIGNS OF FLOATING FOUNDATIONS FOR OFF-SHORE WIND TURBINES



Source: U.S. Department of Energy

Other innovations that have the potential to impact the industry during the next three decades include new turbine designs (e.g. airborne wind), integrated turbine installation, site layout optimisation array cables and the deployment of HVDC infrastructure and DC power take-off.

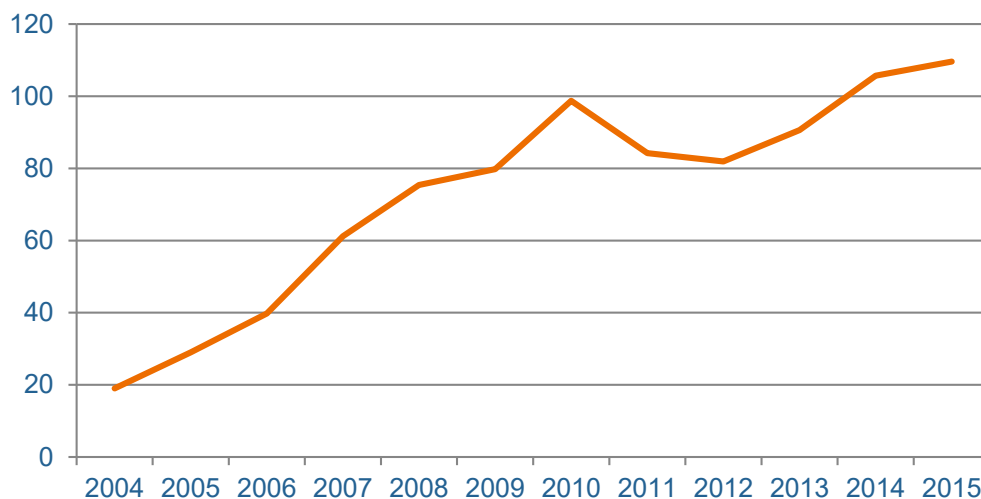
Repowering offshore wind farms may become an option to guarantee operations in a decade, when the first wind farms will reach the end of their operative lives. Repowering activities revolve around the substitution of obsolete generating assets and infrastructure, such as turbines, foundations and array cables, by more advanced units. Provided that such units may be more powerful or larger in size, repowering activities might also involve spacing the units further and adjusting the farm configuration. Repowering activities may retain transmission assets, which could reduce the cost of repowering the wind farms and thus, lead to a reduction on the levelised cost of energy²³.

²³ IRENA ibid

2. ECONOMICS & MARKETS

The total investments in the global wind sector reached a record level of US\$109.6 billion over the course of 2015. From 1983 to 2014, the global stock of investments in onshore wind was in excess of US\$647 billion²⁴. More than 93% of these investments occurred after the year 2000. United States, China, Germany and Spain account for the bulk of these investments. During 1983 and 2000, onshore wind investment stock was estimated to be around US\$40 bln. United States, Germany and Denmark accounted for the vast majority of these investments.

FIGURE 7: YEARLY NEW INVESTMENTS IN WIND ENERGY, 2004-2015 (USD BILLION)



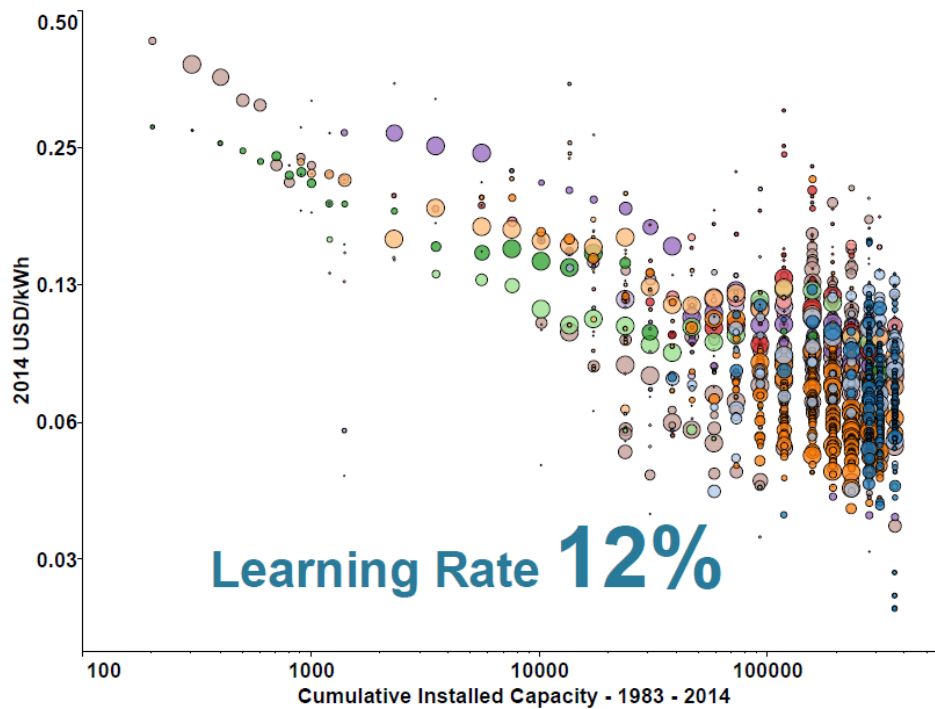
Source: Bloomberg New Energy Finance (2016)

IRENA has also updated the global learning curve for investment costs and LCOE of onshore wind. The analysis used a database of more than 3200 individual wind farms with data on costs and performance within a panel of 12 countries (Brazil, Canada, China, Denmark, France, Germany, India, Italy, Spain, Sweden, United Kingdom and United States) that accounted for 87% of onshore wind capacity at the end of 2014. The analysis covered the period 1983 to 2014 and concluded the following facts. Onshore wind power

²⁴ IRENA (2016), The Power of Change: Cost reduction potentials for solar and wind power technologies.

has seen a significant cost decline since its championing in early 1980s by Denmark and United States. Globally weighted average investment costs declined from 4,766 US\$/kW in 1983 to 1,623 US\$/kW in 2014, translating into an overall reduction of 66%. A learning rate of 6% fits the investment costs evolution. Thus, every time global cumulative installed capacity doubled, investment costs declined by 6%. The LCOE of onshore wind power experienced a higher rate of decline in comparison to investment costs to calculate the LCOE of onshore wind, so it was assumed a constant weighted average cost of capital of 7.5% for OECD countries and China, and 10% for the rest of the world. Globally, the weighted average LCOE of onshore wind declined from 0.38 US\$/kWh in 1983 to 0.07 US\$/kWh in 2014. Thus, the LCOE of onshore wind was 81% lower in 2014 in comparison to the estimated value in 1983. This represents a learning curve of 9%. The learning rate of LCOE is higher than the one estimated for investment costs because technological improvements allowed for lower investment costs and higher capacity factors at the same time. Additionally, lower Operation & Maintenance costs for higher rated wind turbines have helped to bring down the LCOE of onshore wind.

FIGURE 8: IRENA ONSHORE WIND LEARNING RATE



Source: IRENA Renewable Cost Database

ONSHORE WIND

Historic and Current Trends

The onshore wind sector has been characterised by a significant fall in cost of energy production, and a likewise expansion in generation capacity worldwide. 64 GW of new onshore wind capacity was added in 2015, taking total cumulative capacity to 435 GW²⁵. Since 2000, installed capacity has grown at a CAGR of nearly 25%. While policy initiatives since the turn of the century have been vital to the uptake of onshore wind in key markets, much of the growth within the sector has been organic – driven by economies of scale, technology improvements and increased market competition. Interestingly, current growth in onshore wind is being led by the ‘emerging’ wind markets in Latin America and Africa, along with China, currently the world’s largest wind market.

From a levelised cost perspective, onshore wind energy boasts some of the lowest electricity costs amongst the renewable energy sources, and in some mature markets it is now cost-competitive with conventional sources of generation if variability is not taken into account. As far as wind generation is intermittent, price of electricity is the right concept for the consumer, this price must take into account back up by other generation assets or by storage.

Drivers within the Wind Market

The following are the key drivers for general trends within the global onshore wind market:

- Technology maturity & improvement (higher capacity factors and availability, production in low wind speed sites)
- Investor familiarity
- Policy support

COST OF TECHNOLOGY

Installation Costs

Turbines represent the single largest cost item for onshore wind energy development. Turbine cost (including electrical infrastructure and transportation) can represent a range of 64% to 84% of capital costs²⁶. Shortly after the turn of the century, wind turbine average prices increased to above US\$1,500/KW by 2008, although they had reached US\$750/kW between 2000 and 2002 in the United States²⁷. The upward trend in prices was caused by significant increases in the prices of commodities, such as copper, steel, cement and rare earth magnet material. Other factors attributed to the increase of turbine prices are the development and sale of larger (and initially more expensive turbines), a shortage in wind

²⁵ IRENA (2015)

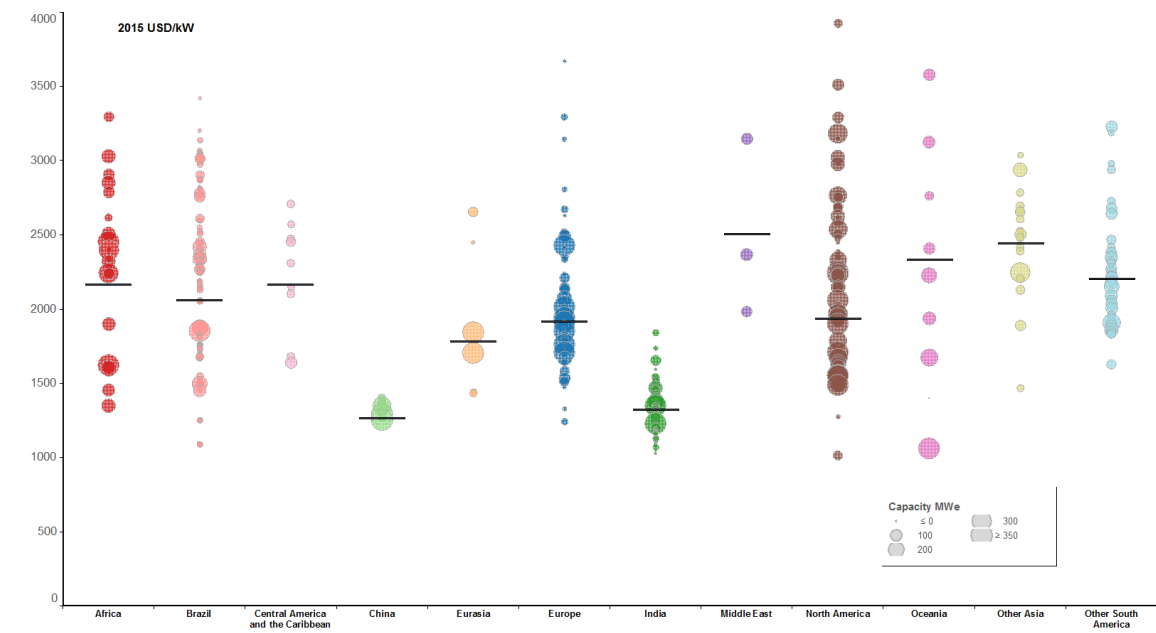
²⁶ IRENA (2015), Renewable power generation costs

²⁷ Lawrence Berkeley National Laboratory (2015)

turbines to meet a sharp rise in global demand and inflation in the costs attributed to civil engineering work. Since then, turbine prices have fallen and preliminary estimations indicate that prices have reached between US\$950 and US\$1,240 for projects in 2016, suggesting cost reductions of 30-40%.

Chinese wind turbines fell by 37% from 2007 to 2016. A crash in commodity prices since the financial crisis, and increased competition among OEMs thanks to added manufacturing capacity in China and India have contributed to the downward trend in turbine prices. Installation costs of wind farms are dependent on project size, turbine costs, wind resource, difficulty of terrain, transport costs and local labour costs. Total installation costs mirrored the trend of turbine prices, peaking in 2009.

FIGURE 9: TOTAL INSTALLATION COSTS AND WEIGHTED AVERAGES OF COMMISSIONED AND PROPOSED WIND FARMS BY COUNTRY AND REGION, 2015



Source: IRENA Renewable Cost Database (2016)

From Figure 9 average installed costs in China and India are the lowest in the world, with weighted average installed costs between 26% and 43% lower than other regions. China and India also have the narrowest cost range for different-sized projects. Both the Chinese and Indian markets are approaching ‘mature’ status for onshore wind – the Chinese market saw modest reduction in costs from 2010-2014 (about 12%), while costs in India declined by 6% between 2010 to 2015. The fastest drop in costs were witnessed in South America

(about 20% between 2011 and 2015), highlighting the sizeable room for growth in onshore wind in these countries.

Studies on projects completed in the United States suggest that average installation costs exhibit economies of scale, especially when moving from projects of 5 MW and below to projects within the 5-20 MW range (>30% cost reduction). The trend is less evident for larger projects, however²⁸.

Analysis by the IRENA Renewable Cost Database has also shown a strong correlation between installed costs and capacity factors of onshore wind farms once in operation, when examined at a global level. As capacity factor is heavily dependent on the quality of the wind resource, it appears that higher-cost projects are being installed at sites with better wind resources (and hence higher capacity factors) and vice-versa, in an effort to minimise the levelised costs of the projects.

Operation & Maintenance (O&M) Costs

Though available data from commissioned wind projects is hard to come by, it is clear that annual average O&M costs have declined significantly since 1980. Average total O&M costs for onshore wind reported by publicly traded developers in United States stood at US\$24 per MWh in 2013²⁹, while estimated costs for European wind farms were in the range of US\$11-40 per MWh in 2011³⁰. In addition, projects installed in the United States since 2010, using state-of-the-art equipment, show O&M costs as low as US\$9 per MWh over the period 2010-2014³¹. Caveats exist for these figures, however. Firstly, they are expressed as purely variable costs (in per unit MWh), when in actuality O&M cost has both a fixed and a variable component. Secondly, it must be stated that it is not clear whether the same boundaries to the cost structures for projects within and between the United States and Europe are applied. Recently developed projects using current generation turbines exhibit higher availability rates than older projects, hence they are out of service less frequently and have shorter downtimes, and generally lower O&M costs. The O&M market is also getting more competitive, especially in large markets such as Europe, US and China; as more turbines reach the end of their service life, O&M contractors and even turbine manufacturers hope to secure long-term service contracts.

Financing Trends

Wind projects, both onshore and offshore, are now seen as low-risk investments. The sector has a credible growth track record. It is regarded as the preferable source of grid-scale renewable electricity in many countries, hence further growth potential and deployment rates expected to increase.

^{28,18} Wiser and Bolinger (2015)

²⁹ Wiser and Bolinger (2014)

³⁰ IEA Wind (2011)

A number of trends have been witnessed in the financing of wind projects in recent times. Firstly, there is increasing competition among financial institutions to provide debt to large projects. As of early 2015, banks were willing to provide over twice as much debt funding to projects as they were only 18 months earlier. Green bonds have been issued with yields as low as 0.25%, and the majority within the 2.5-3.0% range³². Secondly, more players are participating in the debt market – institutional investors (e.g. pension funds or insurance companies) have joined commercial and multilateral banks and public export credit agencies in providing debt funding for wind projects. The expectation in the near future is that new projects will receive funding with lower interest rates and higher gearing (debt-to-equity) ratios (as much as 80% or more); which will contribute to increasing the internal rate of return of projects and lower the overall cost of energy.

LEVELISED COST OF ELECTRICITY³³ (LCOE)

Historical Trends in LCOE

Levelised cost of electricity for wind energy is directly affected by the combination of installation costs and energy production (i.e. capacity factor). From the 1980s to the turn of the century, significant reductions in capital costs and improvement in turbine performance combined to reduce the levelised cost of onshore wind energy, by as much as a factor of three over this period. Historical data from the United States and Denmark shows that LCOE dropped from above US\$150 per MWh in 1980 to about US\$55 per MWh in the early 2000s^{34,35,36}. IRENA estimated that the global LCOE for onshore wind was 380 US\$/MWh in 1983 and 70 US\$/MWh in 2015 (in real, 2015 US\$ values). From 2003 to 2008, the aforementioned increase in turbine costs and hence capital costs put upward pressure on the total LCOE. However, the increase in capital costs observed in the period up to 2009 did not have a proportional equal effect on LCOE due to the fact that the period coincides with the introduction of novel technologies with higher hub heights, rotor diameters and MW rating that offset an estimated 10-15% of CAPEX increase by increasing capacity factors.

Capital costs have since declined, but not to the lows experienced pre-2003 but accounting for the technological improvements allowing for higher energy capture, costs might be overall lower from an LCOE perspective as the estimated global weighted average LCOE in 2015 was lower than its equivalent in 2003 or any other point in time before. However, continued performance improvements mean that LCOE for onshore wind are now at record lows. This illustrates that wind project developers and OEMs are more concerned with decreasing LCOE rather than capital expenditure.

³² Arántegui and González (2015)

³³ LCOE is the average revenue required per unit of electricity generated to make a market rate of return over the total lifetime investment in a project.

³⁴ Wisser and Bolinger (2011)

³⁵ Lemming *et al* (2009)

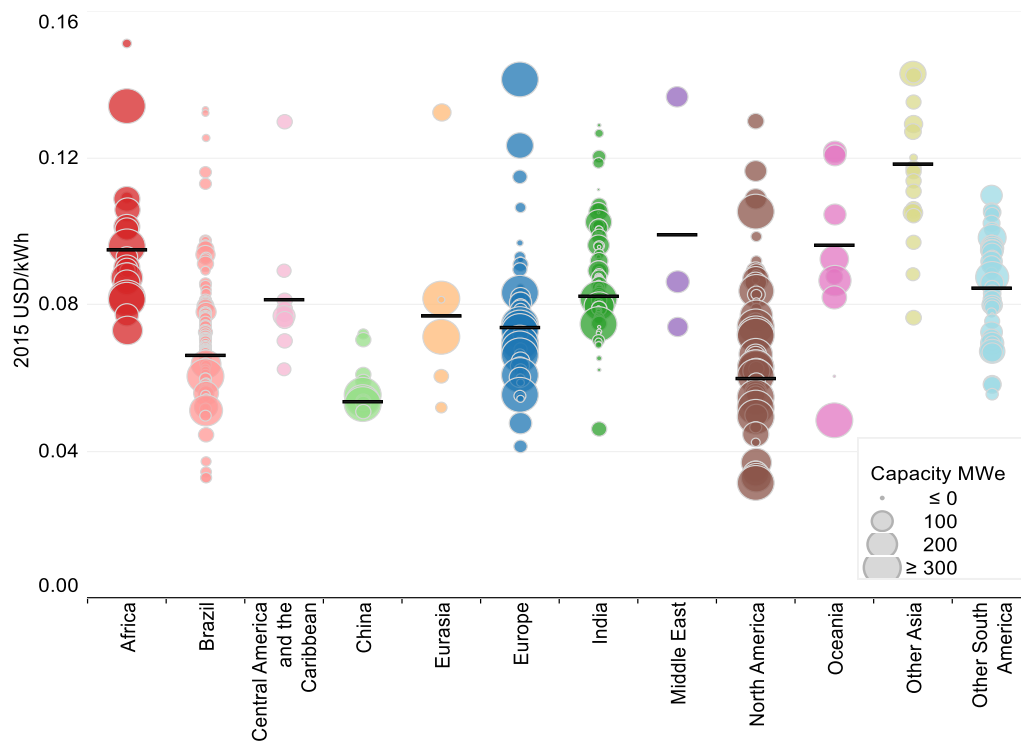
³⁶ Danish Energy Agency (1999)

Regional Differences in LCOE

From Figure 10, China has the lowest weighted average LCOE for onshore wind projects, 52 US\$/MWh, with a very narrow range, between 50 US\$/MWh and 72 US\$/MWh. India exhibits a relatively low weighted average LCOE, at 82 US\$/MWh with a wider range, between 46US\$/ MWh and 129 US\$/kWh. Overall, in Asia, the most expensive projects cost more than 142 US\$/MWh.

The LCOE of onshore wind has a very competitive weighted average in North America and Brazil with 60 US\$/MWh and 66 US\$/MWh respectively and virtually the same ranges of 31 US\$/MWh to 130 US\$/MWh. The highest weighted average LCOE are to be found in Africa, Oceania and Middle East with 95 US\$/MWh, 97 US\$/MWh and 99 US\$/MWh respectively.

FIGURE 10: LCOE AND WEIGHTED AVERAGES OF COMMISSIONED AND PROPOSED WIND FARMS BY COUNTRY AND REGION, 2015



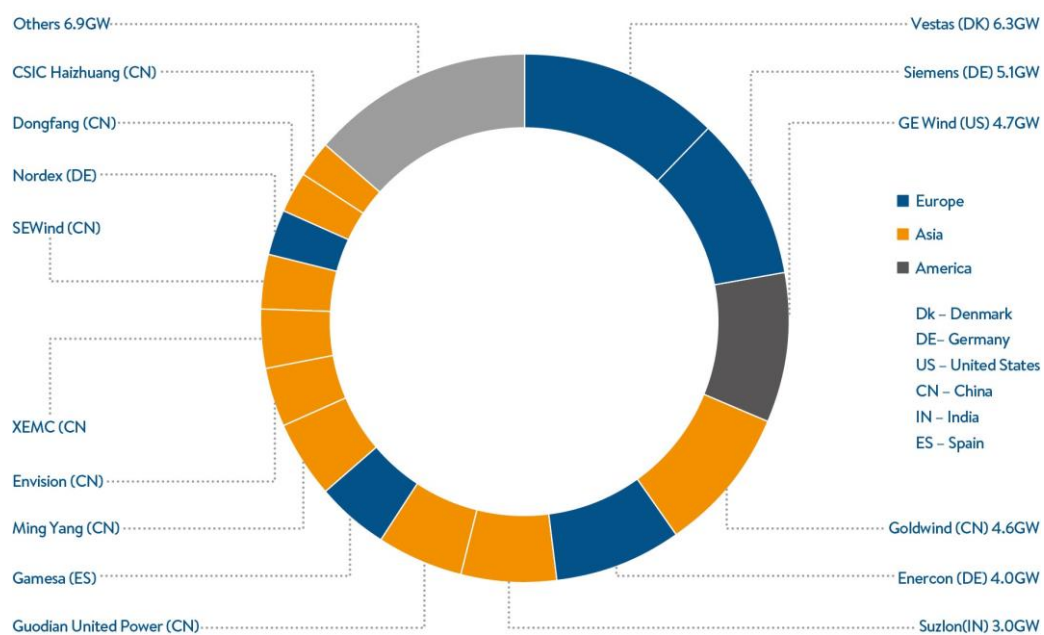
Source: IRENA Renewable Cost Database

INDUSTRY TRENDS

Turbine Manufacturers

Figure 11 gives a breakdown of the global wind market in 2014 (by capacity additions), according to turbine manufacturer. Vestas (Denmark, 12.3% of global market) was the top supplier of wind turbines globally in 2014, followed by Siemens (Germany, 9.9%), GE (United States, 9.1%) and Goldwind (China, 9.0%)³⁷.

FIGURE 11: SHARE OF THE GLOBAL TURBINE MANUFACTURER MARKET, WITH RESPECTIVE CAPACITY ADDITIONS, IN 2014



Source: BTM Navigant (2015)

Trends within the supplier industry in recent years show strong consolidation of the major companies and the shift in the global wind market eastwards to China and India. In 2003, only one Chinese manufacturer (Goldwind, 0.5% share) made any substantial contribution to the global wind market. Nine Asian companies, eight of which from China, made up the global top 15 turbine manufacturers - compared to five from Europe - in 2014, each with at least with a 2% share of the global market. Since 2009, China has contributed 35-50% of annual wind installations. The Indian manufacturer Suzlon has nearly 6% global market

³⁷ BTM Navigant (2015)

share. It should be noted however that the growth of the Chinese manufacturers thus far has been largely restricted to the domestic market. On the other hand, the European manufacturers commanded a 78% share of the global non-Chinese market in 2014 (Vestas and Siemens had virtually no home market in that period). GE, the only major manufacturer from the United States, had over 60% of its supplied capacity installed domestically in 2014.

The financial health of turbine manufacturers has rebounded after the witnessed dip in earnings in 2011-12. Strong competition between manufacturers and production overcapacity were adjudged to be the main reasons for the dip in this period, but now the market presents a much healthier financial situation.

RISKS TO INVESTMENT

Policy Uncertainty

With the dramatic fall in costs for onshore wind, governments are re-considering their policy support structures for the technology. Policy uncertainty in Europe and the United States in 2013 was largely responsible for the fall in net capacity additions in both markets for that year. However, it has been commented that high levels of incentives are no longer necessary for onshore wind, though their economic attractiveness still depends on adequate regulatory frameworks and market design³⁸.

Longevity of Assets

Wind projects are developed with an assumed operational lifetime of 20-25 years. As more operational turbine fleet approach retirement, there is the realisation that the performance of some projects may have been over-estimated during the planning phase of the project. In addition, long-term O&M profiles of projects are variable and not yet fully understood and this could have led to underestimate costs attributed to maintenance and, eventually, decommissioning.

PIONEER HYBRID ELECTRICITY SYSTEM IN SPAIN: WIND AND HYDRO-PUMP ENERGY STORAGE IN ISLANDS

In July 2014, the Gorona del Viento wind-hydro plant was inaugurated in the Spanish island of El Hierro. Thanks to this project, El Hierro relies mostly on wind its electricity supply. The pumped hydro plant stores the excess energy from the five

³⁸ IEA (2015)

wind turbines by pumping water to an artificial reservoir located further up on a hill. When the wind resource is not sufficient to meet the electricity demand, the water in the reservoir is released and channelled through turbines to produce electricity³⁹. Through this system, the electricity demand of the 10,000 locals of El Hierro has been met by 100% renewables for extended periods of time, beyond 40 hours at times⁴⁰.

The case of El Hierro presents a number of innovative aspects. Unlike most of the existing pumped storage systems, which use a river or a conventional dam as reservoir, Gorona del Viento's artificial reservoir was created specifically for storage purposes. By doing this in an island, El Hierro became a pioneer island to rely on such hybrid electricity system. Still, opportunities for innovation exist. For example, smart grids that enable electricity consumption mostly at generation peaks and postpone non-critical uses of the electricity when the wind resource is insufficient pose opportunities to increase the duration of storage.

It is estimated that this US\$91 million project, has contributed to save more than 3,200 tonnes of fuel and thus, prevented 10,800 tonnes of CO₂ to be released to the atmosphere in less than a year⁴¹. Systems like Gorona del Viento can contribute to diminish the reliance on fossil fuels in islands, where diesel is generally imported at a particularly high price due to transportation. In addition, the combination of wind and pumped hydro energy storage mitigates the variability intrinsic to wind power generation⁴².

OFFSHORE WIND

In 1991 Elkraft (now DONG Energy) installed the first offshore wind farm in Vindeby, Denmark. It comprised eleven Siemens (formerly Bonus) 450 kW, 35 m rotor diameter machines with a total capacity of 4.95 MW. The project was 2 km from shore in 2 to 4 m water depth and the project is still operational. The industry has developed significantly in the 24 years since then and a single 5 MW turbine can now produce the energy produced by all 11 turbines.

Global installed capacity of offshore wind capacity reached around 12,107 MW end-2015, with 2,739 turbines across 73 offshore wind farms in 15 countries. Currently, more than 92% (10,936 MW) of all offshore wind installations are in European waters but governments outside of Europe have set ambitious targets for offshore wind and development is starting

³⁹ Kenning (2015)

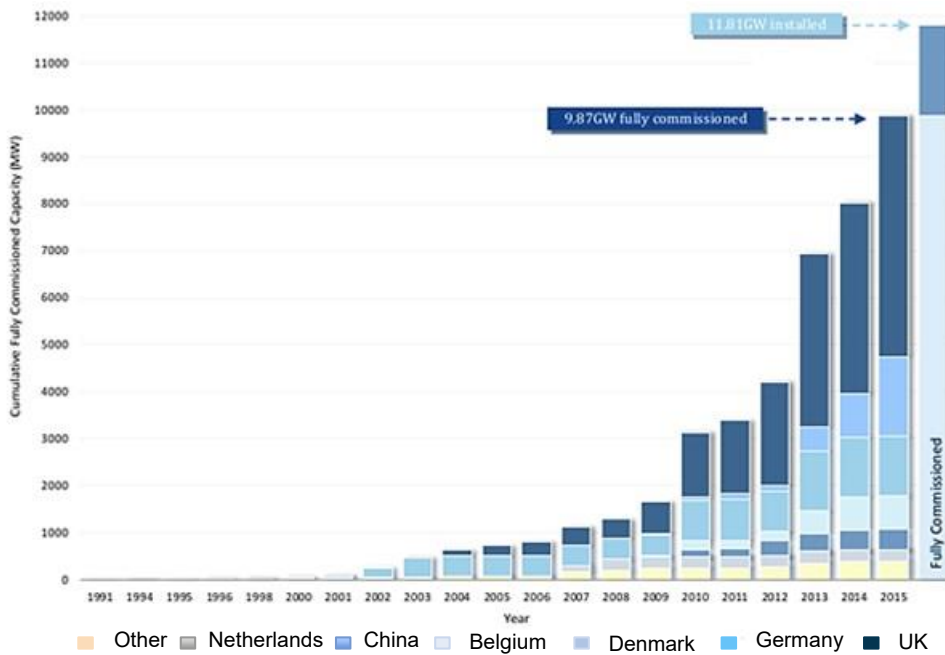
⁴⁰ REE (2016), <https://demanda.ree.es/visionaCan/VisionaHierro.html#app=2547&9127-selectedIndex=0>

⁴¹ Gorona del Viento, n.d.,

⁴² Fillon (2016)

to take off in China, Japan, South Korea, Taiwan and the US. This will be extremely beneficial for the technology, reducing market risk, increasing the supply base and allowing innovations to emerge.

FIGURE 12: PLANNING CAPACITY BREAKDOWN BY COUNTRY



Source: 4C Offshore Wind Overview Report (2016)

Although Denmark was the first mover in the industry, the UK is now the leader with 5,144 MW of installed capacity, over 40% of the total and more than all other countries in the world combined (see Figure 12). The 5 GW threshold was crossed when Gwynt y Mor wind farm, off the coast of North Wales, was officially inaugurated on 18 June 2015. Following the UK in Europe is Germany (3,137 MW), Denmark (1,271 MW), Belgium (712 MW) and the Netherlands (376 MW). Outside of Europe, offshore wind projects can be found in Asia with China as the leader with 718.9 MW of installed capacity; Japan, 52 MW; and South Korea, five MW as of October 2015⁴³.

⁴³ Environmental and Energy Study Institute (2016)

Looking forward, globally, it is expected that there will be 41 GW of installed capacity by 2020⁴⁴ and 84.2 GW by 2024⁴⁵

MAIN MARKET REGIONS

Europe

The UK will remain a key market and is expected to double the capacity installed to around 10 GW by 2020. Germany however, is developing its market rapidly. In the first six months of 2015, 1.77 GW of new offshore wind was connected to the grid in German waters. An additional roughly 2.1 GW is in the pipeline bringing the total to around 5.4 GW in the next few years⁴⁶. The Netherlands will also grow rapidly with a target of 4,450 MW by 2023. Belgium is targeting 2 GW by 2020 and has limited capacity to 8 GW due to space for offshore wind. France has not defined a specific target but has held two tender rounds with combined capacity of 2,924 MW for installation by 2025.

Asia

China has ambitious plans with a target of 10 GW by 2020 and 30 GW by 2030. With only around 718.9 MW installed so far, it is questionable if these targets are achievable. In Japan, an estimated 900 MW of fixed-foundation offshore capacity is under development at 11 locations⁴⁷. The anticipated start of construction on SoftBank's 100MW wind farm at Kashima — the country's first commercial-scale offshore project — and the recent announcement that a consortium led by Hitachi Zosen Corp. will invest around ¥100b (US\$850m) in a 220 MW wind farm off the northwest coast, should also help build momentum⁴⁸. The government in Taiwan has turned its attention to offshore as onshore wind is not expected to grow beyond 1.2 GW of installed capacity because of land restrictions and the west coast of the country is considered to be one of the best global locations for offshore wind. There are currently 36 pre-identified zones for construction and the government has targeted 4 GW of offshore wind capacity by 2030. South Korea installed its first offshore wind turbines in 2012, following a 2011 announcement that the government would provide nearly US\$8 billion to fund the phased development of a 2,500 MW offshore project, with operations beginning in 2019. Although development appears to be lagging, as a result of concerns raised by the fishing industry, approximately 500 MW of projects are advancing through the Korean pipeline⁴⁹. There is currently no offshore wind in India but The Indian Ministry of New and Renewable Energy has introduced an offshore wind policy targeting 1 GW by 2020 and Suzlon Energy is working on 600 MW offshore wind farm off coast of Gujarat⁵⁰.

⁴⁴ Bloomberg New Energy Finance (2015), Global Wind Market Outlook,

⁴⁵ Bloomberg New Energy Finance (2015), Q3/2015 Global Wind Power Market Outlook Update

⁴⁶ Morris (2015)

⁴⁷ Anticipated

⁴⁸ EY (2015)

⁴⁹ NREL (2015), 2014-2015 Offshore Wind Technologies Market Report

⁵⁰ GWEC (2014)

United States of America

A project has yet to be commissioned in the US and there is no official target for offshore wind. However, in 2015 the 30 MW Block Wind offshore wind farm became the first offshore wind farm to reach financial close and from a report released by the Department of Energy in September 2015, there are 21 offshore wind projects in development in the US, for a total of 15,650 MW of potential capacity⁵¹.

LCOE AND COST REDUCTION⁵²

Advancements in wind power technologies continue to move forward towards cost reduction as well as the expansion into new markets. With onshore wind power reaching cost competitiveness against conventional power generation technologies, more attention is now paid to technology developments for offshore applications. The offshore wind market may represent an increase of the additional installed wind power capacity of up to 100 GW by 2030 and 400 GW by 2045 globally.

Progress in offshore wind has been observed since the beginning of the century. The LCOE from offshore wind was about 260 US\$/MWh in 2001 and it decreased to approximately 196 US\$/MWh by the end of 2015. While finance, O&M and turbines are the elements contributing more significantly to the LCOE, decommissioning would represent the less significant expenditure of around 0.7% of the LCOE⁵³. Currently, the global operating offshore wind power capacity at present is 12.7 GW, located mainly in northern Europe. This has been enabled by a wide range of innovations, including offshore-specific turbine designs, bespoke offshore wind installation vessels and advanced offshore electrical interconnection equipment. From 2001 to 2015, the rated capacity of commercially deployed offshore wind turbines has also grown from 2 MW to more than 6 MW. This progress not only improved the efficiency of the turbines but also resulted in cost economies across the rest of the wind farm. Nonetheless, the offshore wind sector has to continue and reinforce its efforts to reduce cost and ease its integration into the grid to become a competitive energy supply technology.

Industrialisation and Maturation of the Supply Chain

The offshore wind supply chain has matured over the past five years, stepping out of the shadow of other sectors. For instance, offshore wind specific turbines are now built in offshore wind specific factories and installed from offshore wind specific installation vessels. This is in part due to companies (such as DONG Energy, Siemens Wind & Bladt) having offshore wind as a core part of their business, generating revenue and profit in the process. This creates a strong incentive for these companies to innovate to ensure a sustainable business in the long term. Risk management has also improved with experience, with installation times per turbine decreasing. Finally, chronic supply shortages in certain areas

⁵¹ Environmental and Energy Study Institute *ibid*

⁵² IRENA (forthcoming) – Off-shore wind technology: an innovation outlook

⁵³ IRENA *ibid*

(e.g. installation vessels in 2010/11) have eased, with reasonable levels of competition across the value chain.

Collaboration between suppliers and developers is also important. If a design of a substation for example, can be standardised across a number of windfarms, this helps suppliers to efficiently utilise their manufacturing capabilities as well as giving visibility of project's pipeline to justify investment in manufacturing facilities. DONG Energy for example, commissioned Atkins to design eight substations across four of their windfarms (Burbo Bank Extension, Race Bank, Walney Extension and Hornsea) with the key aim of reducing costs.

Finance Cost Reductions

Offshore wind is very capital intensive with financing costs at around a third of the LCOE. Improvements in financing therefore have a large impact on the cost base.

Traditionally, offshore wind was financed off the balance sheet of utilities yet there is an increasing trend towards project finance. At the same time, the offshore wind sector has seen a huge increase in appetite from investors to finance projects. The size and scale of offshore wind, combined with the secure, long term, inflation linked returns have been particularly attractive for investors, with significant competition between parties to invest in good projects. As a result, the cost of debt and equity has fallen, while debt-to-equity ratios have improved. There is evidence in the market of projects achieving up to 70% gearing as with the case of the Green Investment Bank (GIB) and Marubeni who in August 2014 raised £370m debt to refinance their 50% share in DONG Energy's Westernmost Rough project, bought in May for £500m⁵⁴. The sector is also developing a strong project finance record - as an example, see Case Study on Gemini Offshore Wind Farm.

Another approach that is producing competitive debt and new participants to the market is bond financing which helps to access a larger pool of investors. In September 2015, DONG Energy signed an agreement to divest 50% of the 330 MW German offshore wind construction project, Gode Wind 1, to Global Infrastructure Partners (GIP), a leading global, independent private equity infrastructure investment fund. The total sales price amounts to approximately €780 million (DKK 5.8 billion) which will be paid in the period 2015 to 2016. As a part of the transaction, GIP will issue a rated project bond to a consortium of renowned German insurance companies with Talanx, one of the largest German insurance groups, as cornerstone lender. This transaction marks the issuance of the first non-recourse, investment grade, certified green bond dedicated to part-finance an offshore wind farm asset under construction.

One of the key challenges for the industry has been finding an investment partner willing to take on construction risk. Thankfully, the participation of state banks, multilateral banks and

⁵⁴ <https://ore.catapult.org.uk/documents/10619/110659/CRMF+Qualitative+Summary+report/dc37fb9c-e41e-429c-862e-747f8db091c0>

export credit agencies such as GIB and the European Investment Bank (EIB) are helping to bridge this investment gap.

FINANCING GEMINI OFFSHORE WIND PROJECT

A big financing success came in May 2014 when the 600 MW Gemini project⁵⁵, 85km of the coast of the Netherlands became the largest-ever project financed offshore wind farm raising €2.8 billion. More than 22 parties, including 12 commercial creditors, 4 public financial institutions, together with one pension fund and Northland as subordinated debt lenders, and the four members of the equity consortium were involved in the signing of the financing contracts. €2.2 billion of the financing was debt equivalent to 70% of the total project cost⁵⁶.

FIGURE 13: GEMINI PROJECT'S CAPITAL STRUCTURE

Financing type	Financing volume	Percentage of total investment requirement	Investors
Senior debt	€2,000 million	70%	12 commercial banks, 3 ECAs (Ekspert Kredit Fonden, Euler Hermes & Delcredere/Ducroire) & the European Investment Bank
Sponsor equity	€400 million	15%	Northland Power, Siemens Financial Services, Van Oord & HVC Group
Subordinated debt	€200 million	7.5%	Northland Power and Danish pension fund PKA
Pre-completion revenues	€200 million	7.5%	
Total	€2,800 million	100%	

⁵⁵ Gemini is owned by a consortium consisting of Northland Power (60%), Siemens Financial Services (SFS - 20%), Van Oord Dredging and Marine Contractors BV (Van Oord - 10%) and N.V. HVC (HVC - 10%).

⁵⁶ BNEF (2014), Gemini Offshore Wind

Other Drivers

Substantial cost levers for cost of electricity can be found in site selection considering wind speed, distance to shore, water depth, ground conditions and project size. These factors do not always move in the same direction. For example, a site further offshore will have higher O&M costs and CAPEX costs related to the transmission system but these costs should be offset by the higher wind speeds.

Design life assumption is also an important driver for LCOE and this has improved with the market moving towards a 25-year design life up from a previous baseline of 20 years. Siemens' direct drive SWT -6.0- 154 turbine has been certified for a 25 lifetime, which is an additional five years compared with the previous turbine lifetime Siemens has designed towards⁵⁷.

COMPETITIVE AUCTIONS

The major policy trend is the continued move towards competitive tendering of financial support in auctions. This is not specific to offshore wind; most renewables technologies have been subject to the same pressures, driven by governments' targets to reduce support to renewable technologies and to push developers to deliver cost reductions in order to eventually be subsidy free.

The results for cost reductions are promising. For instance, in the UK, East Anglia 1 will deliver 719 MW at £119.89/MWh, while Neart na Gaoithe will deliver at £114.39/MWh⁵⁸. This is a strong result for the first competitive bidding process for the new support regime – Contracts for Difference – delivering 38% reductions when compared to support under the previous support scheme – Renewables Obligations⁵⁹. The results from the Danish auction for Horns Rev 3 also delivered cost savings with a winning bid from Vattenfall at €10.31 kWh, 32% cheaper than the last offshore wind farm constructed in Denmark, Anholt offshore wind farm⁶⁰. The Netherlands is also pushing for lower costs through competitive allocation with maximum prices for the upcoming auction rounds in the Netherlands.

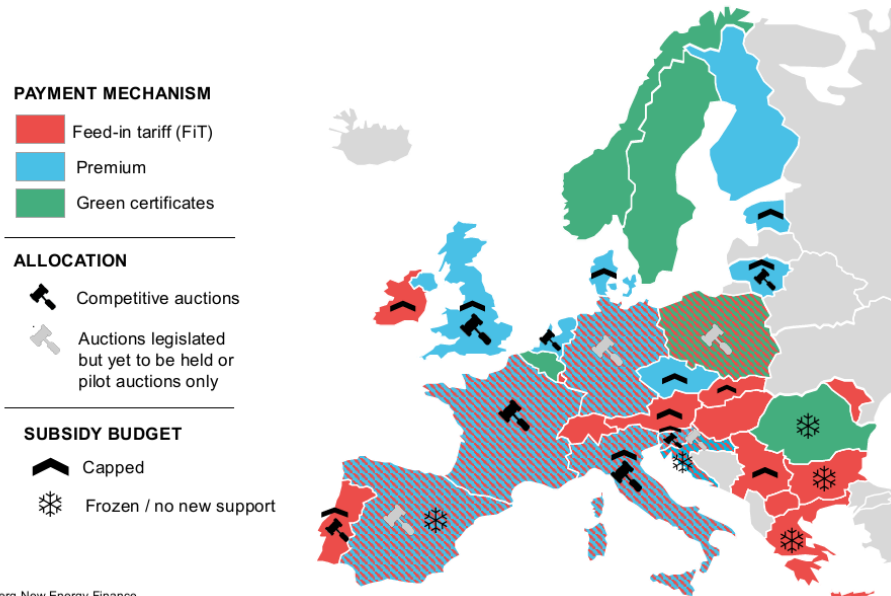
⁵⁷ Smith (2014)

⁵⁸ DECC (2015)

⁵⁹ This is comparing 2 ROCs at £45 for 20 years to a CfD for 15 years at a strike price of £120/MWh, assuming a wholesale price of £45/MWh, <http://offshorewind.works/offshore-wind-vision/>

⁶⁰ Danish Ministry of Energy, Utilities and Climate (2015)

FIGURE 14: SUPPORT SCHEMES FOR LARGE SCALE RENEWABLE ENERGY PROJECTS IN THE EU



Source: Bloomberg New Energy Finance.

Source: BNEF

The move towards auctions radically changes the development process and risk profile of the individual projects. Developers and suppliers are still coming to terms with this change.

The sector has rapidly cut costs, yet the sector remains an expensive energy generating technology. Further reductions are therefore needed to allow the sector to be viable, independent of government support and in turn secure a sustainable industry. There is huge potential to cut costs further. Yet to do this will need partnership between government and industry, with government setting the right policy environment with long term certainty to allow industry the confidence to invest and innovate further reductions.

3. SOCIO-ECONOMICS

GLOBAL RENEWABLE ENERGY BENEFITS

There is growing evidence that renewable energy can ensure both economic growth and decarbonisation across the globe and the conventional consideration of trade-offs between the two is outdated. IRENA analysis shows that renewables deployment not only contributes to a climate safe future, but also fuels economic growth, creates new jobs, develops new industries and enhances human welfare.

IRENA's report *Renewable Energy Benefits: Measuring the Economics* provides the first global estimation of the macroeconomic impact of accelerated deployment of renewable energy. It finds that doubling the share of renewables in the global energy mix by 2030 would increase global GDP in 2030 up to 1.1%, or US\$1.3 trillion, versus the business-as-usual case. This is equivalent to adding the combined economies of Chile, South Africa and Switzerland today. The increased economic activity is mainly a result of the larger investment in renewable energy deployment, which triggers ripple effects throughout the economy⁶¹

Renewable energy benefits go beyond the traditional (and limited) measurements of economic performance, improving human welfare in a much broader manner. Welfare improvements would go beyond GDP gains, since doubling the share of renewables by 2030 would increase global welfare by around 3%. The largest contributor to welfare improvement is the reduction of greenhouse gas emissions and associated climate change impacts, followed by improved health and education.

Doubling the share of renewables would also affect international trade, increasing trade in renewables equipment and other investment goods and services such as engineering services, steel or cables. This brings new export opportunities, including for today's fossil fuel exporters.

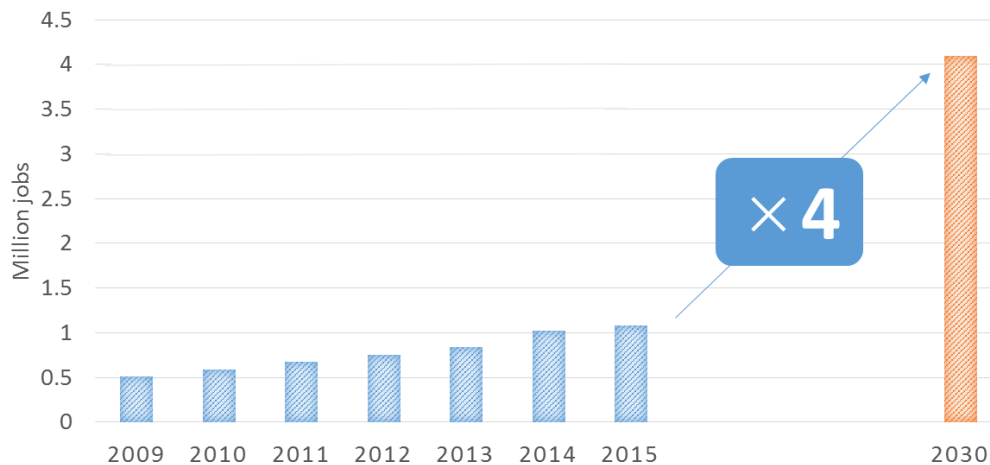
Lastly, IRENA estimates that doubling the share of renewables could increase global employment in the renewable energy sector to beyond 24 million people by 2030, up from the 9.4 million employed today in all technologies including large hydropower.

⁶¹ IRENA (2016a)

JOBS IN THE WIND INDUSTRY

Wind power alone could support more than 4 million jobs in 2030, four times more than the level today. This represents a rapid increase in wind energy employment, which has been growing at a steady pace of 13% over the last five years (Figure 15).

FIGURE 15: TRENDS IN WIND ENERGY EMPLOYMENT



Source: IRENA (2016b)

Currently employment in the sector stands at 1.1 million jobs, more than half of which are concentrated in Asia. In fact, the share of Asia in global wind energy employment has increased from 48% in 2013 to 53% in 2015, primarily due to increased deployment, but also due to a rise in manufacturing. While Asia is the leading the job growth in the technology, the European Union, North America and Latin America have also benefitted from jobs gains (up 4%, 18% and 20% respectively) according to the last available estimates.

China is the leading wind energy employer with more than 0.5 million jobs. Germany and the United States are also top players, followed by Brazil and India.

China's position as a leading wind energy employer is rooted in the rise of strong installations and manufacturing companies. Goldwind, for example, now ranks as the

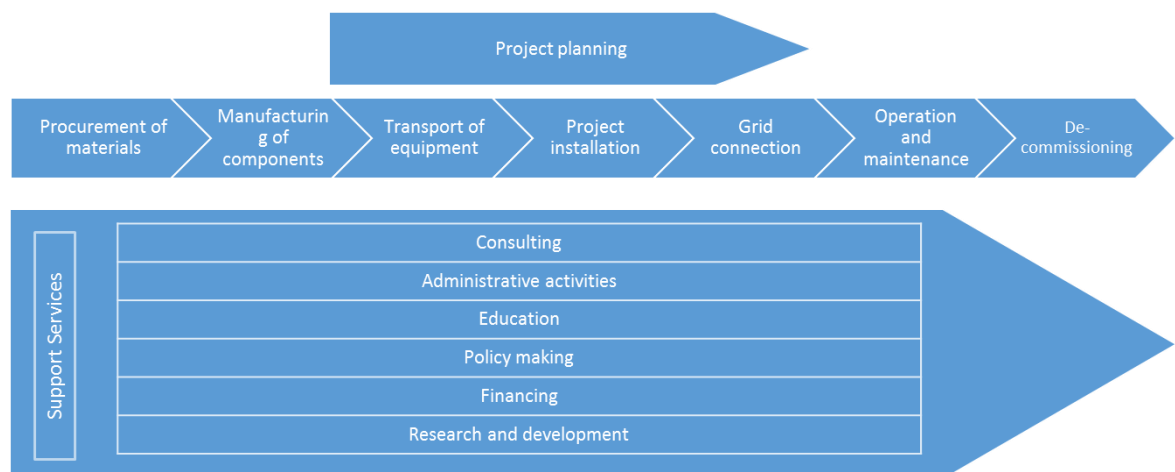
world’s largest wind energy company in terms of new capacity commissioned. Five out of the top 10 wind companies in terms of new commissioned capacity in 2015 are Chinese⁶².

Germany was the leading employer in the European Union with 149,000 jobs in 2014, well ahead of the next 6 largest countries put together⁶³. Wind employment in the United States increased by 20% in 2015 to reach 88,000 jobs, as new capacity additions grew by two-thirds over 2014⁶⁴. In Brazil, wind energy auctions and financing rules that encourage local content have resulted in a 14% growth in jobs in 2015 to reach 41,000 wind jobs. Indian wind energy industry currently employs 48,000 people, and can add more than 180,000 jobs by 2022 if the 60 GW wind target is realised.

Creating Local Value

The potential for job creation and income generation in a country deploying wind energy depends on the extent to which the value chain is localised and existing industries are leveraged. Figure 16 illustrates the different segments of the value chain where value-creating activities take place.

FIGURE 16: WIND ENERGY VALUE CHAIN



Source: IRENA (2016c)

Some activities require specific expertise and knowledge in the wind sector that are not necessarily available locally at the initial stages of development of the sector. Initial activities in the project planning phase related to site selection, technical and financial

⁶² BNEF (2016)

⁶³ The next largest wind employers are Denmark, the United Kingdom, Portugal, France, Italy and Spain. The employment data for the European Union is only available until 2014.

⁶⁴ AWEA (2016)

feasibility studies and engineering design, for example, require wind sector-specific expertise that might need to be imported. The project development activity in this phase, however, can solely rely on local labour with knowledge of the domestic markets, be it legal, administrative, regulatory, etc.

Table 3 shows the human resources (human-days) needed for planning a 50 MW wind farm, where local knowledge represents a fair share of the total human requirements.

TABLE 3: HUMAN RESOURCES NEEDED FOR PROJECT PLANNING ACTIVITIES (HUMAN-DAYS/50 MW)

Professions needed	Human resources needed for project planning activities (human-days/50 MW)			
	Site selection	Feasibility analyses	Engineering design	Project development
Environmentalists	50	30	-	-
Geotechnical experts	50		-	-
Electrical/civil/mechanical/energy engineers	50	90	150	-
Lawyers, experts in energy regulation, experts in real estate, land property and taxation	140	60	100	720
Financial analysts	-	30	-	700
Safety experts	-	-	50	-
Experts in logistics	-	-	-	360
Total for activities	290	210	300	1,780
Total for project planning	2,580			

Source: IRENA (2016c)

Other activities are less reliant on wind-specific knowledge, offering large potential for local value creation, such as manufacturing. The cost of a wind turbine constitutes between 65% and 85% of the total cost of the project, offering considerable potential for employment, and most of the jobs created can be fulfilled by the local workforce. Indeed, Table 4 shows that a large share of human resources required are factory workers with little or no wind-specific skills. It should be noted, however, that this phase is very capital-intensive, and its long-term value relies heavily on the existence of a market for the products, and on the implementation of specifications and standards that ensure good quality and timely delivery of products at competitive costs with international markets.

TABLE 4: HUMAN RESOURCES NEEDED FOR MANUFACTURING MAIN COMPONENTS (HUMAN-DAYS/50 MW)

Professions needed	Human resources to manufacture main components (human-days/50 MW)			
	Nacelle	Blades	Tower	Monitor and control system
Management	185	110	90	-
Industrial engineers	480	277	232	15
Factory workers	5,890	3,400	2,850	300
Experts in logistics	620	125	300	15
Experts in quality control	620	125	300	15
Marketing and commercial professionals	480	290	230	45
Administrative and accountant personnel	480	113	230	45
Safety experts	620	125	300	30
Telecommunication engineers	-	-	-	15
Experts in regulation and standardization	-	-	-	15
Total for main components	9,375	4,565	4,532	495

Total for manufacturing	18,967
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Source: IRENA (2016c)

An important factor that would maximise the benefits of manufacturing components locally is the availability of existing industries that produce the raw materials needed. Countries that have a domestic steel industry, for example, can benefit more from producing some of the components locally. Table 5 shows that there are required between 64 and 87 tonnes of steel to manufacture the subcomponents of a nacelle for a 3 MW wind turbine.

TABLE 5: RAW MATERIALS FOR A NACELLE OF A 3 MW TURBINE (TON/TURBINE)

Components	Raw materials to manufacture and assemble a nacelle of a 3 MW turbine (ton/turbine)			
	Steel (grey cast iron)	Aluminium	Copper	Glass Reinforced plastic
Hub	12.8 - 17.3	-	-	-
Gearbox	19.2 - 25.9	0.2 - 0.3	0.2 - 0.3	-
Generator	4.7 - 6.4		2.5 - 3.4	-
Frame, machinery and shell	27.5 - 37.2	2.9 - 4.0	1.3 - 1.8	1.0 - 1.3
Total	64.2 - 86.8	3.1 - 4.3	4.0 - 5.5	1.0 - 1.3

Source: IRENA (2016c)

Another factor that facilitates the decision to manufacture wind equipment locally is the logistical requirements associated with importing bulky parts, such as 53 meters long blades, especially when destined to remote areas with abundant wind resources. In some cases, setting up a manufacturing facility close to the location of the wind farm is more economic.

In the absence of manufacturing experience, some components can be transported, but at high cost. The estimated cost of transport of the components of a 50 MW wind farm by truck over a distance of 300 miles can reach up to US\$750,000. The human resources needed are summarised in Table 6, with a majority that can be sourced locally. Special equipment is needed for this activity, including high capacity trucks and specific trailers. Trains can be used if the land is flat and if tunnels, bridges and sharp curves can be avoided. Moreover, vessels can be used if the transport is carried out by sea, with cranes needed to lift the equipment in the lorry or the boat.

TABLE 6: HUMAN RESOURCES FOR TRANSPORTING PARTS BY TRUCK (HUMAN-DAYS/50 MW)

Human resources for transport by truck over 300 miles (human-days/50 MW)	
Truck drivers	500
Crane operators	125
Administrative personnel	125
Logistic experts	50
Experts in regulation	50
Technicians to supervise the loading and unloading	25
Total	875

Source: IRENA (2016c)

Parallel to the transport of equipment, installation of the project can start. This phase, lasting between 12 to 20 months, offers considerable opportunities for value creation, in particular, in construction and grid connection, where existing resources (equipment, labour, and expertise) can be leveraged. Table 7 shows the considerable number of job opportunities for construction workers and technicians in a 50 MW wind farm for installation and grid-connection.

TABLE 7: HUMAN RESOURCES NEEDED FOR PROJECT INSTALLATION AND GRID CONNECTION ACTIVITIES (HUMAN-DAYS/50 MW)

Professions needed	Human resources needed for project installation and grid connection (human-days/50 MW)				
	Site	Civil	Assembling	Grid	Commissio

	preparation	works	equipment	connection	ning
Engineers/construction foremen	320	1,000	600	-	-
Electrical/mechanical engineers	-	-	-	180	200
Construction workers and technicians	1,600	12,000	6,000	6,000	1,000
Logistic experts	120	120	-	-	-
Environmentalists	120	600	-	-	-
Safety experts	120	600	600	100	100
Quality control experts	-	-	-	100	-
Professionals managing cranes, trucks, etc.	-	-	3,000	-	-
Total for each activity	2,280	14,320	10,200	6,380	1,300
Total	34,480				

Source: IRENA (2016c)

O&M of a wind farm ensures more long-term activities (up to 25 years). Modern wind farms are automated and controlled by a supervisory control and data acquisition system (SCADA), and their operation is normally undertaken by remote operators that reset the systems after line or grid outages. As for the maintenance, it involves preventive and corrective maintenance and constitutes almost 50% of the total O&M costs (Table 8). However, the maintenance is usually undertaken by the original turbine manufacturer and/or subcontracted to engineering companies and is not necessarily localised. However, there is a considerable percentage of total O&M cost that is always spent domestically, such as insurance and land rental that can benefit local industries.

TABLE 8: OPERATION AND MAINTENANCE COST BREAKDOWN OF WIND ENERGY PROJECT

Onshore wind energy operation and maintenance cost breakdown		
Cost	US\$/MW	%
Wind turbine maintenance	20,100 - 24,500	47.6% - 49.3%
Electrical installation maintenance	1,100 - 1,300	2.6% - 2.6%
Insurances	7,500 - 9,800	18.9% - 18.4%
Land rental	4,000 - 6,000	11.7%-9.8%
Management and administration	8,100 - 9,900	19.2%-19.9%
Total	40,800 - 51,500	100%

Source: IRENA (2016c)

Finally, the decommissioning of the wind farm consists of planning the activity, dismantling the farm, recycling and disposing of equipment and clearing the site. These can be localised with little import requirements, as skills and equipment are usually available domestically.

The human resources for the decommissioning of a 50 MW wind farm are summarised in Table 9, with the majority required as technicians and civil works.

TABLE 9: HUMAN RESOURCES NEEDED FOR PROJECT DECOMMISSIONING ACTIVITIES (HUMAN-DAYS/50 MW)

Professions needed	Human resources needed for decommissioning (human-days/50 MW)			
	Planning the activity	Dismantling the project	Disposing of equipment	Clearing the site
Industrial/mechanical/electrical engineers	30	360	-	40
Environmentalists	25	180	40	90
Logistic experts	25	180	20	-
Technicians and civil workers	-	3,700	800	1,000
Lorry drivers and crane operators	-	1,800	-	-

Safety experts	-	-	40	90
Total for main activities	80	6,220	900	1,220
Total for decommissioning	8,420			

Source: IRENA (2016c)

In order to support local value creation from the deployment of wind project, when feasible, a broad range of cross-cutting policy instruments need to be implemented. Tailored to the specific country conditions and the level of maturity of the sector, the mix of policies should focus on building institutional and human capacity, promoting research and development, strengthening the domestic industry and creating an investment-friendly environment.

4. ENVIRONMENTAL IMPACTS

Wind energy is continually hailed as one of most the environmentally friendly energy resources; particularly that it is a low-carbon source. In addition to this, turbines have no water requirement during operation, and its effective land footprint can be minimised by 'sharing' the land with other activities. Wind power does have some substantial environmental impacts, not least determined by the perception within the local population of the severity of the impacts.

LAND USE

The land use requirement for wind energy is dependent on the size of the wind turbines and the terrain of the site used. Installations in hilly terrain may take advantage of the ridgelines for positioning the turbines. Meanwhile, installations on flat terrain are positioned more uniformly, and have a larger footprint. Research by NREL showed the total land footprint for wind farms in the United States averaged at 82 acres (333,000 m²) per MW⁶⁵.

As a general rule, the distance between turbines in the prevailing wind direction should be equivalent to 5-12 times the turbines' rotor diameter, while the spacing between turbines in a row perpendicular to the wind direction is 3-5 times the rotor diameter⁶⁶ (depending on various factors such as the wind direction distribution, ground roughness, vegetation or wind speed). While the spacing requirements of turbines averages for a very large land footprint, only a fraction (3-5%) of the land required is actually disturbed by the wind energy infrastructure (including roads, transmission lines and maintenance equipment); and the remainder of the land could be utilised for agriculture and transport links.

As offshore turbines are not situated on land, there is virtually no direct land footprint from offshore wind energy; however, their presence may have an effect on sea-based activities such as fishing, sea travel, and oil & gas extraction. Over the past years, the European research community has increased its interest on application of offshore aquaculture within offshore wind farms to combine sustainable uses of the ocean space⁶⁷.

LIFE-CYCLE EMISSIONS

Wind energy has some of the lowest life-cycle emissions of all the energy resources. Greenhouse gas emissions from wind energy are in the magnitude of 10-20 gCO_{2e}/kWh, up to 80% less than that from solar photovoltaics. About 86% of total GHG emissions occur

⁶⁵ NREL (2012)

⁶⁶ Langreder n.d.

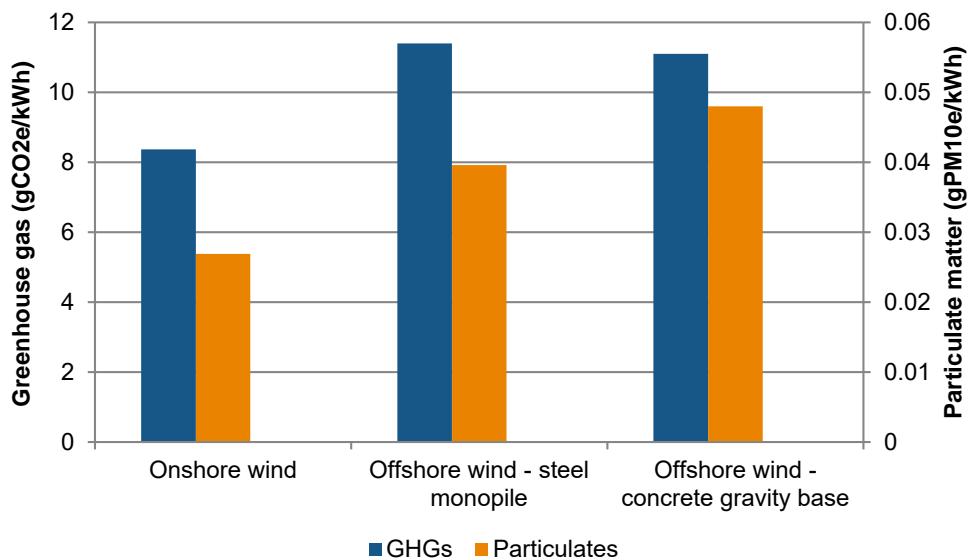
⁶⁷ Wever, Krause and Buck (2015)

in upstream processes⁶⁸, while up to half of emissions for offshore wind come from the extraction of the raw materials required for construction⁶⁹.

Operational wind power, however, will have an additional 'carbon cost', associated with the need to balance the grid in the face of wind intermittency. Fossil fuel generation required to back-up wind power operate at lower efficiencies, however the emissions savings obtained from wind power are still significant. For instance, the marginal displacement of wind power in the UK in 2012 was estimated at 550gCO₂/kWh, with 20% higher than the reported average emissions from electricity⁷⁰.

Figure 17 shows greenhouse gas, particulate matter and eco-toxicity emissions from wind energy.

FIGURE 17: LIFE-CYCLE EMISSIONS FROM WIND ENERGY, BY TECHNOLOGY



Source: Hertwich *et al.* (2014)

ECOLOGICAL IMPACTS

Concerns remain with the impacts of wind energy development on wildlife, in particular on bird species and bats. Bird and bat populations are directly affected through deaths from

⁶⁸ NREL (2013)

⁶⁹ Weisser, IEA

⁷⁰ Thomson and Harrison (2015a)

colliding with wind turbines. Wildlife may also deliberately avoid areas with turbines due to habitat fragmentation and degradation. Offshore wind farms may have effects on fish and marine life, particularly during the installation phase due to noise impact of piling operations on migratory fish. However, studies have continuously shown that these effects, in relative terms, are minimal; so long concerted efforts are made in the planning phase to ensure wind farms are not installed in areas where there will be a high risk of conflict with wildlife (e.g. bird migration routes).

PUBLIC HEALTH

Concerns with wind turbines on public health are mostly related to the sound and visual impacts of turbines. The sound emitted by turbines is predominantly of two types – aerodynamic noise from the movement of turbine blades through the air, and mechanical noise from the gearbox, generator etc. Newer turbine models generate significantly less mechanical noise. A general acceptable noise threshold for a wind farm is 35-45 db(A)⁷¹, about the same level of a quiet urban dwelling at night.

Visual impacts are more subjective, and depend on the opinion of the viewer. Anti-wind farm campaigners claim that wind turbines and associated infrastructure are an eyesore to the (especially rural) landscape. Shadow flicker is another potential problem with wind turbines, hence lighting conditions at a potential site are also taken into consideration during planning. Turbine towers and their moving blades may also interfere with electromagnetic signals, and may also affect radar systems. In the United States, measures are taken to eliminate any potential impacts from turbines on air travel. As with all structures 200 feet high and above, some turbines within a wind farm must have lighting to alert nearby aircraft.

⁷¹ Stevenson (2009)

5. OUTLOOK

PROSPECTS FOR DEPLOYMENT: GROWTH IN EMERGING AND NEW MARKETS

Market growth in the emerging markets of China, India, South America and Eastern Europe are expected to be maintained in the short-to-medium term. With the possible exception of Northern and Central Europe and Japan, overall onshore wind is expected to be further deployed, supported by continual cost reductions. For example, the highly competitive auction system implemented in Brazil will see installation costs drop sharply, from an average of US\$1,840 per kW in 2015 to around US\$1,600 by 2017⁷².

Offshore wind energy market is expected to continue growing in Europe and Asia, but also opportunities for new markets might emerge. The 30 MW offshore wind project under construction at Block Island, as well as increased activities to secured site control and conduct environmental surveys suggests that the next few years could see an expansion of offshore wind in North America⁷³.

GLOBAL FUTURE OUTLOOK

IRENA Remap analysis suggests that with current policy plans account for a global wind capacity rise from 435 GW in 2015 to 977 GW in 2030.⁷⁴ This includes 905 GW onshore and 72 GW offshore wind capacity. These projections significantly underestimate the wind sector dynamics. Even stabilisation at the annual capacity addition rate of 2015 would yield 1400 GW capacity in 2030. A technical and economic potential exists to accelerate deployment and reach 1879-2318 GW in 2030. This would imply a doubling of onshore wind and a quadrupling of offshore wind growth, compared to the reference case in 2030. It would imply more than a fourfold increase of the installed capacity from 2015 levels. The share of wind power could increase to more than 12% of total global power generation.

SCOPE FOR COST REDUCTION

Opportunities for cost reduction remain in the onshore wind sector. A study by KIC InnoEnergy suggests that thorough improvements in technology and operational processes could lower the average LCOE of onshore wind in Europe by 5.5% when comparing costs at final investment decision for 2014 and 2025⁷⁵. As shown in Figure 18, the biggest opportunities for reduction in LCOE come from improvements to the wind turbine rotor. Also, in some instances, improvements actually contribute to increase capital or O&M costs; indeed, CAPEX is predicted to rise by 3% during this period. However, these are

⁷² IRENA (2014) Renewable Cost Database

⁷³ IRENA (forthcoming), Off-shore wind technology: an innovation outlook

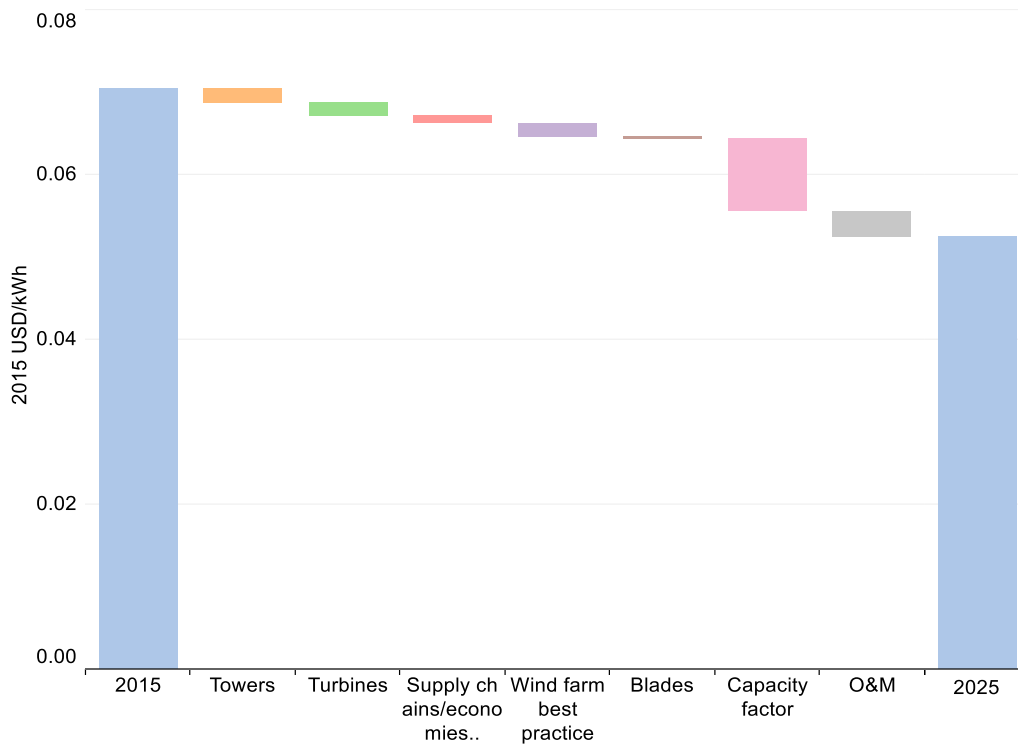
⁷⁴ IRENA (2016), REmap: A roadmap for a renewable energy future.

⁷⁵ KIC InnoEnergy (2014), Future renewable energy costs: Onshore wind

more than offset by increases in energy production – hence reiterating the desire of the industry to lower LCOE despite a possible increase in installation costs.

IRENA estimates that the global LCOE of onshore wind is likely to decrease to 26% in the period to 2025 mainly due to lower installed costs, higher capacity factors and declining O&M costs. Higher hub heights, rotor diameters and turbine rating will account for most of the decline in the LCOE of onshore wind.

FIGURE 18: ONSHORE COST REDUCTION POTENTIAL FROM 2015 TO 2025



Source: IRENA (2016)

TABLE 10: IMPACT OF INNOVATIONS IN ONSHORE WIND SECTOR BETWEEN 2014 AND 2025 ON COSTS FOR A WIND FARM AT A HIGH WIND SITE*

	Innovations	Impact on CAPEX	Impact on OPEX	Impact on AEP**	Impact on LCOE
Wind farm development	<ul style="list-style-type: none"> • Improvements in resource measurement • Improvements in resource modelling • Improved complex terrain and forest modelling 	0%	0%	0.4%	-0.4%
Turbine nacelle	<ul style="list-style-type: none"> • Improvements in mechanical geared high-speed drivetrains • Introduction of mid-speed drivetrains • Improvements in workshop verification testing • Improvements in AC power take-off system design 	-0.4%	-2.8%	0.3%	-1.1%
Turbine rotor	<ul style="list-style-type: none"> • Optimisation of rotor size with improved materials • Improvements in blade aerodynamics • Improvements in blade design standards and process • Improvements in blade pitch control • Introduction of inflow wind measurement • Introduction of active aero control on blades • Improvements in hub assembly components 	3.4%	-0.3%	5.9%	-3.0%
Balance of plant	<ul style="list-style-type: none"> • Introduction of concrete hybrid towers • Introduction of space frame steel towers 	0%	0.2%	0.4%	-0.4%
Construction and commissioning	<ul style="list-style-type: none"> • Improvement of transport vehicle design for site access • Introduction of multi-part blades 	0%	0%	0%	0%
Operation maintenance and	<ul style="list-style-type: none"> • Improvements in weather forecasting • Improvements in inventory management 	0.2%	-3.0%	0.5%	-0.9%

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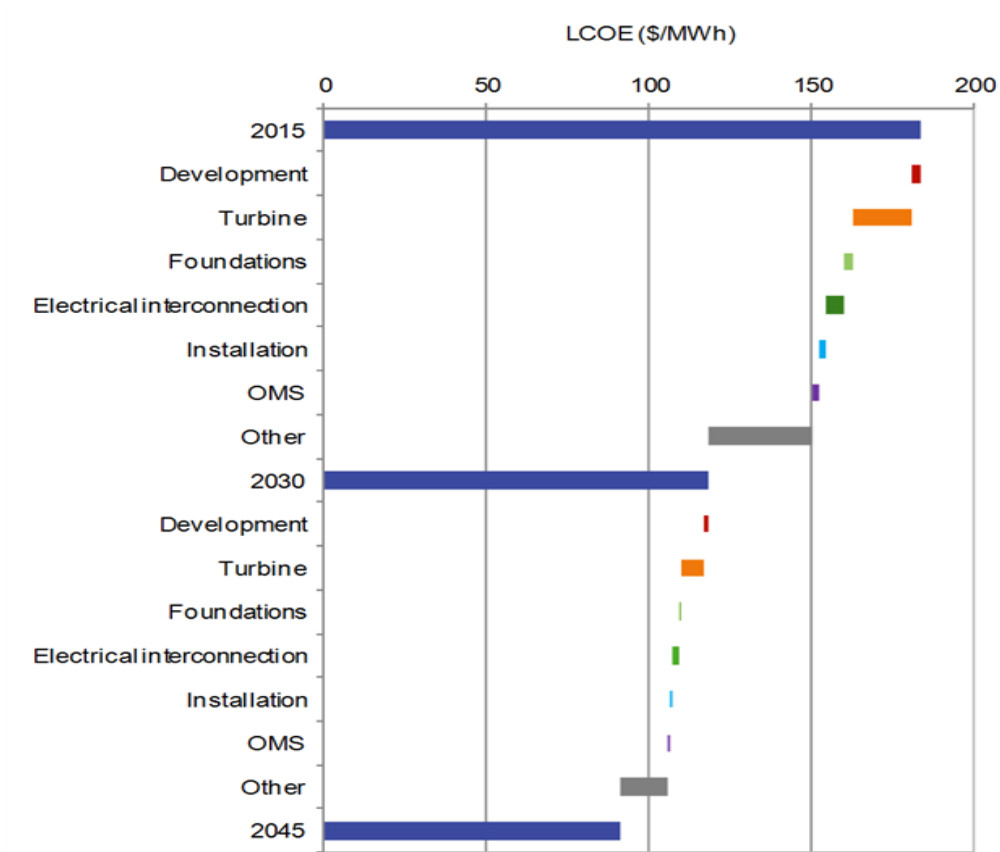
service	<ul style="list-style-type: none"> • Optimisation of blade inspection and repair • Introduction of turbine condition-based maintenance • Introduction of wind farm wide control strategies • Improvements to wind farm condition monitoring • Introduction of holistic asset management strategies 				
Total		3.2%	-5.8%	7.5%	-5.5%

**Negative values indicate a reduction in the item and positive values indicate an increase in the item. All OPEX figures are per year, beginning from year six of the wind farm's operation*

***AEP = annual energy production*

Source: KIC InnoEnergy (2015)

FIGURE 19: IMPACT OF INNOVATION IN EACH ELEMENT ON COST OF ENERGY FOR OFFSHORE WIND PROJECTS COMMISSIONED IN 2015 THROUGH 2045



Source: IRENA (forthcoming)

IRENA analysis⁷⁶ indicates that together technology innovations, added to a range of other non-technology factors, such as the characteristics of available sites, market scale and competition and, importantly, decreasing financing risk, may result in a decrease in the LCOE for off-shore wind farms up to 121 US\$/MWh by 2030 and 91 US\$/MWh by 2045. The cumulative impact of innovation in each element of the wind farm is shown in Figure 19.

⁷⁶ IRENA (forthcoming), Off-shore wind technology: an innovation outlook.

6. GLOBAL TABLE

TABLE 11: WIND POWER GLOBAL TABLE

Country	Total Wind Installed Capacity (MW) in 2015 IRENA (2016)	Onshore Wind (MW) in 2015 IRENA (2016)	Offshore Wind (MW) in 2015 IRENA (2016)	Wind Energy Consumption In 2015 Gigawatt-hours (GWh) ⁷⁷ BP (2016)	Total Wind Energy Generation in 2014 (GWh) IRENA (2016)	Share of Wind in Total Installed Capacity in 2015 (%) ⁷⁹ BP (2016)
Algeria	10	10	-	-	1	-
Argentina	279	279	-	706	619	0.1%
Armenia	4	4	-	-	4	-
Aruba	30	30	-	-	158	-
Australia	4 187	4 187	-	10 692	10 252	1.0%
Austria	2 411	2 411	-	5 119	3 846	0.6%
Azerbaijan	66	66	-	-	2	-
Bahrain	1	1	-	-	1	-
Bangladesh	2	2	-	-	4	-
Belarus	3	3	-	-	11	-
Belgium	2 229	1 517	712	5 564	4 614	0.5%

⁷⁷ Data from BP Statistical Review of World Energy (2016)

⁷⁹ Ibid

WORLD ENERGY COUNCIL | WIND

Country	Total Wind Installed Capacity (MW) in 2015 IRENA (2016)	Onshore Wind (MW) in 2015 IRENA (2016)	Offshore Wind (MW) in 2015 IRENA (2016)	Wind Energy Consumption In 2015 Gigawatt-hours (GWh) ⁷⁷ BP (2016)	Total Wind Energy Generation in 2014 (GWh) IRENA (2016)	Share of Wind in Total Installed Capacity in 2015 (%) ⁷⁹ BP (2016)
BES Islands	11	11	-	-	41	-
Bolivia	3	3	-	-	8	-
Brazil	8 715	8 715	-	21 737	12 210	2.0%
Bulgaria	700	700	-	1 450	1 331	0.2%
Cabo Verde	24	24	-	-	100	-
Cambodia	1	1	-	-	1	-
Canada	11 200	11 200	-	24 589	22 538	2.6%
Chile	904	904	-	2,125	1 443	
China	145 104	144 086	1 018	185 100	158 271	33.4%
Chinese Taipei	647	647	-	1 525	1 501	0.1%
Colombia	18	18	-	68	70	-
Costa Rica	268	268	-	-	753	0.1%
Croatia	423	423	-	-	730	-
Cuba	12	12	-	-	19	-
Curacao	30	30	-	-	200	-
Cyprus	158	158	-	-	182	-

Country	Total Wind Installed Capacity (MW) in 2015 IRENA (2016)	Onshore Wind (MW) in 2015 IRENA (2016)	Offshore Wind (MW) in 2015 IRENA (2016)	Wind Energy Consumption In 2015 Gigawatt-hours (GWh) ⁷⁷ BP (2016)	Total Wind Energy Generation in 2014 (GWh) IRENA (2016)	Share of Wind in Total Installed Capacity in 2015 (%) ⁷⁹ BP (2016)
Czech Republic	281	281	-	572	477	1.3%
Denmark	5 063	3 792	1 271	14 275	14 453	1.1%
Dominica	7	7	-	-	1	-
Dominican Republic	80	80	-	-	247	-
Ecuador	21	21	-	98	80	-
Egypt	610	610	-	1 505	1 332	0.2%
Eritrea	1	1	-	-	2	-
Estonia	341	341	-	-	604	-
Ethiopia	324	324	-	-	526	0.1%
Falklands Malv	2	2	-	-	5	-
Faroe Islands	20	20	-	-	35	-
Fiji	10	10	-	-	4	-
Finland	1 027	1 001	26	2 334	1 107	0.2%
France	10 358	10 358	-	20 166	17 249	2.4%
Germany	44 947	41 652	3 295	87 975	57 357	10.4%

WORLD ENERGY COUNCIL | WIND

Country	Total Wind Installed Capacity (MW) in 2015 IRENA (2016)	Onshore Wind (MW) in 2015 IRENA (2016)	Offshore Wind (MW) in 2015 IRENA (2016)	Wind Energy Consumption In 2015 Gigawatt-hours (GWh) ⁷⁷ BP (2016)	Total Wind Energy Generation in 2014 (GWh) IRENA (2016)	Share of Wind in Total Installed Capacity in 2015 (%) ⁷⁹ BP (2016)
Greece	2 152	2 152	-	4 631	3 689	0.5%
Grenada	1	1	-	4.6	-	-
Guadeloupe	23	23	-	-	54	-
Guatemala	50	50	-	-	-	-
Honduras	176	176	-	-	397	-
Hungary	329	329	-	696	657	0.1%
Iceland	3	3	-	-	8	-
India	25 088	25 088	-	41 404	33 455	5.8%
Indonesia	1	1	-	-	1	-
Iran	117	117	-	245	256	-
Ireland	2 486	2 461	25	6 570	5 140	0.6%
Israel	6	6	-	-	9	-
Italy	9 126	9 126	-	14 675	15 178	2.1%
Jamaica	42	42	-	-	119	-
Japan	3 035	2 985	50	5 398	2 196	0.7%
Jordan	119	119	-	-	2	-
Kazakhstan	68	68	-	-	13	-

Country	Total Wind Installed Capacity (MW) in 2015 IRENA (2016)	Onshore Wind (MW) in 2015 IRENA (2016)	Offshore Wind (MW) in 2015 IRENA (2016)	Wind Energy Consumption In 2015 Gigawatt-hours (GWh) ⁷⁷ BP (2016)	Total Wind Energy Generation in 2014 (GWh) IRENA (2016)	Share of Wind in Total Installed Capacity in 2015 (%) ⁷⁹ BP (2016)
Kenya	19	19	-	-	18	-
Korea Republic	869	859	11	1 605	1 077	0.2%
Latvia	69	69	-	-	141	-
Lebanon	1	1	-	-	1	-
Lithuania	424	424	-	808	639	
Luxembourg	58	58	-	-	80	-
Macedonia	37	37	-	-	71	-
Madagascar	1	1	-	-	-	-
Martinique	1	1	-	-	2	-
Mauritania	35	35	-	-	10	-
Mauritius	1	1	-	-	3	-
Mexico	3 073	3 073	-	7 947	6 426	0.7%
Moldova	1	1	-	-	1	-
Mongolia	51	51	-	-	125	-
Morocco	787	787	-	-	1 924	0.2%
Netherlands	3 431	3 004	427	7 491	5 797	0.8%

WORLD ENERGY COUNCIL | WIND

Country	Total Wind Installed Capacity (MW) in 2015 IRENA (2016)	Onshore Wind (MW) in 2015 IRENA (2016)	Offshore Wind (MW) in 2015 IRENA (2016)	Wind Energy Consumption In 2015 Gigawatt-hours (GWh) ⁷⁷ BP (2016)	Total Wind Energy Generation in 2014 (GWh) IRENA (2016)	Share of Wind in Total Installed Capacity in 2015 (%) ⁷⁹ BP (2016)
New Caledonia	38	38	-	-	57	-
New Zealand	623	623	-	2 357	2 214	0.2%
Nicaragua	186	186	-	-	846	-
Nigeria	2	2	-	-	2	-
Norway	863	861	2	2 515	2 216	0.2%
Pakistan	256	256	-	639	459	0.1%
Panama	270	270	-	-	116	-
Peru	143	143	-	602	258	-
Philippines	387	387	-	641	152	-
Poland	5 100	5 100	-	10 800	7 676	1.2%
Portugal	5 034	5 032	2	11 593	12 111	25%
Puerto Rico	125	125	-	-	218	-
Reunion	15	15	-	-	16	-
Romania	3 244	3 244	-	7 044	6 201	0.7%
Russian Federation	103	103	-	-	5	-

Country	Total Wind Installed Capacity (MW) in 2015 IRENA (2016)	Onshore Wind (MW) in 2015 IRENA (2016)	Offshore Wind (MW) in 2015 IRENA (2016)	Wind Energy Consumption In 2015 Gigawatt-hours (GWh) ⁷⁷ BP (2016)	Total Wind Energy Generation in 2014 (GWh) IRENA (2016)	Share of Wind in Total Installed Capacity in 2015 (%) ⁷⁹ BP (2016)
Samoa	1	1	-	-	2	-
Serbia	10	10	-	0.42	-	0.14%
Seychelles	6	6	-	-	7	-
Slovakia	3	3	-	-	6	-
Slovenia	4	4	-	-	4	-
Somalia	2	2	-	-	6	-
South Africa	1 053	1 053	-	2 135	600	0.2%
Sri Lanka	76	76	-	-	147	-
Spain	23 008	23 003	5	49 289	52 013	5.3%
St Kitts Nevis	2	2	-	-	8	-
St Pierre Mq	1	1	-	-	2	-
Sweden	6 025	5 813	212	16 617	11 234	1.4%
Switzerland	60	60	-	101	101	-
Syria	1	1	-	-	1	-
Thailand	223	223	-	427	305	0.1%
Tunisia	245	245	-	-	507	0.1%

WORLD ENERGY COUNCIL | WIND

Country	Total Wind Installed Capacity (MW) in 2015 IRENA (2016)	Onshore Wind (MW) in 2015 IRENA (2016)	Offshore Wind (MW) in 2015 IRENA (2016)	Wind Energy Consumption In 2015 Gigawatt-hours (GWh) ⁷⁷ BP (2016)	Total Wind Energy Generation in 2014 (GWh) IRENA (2016)	Share of Wind in Total Installed Capacity in 2015 (%) ⁷⁹ BP (2016)
Turkey	4 694	4 694	-	11 552	8 520	1.0%
Ukraine	426	426	-	1 025	1 172	
United Arab Emirates	1	1	-	-	1	-
United Kingdom	13 855	8 750	5 105	40 442	32 016	3.3%
United States of America (USA)	72 578	72 578	-	192 855	183 892	17.2%
Uruguay	845	845	-	-	733	-
Vanuatu	3	3	-	-	5	-
Venezuela	50	50	-	-	88	-
Vietnam	135	135	-	204	68	-
World Total	431 948	419 787	623	841 231	713 846	100%

Source: International Renewable Energy Agency IRENA (2016); BP Statistical Review of World Energy 2016 Workbook

Note: Numbers are approximated, with for instance figures between 1 and 1.5 shown as 1, and between 1.5 and 2, shown as 2.

Note: With regards to the Wind Generating Capacity (first column in the table above) the data per country exhibited above from IRENA, 2016 is slightly different than the data presented in BP Statistical Review of World Energy 2016. The former data source refers to the Installed Generating Capacity, while the latter refers to Cumulative Installed Wind Turbine Capacity. In this context, we included only the data from IRENA because it is more detailed in terms of countries reported and onshore/offshore division; in contrast with BP Statistical Review 2016, which was used for completing the last two columns.

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REFERENCES

- American Wind Energy Association AWEA (2016) *U.S. Wind Industry Annual Market Report Year Ending 2015*, Washington DC.
- American Wind Energy Association AWEA (2016) *U.S. Wind power jobs hit record, up 20 percent in 2016*, April 12, <http://www.awea.org/MediaCenter/pressrelease.aspx?ItemNumber=8736>
- Andrew (2016) 'Capacity factors at Danish offshore wind farms', *Energy Numbers*, May 19, <http://energynumbers.info/capacity-factors-at-danish-offshore-wind-farms>
- Arántegui, R. L. and González, J. S. (2015), *JRC wind status report. Technology, market and economic aspects of wind energy in Europe*, https://setis.ec.europa.eu/system/files/2014JRCwindstatusreport_EN_N.pdf
- ASX n.d. *New Zealand electricity*, <http://www.asx.com.au/products/energy-derivatives/new-zealand-electricity.htm>
- Bloomberg New Energy Finance, UNEP (2016) *Global trends in renewable energy investments*, http://fs-unep-centre.org/sites/default/files/publications/globaltrendsinrenewableenergyinvestment2016lowres_0.pdf
- Bloomberg New Energy Finance (2016) *In a first, Chinese firm tops annual rankings of wind turbine makers*, <http://about.bnef.com/press-releases/in-a-first-chinese-firm-tops-annual-ranking-of-wind-turbine-makers/content/uploads/sites/4/2016/02/2015-Wind-Market-Share.pdf>
- Bloomberg New Energy Finance (2015) *Q3 2015 Global Wind Market Outlook*.
- Bloomberg New Energy Finance (2015) *Q3/2015 Global Wind Power Market Outlook Update*, MAKE
- Bloomberg New Energy Finance BNEF (2015) *How Extending the Investment Tax Credit Would Affect US Solar Build*, 15 September.
- Bloomberg New Energy Finance BNEF (2014) *Gemini Offshore Wind*
- Broehl, J., R.R. Labastida and Hamilton, B. (2015) *World Wind Energy Market Update 2015*. Navigant Consulting. Boulder, Colorado. <http://www.navigantresearch.com/research/world-wind-energy-market-update-2015>.
- BTM Navigant (2015) *World Wind Energy Market Update 2015*, <http://www.provedor.nuca.ie.ufrj.br/estudos/navigant1.pdf>
- Danish Ministry of Energy, Utilities and Climate (2015) *Denmark gets cheaper power from offshore wind turbines*, February 27, <http://www.efkm.dk/en/news/denmark-gets-cheaper-power-from-offshore-wind-turbines>
- Deloitte for the New Zealand Wind Energy Association (2011) *Economics of wind development in New Zealand*.

- Department of Energy & Climate Change DECC (2015) *CFD auction allocation round one – a breakdown of the outcome by technology, year and clearing price*,
<https://www.gov.uk/government/statistics/cfd-auction-allocation-round-one-a-breakdown-of-the-outcome-by-technology-year-and-clearing-price>
- Environmental and Energy Study Institute (2016) *Fact Sheet: Offshore Wind - Can the United States Catch up with Europe?*, January 4, <http://www.eesi.org/papers/view/factsheet-offshore-wind-2016>
- EY (2015) *Renewable Energy Country Attractiveness*, Issue 43,
[http://www.ey.com/Publication/vwLUAssets/Renewable_Energy_Country_Attractiveness_Index_43/\\$FILE/RECAI%2043_March%202015.pdf](http://www.ey.com/Publication/vwLUAssets/Renewable_Energy_Country_Attractiveness_Index_43/$FILE/RECAI%2043_March%202015.pdf)
- Fillon, L. (2016) 'El Hierro, the Spanish island vying for 100% clean energy', in *Phys*, April 20,
<http://phys.org/news/2016-04-el-hierro-spanish-island-vying.html>
- Global Wind Energy Council GWEC (2014) *Global Wind Report – Annual market update*,
http://www.gwec.net/wp-content/uploads/2015/03/GWEC_Global_Wind_2014_Report_LR.pdf
- Gorona del Viento, n.d.
<http://www.goronadelviento.es/index.php?accion=articulo&IdArticulo=170&IdSeccion=89>
- International Energy Agency IEA (2013) *Technology Roadmap Wind Energy*,
https://www.iea.org/publications/freepublications/publication/Wind_2013_Roadmap.pdf
- International Energy Agency Wind IEA (2011) *2011 Annual Report*,
http://www.ieawind.org/annual_reports_PDF/2011/2011%20IEA%20Wind%20AR_1_small.pdf
- International Energy Agency-Energy Technology Systems Analysis Program and IRENA (2016) *Wind power technology brief E07*. Abu Dhabi.
- International Renewable Energy Agency IRENA (2016) *Renewable Energy Capacity Statistics*,
http://www.irena.org/DocumentDownloads/Publications/IRENA_RE_Capacity_Statistics_2016.pdf
- International Renewable Energy Agency IRENA (2016) *Remap: A roadmap for a renewable energy future*. Abu Dhabi.
- International Renewable Energy Agency IRENA (2016) *Quality Infrastructure for Renewable Energy Technologies: Small Wind Turbines*, Abu Dhabi.
- International Renewable Energy Agency IRENA (2016) *Scaling up Variable Renewable Power: The Role of Grid Codes*. Abu Dhabi.
- IRENA (2016a) *Renewable Energy Benefits: Measuring the Economics*, Abu Dhabi.
- IRENA (2016b) *Renewable Energy and Jobs: Annual Review 2016*, Abu Dhabi.
- IRENA (2016c) *Renewable Energy Benefits: Leveraging Local Industries*, Abu Dhabi.
- IRENA (2016) *Renewable energy statistics 2016*.
- IRENA (2015) *Renewable power generation costs*.

- IRENA (2016) *The Power of Change: Cost reduction potentials for solar and wind power technologies*. Abu Dhabi.
- IRENA (forthcoming), *Off-shore wind technology: an innovation outlook*. Abu Dhabi.
- IRENA, *Renewable Cost Database*
- Kenning, T. (2015) 'Spanish island's run of four hours on 100% renewables 'very significant', says IRENA expert', in *Energy Storage News*, august 26, <http://www.energy-storage.news/news/only-renewables-plus-energy-storage-power-spanish-island-for-four-hours>
- KIC InnoEnergy (2014) *Future renewable energy costs: Onshore wind*
- Kirk-Davidoff, D.B. (2012) 'Wind Power Forecasting', *Wind Systems*, <http://windsystemsmag.com/article/detail/355/wind-power-forecasting>
- Langreder n.d. *Siting of Wind Farms: Basic Aspects*, http://www.wwindea.org/technology/ch02/en/2_4_1.html
- Lawrence Berkeley National Laboratory (2015) *2014 Wind technologies Market Report*. CA: LBNL.
- Lemming JK, Morthorst PE, Clausen NE, Hjuler Jensen P. (2009) *Contribution to the Chapter on Wind Power in Energy Technology Perspectives 2008*, IEA. Roskilde, Denmark: Risø National Laboratory.
- Ministry of Business, Innovation & Employment MBIE n.d. *Electricity demand and generation scenarios*, <http://www.mbie.govt.nz/info-services/sectors-industries/energy/energy-data-modelling/modelling/electricity-demand-and-generation-scenarios/>
- Morris, C. (2015) *German offshore wind progress*, August 17, <http://energytransition.de/2015/08/german-offshore-wind-progress/>
- National Renewable Energy Laboratory NREL (2015) *2014-2015 Offshore Wind Technologies Market Report*, <http://www.nrel.gov/docs/fy15osti/64283.pdf>
- National Renewable Energy Laboratory NREL (2013) *Wind LCA Harmonization*, <http://www.nrel.gov/docs/fy13osti/57131.pdf>
- National Renewable Energy Laboratory NREL (2012) *Renewable electricity futures study*
- New Zealand Wind Energy Association n.d. *A kiwi success story*, <http://www.windenergy.org.nz>
- Rapin, M. and Noël, J. M. (2010) *Energie Eolienne, Principe et Etudes de cas*. Dunod, Paris
- REE, Red Electrica de España (2016) <https://demanda.ree.es/visionaCan/VisionaHierro.html#app=2547&9127-selectedIndex=0>
- Renewable UK, n.d. *UKWED Figures explained*, <http://www.renewableuk.com/en/renewable-energy/wind-energy/uk-wind-energy-database/figures-explained.cfm>
- Smith, P. (2014) *Question of the week: Are offshore projects built to last?*, November 3, <http://www.windpowermonthly.com/article/1320109/question-week-offshore-projects-built-last>
- Stevenson, R. (2009) *Environmental Impact Assessment for Wind Farms*

- Thomson, R. C. and Harrison, G. P. (2015a) *Life cycle costs and carbon emissions of offshore wind power: Main report*. Edinburgh, Scotland: ClimateXChange.
- WASP n. d. *Toolbox for wind and site data analysis*, http://www.wasp.dk/DataandTools#wind-atlas__global-wind-atlas
- Wever, L., Krause, G. and Buck, B. H., (2015) 'Lessons from stakeholder dialogues on marine aquaculture in offshore wind farms: Perceived potentials, constraints and research gaps', *Marine Policy*, 51, pp. 251–259
- Wind Energy (2010) *The facts*, <http://www.wind-energy-the-facts.org/>
- Windpower Monthly, *Optimising wind farms in cold climates*, <http://www.windpowermonthly.com/>
- Wiser, R. and Bolinger, M. (2015) *2014 Wind Technologies Market Report*, U.S. Department of Energy, <http://energy.gov/sites/prod/files/2015/08/f25/2014-Wind-Technologies-Market-Report-8.7.pdf>
- Weisser, International Energy Agency n.d. *A guide to life-cycle greenhouse gas (GHG) emissions from electric supply technologies*, https://www.iaea.org/OurWork/ST/NE/Pess/assets/GHG_manuscript_preprint_versionDanielWeisser.pdf
- Wiser, R. and Bolinger, M. (2014) *2013 Wind Technologies Market Report*, U.S. Department of Energy, https://emp.lbl.gov/sites/all/files/2013_Wind_Technologies_Market_Report_Final3.pdf
- World Wind Energy Association (2016) *The World sets New Wind Installations Record: 63,7 GW New Capacity in 2015*, <http://www.wwindea.org/>
- World Wind Energy Association WWEA (2015) *Small wind world report, 2015 summary*. Bonn.
- 4C Offshore (2016) *Offshore Wind Farm Subscription, Market Overview Report Sample*. Available at: http://www.4coffshore.com/windfarms/downloads/samples/20160404_OverviewReportSample.pdf

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KEY FINDINGS

1. Marine is more viable.
2. Tidal is the more developed, but strong degree of support for ocean technologies.
3. Resources potential is huge.
4. Hostile financial environment, costs are high.
5. There could be a 'high scenario' for wave and tidal energy deployment the global market.
6. 0.5 GW of commercial marine energy generation capacity is in operation and another 1.7 GW under construction, with 99% of this accounted for by tidal range.
7. Environmental impacts on marine animals, underwater noise and disruption of natural movement of water are still a challenge.
8. 'High scenario' for wave and tidal energy deployment the global market could be 'worth up to c.£460bn (cumulative, undiscounted) in the period 2010-2050, with the market reaching up to c.£40bn per annum by 2050
9. If ocean energy deployment was on track to reach 748 GW by 2050 this could create approximately 160,000 direct jobs by 2030
10. The total theoretical wave energy potential is said to be 32 PWh/y, but is heterogeneous and geographically distributed, technology costs for marine energy are still very high, hindering deployment

INTRODUCTION

The conversion of ocean energy resources to electricity could play an important role in meeting rising global energy demand, mitigating climate change, diversifying our energy supply and bolstering economic activity. However, at to date only a handful of commercial ocean energy projects have been delivered, reflecting the current immaturity and high costs of these technologies, as well as the challenging market environment in which they operate.

This chapter examines four key sub-categories of ocean energy technology: wave, tidal stream, tidal range and ocean thermal energy conversion (OTEC). Unfortunately, it is difficult to draw a meaningful comparison of the theoretical global energy resource for each of these technologies but we find that in general wave energy and OTEC have a more abundant and spatially distributed resource versus tidal stream and range. Taken together, ocean energy presents a huge untapped resource available to most coastal countries in one form or another.

Today 0.5 GW of commercial ocean energy generation capacity is in operation and another 1.7 GW under construction, with 99% of this accounted for by tidal range. While relatively few commercial scale wave, tidal stream or OTEC projects are operational we find three tidal stream commercial projects accounting for 17 MW of capacity (two in Scotland and one in France) and a 1 MW commercial wave energy array in Sweden are to be commissioned shortly. A host of OTEC projects are also gathering momentum, with two 10 MW schemes being developed, one by DCNS in Martinique and the other by Lockheed Martin in China. If all planned commercial projects reach fruition then an additional 15 GW of ocean energy capacity will come online over the coming years, however in reality a fraction of this is likely to be delivered. Whilst the traditional leaders of this sector, namely the UK and US, continue to develop flagship projects we find other countries such as South Korea, Ireland, the Netherlands and China are now challenging their dominance.

Despite these positive developments a large number of projects have been suspended largely as a result of public and private funds having been withdrawn due to slow economic growth, falling oil prices and a failure by marine energy technology developers to deliver on initial expectations about their technologies' potential cost-effectiveness. The wave energy sector has been hit particularly hard by leading companies such as Pelamis and Aquamarine falling into administration.

Looking forward we find that the respective costs of these different ocean energy technologies remain a significant barrier to deployment. Innovation will be key to reducing and efforts will need to focus on sub-component (e.g. power take off, prime mover, control systems), component integration and array optimisation RD&D. In addition, various socio-economic, infrastructural and environmental barriers also need to be addressed such as developing supportive energy market conditions, delivering facilitative infrastructure,

providing grid connection, growing supply chains and mitigating against associated environmental impacts.

1. ENERGY RESOURCE POTENTIAL

DEFINITIONS AND RESOURCE POTENTIAL

In this section we provide an overview of the four types of ocean energy resources under consideration and the level of resource that could potentially be extracted.

Wave energy

Waves are generated when the wind blows over the ocean's surface, which itself is a function of temperature and pressure differences across the globe caused by the distribution of solar energy¹. Wave energy carries both kinetic and gravitational potential energy, the level of which is a function of both the height and period of the wave². Harnessing this energy using a wave energy convertor (WEC) can in turn generate electricity.

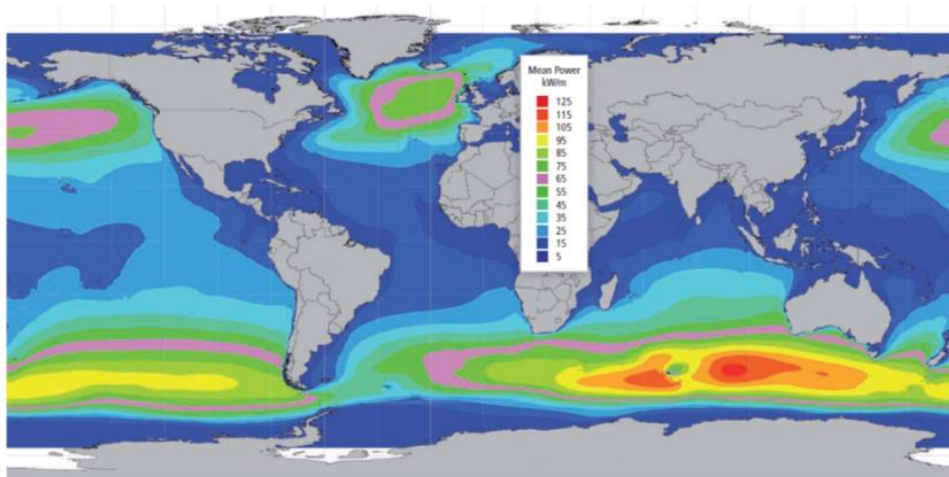
Following a study conducted on behalf of the International Panel on Climate Change (IPCC)³ we find that Mørk et al.(2010) estimate the total theoretical wave energy potential to be 32 PWh/yr, roughly twice the global electricity supply in 2008 17 PWh/yr. Figure 1 shows the regional distribution of the global annual wave energy potential, demonstrating how this resource is most abundant in the mid to high latitudes of both hemispheres.

¹ Barstow et al. (2007)

² Barstow et al. (2007)

³ Lewis et al. (2011)

FIGURE 1: GLOBAL OFFSHORE ANNUAL WAVE POWER LEVEL DISTRIBUTION



Source: Cornett (2008)

In absolute terms Table 1 illustrates how Asia and Australasia receive the largest quantity of wave energy, with South and North America also receiving impressive amounts. Despite its rich resource on its western seaboard Western and Northern Europe performs moderately well given its relatively small size. Finally, Central America and the Mediterranean Sea and Atlantic Archipelagos perform poorly given their mid-latitude position.

TABLE 1: REGIONAL THEORETICAL POTENTIAL OF WAVE ENERGY

REGION	Wave Energy TWh/yr
Western and Northern Europe	2,800
Mediterranean Sea and Atlantic Archipelagos (Azores, Cape Verde, Canaries)	1,300
North America and Greenland	4,000
Central America	1,500
South America	4,600

Africa	3,500
Asia	6,200
Australia, New Zealand and Pacific Islands	5,600
TOTAL	29,500

Source: Mørk et al. (2010)

Note: The total resource potential is less than 32,000 TWh/yr quoted previously as the table accounts for only theoretical wave power $P \geq 5 \text{ kW/m}$ and latitude $\leq 66.5^\circ$

These estimates do not account for geographical, technical or economic constraints and the sum of energy that could be practically recovered will ultimately be an order of magnitude less. Various estimates about what can practically be recovered have been made with Pelc and Fujita (2002) estimating that 5.5 PWh/yr is realistic, while both Thorpe (1999) and Cornett (2008) are less optimistic estimating approximately 2 PWh/yr. Naturally these estimates are based on different underpinning assumptions and what is deemed 'economically viable' will undoubtedly change over time if existing technologies fall in cost or new technologies emerge.

Tidal stream

Oceanic tides are the function of the motion of the moon and sun relative to the earth. These gravitational forces in combination with the rotation of the earth on its axis cause periodic movements of the oceans and seas⁴. As explained by Mofor et al.(2014) 'the vertical rise and fall of water, known as tides...is accompanied by an incoming (flood) or outgoing (ebb) horizontal flow of water in bays, harbours, estuaries and straits' (p.4). It is this flow that is known as tidal current or tidal stream. Tidal stream devices working in a similar fashion to wind turbines using water currents instead of wind to convert kinetic energy into electricity.⁵

The energy potential of tidal currents is typically located in areas with the greatest tidal range. Consequently, Figure 2 is a good indicator of where the greatest tidal stream potential exists. However, this potential increases in areas where the flow of water is constrained or funnelled by local topography such as narrow straits and headlands, and where the water depth is relatively shallow⁶. 'In particular, large marine current flows exist

⁴ SI Ocean (2012)

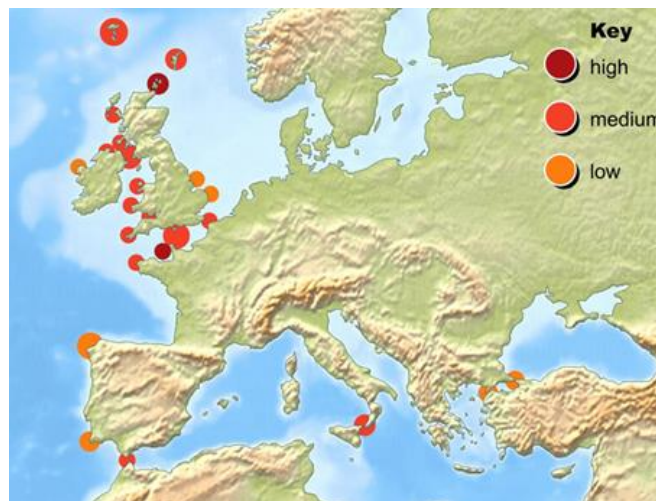
⁵ Magagna & Uihlein (2015)

⁶Aqua-RET (2012); Mofor et al. (2014)

where there is a significant phase difference between the tides that flow on either side of large islands⁷.

It is difficult to identify reliable estimates for global tidal stream energy potential but Charlier & Justus (1993) estimate total tidal energy potential (i.e. tidal range and tidal stream) at 3 TW, with 1 TW located in relatively shallow waters. However, due to geographical, technical and environmental constraints only a fraction of this could be captured in practical terms. In practice, suitable locations need mean spring peak tidal currents that are faster than 2-2.5 m/s to offer an energy density that allows for an economically viable project,⁸ accounting for the fact that as the tide changes there will be little or no horizontal flow of water.⁹ Importantly, 'major tidal streams have been identified along the coastlines of every continent, making it a global, albeit site specific, resource'¹⁰. For example, at the European level 106 locations with a strong tidal stream potential were identified, together offering 48 TWh/yr (0.17 EJ/yr) of potential resource¹¹. A similar study examined Europe's tidal stream potential identifying that it was predominantly concentrated around the British Isles and English Channel¹² (Figure 2).

FIGURE 2: EUROPEAN TIDAL STREAM RESOURCE DISTRIBUTION (AQUA-RET 2012)



Source: Aqua-RET (2012)

⁷ Aqua-RET (2012)

⁸ Aqua-RET (2012)

⁹ Mofor et al. (2014)

¹⁰ Mofor et al. (2014) p.4

¹¹ CEC (1996)

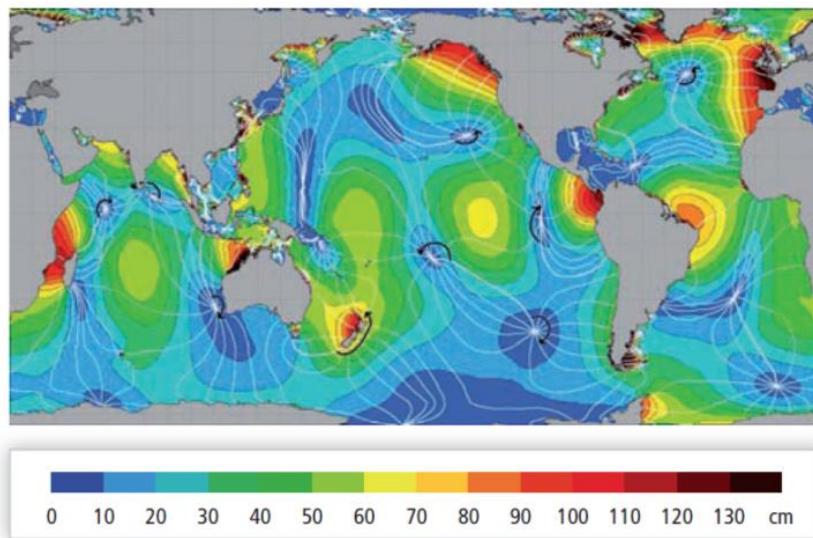
¹² Aqua-RET (2012)

Tidal range

The gravitational forces from the sun and moon generate oceanic tides and the difference in sea level between high and low tide is known as the tidal range. At most coastal sites high and low tides occur twice a day (semi-diurnal tides), however in some places just one high and low tide takes place per day (diurnal tides) whilst others experience a combination of diurnal and semi-diurnal oscillations (mixed tides)¹³. Even so these tides have been studied for centuries and can be easily forecast meaning that tidal range energy offers both a consistent and predictable form of energy.

Figure 3 demonstrates how the tidal range resource potential varies considerably across the globe and is ‘amplified by basin resonances and coastline bathymetry to create large surface elevation changes at specific geographic locations’.¹⁴ Consequently, some areas exhibit huge tidal ranges, like the Bay of Fundy in Canada (17 m tidal range), Severn Estuary in the UK (15 m) and Baie du Mont Saint Michel in France (13.5 m).¹⁵ In contrast other locations such the Mediterranean see a tidal range of less than 1 m.¹⁶

FIGURE 3: GLOBAL SEMIDIURNAL (M2) TIDAL AMPLITUDE



Source: NASA (2006)

¹³ Mofor et al. (2014)

¹⁴ Mofor et al. (2014 p.2).

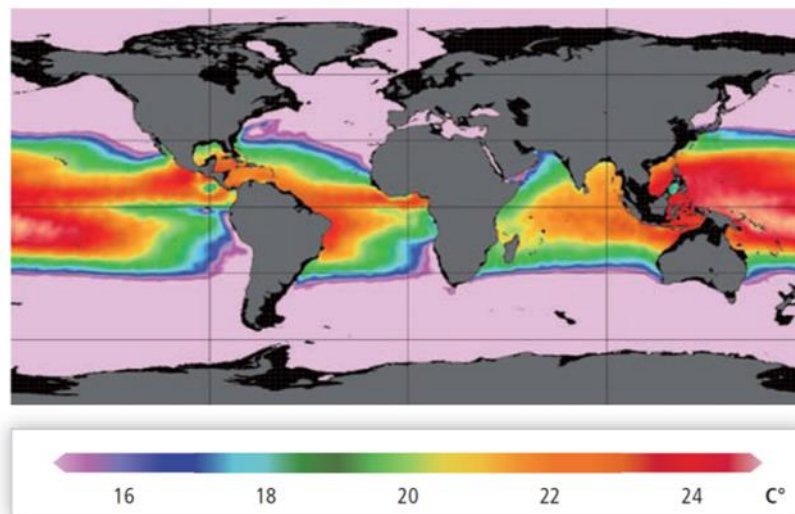
¹⁵ Kerr (2007)

¹⁶ Usachev (2008)

OTEC

Approximately 15% of the total solar energy falling incident on the oceans is retained as thermal energy and stored as heat in the upper layers of the ocean.¹⁷ This energy is concentrated in the top layers and falls exponentially with depth as the thermal conductivity of sea water is low¹⁸. As illustrated by Figure 4, the temperature differential in the tropics can exceed 25°C between 20 m and 1 km in depth¹⁹. The temperature gradient between the relatively warm sea surface water and the colder, deep seawater can be harnessed using different ocean thermal energy conversion (OTEC) (see Technologies section). OTEC typically requires a differential of about 20°C to work effectively meaning where cool water (~5°C) is drawn from depths of around 800–1000 m and surface water temperatures sit at a constant 25°C²⁰. Consequently, its potential application is limited to between 35° latitude north and south of the equators. Whilst small seasonal variations do occur this energy potential is available all-year round, although its power density is considered relatively low.²¹

FIGURE 4: WORLDWIDE AVERAGE OCEAN TEMPERATURE DIFFERENCES (°C) BETWEEN 20 AND 1,000 M WATER DEPTH (NIHOUS 2010)



Source: Nihous (2010)

¹⁷ Lewis et al. (2011)

¹⁸ Lewis et al. (2011)

¹⁹ Nihous (2010)

²⁰ NOAA (2014); Kempener & Neumann (2014a)

²¹ Lewis et al. (2011); Mofor et al. (2014)

Estimates of the total potential global OTEC energy resource that could be extracted without having a major impact on the thermal characteristics of the world's oceans range between 30 and 90 PWh.²² On this basis there is a much larger potential resource versus the other forms of ocean energy. However, the resource that could practically and economically be captured is significantly limited by economic and technical constraints.

²² Pelc & Fujita (2002); Nihous (2010); Charlier & Justus (1993)

2. TECHNOLOGIES

In this section we provide an overview of the key characteristics of the four ocean energy technologies covered in this report. We begin by examining wave and tidal stream energy, before turning to tidal range and OTEC.

WAVE ENERGY

Six key dimensions make up a wave energy device, which together ultimately convert the movement or flow of the oceans into electricity²³. These are equally applicable to tidal stream covered in the following sub-section:

1. **Structure and Prime Mover:** The physical structure of the device which captures energy and the main interface between the resource and the power take off equipment within the ocean energy converter. The predominant structural material is steel, although certain concepts are exploring alternatives. Prime movers such as turbine blades are made of composite materials.
2. **Foundations and Moorings:** The method used to secure the device to the sea bed. This includes permanent foundation constructions such as gravity bases or pile-pinned foundations, or could consist of moorings such as tight or slack moored systems.
3. **Power Take Off:** The means by which the mechanical energy extracted from the waves or tides is converted into electrical energy. Several types of Power Take Off (PTO) exist including mechanical, hydraulic, or electrical direct drive using permanent magnet generators.
4. **Control:** Systems and software to safeguard the device and optimise the performance under a range of operating conditions. Control systems may adjust certain parameters of the device autonomously in order to ensure favourable operation.
5. **Installation:** The method of placing the structure and device at its power generating location. This includes all vessels and ancillary equipment needed to fully deploy an ocean energy device.

²³ SI Ocean (2012)

6. **Connection:** The cables and electrical infrastructure for connecting the power output from the device to the electricity network. Alternatively, water is pumped ashore for conversion to electricity and/or desalinated water. Subsequently, power conditioning systems and transformers are needed to provide a grid code compliant electrical output.

Wave energy devices are broadly located in three different ocean environments: onshore, nearshore and offshore. In the following we provide a description of these and their relative strengths and weaknesses:

- **Shoreline devices** - integrated into a natural rock face or man-made breakwater²⁴ having the advantage of being close to the utility network and relatively easy to maintain. Less likely to be damaged as energy is lost due to friction with the seabed, however this reduces the potential resource that could be captured.²⁵
- **Near-shore devices** - located in water shallow enough to allow the device to be fixed to the seabed either via pinned pile foundations or gravity mass²⁶. This in turn provides 'a suitable stationary base against which an oscillating body can work'²⁷. Disadvantages are similar to shoreline devices.
- **Offshore devices** - located in water tens of metres deep and tethered to the seabed using tight or slack moorings mass.²⁸ Much greater potential energy resource versus on - or nearshore but more difficult to construct, operate and maintain and must be designed to survive more extreme conditions.²⁹

In each of these locations we typically find different types of devices as outlined in Figure 5, which are described in detail in Table 2.

²⁴ SI Ocean (2012)

²⁵ SI Ocean 2012; Drew et al. (2009)

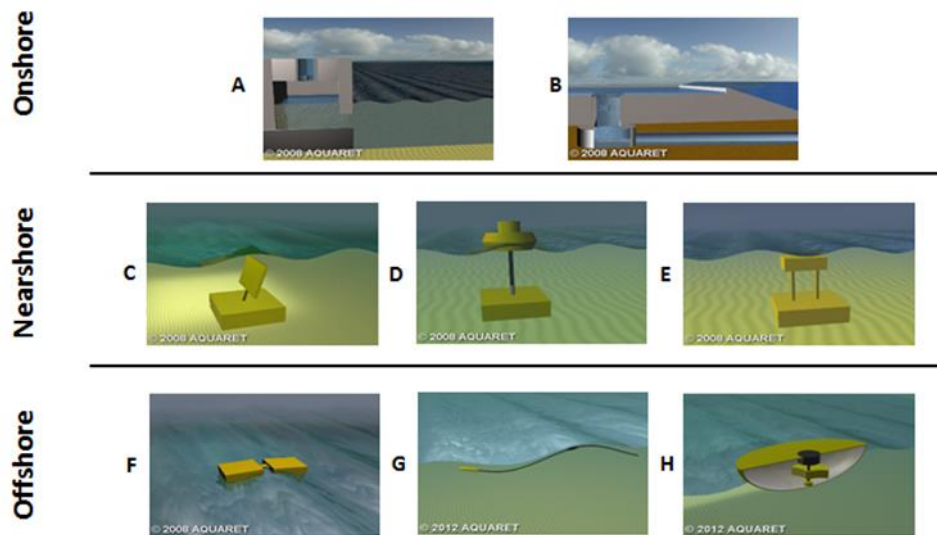
²⁶ SI Ocean (2012)

²⁷ Drew et al. (2009 p.888)

²⁸ Drew et al. (2009; SI Ocean (2012)

²⁹ Drew et al. (2009)

FIGURE 5: SCHEMATIC OF TYPICAL WAVE ENERGY DEVICES³⁰



Source: Aquaret (2012)

TABLE 2: TYPICAL WAVE ENERGY CONVERTORS

Location	Device type	Description
Onshore	Oscillating water columns (OWC)	Oscillating water columns (OWC) use the oscillatory motion of a mass of water induced by a wave in a chamber to compress air to drive an air turbine. The water column thus acts as a piston on the air volume, pushing it through the turbine as the waves increase the water level in the chamber, and drawing it as the water level decreases. OWCs are one of the first types of wave energy converters developed, and different operational ones are installed onshore in self-contained structures. Floating OWCs have been tested and are currently under development for offshore deployment.
	Overtopping devices or	Overtopping devices or terminator WECs convert wave energy into potential energy. This is stored in a reservoir and used to drive low-head turbines. The

³⁰ Note: A - Oscillating water columns (OWC); B - Overtopping devices or terminator WECs; C - Oscillating wave surge converters; D - Point Absorber; E - Submerged Pressure Differential devices; F – Attenuator, G - Bulge wave devices; H - Rotating mass converters

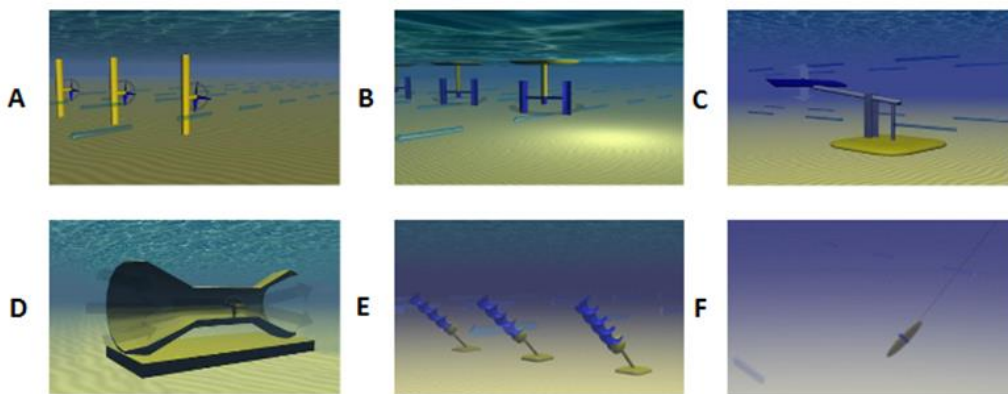
	terminator WECs	design of overtopping devices facilitates waves breaking on a ramp to be collected in a reservoir above the free water surface. Water contained in the reservoir can produce energy by flowing through a low-head hydraulic turbine. Overtopping devices have been proposed to be built for integration in breakwaters, for self-contained onshore operation and for offshore installation.
Nearshore	Oscillating wave surge converters	Oscillating wave surge converters exploit the surging motion of near-shore waves to induce the oscillatory motion of a flap in a horizontal direction. OWSCs are bottom-mounted devices, although prototypes of floating OWSC are already under development.
	Point Absorber	Point absorbers are normally heaving/pitching devices that exploit the relative motion between an oscillating body and a fixed structure or component, which can be either moored to the seabed or installed on the seabed through a large foundation mass. Point absorbers are normally smaller in dimension compared to other WECs. They are non- directional devices, as their performances are not affected by wave directionality.
	Submerged Pressure Differential devices	Submerged Pressure Differential devices are fully submerged devices, exploiting the hydro- dynamic pressure induced by waves to force an upward motion of the device, which then returns to its starting position once the pressure differential is reduced.
Offshore	Attenuator	Attenuators exploit the incoming wave power to generate an oscillatory motion between adjacent structural components. The resulting motion activates the power take-off (PTO), either by pumping high-pressure fluids through a hydraulic motor or by operating a direct- drive generator. Attenuators are designed to operate offshore, and are commonly surface floating, although fully submerged devices have been proposed.
	Bulge wave devices	Bulge wave devices use wave-induced pressure to generate a bulge wave within a flexible tube. As the bulge wave travels within the device it increases in size and speed. The kinetic energy of the bulge is used to drive a turbine at the end of the tube.
	Rotating mass converters	Rotating mass converters exploit the relative motion of waves to induce pitching and rolling in a floating body, thus forcing the rotation of an eccentric mass contained within the device. As the mass rotates it drives an electrical generator.
	Other	Novel wave energy devices currently under development that do not fit any of the above categories.

Source: Magagna & Uihlein (2015); EMEC (2016)

TIDAL STREAM

Tidal stream devices convert the kinetic energy of free flowing water into electricity. Numerous different types of devices exist and these typically fall into six categories as illustrated in Figure 6 and described in Table 3.

FIGURE 6: SCHEMATIC OF TYPICAL TIDAL STREAM ENERGY DEVICES³¹



Source: Aquaret (2012)

TABLE 3: TYPICAL TIDAL ENERGY CONVERTORS

Device type	Description
Horizontal-Axis Turbine	Similarly, to wind energy converters, this technology exploits the lift from the tidal flow to force the rotation of the turbine mounted on a horizontal axis. This operates a rotor, converting mechanical energy to electrical energy through use of a generator.
Vertical-Axis Turbine	The principle of operation of vertical axis turbines is similar to the horizontal devices, except the turbines are mounted on a vertical axis.
Oscillating Hydrofoil (Reciprocating)	Oscillating hydrofoils comprise a hydrofoil located at the end of a swing arm, which is allowed to oscillate in pitching mode by a control system. The motion is then used to pump hydraulic fluid through a motor. The rotational motion that results can be

³¹ Note: A - Horizontal-Axis Turbine; B - Vertical-Axis Turbine; C - Oscillating Hydrofoil (Reciprocating Device); D - Ducted Turbine or Enclosed Tips; E - Archimedes' Screw; F - Tidal Kite

Device)	converted to electricity through a generator.
Ducted Turbine or Enclosed Tips	Enclosed tips (ducted) turbines are essentially horizontal-axis turbines contained within a Venturi duct. This is designed to accelerate and concentrate the fluid flow. Ducted structures could also reduce turbulence around the turbines and facilitate the alignment of water flow towards the turbines.
Archimedes' Screw	These devices are a variation of the on vertical-axis turbines, drawing power from the tidal stream as the water flows up through the helix.
Tidal Kite	Tidal kite devices comprise a tethered kite with a small turbine. The kite effectively flies through the flow, increasing the relative flow velocity entering the turbine.
Other	Novel tidal concepts currently under development that do not fit any of the above categories.

Source: Magagna & Uihlein (2015); EMEC (2016)

To date tidal stream has exhibited a much stronger degree of technological convergence compared with wave energy, with approximately $\frac{3}{4}$ of all R&D investments focusing on horizontal axis turbines versus other designs³². A contributing factor may well be the dominance of horizontal axis turbines in the wind industry, which work on very similar engineering principles and the ability to draw upon expertise from this sector for technology development. Importantly tidal devices must be 'designed to suit the higher density and different characteristics of the surrounding environment'³³, as well as accounting for factors such as reversing flows, cavitation and harsh underwater marine conditions (e.g. corrosion, debris and fouling).³⁴

TIDAL RANGE

Tidal range technology shares a range of similarities with hydropower, capitalising on the artificial height differential of two bodies of water created by a dam or barrier, and the gravitational potential energy this provides, to generate electricity via a low-head hydroelectric turbine.³⁵

Tidal range plants normally take two forms: tidal barrage or tidal lagoon. Tidal barrages work on a very similar basis to a hydroelectric power plant by damming the flow of water

³² Corsatea & Magagna (2013)

³³ Mofor et al. (2014 p.4)

³⁴ Lewis et al. (2011)

³⁵ Mofor et al. (2014)

either into or out of a tidal inlet (Figure 7). The gravitational potential difference between the two bodies of water either side of the barrage drives an electrical turbine, normally a bulb turbine commonly found in hydro plants as at the La Rance tidal range facility in France.³⁶ A tidal lagoon is different in the sense that it is an independent enclosure that is typically located away from estuarine areas.³⁷ These offer greater flexibility in terms of capacity, are considered less costly and offer little or no impact on delicate estuarine environments.³⁸

FIGURE 7: LA RANCE TIDAL RANGE BARRAGE IN FRANCE



Source: Tethys (2012)

Traditional tidal range plants can also be single or multi-basin schemes. Single basin plants are the traditional model where a barrage or lagoon creates a single basin of water that drains or fills in sync with the tides, thus constraining the flexibility of its generating capacity. Multi-basin schemes on the other hand 'are filled and emptied at different times with turbines located between the basins' thus offering 'more flexible power generation availability over normal schemes, such that it is possible to generate power almost continuously'.³⁹

The main advantage of tidal range technology is that it is highly predictable and could therefore, offer an important source of baseline electricity generation at easily forecastable

³⁶ Bosc (1997)

³⁷ Magagna & Uihlein (2015); Mofor et al. (2014)

³⁸ Lewis et al. (2011)

³⁹ Lewis et al. (2011 p.510)

times of the day.⁴⁰ However, there are numerous concerns in relation to its impact on the local estuarine environment and socio-economic activities such as shipping, tourism etc. explored (see Economics and Markets section).

OTEC

OTEC takes advantage of the temperature differential between the relatively warm surface waters and the significantly cooler deep waters to drive an electrical turbine. Ocean thermal energy conversion (OTEC) plants fall into three conversion types: open, closed and hybrid.⁴¹

- **Open-cycle** - Warmer surface water is flash evaporated in a very low-pressure environment and the water vapour is then used to drive the electrical generator. The vapour is condensed using the cold sea water pumped up from below to complete the cycle⁴². This system has the advantage of generating desalinated water.⁴³
- **Closed-cycle** - Warm water (25°C) is used to ‘flash evaporate’ a working fluid such as ammonia, propane or chlorofluorocarbon (CFC) with a much lower boiling point than water by passing it over a heat exchanger. The vaporised working fluid drives an electrical turbine before condensing as it comes into contact with a heat exchanger cooled with cool sea water (5°C), which is then pumped back to the evaporator to start the cycle once again.⁴⁴ Closed-cycle systems operate more efficiently than open-cycle but are often smaller in scale as the secondary working fluid operates at a higher pressure⁴⁵ (Figure 8).
- **Hybrid** - Firstly electricity is generated using the closed cycle system, however instead of discharging the warm seawater it is evaporated using the open-cycle OTEC system and then later condensed with cool water.⁴⁶ This has the advantage of harnessing the advantages of both closed- and open-loop systems.

⁴⁰ Magagna & Uihlein (2015)

⁴¹ Charlier and Justus (1993)

⁴² Kempener & Neumann (2014a)

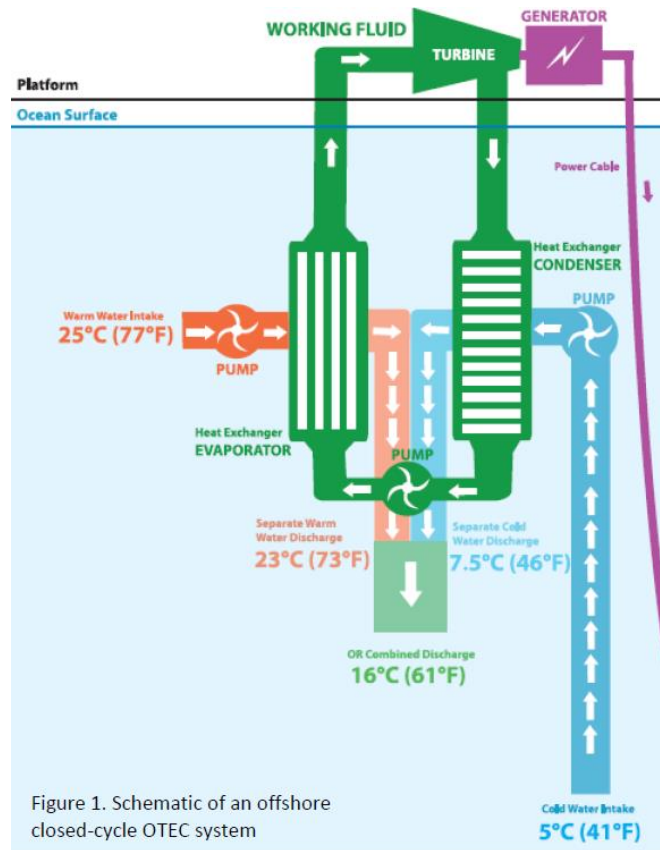
⁴³ Magagna & Uihlein (2015)

⁴⁴ Magagna & Uihlein (2015)

⁴⁵ Charlier & Justus (1993); Lewis et al. (2011)

⁴⁶ Kempener & Neumann (2014a)

FIGURE 8: OFFSHORE CLOSED-CYCLE OTEC SYSTEM



Source: NOAA (2014)

OTEC plants can be located onshore or offshore. Onshore facilities have the advantage of being cheaper and easier to maintain, as well as providing the option for producing desalinated water, however they typically demand a very long cold water intake pipe that is costly and subject to heat gains from friction, air temperature etc.⁴⁷ They also tend to suffer from having access to a limited ocean thermal energy resource and posing negative impacts on tourism given their coastal location.⁴⁸ On the other hand, floating offshore plants have shorter inlet pipes and better thermal resource availability but are subject to higher construction and O&M costs given their remote location and exposure to harsh conditions.

⁴⁷ WEC (2010).

⁴⁸ Devis-Morales et al. (2014); Magagna & Uihlein (2015)

Furthermore, significant costs will be incurred by integrating the offshore facility to the grid.⁴⁹

A key advantage of some OTEC plants is their ability to generate desalinated water that can be used for drinking water, irrigation etc. and provide cool water to be used for air-conditioning systems post-cycle.⁵⁰ This cool ocean water is also rich in nutrients like nitrogen and phosphates and can be used in aquaculture. Finally, OTEC is also a non-intermittent renewable energy technology with a very strong capacity factor (90-95%), however this is undermined to some extent by the very low efficiency of the Carnot cycle (maximum 7%) and the energy losses suffered as a result of pumping (approximately 20%-30%).⁵¹

⁴⁹ Magagna & Uihlein (2015); WEC (2010)

⁵⁰ Kempener & Neumann (2014a); Magagna & Uihlein (2015)

⁵¹ Kempener & Neumann (2014a).

3. ECONOMICS & MARKETS

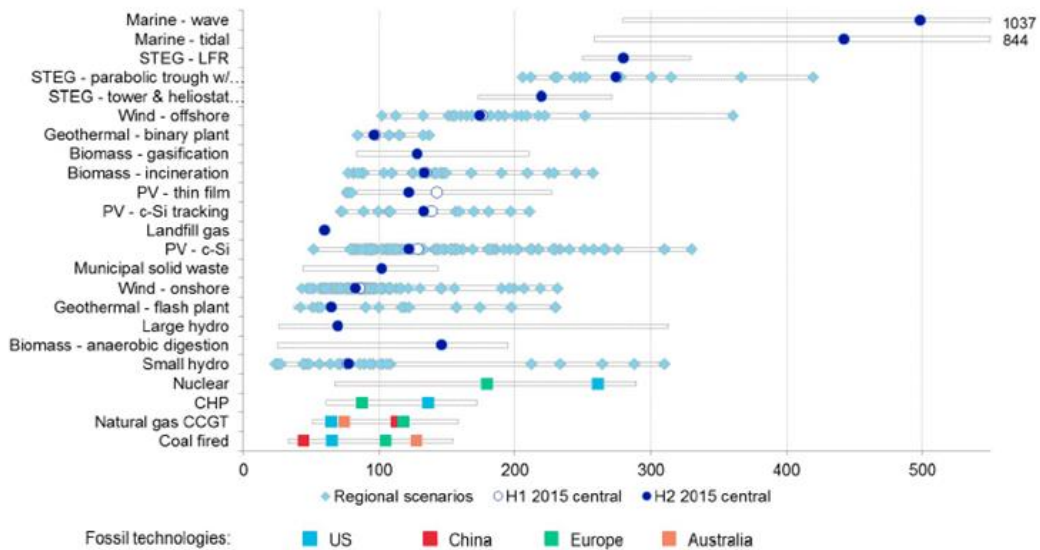
This section begins with an overview of the economic costs associated with these four technologies and is followed by a review of historical, recent and forthcoming developments relating to these technologies' development and deployment.

TECHNOLOGY COSTS

Bloomberg New Energy Finance's (BNEF) analysis of energy technologies levelised cost of electricity (LCOE) identifies the major disparity between the cost of ocean energy versus other forms of generation (Figure 9). The central scenario for 2015 (H2) estimates the LCOE of wave energy at approximately US\$500/MWh whilst tidal sits at approximately US\$440/MWh. It could be argued that there is a stronger degree of certainty over the costs of tidal versus wave energy given the stronger technological convergence and greater installed capacity. More broadly, Figure 9 illustrates the extremely high cost of ocean energy versus other renewables, for example offshore wind (US\$174/MWh), crystalline silicon solar PV (US\$122/MWh), onshore wind (US\$83/MWh) and large hydro (US\$70/MWh).⁵²

⁵² BNEF (2015b)

FIGURE 9: LEVELISED COST OF ELECTRICITY TECHNOLOGIES (\$/MWH) FOR 2015



Note: STEG = solar thermal electric generation

Source: Bloomberg New Energy Financi

Source: BNEF (2015a)

BNEF’s analysis does not cover OTEC and so in order to offer a more complete picture we consider a review conducted by Kempener & Neumann (2014a). They identified that the LCOE for small-scale OTEC plants (1-10MW) ranges somewhere between US\$190/MWh and US\$940/MWh, however if the facility were to be scaled up to between 50-400 MW the cost would fall dramatically and likely range between US\$70/MWh and US\$320/MWh.

These high costs illustrate the immaturity of these technologies and the relatively short gestation period that ocean energy technologies, with the exception of tidal range, have undergone. Consequently, many of the cost issues could be addressed through ongoing RD&D efforts examined in the next section. Tidal range is slightly different in the sense that the technology was first installed on a commercial basis in mid-20th century in countries like Canada, France and China. Consequently, the underpinning technological principles are well understood and many of the installations have operated without significant issues suggesting that further RD&D is unlikely to dramatically reduce its costs.⁵³ Even so, it is possible to improve the relatively poor load factor (25%) of tidal range technology due to

⁵³ Kempener & Neumann (2014b)

tidal cycles and turbine efficiency and in turn improve its LCOE by using multi-basin designs and/or turbines for ebb and flood generation.⁵⁴

Whilst not always the case, energy technology costs typically fall as deployment increases due to a combination of learning by doing and learning by using, as well as other factors such as supply chain maturity and increased investor confidence. In this context Table 4 presents an assessment of ocean energy costs in relation to different stages of deployment. Here we find that ocean energy costs are expected to fall with increased deployment and that the LCOE of wave, tidal stream and OTEC could fall in line with today's cost of competing renewable and fossil fuel technologies.⁵⁵

⁵⁴ Kempener & Neumann (2014b)

⁵⁵ BNEF (2015a)

TABLE 4: SUMMARY DATA AVERAGED FOR EACH STAGE OF DEPLOYMENT AND EACH TECHNOLOGY TYPE

Deployment stage	Variable	Wave		Tidal Stream		OTEC	
		Min	Max ⁵⁶	Min	Max	Min	Max
First pre-commercial array / First Project	Project Capacity (MW)	1	3	0.3	10	0.1	5
	CAPEX (\$/kW)	4000	18100	5100	14600	25000	45000
	OPEX (\$/kW per year)	140	1500	160	1160	800	1440
Second pre-commercial array/ Second Project	Project Capacity (MW)	1	10	0.5	28	10	20
	CAPEX (\$/kW)	3600	15300	4300	8700	15000	30000
	OPEX (\$/kW per year)	100	500	150	530	480	950
	Availability (%)	85%	98%	85%	98%	95%	95%
	Capacity Factor (%)	30%	35%	35%	42%	97%	97%
	LCOE (\$/MWh) ⁵⁷	210	670	210	470	350	650
First Commercial-scale Project	Project Capacity (MW)	2	75	3	90	100	100
	CAPEX (\$/kW)	2700	9100	3300	5600	7000	13000
	OPEX (\$/kW per	70	380	90	400	340	620

⁵⁶ For wave, the maximum value in the table is either that from the responses of consulted developers or from any of the reference studies analysed, this is particularly relevant for OPEX, where developers are now presenting costs that are significantly more optimistic than past studies have suggested.

⁵⁷ This study has used the standard method for LCOE assessment proposed by the IEA.

	year)						
	Availability (%)	95%	98%	92%	98%	95%	95%
	Capacity Factor (%)	35%	40%	35%	40%	97%	97%
	LCOE (\$/MWh)	120	470	130	280	150	280

Source: OES - IEA (2015)

HISTORIC, RECENT AND FORTHCOMING MARKET DEVELOPMENTS

At present 0.5 GW of commercial ocean energy generation capacity is in operation with another 1.7 GW under construction. However, 99% of this is tidal range with only 11 MW of tidal stream, 2 MW of wave and no OTEC. Instead these technologies are typically deployed via pre-commercial demonstration schemes as outlined in the Country Notes. There is also 15 GW of ocean energy projects at various stages of the development pipeline with, the majority of these are tidal range (11.5 GW) followed by tidal stream (2.6 GW), wave (0.8 GW) and OTEC (0.04 GW). However, only 0.8 GW of these projects have received consent with the vast majority for tidal range. Below we consider historic, recent and forthcoming developments across these four technologies, examining both commercial and pre-commercial projects.

Wave energy

Historic developments

Wave energy can be traced back to 1799, when Pierre Girard and his son filed the first wave energy patent in France.⁵⁸ Following the pioneering post-war work of Yoshio Masuda in Japan and Walton Bott in Mauritius wave energy innovation really gathered pace following the work of Stephen Salter on his device ‘the Salter Duck’ in the UK during the 1970s.⁵⁹ Subsequently, the UK government moved to establish the world’s first major wave energy programme in 1976, but following slow progress in terms of cost reductions the programme was halted in 1982. While the UK stalled, other countries forged ahead like Norway who in 1985 launched the world’s first wave power station: two full-sized (350 and 500 kW rated power) shoreline OWC prototypes at a site near Bergen.⁶⁰ The UK eventually

⁵⁸ Ross (1996)

⁵⁹ Ross (1996)

⁶⁰ Ross (1996); Falcão (2010)

followed suit in 1991 by installing its own 75 kW prototype Limpet OWC on Islay, Scotland, officially the UK's first commercial wave energy plant.⁶¹

The 1990s was characterised by a move from European government to support wave energy innovation following its commitment of 2 million ECUs⁶² to ocean energy under its Joule 2 programme leading to further demonstration projects include an OWC on Pico island in the Azores.⁶³ However, confidence in wave energy was soon shaken again following the high-profile sinking of a 2 MW OWC 'OSPREY' device on its UK launch in 1995 following damage from a storm while still undertaking installation.⁶⁴ Despite this setback the UK delivered the world's first commercial grid connected wave energy device when it commissioned its upgraded 500 kW Limpet device on Islay in 2001.⁶⁵ The 1990s also saw two key players enter the market, namely the US's Ocean Power Technologies and UK's Pelamis (formerly known as Ocean Power Delivery) who committed significant resources towards developing their respective devices during the 2000s in the context of growing concerns about climate change, energy security and increasing oil prices.

Major developments in the 2000s included the establishment of the European Marine Energy Centre (EMEC) Ltd in 2003, a centre offering 'at-sea' testing capabilities for both wave and tidal energy devices in both challenging and less challenging (nursery) conditions. This enabled Pelamis to become the first company in the world to generate electricity into a grid system from an offshore WEC in 2004 and the first to deliver a wave energy array, installing 3 Pelamis devices (2.25 MW total nominal rating) off the coast of Portugal at Aguacadora in 2008. Unfortunately, this was decommissioned shortly after due to technical faults.⁶⁶

Following an increase in the number of successful demonstration projects during the mid to late 2000s the wave energy sector saw energy utilities like E. On and Scottish Power, Original Equipment Manufacturers (OEMs) like Voith Hydro in WaveGen and ABB in Aquamarine, as well as Venture Capitalists, enter the wave energy market. Subsequently, a worsening financial environment, falling oil prices and a failure to deliver on initial expectations about reductions in LCOE meant investors began to pullback from the wave energy sector, resulting in major job losses and large companies like Pelamis and Aquamarine falling into administration, with numerous planned demonstration projects cancelled.

Ongoing developments

While the UK has scaled back its commercial deployment activities, Sweden's Seabased has begun construction the world's largest commercial wave energy array at Sotenas. It will

⁶¹ Ross (1996); Cleveland (2014)

⁶² European Currency Units

⁶³ Ross (1996).

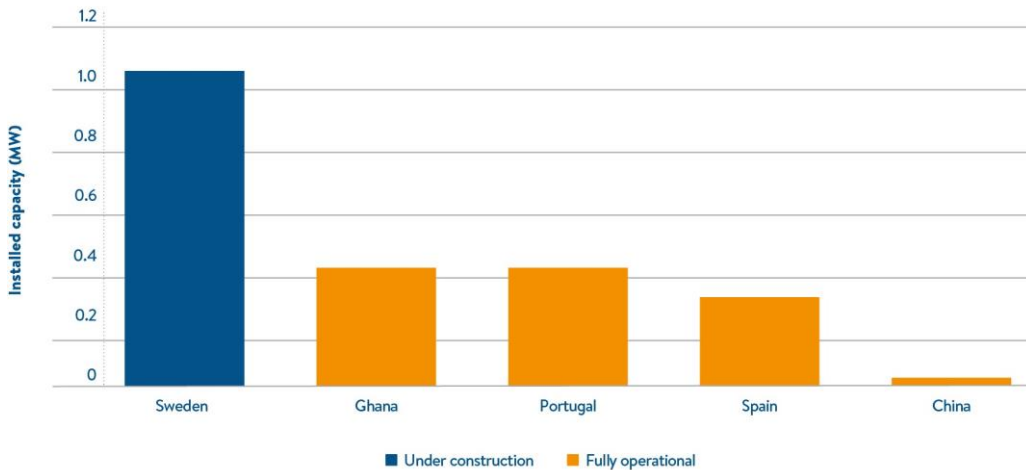
⁶⁴ Ross (1996).

⁶⁵ Whittaker et al. (2004).

⁶⁶ Cleveland (2014)

incorporate 42 devices and deliver 1.05 MW of capacity. They have also recently installed a second project in Ghana consisting of 6 devices, together providing 400 kW of capacity (Figure 10).

FIGURE 10: WAVE ENERGY INSTALLED CAPACITY IN OPERATION OR UNDER CONSTRUCTION



Source: OES (2016a)

A host of pre-commercial demonstration projects are also underway and one of the highest profile has been in Australia where Carnegie has demonstrated 3 of its CETO 5 devices rated at 240 kW off Garden Island. Numerous other demonstration projects are taking place across the UK, Canada, Denmark, Korea, Spain and the United States among others.

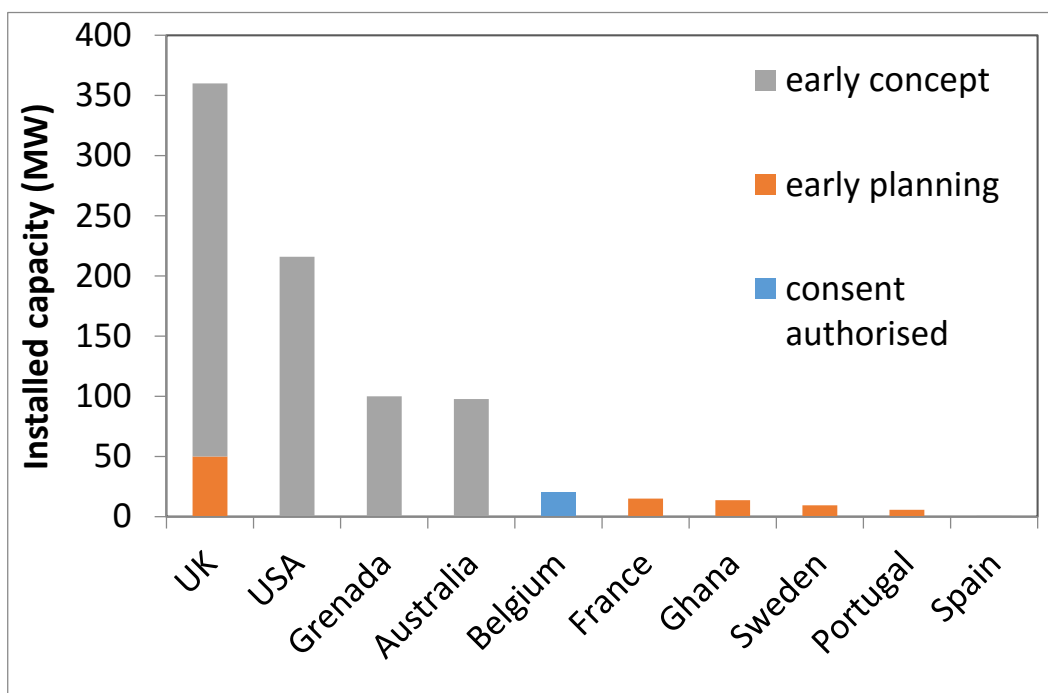
Forthcoming developments

In total, 838 GW of wave energy projects are currently at different stages of development, however only 20 MW of this has received authorised consent relating to a project at Mermaid/Bligh Bank in Belgium (Figure 11). In addition, there is 94 MW at the early planning and 725 MW at the early concept stage. Importantly a second phase of both Seabased’s projects in Sweden and Ghana are at an early planning stage and will be contingent of the performance of the first phase. The former delivering a further 378 devices and 9.5 MW of capacity, with the second delivering a further 560 devices and 14 MW of capacity. Portugal’s 5.6 MW SWELL project north of Peniche Peninsula is also at

the early planning stage and will consist of sixteen 350 kW oscillating Wave Surge Converters.⁶⁷

At the early concept stage is Ocean Power Technologies' three major commercial projects in Australia equating to almost 100 MW, whilst AWS Ocean Energy have proposed a two phase project in the north of Scotland, the first phase would be for 4 devices (10 MW) and the second for 76 devices (190 MW). However, given the early stage of these projects very little capacity is expected to come online in the near future.

FIGURE 11: WAVE ENERGY INSTALLED CAPACITY IN DEVELOPMENT



Source: OES (2016a)

At a pre-commercial stage, the UK is looking to take the lead once more with a number of major projects are in development at the UK's WaveHub including a 10-15 MW array of Carnegie CETO 6 devices, a 10 MW array of Fortum devices and a 10 MW array of Seabased devices.⁶⁸ Furthermore, after the loss of Pelamis and Aquamarine Power, the Scottish Government recently established Wave Energy Scotland that has a budget of £10m between 2014 and 2017. Unlike previous UK wave energy RD&D funding schemes,

⁶⁷ European Commission (2012); European Commission (2014)

⁶⁸ Ocean Energy Systems (2016)

this offers 100% funding throughout procurement, negating the needs to rely on difficult to secure match funding from the private sector. It also incorporates a strong focus on developing commercial sub-components prior to commercial device, as well as a clear 'stage-gating' approach that demands concepts meet stringent criteria before being eligible for further funding and finally, a much stronger focus on collaboration via a requirement for consortia.

Outside the UK, Carnegie is planning to deploy its CETO 6 device at its Garden Island facility in Australia prior to UK deployment. Another major planned demonstration projects includes Ireland's 5 MW WestWave project located at Killard Point in County Clare and due for commissioning in 2018.

Tidal stream

Historic developments

One of the very first tidal stream prototypes can be traced back to the UK's Peter Fraenkel and his work in southern Sudan in the 1970s, where he used a catamaran raft and vertical axis rotor to generate 2–3 kWh in order to pump 50 m³ of water a day for local communities.⁶⁹ Fraenkel's Marine Current Turbines subsequently developed a 15 kW prototype called SeaGen and tested this in Loch Linnhe in 1994 followed by a 300 kW pillar mounted prototype system called SeaFlow in the Bristol Channel.⁷⁰ This work ultimately led to the world's first large-scale, grid-connected commercial tidal stream generator, a 1.2 MW device in the Strangford Narrows between Strangford and Portaferry in Northern Ireland,⁷¹ which is set to be decommissioned shortly.

Despite the UK's rich heritage, it has by no means been the only pioneer in this field. Other major developers that delivered successful demonstration projects in the 2000s included Italy's University of Naples Federico II (2000), Norway's Hammerfest Strom (now Andritz Hydro Hammerfest) (2003), Ireland's OpenHydro (2006), Australia's Atlantis Resources (2006), Netherlands' Tocardo (2008) and Korea's Korea East West Power Co (2009).

Despite these positive developments a large number of projects have been suspended largely as a result of public and private funds having been withdrawn due to slow economic growth, falling oil prices and a failure by marine energy technology developers to deliver on initial expectations about their technologies' potential cost-effectiveness. The wave energy sector has been hit particularly hard by leading companies such as Pelamis and Aquamarine falling into administration.

Looking forward, we find that the respective costs of these different ocean energy technologies remain a significant barrier to deployment. Innovation will be key to reducing

⁶⁹ Whitaker (2011).

⁷⁰ WEC (2010); Cleveland (2014)

⁷¹ Cleveland (2014)

and efforts will need to focus on sub-component (e.g. power take off, prime mover, control systems), component integration and array optimisation RD&D. In addition, various socio-economic, infrastructural and environmental barriers also need to be addressed such as developing supportive energy market conditions, delivering facilitative infrastructure, providing grid connection, growing supply chains and mitigating against associated environmental impacts.

Following a range of successful demonstration projects, the late 2000s saw a large number of Original Equipment Manufacturer (OEMs) move into the tidal stream market. For example, Rolls Royce acquired Tidal Generation Ltd (TGL) in 2009, Siemens AG acquired Marine Current Turbines (MCT) in 2012, Andritz Hydro acquired Hammerfest Strom in 2012 and DCNS acquired OpenHydro in 2013. However, following the financial crisis many of these large companies began to retrench in the early 2010s to focus on their core competencies, with Siemens and Rolls Royce both withdrawing. However, other OEMs moved in with Alstom acquiring TGL in 2013 and Atlantis acquiring MCT and SeaGen Ltd in 2015. Additionally, Lockheed Martin, one of the highest profile aerospace and defence OEMs, began to co-develop the AR1500 turbine with Atlantis in 2014 (Figure 12).

FIGURE 12: ATLANTIS AND LOCKHEED MARTIN'S CO-DEVELOPED AR1500



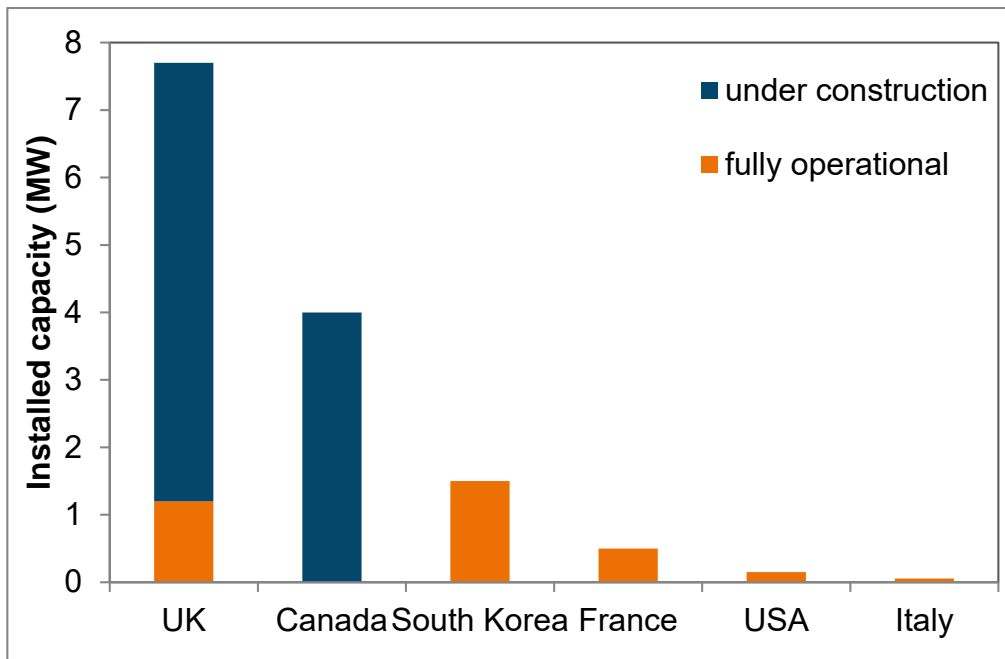
Source: Atlantis (2016)

Ongoing developments

Today there is almost 4.3 MW of commercial tidal stream installed capacity and the largest two plants are at the Uldolmok Tidal Power Station in South Korea and MCT's SeaGen installation in Strangford Lough, Northern Ireland. There is however a further 10.5 MW of commercial capacity under construction across three projects, all of which incorporate horizontal axis-turbines. The largest is the 6 MW MeyGen Phase1, the world's first commercial tidal stream array, located north of Caithness in Scotland. It will incorporate three Andritz Hydro Hammerfest HS1500 turbines and one Lockheed Martin-designed Atlantis AR1500 turbine due to be installed in summer 2016. The second is the 4 MW Cape

Sharp project in the Bay of Fundy, Canada that will incorporate two 2 MW OpenHydro turbines. The third is the Shetland Tidal Array where Nova Innovation has recently commissioned the first of three 100 kW devices targeting a community ownership model, with a view to deploy two more. The third scheme is a single 0.5 MW device deployed by Sabella in Brittany, France (Figure 13).

FIGURE 13: TIDAL STREAM INSTALLED CAPACITY IN OPERATION OR UNDER CONSTRUCTION



Source: OES (2016a)

Numerous pre-commercial demonstration projects are also underway. One of the largest is DCNS/Open Hydro's project at Paimpol Bréhat in France incorporating two 0.5 MW ducted turbine devices, the first of which has now been deployed. This builds upon the extensive demonstration of a 250 kW device at EMEC during the preceding few years. The largest capacity tidal stream device developed to date has also recently been deployed at EMEC, namely ScotRenewables' 2 MW (twin turbine) SR2000 M1 full scale prototype. They have also recently won €10m via the EU development fund Horizon2020 to construct and deploy a second generation SR2000 device to be deployed in parallel to the first at EMEC over the next year. Other notable projects include Bluewater's pilot 200kW BlueTEC device in the Netherlands, as well as the numerous projects underway in both Canada (and specifically the FORCE test site) and South Korea.

Forthcoming developments

At present planning consent has been granted for 44 MW of installed capacity with consent having been applied for a further 42 MW of capacity. Whilst Atlantis MCT has shelved two major UK schemes including the 10 MW Anglesey Skerries array in Wales and the 8 MW Kyle Rhea array in Scotland to focus on its MeyGen project.⁷² Following the deployment of Phase 1A (4 turbines) it will look to deliver Phase 1B that will deliver a total of 86 MW installed peak capacity followed by Phase 2 will raise the total capacity to 398 MW.

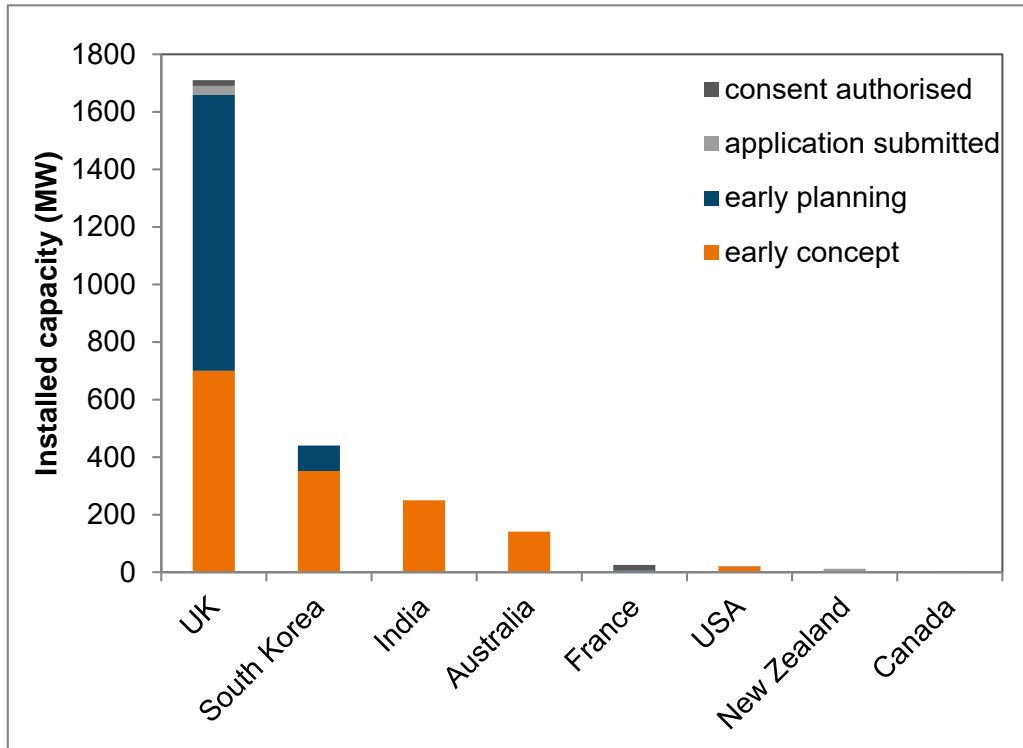
Other large consented projects include the 10MW array of 9 devices (each holding three turbines) rated at 400 kW off St. Davids Head, Wales. Consent has been authorised and at the time of writing the first 400kW device had been installed off Ramsey Sound, Wales in 2015. Developers will wait to see how it performs before continuing with the installation of the remaining 8 devices.⁷³ Two other large projects are proposed both in northern France, are the Normandie Hydro project, a 5.6 MW 4 device scheme led by General Electric⁷⁴ (2017) and the Raz Blanchard project, a 7 device 14 MW scheme led by OpenHydro (2018). A 10 device 10MW scheme is also proposed by Andritz Hydro Hammerfest UK within the Sound of Islay, with a targets date of 2017. With regards to non-consented projects, 1 GW of projects is at the early planning stage and 1.5GW at the early concept stage Figure 14.

⁷² Harris (2016)

⁷³ Ocean Energy Systems (2016)

⁷⁴ Formerly Alstom, which was acquired by General Electric in 2015

FIGURE 14: TIDAL STREAM INSTALLED CAPACITY IN DEVELOPMENT



Source: OES (2016a)

Tidal range

Historic developments

The first instance of capturing tidal range power dates back to 787 when the first tide mill was built at the Nendrum Monastery on Strangford Lough in Northern Ireland.⁷⁵ Instead of generating electricity these mills used a dam to contain the tide when it was high, the water then turning a water wheel once the tide fell to turn machinery such as a mill stone grind.⁷⁶ Subsequently, projects were developed to generate electricity using a very similar process. The world's first large-scale tidal range power plant was the la Rance Tidal Power Station (240 MW) that became operational in 1966 in Brittany, France and still operates today.⁷⁷ Other major projects were subsequently developed including the 20 MW Annapolis Royale plant in Canada installed in 1982 and the 254 MW Sihwa tidal plant in South Korea.⁷⁸ A

⁷⁵ Newman (2016)

⁷⁶ TidalPower (2013)

⁷⁷ Mofor et al. (2014)

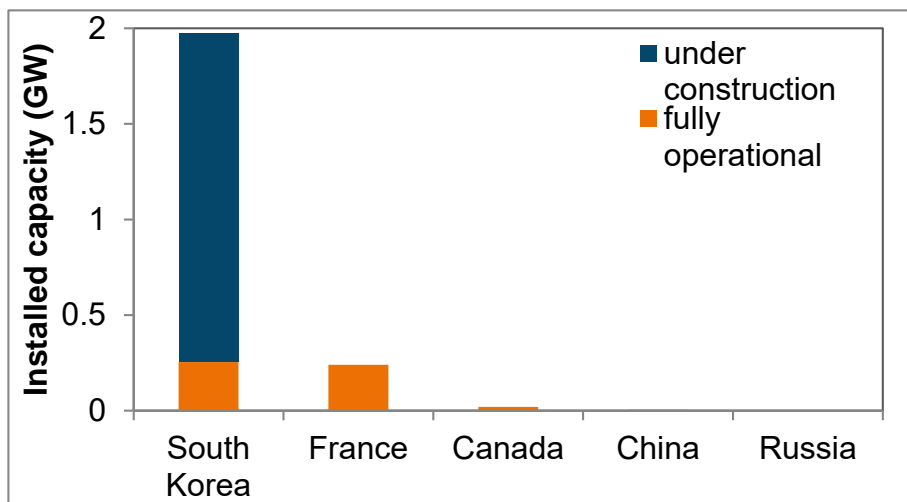
⁷⁸ Mofor et al. (2014); TidalPower (2013); WEC (2010)

smaller but important development was the upgrading of China's Jiangxia tidal power plant originally established in the 1980s from 3.9 MW to 4.1 MW following the upgrading of one of its turbines.

Ongoing developments

These developments along with a host of smaller scale projects have resulted in approximately 521 MW of tidal range capacity worldwide with another 1.7 GW under construction (Figure 15). At present there are two large tidal range projects under construction, both in the South Korean Yellow Sea: The Incheon Tidal Power Plant (1.3 GW) and Saemangeum Reclamation Project (0.4 GW). The former is set to go live in 2017 and together these projects will more than triple existing capacity.

FIGURE 15: TIDAL RANGE INSTALLED CAPACITY IN OPERATION OR UNDER CONSTRUCTION



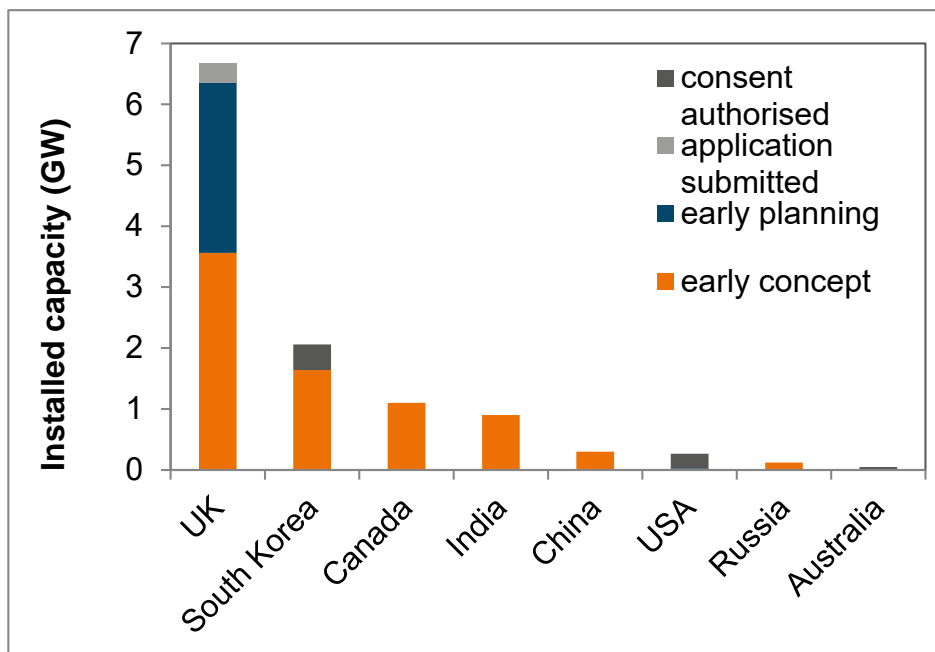
Source: OES (2016a)

Forthcoming developments

Over 13.7 GW of tidal range is currently planned for deployment, however only 0.7 GW of this has received consent. Major projects include the 0.42 GW Ganghwa Tidal plant consented in the East China Sea, South Korea and the 0.24GW Turnagain Arm Tidal Electric Generation Project in the Kenai Peninsula, US.

There is approximately 10.7GW of non-consented projects in the global pipeline with 0.32 GW under consideration for planning⁷⁹, with 2.8 GW at the early planning stage and over 7.6 GW at the early concept stage. With major tidal lagoons proposed at Swansea, Newport, Bridgewater and Cardiff, the UK leads with over 6.7 GW of non-consented planned capacity, however these projects face a wide-range of issues and will have to overcome major political, socio-economic and environmental obstacles if they are to come to fruition. South Korea is also planning to bolster their already significant capacity with another 2 GW, with projects in both the East China and Yellow Seas, whilst Canada continues to develop its 1.1 GW Scots Bay project in the Bay of Fundy (Figure 16).

FIGURE 16: TIDAL RANGE INSTALLED CAPACITY IN DEVELOPMENT



Source: OES (2016a)

OTEC

Historic developments

The principles of OTEC were first described by Jacques D'Arsonval of France who explained how the difference between the warm surface sea water and cold deep ocean water could generate electricity.⁸⁰ The first OTEC facility was built in 1929 by Georges

⁷⁹ This is solely for the Swansea tidal lagoon in the UK.

⁸⁰ Cleveland (2014)

Claude of France in Matanzas Bay, Cuba; rated at 22 kW it required 80 kW to run⁸¹. It wasn't until 1979 that a net gain of electricity generation was achieved from an OTEC facility at the Natural Energy Laboratory of Hawaii via a via a 15 kW⁸² closed-cycle ocean thermal energy conversion mounted on a converted U.S. Navy barge moored offshore⁸³. This was quickly followed by a 32kW⁸⁴ Japanese system in the Pacific Ocean in 1981. The first open-cycle system was constructed in 1992 operating between 1993 and 1998, with peak production of 103 kW and 0.4 l/s of desalinated water⁸⁵. The first major hybrid prototype (30kW) was constructed in Japan in 2006 by the Saga University.⁸⁶

Ongoing developments

A host of pre-commercial demonstration projects are underway including the Goseong, Korea a 200 kW plant that was completed by the Korea Research Institute of Ships & Ocean Engineering (KRISO) in December 2014⁸⁷, while a 100 kW⁸⁸ closed-cycle OTEC plant was constructed by Makai Ocean Engineering in 2015 at the Natural Energy Laboratory of Hawaii Authority (NELHA) in Hawaii, with sufficient capacity to power 120 homes (Figure 17 17). The latter project is with a view to develop a much larger 100 MW offshore OTEC plant on the same site. Japan has also opened its own 100 kW pilot plant in 2013 on Kume Island near Okinawa drawing upon much of the expertise generated from NELHA and Makai from their work in the US. Even so some larger projects have failed to materialise such as a 10 MW scale plant planned by both Lockheed Martin and the US Naval Facility Engineering Command on Hawaii.⁸⁹

⁸¹ Cleveland (2014)

⁸² Net power generation. Rated capacity minus electricity required to run facility.

⁸³ Cleveland (2014)

⁸⁴ Net power generation. Rated capacity minus electricity required to run facility.

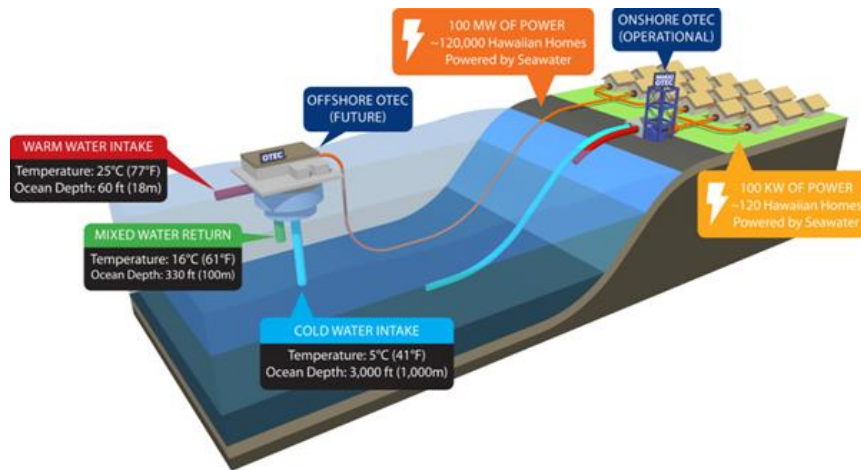
⁸⁵ Lewis et al. (2011)

⁸⁶ Lewis et al. (2011)

⁸⁷ Ocean Energy Systems (2016)

⁸⁸ Net power generation. Rated capacity minus electricity required to run facility.

⁸⁹ (Kempener & Neumann (2014a))

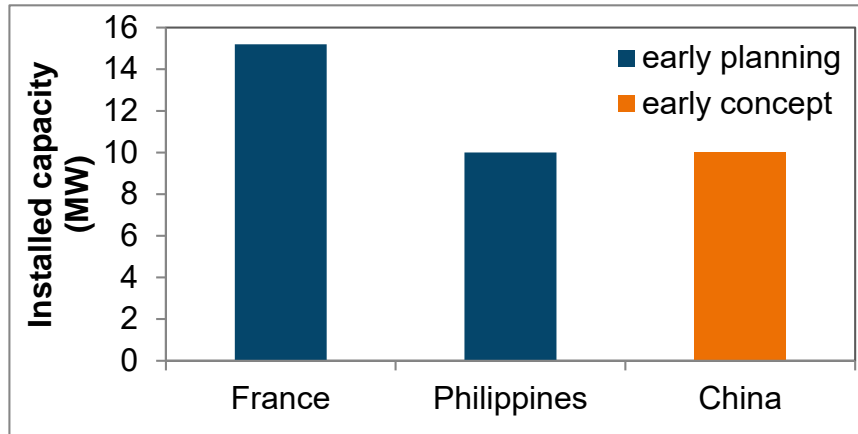
FIGURE 17: SCHEMATIC OF MAKAI OTEC PROJECT


Source: Makai (2016)

Forthcoming developments

In comparison to the other ocean energy technologies there is very little planned deployment of OTEC projects. In total 25 MW of schemes are at the early planning stage (Figure 18). Two French schemes on the Caribbean island of Martinique account for 15 MW with one of these led by the developer DCNS. A 10 MW is also planned by the Philippines in the South China Sea and a small 0.1 MW scheme by the Netherlands also in the Caribbean. In addition, China has a 10 MW scheme is at the early conceptual stage to be located off Hainan Island. However, given the very early stage of these development, very little OTEC capacity is expected to come online in the near future.

FIGURE 18: OTEC INSTALLED CAPACITY IN DEVELOPMENT



Source: OES (2016a)

Given its relatively early stage of development various pre-commercial demonstration projects are also planned, the largest being a 1 MW plant to be launched in mid- 2016 by KRISO. It will be deployed in the equatorial Pacific Ocean and completed by 2020.⁹⁰ The Netherlands' Bluerise will also soon deliver its 500 kW OTEC demonstration plant on the Caribbean Island of Curacao.⁹¹

⁹⁰ Ocean Energy Systems (2016)

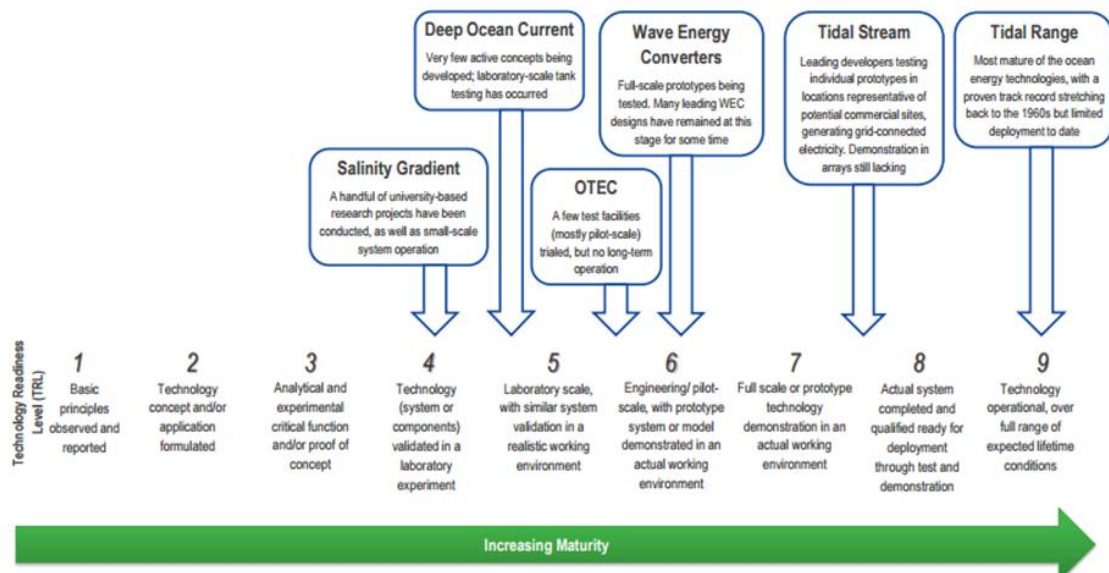
⁹¹ Ocean Energy Systems (2016)

4. INNOVATION CHALLENGES

In comparison to more established technologies, ocean energy is less mature and needs to overcome a wide-range of engineering challenges before costs fall sufficiently for them to enjoy wide-scale deployment. Consequently, this section outlines the major innovation challenges facing ocean energy technologies.

Whilst some cross-cutting challenges face all four technologies we find that there is a different emphasis on innovation for each of these considering they are at different levels of development. Figure 19 illustrates how OTEC is considered the least mature, sitting somewhere between Technology Readiness Levels (TRLs) 5 and 6, with wave energy at a similar stage. Tidal stream is considered to be located somewhere between TRLs 7 and 8 and thus on the brink of commercialisation. Only tidal range is considered to have reached commercialisation. Even so, many of the barriers outlined in the previous sub-section facing these technologies can be addressed by further RD&D.

FIGURE 19: TECHNOLOGY READINESS LEVELS OF MAIN OCEAN ENERGY TECHNOLOGIES



Source: Mofor et al. (2014)

CROSS-CUTTING

There are some cross-cutting technology innovation challenges that face the majority of ocean energy technologies as a whole that include:

- **Advanced materials** – development and utilisation of materials other than steel for the structure and prime mover, such as Steel Reinforced Concrete, rubber or Fibre Reinforced Polymer to provide advantages such as weight savings.⁹² Innovative device coatings will also help protect materials from corrosion, water absorption, cavitation etc. in the marine environment, such as Ceramax manufactured by Bosch Rexroth.⁹³
- **Control systems** - control systems and software that increase yield by improving the way the device interacts with the sea, e.g. adjusting pitch, yaw, height etc. ⁹⁴
- **Electricity infrastructure** - Innovative solutions that reduce the costs of cable installation and operation, specifically solutions to increase the safe range of working conditions for cable installation and trenching, the durability of cables and capacity for dynamic cables to manage device movement.⁹⁵
- **Environmental monitoring** – Remote sensory solutions to better assess the condition and performance of ocean energy devices as a result device-environment interaction, e.g. biofouling, mammal interactions, turbulence. ⁹⁶
- **Foundations and moorings** – Innovative methods like ‘pin’ pile foundations from remote-operated submarine vehicles to reduce array costs. Multiple rotors or devices per foundations or mooring will also help to reduce costs. ⁹⁷
- **Installation** - Innovative solutions to improve the speed of installation and reduce the costs of foundation installation such as fast-setting, non-spilling grout, pin piling techniques etc. Similarly solutions for retrieval and disconnection.⁹⁸
- **Integrated array design** – Develop innovative design software tools and models to optimise array performance.⁹⁹
- **Operation and Maintenance** – Reduce time and cost of retrieval of devices and infrastructure via solutions such as ROVs, and on site sensors (cameras,

⁹² SI Ocean (2013b)

⁹³ Drew et al. (2009); Lewis et al. (2011)

⁹⁴ SI Ocean (2013a)

⁹⁵ ORE Catapult (2016)

⁹⁶ LCICG (2012); ORE Catapult (2016)

⁹⁷ ORE Catapult (2016)

⁹⁸ ORE Catapult (2016)

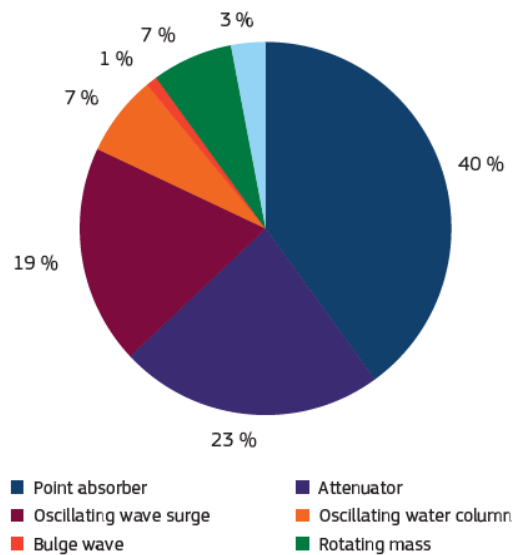
⁹⁹ Hannon et al. (2013)

positioning sensors etc.). Reduce the need to maintain or retrieve array components via solutions such as optimised mooring or anchoring systems.¹⁰⁰

- **Resource characterisation** – Solutions to offer a more detailed and accurate picture of existing and future the ocean energy resource conditions, such as wind speed, atmospheric temperature, wave height, tidal flow etc.¹⁰¹

The relative immaturity of wave energy technology can be illustrated by the lack of convergence around one single device design, with R&D funding split between several different device types (Figure 20).

FIGURE 20: DISTRIBUTION OF R&D EFFORTS ACCORDING TO WAVE ENERGY TECHNOLOGY TYPE



Source: Magagna & Uihlein (2015)

The key priority at present for wave energy innovation at present is to improve the performance and drive down the cost and weight of devices' power take off (PTO) systems. As explained in the previous sub-section a host of different PTOs exist for WECs but direct drive (linear) or rotary generators in particular could provide a route to reduced costs within future generations of WEC.¹⁰² In addition, radical integrated PTO/structure technologies

¹⁰⁰ ORE Catapult (2016); Lewis et al. (2011)

¹⁰¹ ORE Catapult (2016); Hannon et al. (2013)

¹⁰² SI Ocean (2013b)

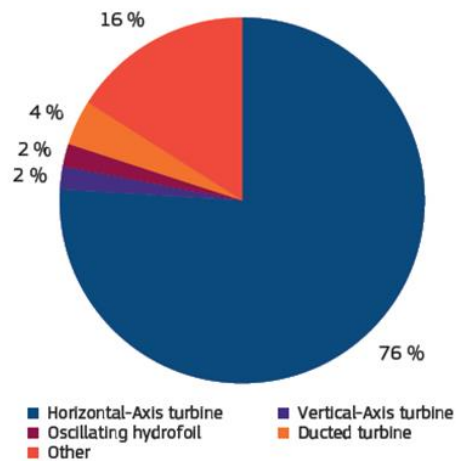
(such as dielectric membrane and bulge devices) could show promise for long term cost reduction. It is also essential that any improved PTO is scalable and applicable across a wide-range of devices.¹⁰³This is evidenced by Wave Energy Scotland’s focus on funding PTO development as a sub-system versus the development of a stand-alone device.

The other main focus is on the WEC’s structure and prime mover. Besides the use of alternative materials highlighted previously, it is key that different structural configurations are devised that yield greater power outputs. These will look to ensure the structure’s ‘geometry and mass will be designed around the resonant frequencies that need to be achieved to maximise energy extraction at a given location’.¹⁰⁴This approach should initially take precedent over simple scaling up of existing devices.¹⁰⁵Furthermore, the structure’s design would look to improve robustness and reliability in higher energy environments while crucially minimising material costs at scale through the use of distensible materials (e.g. polymer) or low cost materials (e.g. concrete).

TIDAL STREAM

Whilst other device types continue to be developed the main commercial scale application of tidal stream has been a strong convergence around the horizontal-axis turbine, with 76% of R&D funds committed to this one device (Figure 21).

FIGURE 21: DISTRIBUTION OF R&D EFFORTS ACCORDING TO TIDAL ENERGY TECHNOLOGY TYPE



Source: Magagna & Uihlein (2015)

¹⁰³ ORE Catapult (2016)

¹⁰⁴ SI Ocean (2013a p.13)

¹⁰⁵ SI Ocean (2013a)

Lewis et al. (2011) explain that horizontal axis turbines are likely to follow a similar development trajectory to wind turbines, where we will see increasingly larger capacity turbines be deployed. This will largely rely on an increase in advances in tidal stream blade design, for example where the blades will sweep a larger area in order to generate more power. Other necessary blade advances will include a reduction in blade erosion to improve durability, including the option of ‘self-healing’ to damaged blades.¹⁰⁶ Additionally improving blade manufacturing quality is essential to improve blade performance and durability, as well as improving blade design and testing.¹⁰⁷ There are also opportunities for PTO advances not least the use of permanent magnet generators that eliminate the need for gearboxes, thus reducing overall weight, performance losses and maintenance frequency.¹⁰⁸

It is also expected that new generations of tidal stream device will come to the fore over the next few years. Whilst first-generation tidal stream devices consisted of bottom mounted designs, second-generation devices, such as floating TECs, may look to capitalise on lower installation costs and faster flowing water in the mid/high water column or fix multiple rotors on one foundation structure. Third-generation devices, such as the tidal kite or Archimedes’ screw, which for example may look to move the PTO through the current rather than relying on an area swept by a static prime mover.¹⁰⁹

TIDAL RANGE

In addition to efforts to progress tidal lagoon and multi-basin technology outlined in the previous section a key innovation focus is to improve the efficiency of the tidal range turbines, which typically have a load factor of 25%. One option could be to develop and implement reversible or bi-directional turbines that generate during both ebb and flood.¹¹⁰ The other major priority is the development of variable frequency generation by developing appropriate gearing system that deliver different rotation speeds.¹¹¹ This would offer greater control over tidal range output and means that supply could be better matched with demand. Finally, efforts are being made to develop dynamic tidal power (DTP) technology. This involves the construction of: “a 30-60 kilometre (km) long dam that runs perpendicular to the coast line. At the end of the dam, there is a barrier forming a large “T” shape. The dam interferes with the oscillating tidal waves on either side of the dam, and creates a height difference between the water levels. This height difference creates potential energy, which can be converted into electricity using the low-head turbines that are being used in tidal ranges”.¹¹²

This approach has a number of advantages versus tidal barrage or lagoons. The first is that it doesn’t require a very high natural tidal range (1-3m) to create sufficient discharge to

¹⁰⁶ ORE Catapult (2016)

¹⁰⁷ ORE Catapult (2016)

¹⁰⁸ SI Ocean (2013a)

¹⁰⁹ SI Ocean (2012)

¹¹⁰ Kempener & Neumann (2014b); Lewis et al. (2011)

¹¹¹ Lewis et al. (2011)

¹¹² Kempener & Neumann (2014b); Lewis et al. (2011). Kempener & Neumann (2014b p.17)

deliver appropriate levels of electricity generation. The second is that if two dams are installed at the correct distance from one another (approx. 125 miles) they offer complementary generation profiles, i.e. one is at full output when the other is not generating.¹¹³

OTEC

The primary focus for OTEC developers is to reach commercialisation, which requires the plants to have a rated capacity of 100 MWe or more.¹¹⁴ One of the biggest innovation challenges facing OTEC systems is the efficiency of heat exchangers used for evaporation and condensation, which account for between 20 to 40% of the total plant cost.¹¹⁵ Given the need for long-term lifespans of OTEC plants and their operation in a hostile marine environment, these heat exchangers need to be highly durable. As such present R&D efforts are focused on 'substituting durable, but low-cost, aluminium alloys for durable, but more expensive, titanium ones'¹¹⁶ that are more corrosion resistant. This would help to increase their load factor and operational lifetime, thus reducing the system's LCOE.

Another pressing innovation challenge for OTEC is the width and length of the pipes that draw the seawater into the system. Huge volumes of water are required by the system, estimated at around 10-20 billion of gallons of water per day.¹¹⁷ Such a volume of water demands pipes wide enough (~10m in diameter)¹¹⁸ to deliver 750 tonnes of water per second through the OTEC system.¹¹⁹ There are however opportunities to draw upon large-riser technology developed from the oil and gas industry.¹²⁰ Another major challenge is to install a cold water pipe at a depth of 1000 m that can withstand the harsh deep-water conditions (e.g. pressure, ocean currents, bio-fouling).¹²¹

¹¹³ Steijn (2015)

¹¹⁴ Mofor et al. (2014)

¹¹⁵ Lewis et al. (2011)

¹¹⁶ Mofor et al. (2014 p.12)

¹¹⁷ NOAA (2014)

¹¹⁸ NOAA (2014); Kempener & Neumann (2014a)

¹¹⁹ DOE (2012)

¹²⁰ Lewis et al. (2011)

¹²¹ Kempener & Neumann (2014a)

5. SOCIO-ECONOMIC & ENVIRONMENTAL FACTORS

In this section we consider the socio-economic and environmental impacts of ocean energy, as well as the related factors that will serve to either support or constrain ocean energy deployment.

SOCIO-ECONOMIC

Economic growth

A common argument for developing a marine energy sector is the potential global market value it presents. Various estimates exist but one of the most comprehensive is from the Carbon Trust (2011), which suggest that in its 'high scenario' for wave and tidal energy deployment the global market could be 'worth up to c.£460bn (cumulative, undiscounted) in the period 2010-2050, with the market reaching up to c.£40bn per annum by 2050' (p.1). Whilst the Carbon Trust do not provide any figures for global job creation the IEA's OES implementing agreement estimate that if ocean energy deployment was on track to reach 748 GW by 2050 this could create approximately 160,000 direct jobs by 2030.¹²²

It is important to note that this economic value would be unequally distributed globally and countries with the greatest manufacturing capabilities for exports and deployed capacity are likely to enjoy the majority of the added value. For example, given the UK's rich heritage in ocean energy the Carbon Trust estimate that 'the UK could capture c.£76bn of the global marine market or around 22% of the accessible global market (cumulative, undiscounted to 2050 in our high scenario) between 2010 and 2050. This would suggest a gross contribution to UK GDP of c.£15bn over the forecasted period (c.£10bn for wave, and c.£5bn for tidal, and not accounting for any displacement effects)' (p.1). One study estimated that this could create over 68,000 jobs in the UK from marine energy by 2050.¹²³ It is important however to consider what the counterfactual would be if public and private funds were redirected elsewhere such as other renewable or non-renewable energy technologies, or even outside the energy sector.

¹²² Executive Committee of the OES (2011)

¹²³ The Carbon Trust (2011)

Energy security

Another important socio-economic consideration is ocean energy's impact on energy security considering the different intermittency and forecasting profiles of the four modes of generation under examination. Wave energy is considered to be a "stochastic" resource similar to wind energy and cannot be accurately predicted over a long time period¹²⁴, with accurate forecasts limited to around one week in advance.¹²⁵ Furthermore, the variability of wave energy is relatively low over a time period of a few hours but can vary greatly on a seasonal or annual basis.¹²⁶ Tidal stream and range energy generation is periodic meaning that highly accurate forecasts are possible over long time horizons.¹²⁷ While monthly or annual variations are relatively small, the nature of diurnal or semi-diurnal tides means that variability is very high on an hourly basis¹²⁸. In contrast, OTEC represents a very low degree of variability when located in tropical climates as ocean surface temperatures exhibit little temporal change.

In the context of other forms of intermittent renewable electricity generation being added to the grid, such as wind or solar, ocean energy offers a complementary form of renewable energy that could 'flatten out' the load on the grid and thus improve the synchronicity of electricity supply and demand.¹²⁹ For example, wave energy is sometimes out-of-synch with wind energy because whilst waves are generated by winds it takes some time for waves generated by winds offshore to reach the shoreline¹³⁰. Even so, it is perfectly possible for the variable peak of these different forms of ocean energy to coincide not just with one another but other forms of intermittent renewable energy (e.g. wind, solar). Under these conditions the grid can come under immense pressure due to the increased electricity load and raise issues with regards to the integrity of the grid¹³¹. Conversely, it is also possible that the lowest output from these forms of renewable energy generation could coincide presenting a real-danger of blackouts. Both situations pose problems for energy security and which would require energy storage to resolve.

Quantifying the economic benefits of incorporating marine energy, however one study by Redpoint (2009) that was included in the UK Department of Energy and Climate Change's Marine Energy Action Plan¹³² identified that it could save ~£900m (\$1.38bn)/year by reducing the need for more intermittent renewable generation capacity provided by the likes of wind and solar.

¹²⁴ Iyer et al. (2013)

¹²⁵ Executive Committee of the OES (2011)

¹²⁶ Lewis et al. (2011)

¹²⁷ Uihlein & Magagna (2015)

¹²⁸ Uihlein & Magagna (2015)

¹²⁹ Blue Energy (2014)

¹³⁰ Executive Committee of the OES (2011)

¹³¹ Uihlein & Magagna (2015)

¹³² DECC (2010)

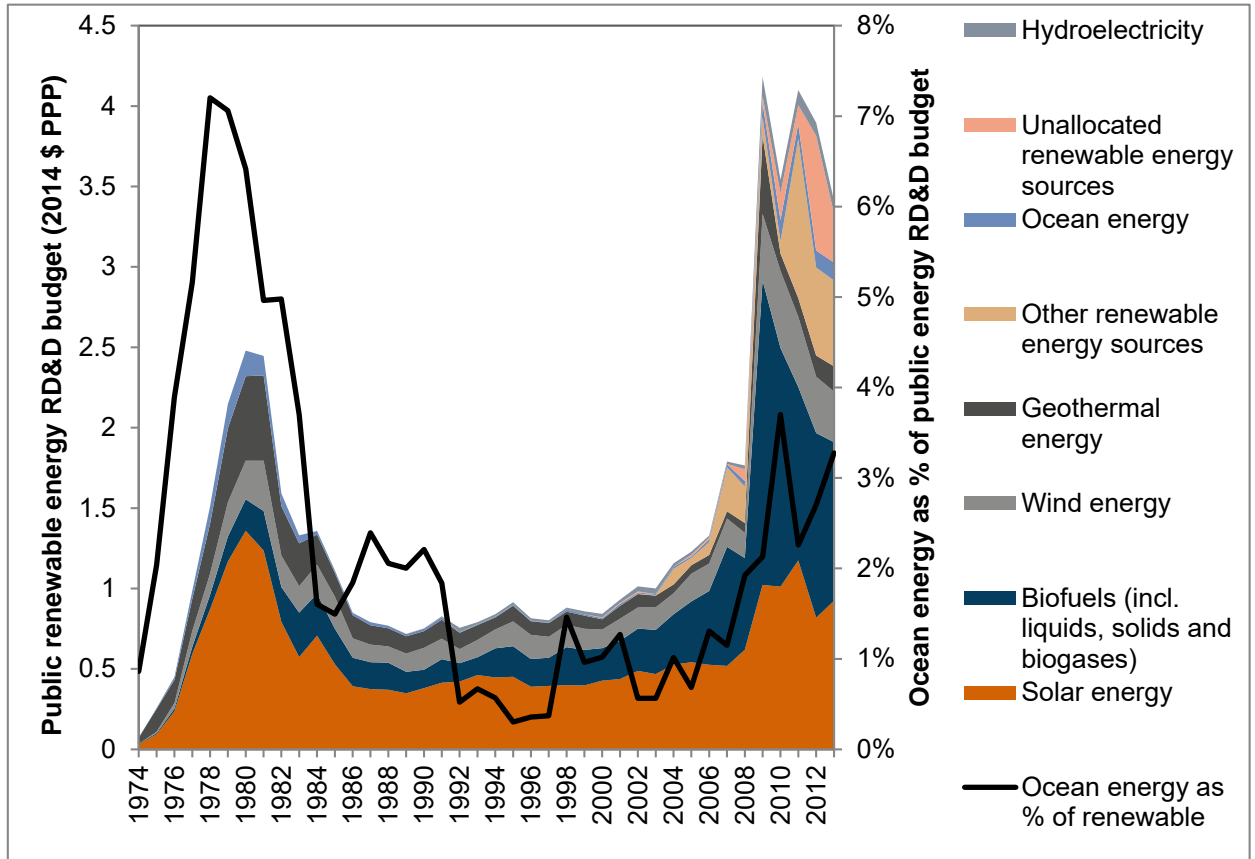
Government policy

Energy innovation policy

Given the relative immaturity of ocean energy technologies versus most other energy technologies much of the focus in terms of barriers to deployment has been on the level and type of energy innovation support for ocean energy. We find that between 1974 and 2013 the global public budget for ocean energy RD&D was \$1.6bn.¹³³ This was however significantly less than for most other renewable energies including solar (US\$23.3bn), biofuels (US\$14.1bn), wind (US\$6.8bn), geothermal (US\$6.2bn) and other renewables (US\$3bn), higher only than hydro (US\$0.8bn). Figure 22 helps illustrate this showing how ocean energy's proportion of total public renewable energy RD&D fell from a high of 7% in the late 1970s to a low of 0.3% in the 1990s. While this did begin to increase once again in 2000s to reach 3.7% in 2010, we find that a much more RD&D support has been committed to other renewable technologies, potentially explaining their greater maturity.

¹³³ PPP (2014)

FIGURE 22: PUBLIC ENERGY RD&D BUDGETS FOR RENEWABLE ENERGY 1974-2013



Source: IEA (2016)

Figure 22 illustrates the intermittent nature of ocean energy funding, which has led to a ‘boom and bust’ funding cycle that has significantly interrupted innovation progress.¹³⁴ Other issues include the unrealistic assumptions by funders and developers alike that marine energy could reach commercialisation in a relatively short timeframe versus other energy technologies, leading to an erosion in confidence in the technology from investors following developers’ failure to deliver on their ambitious promises.¹³⁵ The premature focus on full-scale demonstration has also resulted in an emphasis on device-level versus sub-component innovation (e.g. power take off, prime mover, control system).¹³⁶ This has led to a wide-range of characteristically distinct wave energy devices (Figure 5) based on different

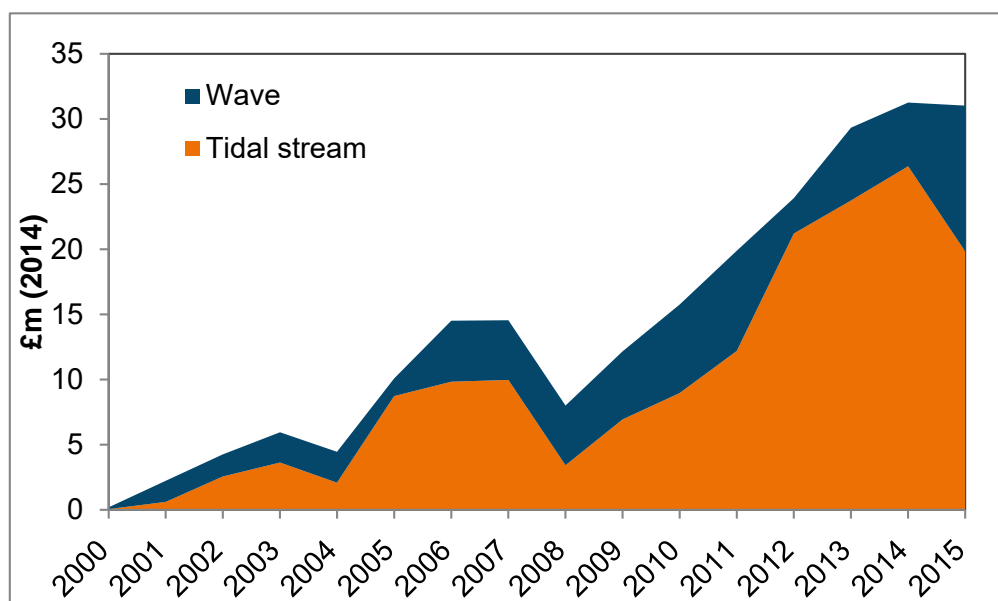
¹³⁴ Vantoch-Wood (2012)

¹³⁵ Jeffrey et al. (2013); Mclachlan (2010)

¹³⁶ Renewables Advisory Board (2008)

components, delaying the design consensus that is key to commercialisation.¹³⁷ Another issue has been public funders' requirement for developers to secure match-funding from the private sector for these high-risk activities before funds are released.¹³⁸ This has resulted in public funds for ocean energy often going unspent, such as the UK's £50m Marine Renewables Deployment Fund. Finally, the conceptual 'bundling' of different ocean energy technologies into the same RD&D programmes despite their different characteristics and maturity¹³⁹, leading to a bias towards certain technologies. For example, Figure 23 illustrates how tidal stream has enjoyed twice the public RD&D funding versus wave in the UK since 2000, potentially a function of its greater maturity versus wave.

FIGURE 23: COMPARISON OF WAVE AND TIDAL STREAM FUNDING OF UK RD&D PROJECTS 2000-2015



Note: Includes public funding for basic or applied research, experimental development, demonstration, training, knowledge transfer and networking for wave and tidal stream projects taking place in the UK.

Source: Hannon forthcoming

Public acceptability

Studies of the public acceptability of ocean energy reveal a strong degree of support for the technology. While no global surveys of ocean energy could be uncovered, a survey carried out in 25 EU member-states reveals that 60% of respondents favour ocean energy use,

¹³⁷ Magagna & Uihlein (2015)

¹³⁸ Winskel (2007)

¹³⁹ Mclachlan (2010); Vantoch-Wood (2012)

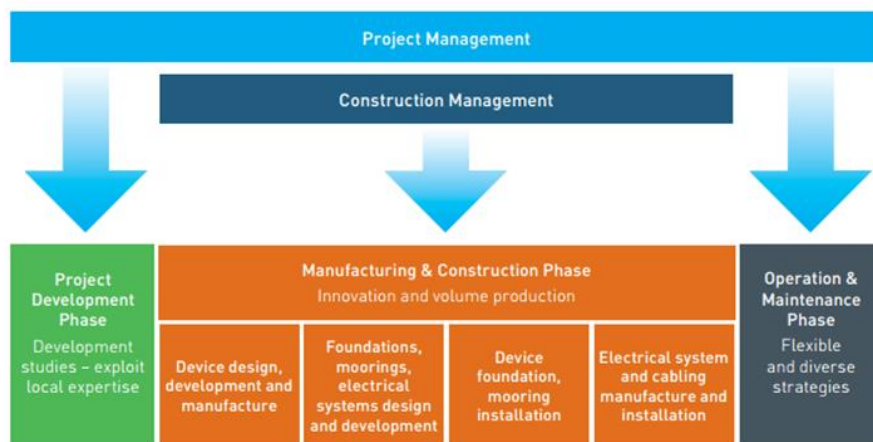
while 24% have a neutral attitude.¹⁴⁰ If we focus on the UK, an international leader of ocean energy development we find that a recent survey from the Department of Energy and Climate Change¹⁴¹ identified that the level of support for wave and tidal energy sat at 73%, higher than biomass (65%) and on-shore wind (66%), identical to off-shore wind (73%) but lower than solar (80%). Compared to nascent fossil fuel generation such as shale gas (23%) it registers a much stronger degree of support. Similar levels of support for ocean energy were also identified in Portugal, the US and Canada.¹⁴²

While public acceptability for ocean energy seems strong at present Mofor et al. (2014) warn that this is likely to be a function of its relatively low levels of deployment. As installed capacity increases, so too will the public's awareness of the technology, at which point we might see growing concerns about the ocean energy's economic and environmental impacts.¹⁴³

Supply chain

The delivery of ocean energy arrays, as with other energy technologies, requires a large number of supporting companies offering different services (Figure 24).

FIGURE 24: OCEAN ENERGY SUPPLY CHAIN



Source: HIE & Scottish Enterprise (2015)

¹⁴⁰ European Commission (2006)
¹⁴¹ DECC (2015)
¹⁴² Stefanovich & Chozas (2010)
¹⁴³ Uihlein & Magagna (2015)

The Syndicat des Energies Renouvelables (ENR) estimate that approximately 170 companies make-up the ocean energy industry in France split across different sub-sectors including installation, mechanical engineering, electrical engineering, marine engineering, steel works etc.¹⁴⁴A recent report by BVGA (2015) identify the following sub-components as critical to the ocean energy supply chain:

- Ocean energy devices and subsystem developers
- Wave / tidal farm design, development, ownership and asset management
- Foundations and mooring systems
- Subsea array and export cables
- Substation electrical systems
- Installation ports
- Foundation and device installation
- Subsea cable installation
- Specialist vessels to support O&M, installation, retrieval etc.
- Consultancy and R&D services to support development of test facilities

One of the major challenges facing ocean energy is the under-development of its supply chain and its lacks of capacity to scale up deployment to capture the economies of scale necessary to drive down LCOE. For example, many of the current companies involved in the ‘fabrication, assembly and installation of prototypes will not always have the capabilities or resource to scale-up production and deliver the value engineering required for mass deployment’.¹⁴⁵ Proposed solutions involve the entry of Original Equipment Manufacturers (OEMs) who can bring the necessary expertise, finances and specialist facilities to accelerate technology development, as well as ‘piggy-backing’ on the closely related offshore oil, gas and wind industries that possess many of the required expertise (e.g. subsea array and export cables, support vessels etc.) but also sectors like aerospace and shipping with regards to large-scale device manufacture and survivability. Even so, each ocean energy technology presents specific supply-chain requirements making the development of a satisfactory ocean energy supply chain more complex and multi-faceted.¹⁴⁶

¹⁴⁴ ENR (2014)

¹⁴⁵ Mofor et al. (2014 p.45)

¹⁴⁶ Mofor et al. (2014).

A related issue is the lack of the skills required for each of these supply chain components to function with a recent study by RenewableUK identifying that across the wind and marine energy sectors, employers reported difficulty in filling vacancies for 42% of listed jobs between 2011 and 2013.¹⁴⁷

Infrastructure

While deployment of ocean energy is relatively low, infrastructural constraints do not pose a huge obstacle to market development at present as test centres (e.g. EMEC, WaveHub, FORCE etc.) offer the necessary infrastructure for developers to test their devices.¹⁴⁸ However, as deployment ramps up infrastructural capacity will pose a critical barrier. The first issue is the site infrastructure to harness ocean energy resources such as a subsea electrical system, submarine cable connection, foundations, moorings etc. The second is grid infrastructure, i.e. the necessary grid connection and capacity to transfer the generated electricity to its market. This is often an obstacle as good ocean energy resources are often located in remote and sparsely populated areas.¹⁴⁹ The third is port infrastructure to provide necessary offshore operations and maintenance services, such as ships, dry-dock facilities etc.¹⁵⁰

This issue is not unique to ocean energy but also affects offshore wind. Consequently, co-locating these two forms of generation could offset some of the high infrastructure costs¹⁵¹. A similar co-location of other offshore activities (e.g. shipping, oil and gas, wind) made to discount the provision of the necessary port infrastructure.¹⁵² This infrastructure could be coordinated internationally as demonstrated by the North Sea Countries Offshore Grid Initiative; a consortium of 10 countries around the North Seas designed 'to maximize the efficient and economic use of the renewable energy resources as well as infrastructure investment'.¹⁵³

ENVIRONMENTAL

Environmental impacts

Environmental impacts from ocean energy technology fall into three main categories.¹⁵⁴ The first relates to the interaction of marine animals with the device. There is a threat of animals colliding with the moving parts of an ocean energy device. For example, tidal stream turbine blades could strike animals or OTEC devices make 'hoover' up animals into the system given the enormous volume of water they take in. This interaction may be harmful to both animals and the device. Devices could also pose a barrier to animals' natural movements or migration.

¹⁴⁷ Renewables UK (2013)

¹⁴⁸ Mofor et al. (2014)

¹⁴⁹ Magagna et al. (2014)

¹⁵⁰ Vosough (2014)

¹⁵¹ Executive Committee of the OES (2011)

¹⁵² Vosough (2014)

¹⁵³ Benelux (2014)

¹⁵⁴ Copping et al. (2014)

The second relates to underwater noise disturbance generated from ocean energy devices such as wave energy and tidal stream devices, which could influence the behaviour of marine animals, not least some species of whales, dolphins, seals, sea turtles, migratory fish and invertebrates. This is because animals tend to use underwater sound rather than light to communicate, navigate etc. and so any ambient noise can affect their ability to perform these functions.¹⁵⁵ Given the low levels of deployment thus far there is a distinct lack of empirical information about how these devices impact upon marine animals.

The final category relates to the potential effects that the installation of ocean energy devices could have on the movement of water by tides, waves, ocean currents and density in reaction to the removal of energy from the marine environment or disruptions to the natural flow of water. However, as Copping et al. (2014) explain it is likely that any major changes will only really be perceptible once large arrays of marine energy devices are in place, unless of course these are simulated via mathematical models like ETI's SmartTide project.¹⁵⁶

Of all the four technologies under examination it is tidal barrage technology that is generally considered to have the greatest potential environmental impact. Tidal barrages can slow down the flow of water and in turn the amount of suspended sediment, resulting in loss of intertidal habitat. There are conflicting studies on whether it poses a positive and negative effect on the concentration of metals, nutrients, and pathogens within estuarine environment. Similarly, it is unclear whether it is an overall increase in biodiversity, but that there is likely to be a change in the species that make-up the local habitat. Finally, it is expected that even with specially designed turbines to reduce fish strikes, some degree of fish mortality is inevitable. Furthermore, a barrage may increase levels of fish mortality due to predation, disease, habitat loss and disruption to movement.¹⁵⁷

In contrast, some scholars emphasize the environmental benefits that ocean energy technologies could pose. For example Kempener & Neumann (2014b) explain that some tidal range installations, such as the Sihwa barrage in South Korea or potentially the Grevelingen lake in the Netherlands, has improved environmental and ecological water quality. Other environmental benefits relate to renewable energies more broadly such as a reduction in air and water pollution. Finally, ocean energy devices could attract marine animals by providing an artificial habitat or reef that acts as a fish aggregating device and safe haven from fishing.¹⁵⁸

Climate change

Renewable energy technology using ocean energy offers an important route for climate change mitigation. Naturally the absolute level of carbon abatement will be in line with the

¹⁵⁵ Clark et al. (2009)

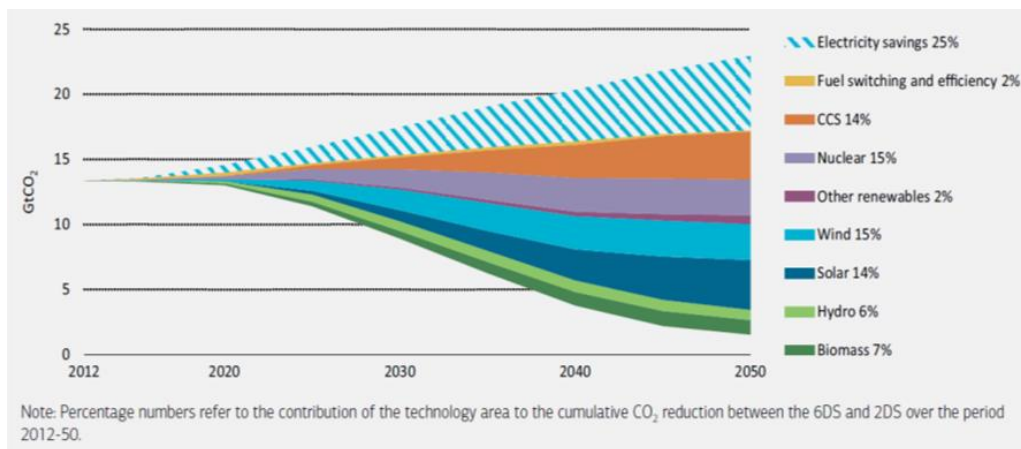
¹⁵⁶ <http://www.eti.co.uk/project/smarttide/>

¹⁵⁷ Wentworth (2013)

¹⁵⁸ Copping et al. (2014)

level of future deployment, average load factor, LCOE etc. Unfortunately, no breakdown of the exact level of carbon savings (GTCO₂) is offered by the IEA as part of either its GEO or ETP publications (see Market Outlook section). Even so Figure 25 indicates that ocean energy, alongside geothermal and ‘other’ renewable technologies, could deliver 2% (0.68 GTCO₂) of the GHG emissions reduction necessary to limit global temperature rise to 2°C versus 6°C by 2050, the latter broadly considered the outcome of business as usual.

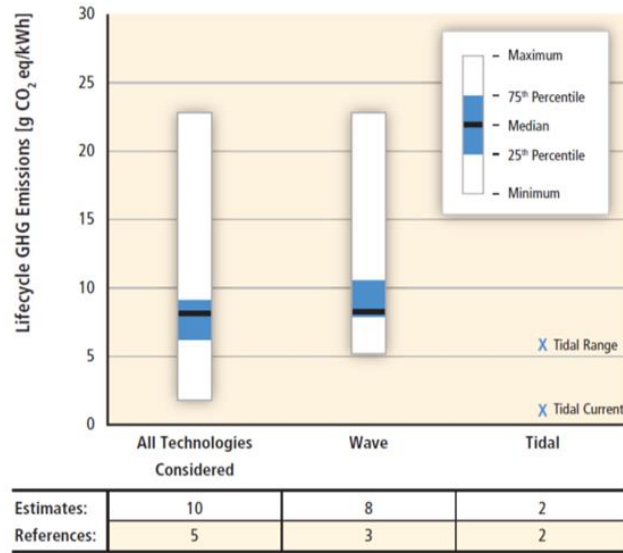
FIGURE 25: KEY TECHNOLOGIES TO REDUCE POWER SECTOR CO₂ EMISSIONS BETWEEN 6DS AND 2DS



Source: IEA (2015a)

In the context of the perceived GHG emissions savings some studies have undertaken a life cycle analysis (LCA) of ocean energy technologies to offer a more complete picture of their associated emissions. Lewis et al. (2011) present a comprehensive review of LCA studies published since 1980 and find that ‘lifecycle GHG emissions from wave and tidal energy systems are less than 23 g CO₂eq/kWh, with a median estimate of lifecycle GHG emissions of around 8 g CO₂eq/kWh for wave energy’ (p.517-8) as demonstrated in Figure 26. They note that the distributions shown represent an assessment of likelihood and that their figure reports the distribution of currently published literature estimates that passed their own quality and relevance controls. Whilst they call for further LCA studies to more accurately uncover the net emissions of ocean energy devices they do conclude that in comparison to fossil energy generation technologies, ocean energy device lifecycle emissions appear low.

FIGURE 26: ESTIMATES OF LIFE-CYCLE GHG EMISSIONS OF WAVE AND TIDAL RANGE TECHNOLOGIES



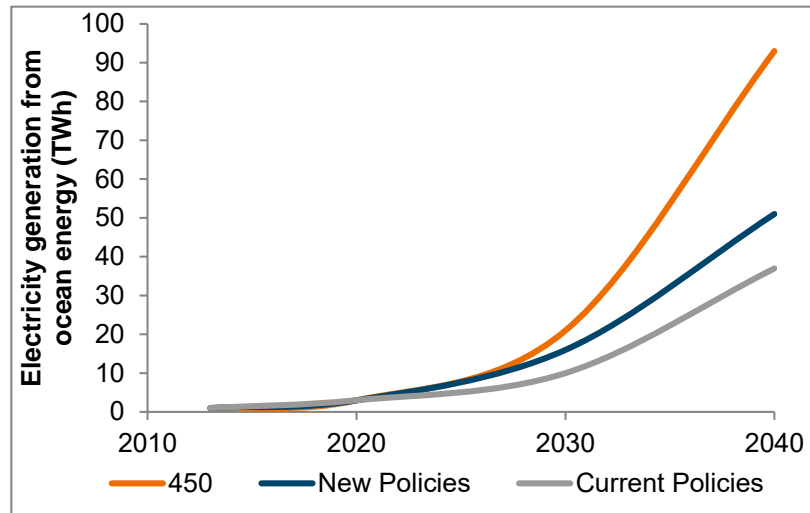
Source: Lewis et al. (2011)

6. MARKET OUTLOOK

This section considers the long-term outlook for ocean energy by examining two long-term global energy scenarios from the International Energy Agency (IEA). The first of these is the World Energy Outlook (WEO) 2015, which offers a vision of what the world's energy sector could look up to 2040 under three scenarios:

- **New Policies scenario** - takes into account the policies and implementing measures affecting energy markets adopted as of mid-2015 (including energy-related components of climate pledges submitted prior to COP21), together with relevant declared policy intentions.
- **Current Policies scenario** - takes into account only policies enacted as of mid-2015.
- **450 scenarios** - depicts a pathway to the 2 °C climate goal that can be achieved by fostering technologies close to commercialisation.

As is evident from Figure 27 the share of renewable electricity is expected to increase across all three scenarios but is most pronounced in the 450 Scenario with 53% of electricity generation from renewables by 2040 with marine energy contributing 93 TWh per annum under this scenario with 36 GW of installed capacity. Compared to the 1 TWh generated in 2013 this would constitute a huge leap in terms of deployment. However, given the advantage other types of renewables enjoy in terms of cost, supply chain maturity etc. marine energy is still expected to play a relatively minor role under this scenario, accounting for only 0.5% of total renewable electricity generation by 2040. Furthermore, it contributes significantly less under the other two scenarios (Figure 27 and Table 5).

FIGURE 27: ELECTRICITY GENERATION FROM OCEAN ENERGY BETWEEN 2013 AND 2040

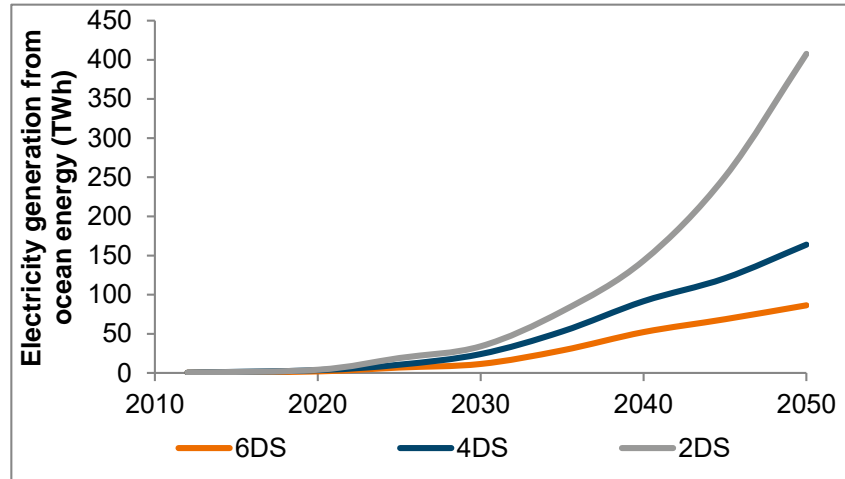
Source: IEA (2015b)

IEA also produces scenarios as part of its annual Energy Technology Perspectives (ETP). The ETP scenarios run to 2050 and explicitly relate to average global rise in degrees centigrade (DS) associated with anthropogenic climate change:

- **2 DS** - this provides at least a 50% chance to limit a mean temperature increase below 2°C.
- **4 DS** - takes into account climate and energy policies being planned or under discussion with a less dramatic temperature increase of 3.7°C.
- **6 DS** - assumes no GHG mitigation efforts beyond policy measures already implemented, which could lead to a 60% increase in annual energy and process-related CO₂ emissions, leading to a temperature increase of 5.5°C.

Figure 28 and Table 5 illustrate the envisaged level of generation from ocean energy under these three scenarios. Overall, the outlook is more positive for ocean energy with 52 TWh generated under 6DS, 92 TWh under 4DS and 144 TWh under 6DS. This is a result of total installed ocean energy capacity increasing from approximately 1 GW in 2013 to 37 GW under 6DS, 71 GW under 4DS and 178 GW under 6DS by 2050. Even so, under all three scenarios ocean energy accounts for under 1% of total renewable electricity generation.

FIGURE 28: ELECTRICITY GENERATION FROM OCEAN ENERGY BETWEEN 2012 AND 2050



Source: IEA (2015a)

Taken together we find that by 2040 the range of electricity generation from ocean energy sits between 51 and 144 TWh and installed capacity between 14 and 62 GW. We also find that ocean energy contributes between 0.3% and 0.7% of renewable electricity generation and 0.1% and 0.4% of total electricity generation.

TABLE 5: OCEAN ENERGY ELECTRICITY GENERATION SCENARIOS BY 2040 FOR IEA’S GEO AND ETP SCENARIOS

	2013 (GEO)	GEO (2040)			ETP (2040)		
		Current Policies	New Policies	450 Scenario	6DS	4DS	2DS
Total electricity (TWh)	23318	43120	39444	33910	41515	40045	35887
Renewable electricity generation (TWh)	5105	11487	13429	17816	11104	13726	19434
Bioenergy	464	1258	1454	2077	1445	1767	2474

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Hydropower	3789	5902	6180	6836	5531	5891	6454
Wind	635	2778	3568	5101	2696	3703	5650
Geothermal	72	299	392	541	285	402	595
Solar PV	139	1066	1521	2232	910	1480	2261
Concentrating solar power	5	147	262	937	185	391	1856
Ocean	1	37	51	93	52	92	144
Renewables as % of total electricity generation	22%	27%	34%	53%	27%	34%	54%
Ocean as % of total renewable electricity generation	0.02%	0.32%	0.38%	0.52%	0.47%	0.67%	0.74%
Ocean as % of total electricity generation	0.00%	0.09%	0.13%	0.27%	0.13%	0.23%	0.40%
Ocean installed capacity (GW)	1	14	20	36	22	40	62

Source: IEA (2015b; 2015a)

GLOBAL TABLES

INSTALLED COMMERCIAL CAPACITY

WAVE ENERGY

Status	Country:	Name:	Region:	Number of devices	Estimated date of commissioning	Converter manufacturer:	Converter type:	Converter working principle:	Converter capacity [MW]:	Capacity [MW]:
Fully Operational	China	Wave Pendulum	Daguan island, Shandong Province	1	1999	-	-	Oscillating wave surge converter	-	0.03
Fully Operational	Ghana	Ada Foah	near Ada Foah	1	2015	Seabased	Seabased WEC	Point Absorber	-	0.4
Fully Operational	Portugal	Pico Wave Power Plant	near Cachorro, Pico Island, Azores	1	1999	-	-	Oscillating Water Column	-	0.4
Fully Operational	Spain	Mutriku Wave Energy	off Mutriku	16 (air chambers)	2011	Voith Hydro Wavegen	Wells turbine	Oscillating Water	0.25	0.3

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		Plant						Column		
Under construction	Sweden	Sotenas Project (1)	northwest of Kungshamn / Smogen	42	2016	Seabased	Seabased WEC	Point Absorber	0.025	1.05
										Operational: 1.1MW Under construction: 1.1MW

Source: OES (2016b)

TIDAL STREAM

Status	Country:	Name:	Region:	Number of devices	Estimated Date of commissioning:	Converter manufacturer:	Converter type:	Converter working principle:	Converter capacity [MW]:	Capacity [MW]:
Fully Operational	France	Sabella D10	off the island of Ouessant, Brittany	1	2015	Sabella	Sabella D10	Horizontal Axis Turbine	0.5	0.5
Fully Operational	Italy	Kobold I	Strait of Messina	1	2006	Ponte di Archimede	Kobold I	Vertical Axis Turbine	0.05	0.055
Fully Operational	South Korea	Uldolmok Tidal Power Station (1)	Jindo Island	-	2009	-	Vertical helical blade turbine	Vertical Axis Turbine	-	1
Fully Operational	South Korea	Uldolmok Tidal Power Station (2)	Jindo Island	-	2011	-	Vertical helical blade turbine	Horizontal Axis Turbine	-	0.5
Fully Operational	United Kingdom	SeaGen	near Portaferry,	1	2008	Marine Current Turbines	SeaGen S Mk 1	Horizontal Axis Turbine	1.2	1.2

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			Northern Ireland			(MCT)				
Fully Operational	USA	Cobscook Bay 1	Maine	1	2012	Ocean Renewable Power Company	TidGen	Horizontal Axis Turbine	0.15	0.15
Under construction	Canada	Cape Sharp (1)	Nova Scotia	2	N/A	OpenHydro Group Ltd.	Open-Centre Turbine	Horizontal Axis Turbine	-	4
Under construction	UK	Shetland Tidal Array	Bluemull Sound, Shetlands	5	N/A	Nova Innovation	Nova 100	Horizontal Axis Turbine	0.1	0.5
Under construction	UK	Inner Sound (1A)	north of Caithness, Scotland	4	2016	Atlantis Resources Corporation, ANDRITZ HYDRO Hammerfest	AR1500, HS1500	Horizontal Axis Turbine	1.5, 1.5	6
									Operational: 4.3MW Under construction:	

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										10.5MW
--	--	--	--	--	--	--	--	--	--	--------

Source: OES (2016b)

TIDAL RANGE

Status	Country:	Name:	Region:	Number of devices	Date of commissioning	Converter manufacturer:	Converter type:	Converter working principle:	Converter capacity [MW]:	Capacity [MW]:
Fully Operational	Canada	Annapolis Royal Generating Station	Maine	1	1984	-	-	-	-	20
Fully Operational	China	Haishan Tidal		-	1972	-	-	-	-	0.25
Fully Operational	China	BaiShakou Tidal Power Station		-	1978	-	-	-	-	0.96
Fully	China	JiangXia	Zhejiang	6	1980	-	-	-	-	4.1

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Operational			Province							
Fully Operational	China	Haishan Tidal		-	1972	-	-	-	-	0.25
Fully Operational	France	Usine maremotrice de la Rance	Rance	24	1967	Alstom Power	Bulb hydro turbine	Other tidal energy conversion	10	240
Fully Operational	Russia	Kislaya Guba Tidal Power Station (1)	in proximity to Ura Guba, Kola Peninsula, Murmansk	1	2004	-	-	-	-	0.2
Fully Operational	Russia	Kislaya Guba Tidal Power Station (2)	in proximity to Ura Guba, Kola Peninsula, Murmansk	1	2007	-	-	-	-	1.5
Fully Operational	South Korea	Sihwa-Lake Tidal Power Plant	Ansan, near Incheon	10	2011	Daewoo Engineering & Construction	Kaplan turbine	Other tidal energy conversion	25.4	254

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Under construction	South Korea	Incheon Tidal Power Plant	Gyeonggi Bay	44	2017	-	-	-	-	1320
Under construction	South Korea	Saemangeum Reclamation Project	Saemangeum	44	N/A	-	-	-	-	400
										Operational: 0.5GW Under construction: 1.7GW

Source: OES (2016b)

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REFERENCES

- Aquaret (2012), Download Images and Illustrations. Available at:
www.aquaret.com/indexea3d.html?option=com_content&view=article&id=203&Itemid=344&lang=en#Animations [Accessed April 14, 2016].
- Aqua-RET (2012), Tidal Stream - European Resource Map. Available at:
www.aquaret.com/indexcd1b.html?option=com_content&view=article&id=112&Itemid=255&lang=en.
- Atlantis (2016) AR1500. Available at: <http://atlantisresourcesltd.com/turbines/ar-series/ar1500series.html> [Accessed May 25, 2016].
- Barstow S, Mollison D, & Cruz J (2007) The Wave Energy Resource. In J. Cruz, ed. *Ocean Wave Energy: Current Status and Future Perspectives*. pp. 93–132.
- Benelux (2014), North Seas Countries' Offshore Grid Initiative. Available at:
www.benelux.int/nl/kernthemas/energie/nscogi-2012-report/ [Accessed March 15, 2016].
- Blue Energy (2014), *COMMUNICATION FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT, THE COUNCIL, THE EUROPEAN ECONOMIC AND SOCIAL COMMITTEE AND THE COMMITTEE OF THE REGIONS. Action needed to deliver on the potential of ocean energy in European seas and oceans by 2020 and beyond*, Available at:
http://ec.europa.eu/maritimeaffairs/policy/ocean_energy/documents/com_2014_8_en.pdf.
- BNEF (2015a), *Levelised Cost of Electricity Update for the second half of 2015*,
- BNEF (2015b), WIND AND SOLAR BOOST COST-COMPETITIVENESS VERSUS FOSSIL FUELS. Available at: <http://about.bnef.com/press-releases/wind-solar-boost-cost-competitiveness-versus-fossil-fuels/> [Accessed May 23, 2016].
- Bosc J (1997), The Rance bulb turbines after 30 years' service: feedback of experience. In *Congrès Colloque du 30e anniversaire de l'Usine Marémotrice de la Rance*. Société Hydrotechnique de France, Paris, France, pp. 18–24.
- BVGA (2015), Wave and Tidal Supply Chain Development Plan : Supply chain capability and enabling action recommendations, (February).
- CEC (1996), *Wave Energy Project Results: The Exploitation of Tidal Marine Currents. - DGXII - Report EUR16683EN*, Commission of the European Communities, Brussels, Belgium.
- Charlier RH, & Justus JR (1993), *Ocean Energies: Environmental, Economic and Technological Aspects of Alternative Power Sources.*, Amsterdam, The Netherlands: Elsevier.
- Clark CW et al (2009), Acoustic masking in marine ecosystems: Intuitions, analysis, and implication. *Marine Ecology Progress Series*, 395, pp.201–222.
- Cleveland CJ, (2014), Handbook of Energy. In C. J. Cleveland & C. Morris, eds. *Handbook of Energy*. MA, USA: Elsevier Science, pp. 323–332. Available at:
www.sciencedirect.com/science/article/pii/B9780124170131000182.
- Copping A et al (2014) An international assessment of the environmental effects of marine energy development. *Ocean and Coastal Management*, 99(C), pp.3–13. Available at:
<http://dx.doi.org/10.1016/j.ocecoaman.2014.04.002>.

- Cornett AM (2008) A Global Wave Energy Resource Assessment. *Proceedings of ISOPE*, 8(March), p.9.
- Corsatea TD, & Magagna D (2013) *Overview of European innovation activities in marine energy technology*, Available at: <http://publications.jrc.ec.europa.eu/repository/bitstream/JRC86301/Idna26342enn.pdf>.
- DECC (2015) *DECC Public Attitudes Tracker – Wave 15*, Available at: www.gov.uk/government/uploads/system/uploads/attachment_data/file/254725/summary_wave_7_findings_decc_public_attitudes_tracker.pdf.
- DECC (2010), *Marine Energy Action Plan 2010. Executive Summary & Recommendations*, London. Available at: [www.decc.gov.uk/assets/decc/What we do/UK energy supply/Energy mix/Renewable energy/explained/wave_tidal/1_20100317102353_e_@@_MarineActionPlan.pdf](http://www.decc.gov.uk/assets/decc/What%20we%20do/UK%20energy%20supply/Energy%20mix/Renewable%20energy/explained/wave_tidal/1_20100317102353_e_@@_MarineActionPlan.pdf).
- Devis-Morales A et al (2014) Ocean Thermal Energy Resources in Colombia. *Renewable Energy*, 66, pp.759–769.
- DOE, (2012), *Modelling the Physical and Biochemical Influence of Ocean Thermal Energy Conversion Plant Discharges into their Adjacent Waters*, Available at: www.osti.gov/scitech/.
- Drew B, Plummer AR & Sahinkaya MN (2009), A review of wave energy converter technology. *Journal of Power and Energy*, 223, pp.887–902. Available at: <http://pia.sagepub.com/content/223/8/887.short?rss=1&ssource=mfr>.
- EMEC (2016), Tidal devices. Available at: <http://www.emec.org.uk/marine-energy/tidal-devices/> [Accessed April 14, 2016].
- ENR (2014), *Syndicat des Énergies Renouvelables: Annuaire de la filière française des énergies marines renouvelables*, Available at: www.enr.fr/rechercheadherents.
- European Commission (2006), *Energy Technologies: Knowledge-Perception Measures*, Available at: <http://ec.europa.eu/research/>.
- European Commission (2012), Questions and Answers on the outcome of the first call for proposals under the NER300 programme. Available at: http://europa.eu/rapid/press-release_MEMO-12-999_en.htm [Accessed December 18, 2015].
- European Commission (2014), Questions and Answers on the outcome of the second call for proposals under the NER 300 programme. Available at: http://europa.eu/rapid/press-release_MEMO-14-465_en.htm [Accessed December 18, 2015].
- Executive Committee of the OES (2011), *An international vision for ocean energy*, Available at: www.ocean-energy-systems.org/library/oes-strategic-plans/document/oes-vision-for-international-deployment-of-ocean-energy/.
- Falcão AF de O (2010), Wave energy utilization: A review of the technologies. *Renewable and Sustainable Energy Reviews*, 14(3), pp.899–918. Available at: www.sciencedirect.com/science/article/pii/S1364032109002652.
- Hannon M, Skea J & Rhodes A (2013), *ENERGY RESEARCH AND TRAINING PROSPECTUS: Wind, Wave and Tidal Energy*, London. Available at: [https://workspace.imperial.ac.uk/rcukenergystrategy/Public/reports/Final Reports/RCUK ESF prospectus - WWT.pdf](https://workspace.imperial.ac.uk/rcukenergystrategy/Public/reports/Final%20Reports/RCUK%20ESF%20prospectus%20-%20WWT.pdf).

- Harris M (2016), Atlantis surrenders Crown Estate leases for two tidal energy sites. *HydroWorld*. Available at: www.hydroworld.com/articles/2016/03/atlantis-surrenders-crown-estate-leases-for-two-tidal-energy-sites.html.
- HIE & Scottish Enterprise (2015), Marine Energy : Seizing the supply chain opportunity. , (March).
- IEA (2015a), *Energy Technology Perspectives 2015. Mobilising Innovation to Accelerate Climate Action*, Paris.
- IEA (2016), *IEA Energy RD&D Data*, Paris. Available at: <http://wds.iea.org/WDS/Common/Login/login.aspx>.
- IEA (2015b), *World Energy Outlook*,
- Iyer AS et al (2013), Variability and phasing of tidal current energy around the United Kingdom. *Renewable Energy*, 51, pp.343–57. Available at: <http://dx.doi.org/10.1016/j.renene.2012.09.017>.
- Jeffrey H, Jay B, & Winskel M (2013), Accelerating the development of marine energy: Exploring the prospects, benefits and challenges. *Technological Forecasting and Social Change*, 80(7), pp.1306–1316. Available at: <http://dx.doi.org/10.1016/j.techfore.2012.03.004>.
- Kempener R & Neumann F (2014a) *Ocean thermal energy conversion*, Available at: www.irena.org/DocumentDownloads/Publications/Ocean_Thermal_Energy_V4_web.pdf.
- Kempener R, & Neumann F (2014b), *TIDAL ENERGY TECHNOLOGY BRIEF*, Available at: www.irena.org/documentdownloads/publications/tidal_energy_v4_web.pdf.
- Kerr D (2007), Marine Energy. *Philosophical Transactions: Mathematical, Physical and Engineering Sciences*, 365(1853, Energy for the Future), pp.971–992. Available at: <http://libproxy.uta.edu:2055/stable/25190483>.
- LCICG (2012), Carbon Innovation Coordination Group Technology Innovation Needs Assessment (TINA) Marine Energy Summary Report. *Energy*, (August 2012). Available at: www.lowcarboninnovation.co.uk/document.php?o=7.
- Lee KS (2015), Outlook for Ocean Energy Development in Korea. In *THE EAST ASIAN SEAS CONGRESS 2015*. Available at: http://eascongress.pemsea.org/sites/default/files/file_attach/PPT-S3W3-10-Lee.pdf.
- Lewis A et al (2011), Ocean Energy. In O. Edenhofer et al., eds. *IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation*. Cambridge, United Kingdom: Cambridge University Press, pp. 497–533. Available at: http://srren.ipcc-wg3.de/report/IPCC_SRREN_Ch06.pdf.
- Magagna D et al (2014), *Wave and Tidal Energy Strategic Technology Agenda*, Available at: www.oceanenergy-europe.eu/images/OEF/140215_SI_Ocean_-_Sstrategic_Technology_Agenda.pdf.
- Magagna D, & Uihlein A (2015), *2014 JRC Ocean Energy Status Report: Technology, market and economic aspects of ocean energy in Europe*, Petten, Netherlands.
- Makai (2016), Offshore OTEC Diagram. Available at: www.makai.com/images/Offshore_OTEC_Diagram_9495x5161.png [Accessed May 25, 2016].

- Mclachlan C (2010), Tidal stream energy in the UK : Stakeholder perceptions study A research report by The Tyndall Centre University of Manchester. , (May).
- MeyGen (2014), £51 million MeyGen Financial Close Completed. Available at: www.meygen.com/the-project/meygen-news/.
- Mofor L, Goldsmith J, & Jones F (2014), *OCEAN ENERGY: Technology Readiness, Patents, Deployment Status and Outlook*, Paris.
- Mørk G et al (2010), Assessing the global wave energy potential. In *Proceedings of OMAE2010 (ASME), 29th International Conference on Ocean, Offshore Mechanics and Arctic Engineering*. Shanghai, China.
- NASA (2006), *TOPEX/Poseidon: Revealing Hidden Tidal Energy*, Greenbelt, Maryland. Available at: svs.gsfc.nasa.gov/stories/topex/.
- Newman S (2016), Technology in the Middle Ages. Available at: www.thefinertimes.com/Middle-Ages/technology-in-the-middle-ages.html [Accessed April 6, 2016].
- Nihous GC (2010), Mapping available Ocean Thermal Energy Conversion resources around the main Hawaiian Islands with state-of-the-art tools. *Journal of Renewable and Sustainable Energy*, 2(4).
- NOAA (2014), *Ocean Thermal Energy Conversion (OTEC) Technology*, Available at: <http://coastalmanagement.noaa.gov/programs/otec.html>.
- Ocean Energy Systems (2016), *Annual Report Ocean Energy Systems 2015*, Available at: <https://report2015.ocean-energy-systems.org/documents/OES-Annual-Report-2015/>.
- OES (2016a), Ocean Energy in the World: GIS Map Page. Available at: www.ocean-energy-systems.org/ocean-energy-in-the-world/gis-map/ [Accessed February 25, 2016].
- OES (2016b), Offshore installations worldwide - GIS map. Available at: www.ocean-energy-systems.org/ocean-energy-in-the-world/gis-map/ [Accessed April 1, 2016].
- OES - IEA (2015), International Levelised Cost Of Energy for Ocean Energy Technologies. , (May), p.35. Available at: www.ocean-energy-systems.org/library/oes-technical-reports/market-overview/document/international-levelised-cost-of-energy-for-ocean-energy-technologies-2015/.
- ORE Catapult (2016), Wave & tidal innovation challenges. Available at: <https://ore.catapult.org.uk/wave-tidal-innovation-challenges> [Accessed March 17, 2016].
- Pelc R, & Fujita RM (2002), Renewable energy from the ocean. *Marine Policy*, 26, pp.471–479.
- Renewables Advisory Board (2008), Marine renewables: current status and implications for R&D funding and the Marine Renewables Deployment Fund. , (January). Available at: www.oceanrenewable.com/wp-content/uploads/2008/02/uk-govt-progress-assess-02-08-2007.pdf.
- Renewables UK (2013), Working for a Green Britain & Northern Ireland. , (September).
- Repoint Energy Limited (2009), *The benefits of marine technologies within a diversified renewables mix*,
- Ross D (1996), *Power from the Waves*, Oxford: Oxford Univeristy Press.

- SI Ocean (2013a), *Ocean Energy: Cost of Energy and Cost Reduction Opportunities*, Available at: http://si-ocean.eu/en/upload/docs/WP3/CoE_report_3_2_final.pdf.
- SI Ocean (2012), *Ocean Energy: State of the Art. EU project Report*, p.79. Available at: http://si-ocean.eu/en/upload/docs/WP3/Technology_Status_Report_FV.pdf.
- SI Ocean (2013b), *Ocean Energy: State of the Art*, Strategic Initiative for Ocean Energy. Available at: http://si-ocean.eu/en/upload/docs/WP3/Technology_Status_Report_FV.pdf.
- Stefanovich MA, & Chozas JF, (2010), *Toward Best Practices for Public Acceptability in Wave Energy: Issues Developers Need to Address.* , pp.1–9.
- Steijn R (2015), *Dynamic Tidal Power Technology Advances*. *RenewableEnergyWorld.com*. Available at: www.renewableenergyworld.com/articles/2015/01/dynamic-tidal-power-technology-advances.html.
- Tethys (2012), *La Rance Tidal Barrage*. Available at: <https://tethys.pnnl.gov/annex-iv-sites/la-rance-tidal-barrage> [Accessed May 25, 2016].
- The Carbon Trust (2011), *Marine Renewables Green Growth Paper*. Available at: www.carbontrust.com/media/597981/marine-green-growth-carbon-trust.pdf.
- Thorpe T (1999) *A Brief Review of Wave Energy*,
- TidalPower (2013), *History of Tidal Power*. Available at: <http://tidalpower.co.uk/history-of-tidal-power> [Accessed April 6, 2016].
- Uihlein A, & Magagna D (2015), *A review of the current state of research in the area of ocean energy*. *Renewable & Sustainable Energy Reviews*, Submitted (MAY).
- Usachev IN (2008), *The outlook for world tidal power development*. *International Journal on Hydropower and Dams*, 15(5), pp.100–105.
- Vantoch-Wood AR, (2012) *Quantifying Methods for an Innovation Systems Analysis of the UK Wave Energy Sector*. University of Exeter. Available at: <https://ore.exeter.ac.uk/repository/bitstream/handle/10871/11122/Vantoch-WoodA.pdf?sequence=1>.
- Vosough A (2014), *Wave Energy: Technology Brief*, Available at: www.irena.org/documentdownloads/publications/wave-energy_v4_web.pdf.
- WEC (2010), *Tidal Energy: 2010 Survey of Energy Resources*,
- Wentworth J (2013), *POSTNOTE: Environmental Impact of Tidal Energy Barrages*, Available at: www.parliament.uk/briefing-papers/POST-PN-435.pdf.
- Whitaker D, (2011), *Sea Turbines : Turning the Tide in Energy Production*, Available at: www.energy.siemens.com/hq/pool/hq/energy-topics/publications/living-energy/pdf/issue-04/Living-Energy4-Marine-Turbines-Tidal-Power.pdf.
- Whittaker TJT et al (2004) *The Limpet Wave Power Project – The First Years Of Operation*. *Scottish Hydraulics Study Group - Seminar on the Hydraulic Aspects of Renewable Energy*, (1997), pp.1–8.
- Winkel M (2007), *Policymaking for the niche: successes and failures in recent UK marine energy policy*. In *International Summer Academy of Technology Studies - Transforming the Energy System*. Available at: www.sts.aau.at/eng/content/download/5044/45551.

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KEY FINDINGS

1. CCS is an essential element of any future low carbon energy and industrial future.
2. Significant experience exists across the CCS chain:
 - Capture: Especially industrial
 - Transportation: After separation and compression usually via pipelines
 - Storage: Operating experience in injection and risk management
3. The large-scale projects in operation around the world demonstrate the viability of CCS technology.
4. Carbon capture technologies can be applied to all types of new coal and gas-based power plants.
5. The exclusion of CCS as a technology option in the electricity sector alone would increase mitigation costs by a very considerable margin.
6. Strong policy is essential for speed of implementation.
7. Policy is in fact the main issue, not technology.

INTRODUCTION

Carbon capture and storage (CCS) sometimes referred to as carbon capture utilisation and storage (CCUS), is an integrated suite of technologies that can prevent large quantities of the greenhouse gas (GHG) carbon dioxide (CO₂) from being released into the atmosphere.

There are three major elements involved in this technology:

- 1. Capture** – the separation and compression of CO₂ from other gases produced at large industrial process facilities such as coal and natural gas power plants, steel mills, cement plants and chemical and petrochemical facilities.
- 2. Transport** – once separated and compressed, the CO₂ is transported, usually via pipelines, to a suitable storage site.
- 3. Storage** – geological storage of CO₂ at an appropriate scale to support CCS deployment can be achieved through injection underground into selected rock formations (mainly deep saline formations and depleted hydrocarbon reservoirs), typically at depths of around 1 km or deeper. Storage can also be achieved through utilisation of CO₂ for underground injection at enhanced oil recovery (EOR) sites over similar depth ranges. Other utilisation options, typically involving industrial processes, are in the early stages of technical development and have much less mitigation potential.

Carbon capture technologies can be applied to all types of new coal and gas-based power plants. The same is true for retrofitting CCS onto existing power plants, which requires space and extensive integration to accommodate the CO₂ capture system.

The world's first large-scale application of CO₂ capture technology in the power sector commenced operation in October 2014 at the Boundary Dam power station in Saskatchewan, Canada. In the US, two additional demonstrations of large-scale CO₂ capture in the power sector – at the Kemper County Energy Facility in Mississippi and the Petra Nova Carbon Capture Project in Texas – are planned to come into operation in 2016-2017.

Industrial processes as used in the manufacture of cement, steel, pulp and paper, chemicals and natural gas processing emit significant amounts of CO₂, accounting for nearly 25% of global CO₂ emissions. Capture technologies can be applied in these industries to make a significant reduction in global CO₂ emissions.

Carbon separation / capture technologies have been operating at large-scale in the natural gas and fertiliser industries for decades. Construction is also underway on the world's first large-scale CCS project in the iron and steel sector, the Abu Dhabi CCS Project in the United Arab Emirates (UAE), which is expected to be launched in 2016.

THE IMPORTANCE AND POTENTIAL OF CCS

At the COP 21 meeting in Paris in December 2015, all 195 UNFCCC Parties reinforced the goal to hold the increase in global temperature to below 2°C. An 'aspiration' to limit the temperature rise to 1.5°C was raised at the meeting and the Intergovernmental Panel on Climate Change (IPCC) is to provide a Special Report in 2018 on the implications of such an 'aspiration'.

Achieving decarbonisation, while delivering more energy and growth is a challenge to be met by a number of clean energy solutions, including energy efficiency and demand management measures, renewables, nuclear and other low-carbon energy sources, and the use of fossil fuels and biomass with CCS.

Over the past decade since the release of the IPCC special report on Carbon Dioxide Capture and Storage in 2005¹, CCS has been accepted as a major climate change mitigation option and included in all major global GHG reduction scenarios. In these scenarios CCS plays a vital role as part of an economically sustainable route to meet longer term climate mitigation goals. The IPCC Fifth Assessment Synthesis Report (2014) noted, amongst other things, that without CCS the costs of climate change mitigation would increase by 138%.² The Synthesis Report also noted that the deployment of CCS, including bio-CCS, will significantly reduce the risk of not meeting climate goals. Many climate models indicate the world will need to achieve 'net negative emissions' during this century. CCS used in the combustion of biomass is a large-scale 'net negative' emissions technology that could play an important role in this period.

CCS is currently the only available technology that can significantly reduce GHG emissions from certain industrial processes and it is a key technology option to decarbonise the power sector, especially in countries with a high share of fossil fuels in electricity production. Independent, credible forecasts are that by 2040 the world will still be predominantly reliant on energy from fossil fuels, even with unprecedented growth in the deployment of low carbon technologies and energy efficiency measures.³

In terms of the scale of CCS deployment, there are 22 large-scale CCS projects currently in operation or under construction around the world, with the capacity to capture up to 40 million tonnes of CO₂ per year (Mtpa). These projects cover a range of industries, including gas processing, power, fertiliser, steel-making, hydrogen-production (refining applications) and chemicals. They are located predominantly in North America, where the majority of CO₂ capture capacity is intended for use in EOR.⁴

¹ IPCC (2005) Carbon Dioxide Capture and Storage, New York: Cambridge University Press.

² IPCC (2014) Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, Geneva.

³ IEA (2015) World Energy Outlook: 2015, Paris: OECD/IEA.

⁴ Projects data is sourced from the Global CCS Institute. <http://www.globalccsinstitute.com/>

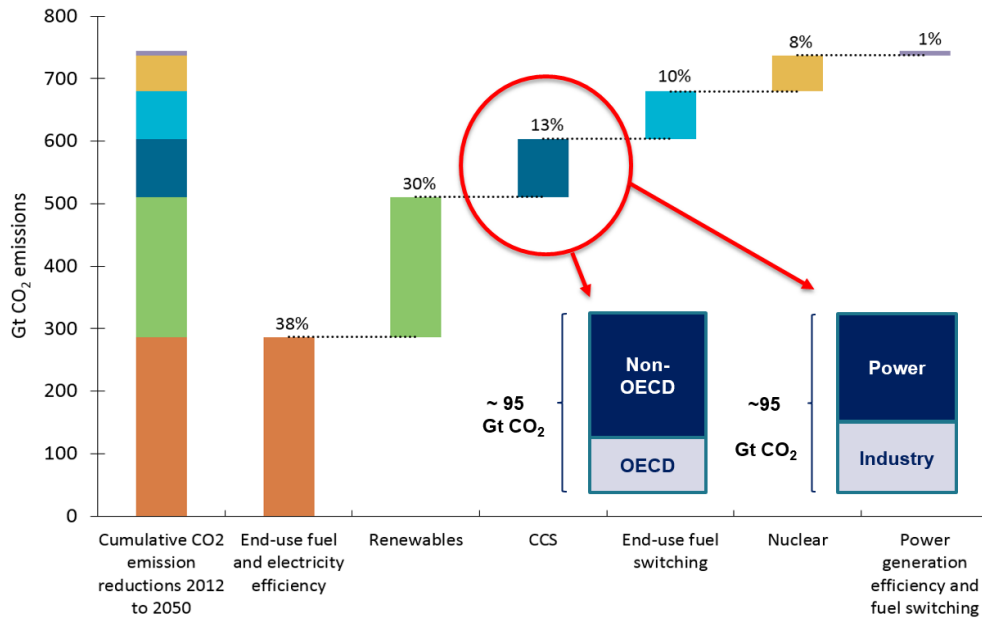
This compares with less than ten large-scale CCS projects in operation or under construction at the time of the release of the above-mentioned IPCC special report on Carbon Dioxide Capture and Storage in 2005 (and with these projects very highly concentrated in natural gas processing). Over the course of the last ten years there has also been very considerable activity at pilot and research scale. All these activities have provided valuable information to assist in the design and development of large-scale CO₂ capture plants, to advance the understanding of the behaviour of CO₂ in the subsurface, and to contribute to public outreach activities.

The IEA's modelling of least-cost outcomes to achieve the 2°C goal suggests global CO₂ capture capacity needs to increase to around 4,000 million tonnes per annum in 2040 and 6,000 million tonnes per annum in 2050. In this modelling, CCS provides around 13% of the cumulative CO₂ reductions through 2050 in a 2°C world compared to 'business as usual' (equivalent to around 95,000 million tonnes of CO₂ emissions reduction).⁵ The application of CCS technologies is equally important in industrial applications as in power generation and will be especially important in non-OECD economies, which will experience continued growth in fossil fuel based power and industrial output (Figure 1). It would be anticipated that the more stringent 'aspiration' of a 1.5°C goal would reinforce the importance of CCS in the portfolio of low-carbon technologies.

A description of the main CCS technologies follows as does a discussion of the main factors relevant to significantly boosting global CO₂ capture (and storage) capacity in the coming decades. These include the need to continue to reduce CO₂ capture costs and to 'prove up' significantly more geologic storage capacity in deep geological formations. While CO₂-Enhanced Oil Recovery (EOR) systems account for the majority of current (and soon to be) operational CCS projects, resource estimates indicate a much greater potential for dedicated geological storage options to meet longer term CO₂ capture and storage requirements.

⁵ IEA (2015) Energy Technology Perspectives 2015, Paris: OECD/IEA.

FIGURE 1: CCS CONTRIBUTES 13% OF CUMULATIVE REDUCTIONS REQUIRED THROUGH 2050 IN A 2°C WORLD COMPARED TO BUSINESS AS USUAL



Source: OECD/IEA (2015), Energy Technology Perspectives 2015, IEA Publishing.
 Licence: <https://www.iea.org/t&c/termsandconditions/>

As with any new technology, it will be important to garner public acceptance by addressing concerns raised and showcasing key project developments to improve stakeholder understanding and familiarisation with CCS as an emissions reduction technology that will need to be widely deployed in a low-carbon future.

Countries that are further advanced along the CCS Lifecycle are developing or have already implemented a CCS pilot or demonstration project. Pilot and demonstration projects are key drivers for 'learning-by-doing'. Projects provide a catalyst or focus for other associated capacity development, enabling and pre-investment activities.

CCS DEVELOPMENT LIFECYCLE

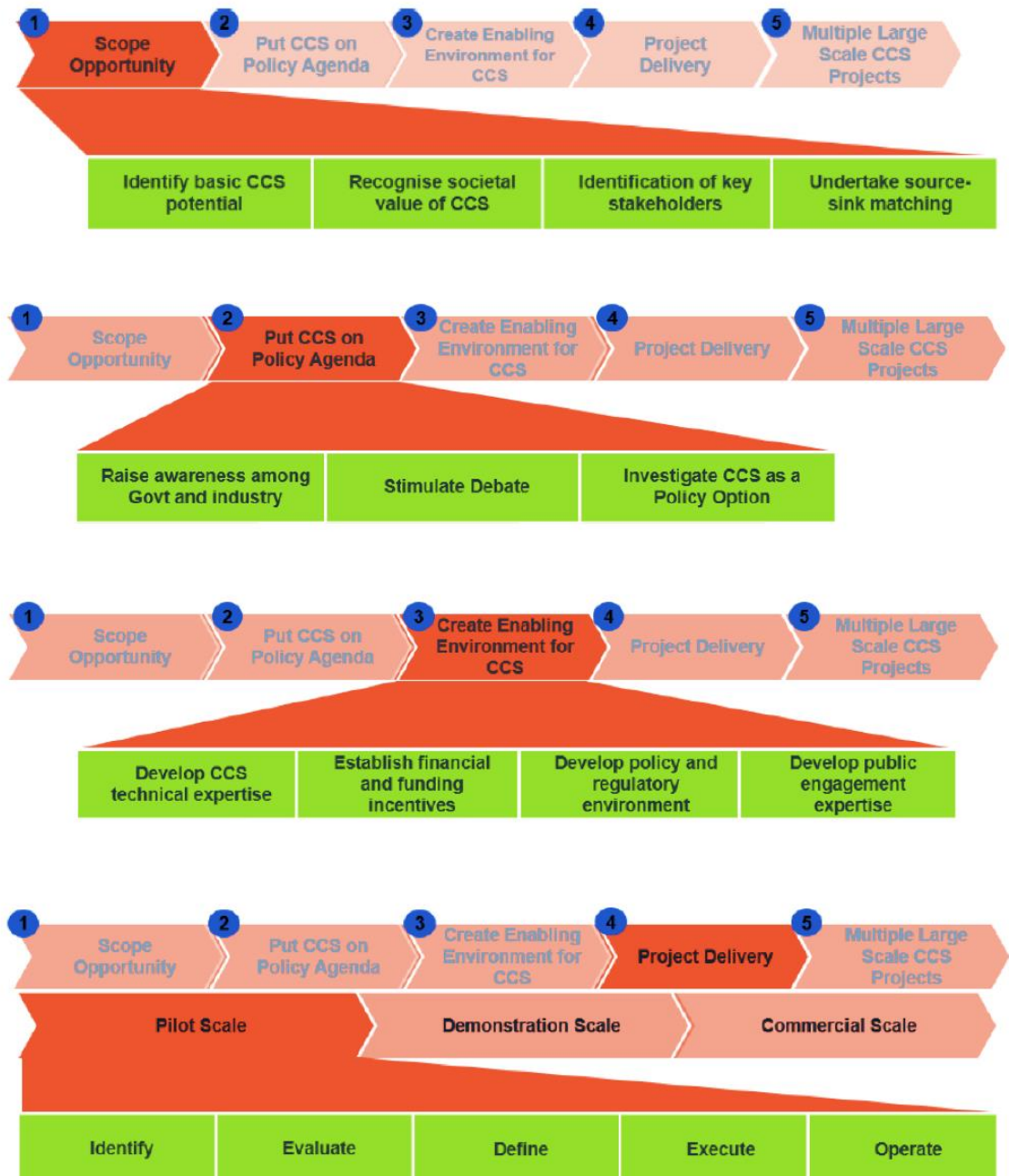
The CCS Development Lifecycle (represented below) is a tool developed by the Global CCS Institute to help conceptualise different stages of CCS development.⁶

The lifecycle comprises five major stages. The rotating circles indicate that movement through the different stages is an iterative process that is not necessarily linear. In fact, countries may operate in different stages, sometimes concurrently, driven by their own needs, interests, approaches and projects.⁶

⁶ <http://www.globalccsinstitute.com/sites/www.globalccsinstitute.com/files/publications/25916/ccs-developing-countries.pdf>

FIGURE 2: CCS DEVELOPMENT LIFECYCLE

CCS DEVELOPMENT LIFECYCLE (GCCSI)



Source: Global CCS Institute (GCCSI)

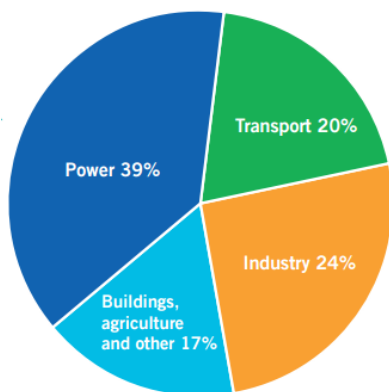
1. TECHNOLOGIES

CO₂ CAPTURE

Carbon capture technologies can be applied to large-scale emissions processes such as fossil-fuel fired power generation and many large industrial processes, including natural gas processing and fertiliser production and the manufacture of industrial materials such as cement and steel. CO₂ emissions from the power and industry sectors account for nearly two-thirds of global energy-related CO₂ emissions (Figure 3).

FIGURE 3: GLOBAL ENERGY-RELATED CO₂ EMISSIONS

2012 CO₂ emissions: 34.5 gigatonnes



Source: OECD/IEA 2015, Energy Technology Perspectives 2015, IEA Publishing.
Licence: <https://www.iea.org/t&c/termsandconditions/>

Fossil fuel-fired power plants generate a larger percentage of CO₂ emissions than any other industry. Therefore, applying carbon capture technology to that sector, whether on new or existing plants, has the potential for the greatest reduction of CO₂ emissions compared to other sectors.

Carbon capture technologies can be applied to all types of new coal and gas-based power plants. The same is true for retrofitting CCS onto existing power plants, which requires space and extensive integration to accommodate the CO₂ capture system.

The world's first large-scale application of CO₂ capture technology in the power sector commenced operation in October 2014 at the Boundary Dam power station in

Saskatchewan, Canada. In the US, two additional demonstrations of large-scale CO₂ capture in the power sector, at the Kemper County Energy Facility in Mississippi and the Petra Nova Carbon Capture Project in Texas, are planned to come into operation in 2016-2017.

Industrial processes as used in the manufacture of cement, steel, pulp and paper, chemicals and natural gas processing emit significant amounts of CO₂, accounting for nearly 25% of global CO₂ emissions. Capture technologies can be applied in these industries to make a significant reduction in global CO₂ emissions.

Carbon separation / capture technologies have been operating at large-scale in the natural gas and fertiliser industries for decades. Construction is also underway on the world's first large-scale CCS project in the iron and steel sector, the Abu Dhabi CCS Project in the United Arab Emirates (UAE), which is expected to be launched in 2016.

In some cases, CO₂ emissions are a by-product of manufacturing processes. In these cases, (such as cement manufacture and blast furnace steel making) CCS is the only technological option that can help secure deep emissions reduction.

How is CO₂ captured?

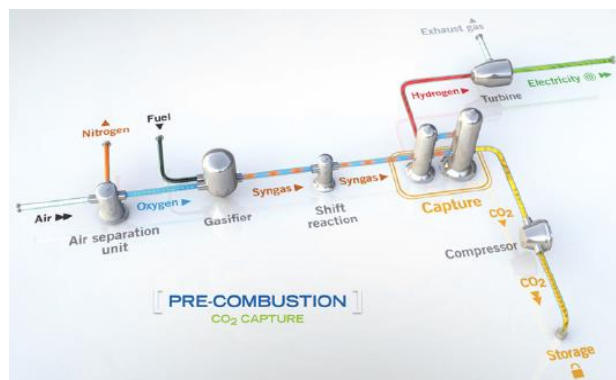
Energy from fossil fuels such as coal, oil and natural gas is released in the combustion (burning) and conversion process, which also results in the emission of CO₂.

In pulverised coal power production, which makes up the vast majority of coal-based power plants through North America, Europe and Asia, the CO₂ concentration in combustion flue gases is somewhat dilute, which makes separation more challenging. In other systems, such as coal gasification (where coal can be converted to power, chemicals, methane or hydrocarbon liquids), the CO₂ concentration is higher and it can be more easily separated.

There are three basic types of CO₂ capture: pre-combustion, post-combustion and oxyfuel combustion.

1. Pre-combustion processes

convert fuel into a gaseous mixture of mostly hydrogen and CO. The hydrogen is separated and can be burnt without producing any additional CO₂; the separated CO₂ can then be compressed for transport and storage. The fuel conversion process for pre-combustion power generation is highly integrated, and thus CO₂



separation needs to be integrated into the process from the beginning. For this reason, pre-

combustion capture on power generation will be advanced through new build projects (such as the Kemper County Energy Facility in the US). Carbon dioxide separation technologies used for pre-combustion power generation are also applicable to some industrial processes (such as natural gas processing).

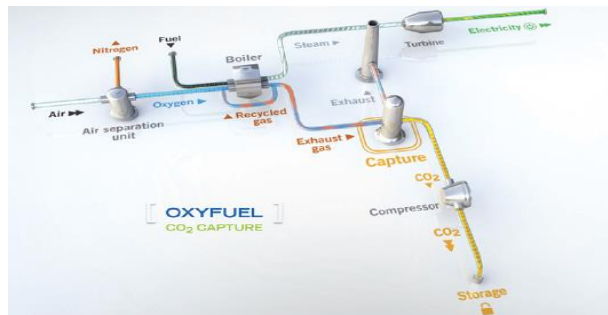
2. Post-combustion processes

separate CO₂ from combustion exhaust gases. CO₂ can be captured by using a liquid solvent or other separation methods. In a solvent absorption-based approach, once absorbed by the solvent, the CO₂ is released by heating to form a high purity CO₂ stream. This technology is widely used to capture CO₂ for use in the food and beverage industry. Post-combustion capture processes are integral in both the Boundary Dam CCS and Petra Nova Carbon Capture projects.



3. Oxyfuel combustion processes

use oxygen rather than air for combustion of fuel. This produces exhaust gas that is mainly water vapour and CO₂ that can be easily separated to produce a high purity CO₂ stream.



Source: Global CCS Institute

Development trends in CO₂ capture technologies

While carbon capture technology has progressed significantly in recent years and industry has gained sufficient experience and confidence to build and operate large-scale capture units, efforts are underway to reduce the cost and energy penalties for the next generation of capture technologies. This is important because in power generation, for example, 70-90% of the overall cost of a large-scale CCS project can be driven by expenses related to capture systems⁷.

⁷ US DOE, 2010: Report of the Interagency Task Force on Carbon Capture and Storage, Washington DC.

For the next generation of CCS projects, significant cost savings can be realised by:

- Optimising the first-generation processes through 'learning by doing'. This will provide valuable information for decreasing the cost of design, construction, and operation of future carbon capture facilities. SaskPower, the Operator of the Boundary Dam CCS Project, has stated that a capital cost reduction of up to 30% is achievable if a project similar to their Boundary Dam effort is undertaken in the future⁸.
- Continuing R&D efforts on promising new concepts followed by pilot testing at facility sizes that can provide confidence for technology users to scale up to commercial projects. Two such pilot test facilities are the National Carbon Capture Center (NCCC) in Alabama in the U.S. and the Mongstad Test Centre in Norway.

A portfolio of next-generation carbon capture technologies is under development. Three main areas are targeted: materials, processes and equipment.

Materials

Research and development (R&D) related to materials will involve the development of higher-performance solvents, sorbents and membranes. For solvents and sorbents, that could mean materials with enhanced separation kinetics. Faster reactions allow for shorter residence times and smaller reaction vessels. Smaller vessels correspond to lower capital costs. In addition, solvents and sorbents that require less energy to strip separated CO₂ would result in lower parasitic energy losses and thus decreased costs. For membranes, materials with enhanced permeability and selectivity would have similar impacts on both capital and operating costs.

Processes

Process improvements can also lead to reductions in both capital and operating costs. Heat integration can lead to efficiency improvements in both the capture system and the associated power plant or manufacturing facility (e.g. boiler feed-water pre-heating). Process intensification involves coupling two or more processes or systems within a single vessel. This can take the form of a hybrid process, such as one that includes both a solvent and a membrane contactor. Another form of process intensification is the combination of CO₂ separation and syngas shift in a water gas shift reactor of an integrated gasification combined cycle system. Combining multiple processes into a single reactor reduces capital costs and, depending on the process, can also reduce energy requirements. Alternatively, in some cases there may be advantages in using separate auxiliary energy units such as combined heat and power modules fueled by natural gas as the energy source for the CO₂ capture system.

⁸ Ball (2014) Presentation to University of Kentucky, University of Kentucky Center for Applied Energy Research, Kentucky.

Equipment

Development activity surrounding equipment for carbon capture is focused on novel designs that allow for size reduction and energy efficient processing. These designs may include features that enhance contacting between the capture medium and flue gases, effectively increasing mass transfer and decreasing the size of sorption equipment. Advanced manufacturing techniques are under development that promotes the construction of heat transfer surfaces that are more efficient and allow for greater process integration. Finally, novel equipment designs that take advantage of technologies not previously pursued for gas separation (e.g. rapid expansion of high pressure gases facilitating cryogenic separation) are being investigated. This approach would result in very significant size (and thus capital cost) reduction.

Priorities for the next generation of capture technologies

Several technologies employing the principles described above are currently under development. Bench-scale efforts have been completed for a variety of second generation technologies, and small pilot-scale (~1 MWe) testing is underway for a limited number of promising approaches. The priority of the US Department of Energy's (DOE) Carbon Capture R&D Program over the next several years is to advance additional 2nd generation technologies through small and large (~5 – 25 MWe) pilot-scales to be ready for demonstration-scale testing in the 2020–2025-time frame. This is a critical step in advancing more cost-effective capture technologies and readying them for widespread future deployment.

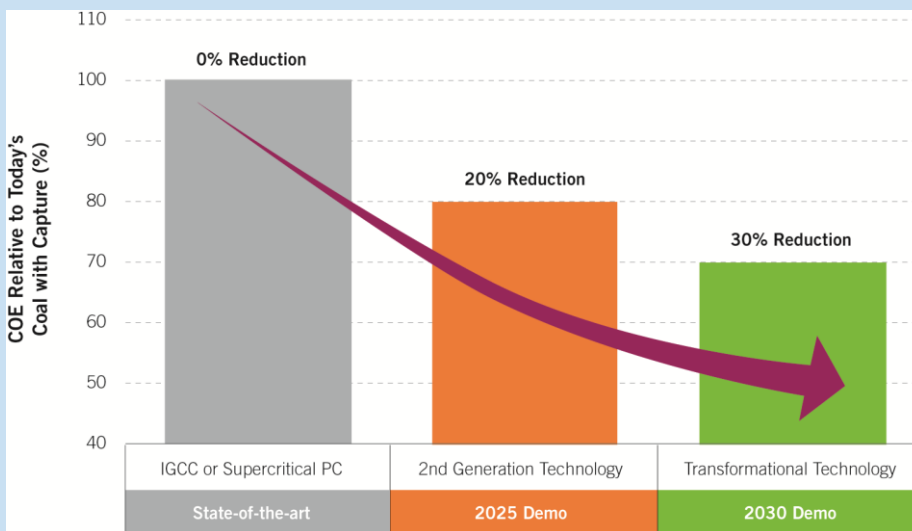
One of the key elements in advancing these technologies is collaboration between researchers, technology developers, and technology users to facilitate integration of individual technological developments into cost-effective capture systems. This will be the most effective pathway to meeting US DOE capture cost goals of US\$40/tonne CO₂ captured for second generation technologies (vs around US\$60/tonne at present).⁹

⁹ US DOE/NETL (2015) Cost and Performance Baseline for Fossil Energy Plants Volume 1a: Bituminous Coal (PC) and Natural Gas to Electricity. Revision 3, July 2015. DOE/NETL-2015/1723

CO₂ CAPTURE COST TARGETS

US DOE cost and timing targets for second generation and transformational technologies are illustrated graphically below. Second generation technologies are targeted to reduce costs (in terms of cost of electricity) by 20% compared to currently available technologies and will be available for demonstration testing in the 2025 timeframe. Transformational technologies are targeted to reduce the cost of electricity by 30% compared to currently available technologies and be available for demonstration testing in the 2030 timeframe. Both the current and future cost of electricity levels are all based on estimates for nth-of-a-kind facilities, which have significantly lower costs than first-of-a-kind facilities. While other R&D funding organisations may not explicitly employ these types of targets, in general, development efforts globally are seeking similar performance and timing.

Relative US DOE cost reduction targets and timing for 2nd generation and transformational carbon capture technologies



Source: from Plasynski, S., 2015: Fueling the future: safe, affordable, secure energy. Proceedings of the 2015 NETL CO₂ Capture Technology Meeting, June 23-26, 2015, Pittsburgh

CO₂ TRANSPORTATION

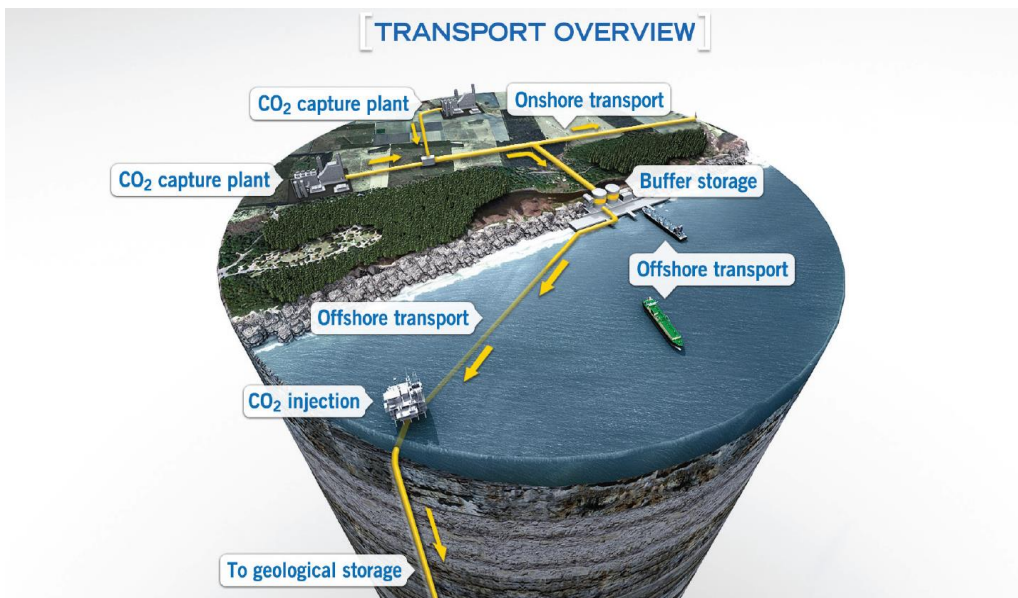
The technology for transporting CO₂ is well established and CO₂ transportation infrastructure continues to be commissioned and built. Transport of CO₂ by pipelines, trucks, trains, and ships is a reality and occurring daily in many parts of the world. Pipelines are, and are likely to continue to be, the most common method of transporting the large quantities of CO₂ involved in CCS projects.

In the US alone there are around 6,500 km of onshore CO₂ pipelines, representing over 50 different pipelines, transporting roughly 68 Mtpa of mainly naturally sourced CO₂ for EOR purposes. These pipelines have been operated with an excellent safety record since the first pipelines were laid in the early 1970s. The longest CO₂ pipeline built in the US is the Cortez pipeline at a length of 800 km and with a capacity of over 20 Mtpa. The only offshore CO₂ pipeline in operation is associated with the Snøhvit CO₂ Storage Project in Norway. The pipeline is 153 km long and has been operational since 2008.¹⁰

Ship transportation can be an alternative option in a number of regions of the world, especially where onshore and near-shore storage locations are not available. Shipment of CO₂ already takes place on a small scale in Europe, where ships transport food-quality CO₂ from large point sources to coastal distribution terminals. Larger-scale shipment of CO₂, with capacities in the range of 10,000 - 40,000 m³, is likely to have much in common with the shipment of liquefied petroleum gas (LPG), an area which has developed into a worldwide industry in recent decades.

Transport of smaller volumes of CO₂ has been undertaken by truck and rail for industrial and food grade CO₂ for over 40 years. However, the cost of transportation by truck or train is relatively high per tonne of CO₂ compared to pipelines, so it is unlikely that truck and rail transport will have a significant role in CCS deployment, except for small pilot projects.

FIGURE 4: TRANSPORT OVERVIEW



¹⁰ For further details on the status of CO₂ transportation see, Global CCS Institute, 2014: The Global Status of CCS 2014, Melbourne.



Source: Global CCS Institute

Even though the cost of CO₂ transportation is relatively low compared to the cost associated with capturing and storing the CO₂, the scale of investment in CO₂ transportation infrastructure required to support large-scale deployment of CCS will be considerable. Researchers involved in the collaborative CO₂ Europipe project have suggested that by 2050 a total ranging from 22,000 to 33,000 km of pipeline will need to be in place in Europe alone for the projected volume of CCS activity.¹¹ Similarly, based on scenario work conducted by ICF International, the total length of CO₂ pipelines to be built in the US to accommodate large scale CCS deployment is estimated to be between 10,000 and 30,000 km.¹²

One way to reduce the cost of CCS is to realise economies of scale by sharing a single CO₂ transport and storage infrastructure system among several operators of separate CO₂ generating plants. Therefore, it is important to think about CO₂ transport infrastructure through a regional lens (as opposed to individual point-to-point systems). The development of main CO₂ lines and distribution systems have proven to be successful in the US in terms of their ability to connect multiple sources of CO₂ (mostly naturally occurring) to a number of mature oil fields.

¹¹ Neele et al. (2011) Large-scale CCS transport and storage networks in North-west and Central Europe. Energy Procedia, vol. 4 (10th International Conference on Greenhouse Gas Control Technologies), pp 2740-2741

¹² ICF (2009) Developing a Pipeline Infrastructure for CO₂ Capture and Storage: issues and challenges, report to INGAA Foundation, Cambridge: Cambridge University Press.

EXPANDING CO₂ TRANSPORTATION NETWORKS

A series of new large-volume CO₂ pipelines have been commissioned recently in the US to allow for new, mainly industrial, sources of CO₂ to be developed and utilised for EOR. Main pipelines that have started operations in recent years include the 515 km Green pipeline in the Gulf Coast (2011) and the 370 km Greencore pipeline in the Rockies (2013), both owned and operated by Denbury Resources, as well as the 110 km Coffeyville to Burbank CO₂ pipeline in Kansas (2013), owned by Chapparral Energy.

In Canada, Cenovus Energy built the 66 km Rafferty pipeline (2014) to transport CO₂ from SaskPower's Boundary Dam capture plant to the Weyburn oil unit in Saskatchewan, while the Quest Project in Alberta constructed a pipeline to cover the 64 km from the CO₂ capture facilities at the Scotford Upgrader to the geologic storage site. Also in Canada, the 240 km Alberta Carbon Trunk Line (ACTL) is planned to begin construction in 2016 and at full capacity is capable of transporting up to 14.6 Mtpa of CO₂ from sources in the Alberta industrial heartland to mature oil fields through South-Central Alberta.

CO₂ STORAGE

The storage stage of CCS predominantly involves injecting anthropogenic CO₂ into rock formations deep underground, thereby permanently removing CO₂ from the atmosphere. This is not a new or emerging technology. At present, over 150 sites are injecting CO₂ underground, many having done so over a number of decades. Numerous geological systems have stored natural CO₂ for millennia.

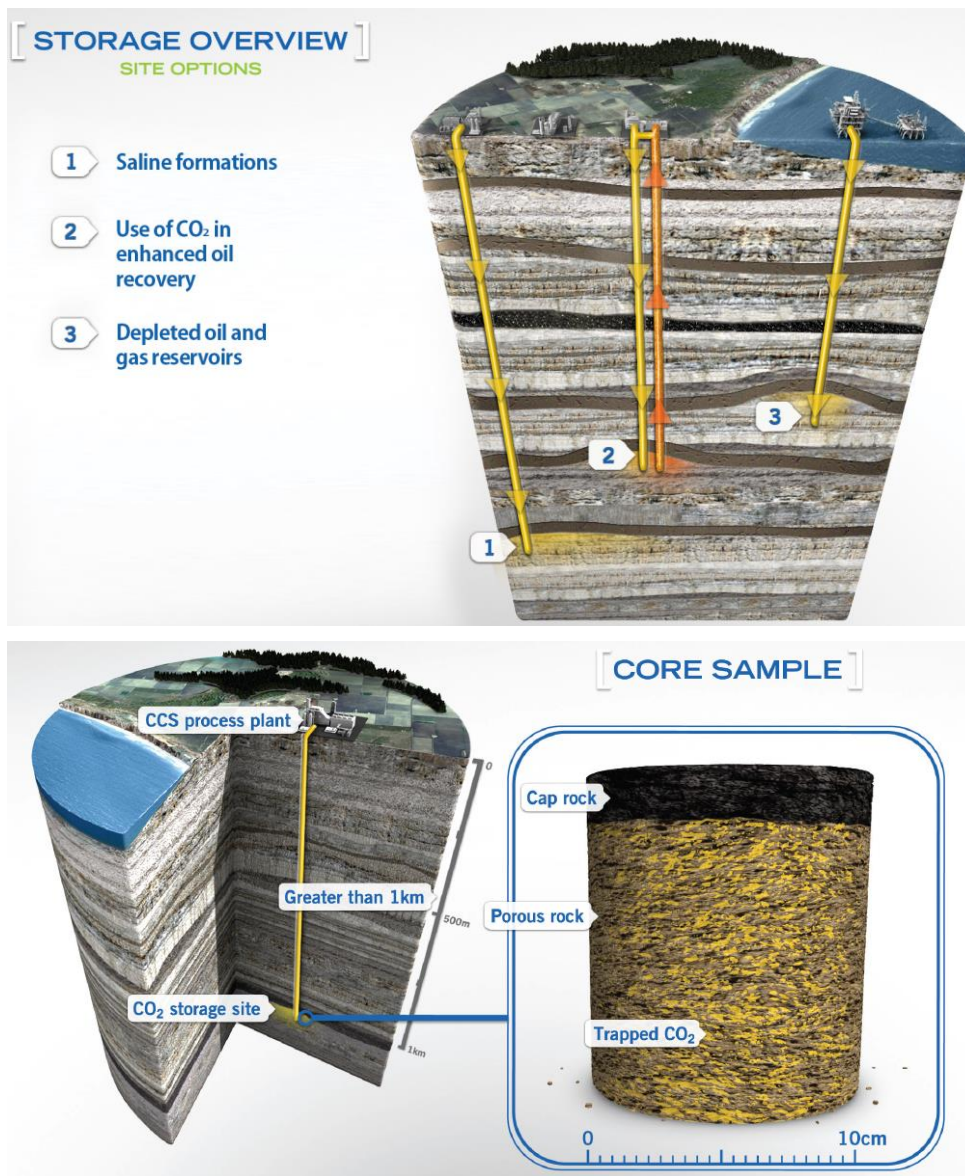
Typically, the following geologic characteristics are associated with effective storage reservoirs:

- rock formations with enough pore spaces between mineral grains (porosity) to provide the capacity to store the CO₂
- connections between pore spaces are sufficient to allow injected CO₂ to move (permeability) and spread out within the formation
- a sealing layer (or cap rock) at the top of the formation to prevent the upward migration of the buoyant CO₂
- The depth below ground level of the reservoir will typically be 800 m or greater. At such depths, CO₂ is stored in a dense phase which leads to efficient use of the reservoir pore space.

Main types of storage options

There are many locations globally that have formations with these characteristics; most are in vast accumulations of sedimentary rock known as basins. Almost all oil and gas production is associated with sedimentary basins, and the main types of rock that contain economic oil and gas (and also naturally occurring CO₂), including sandstones, limestones, and dolomites, are also suitable as storage reservoirs.

FIGURE 5: STORAGE OVERVIEW – MAIN SITE OPTIONS



Source: Global CCS Institute

The above storage overview shows the main types of storage options available (Figure 5). Deep saline formations refer to any saline water ('brine') bearing formation (the water can range from slightly brackish to many times the concentration of seawater and is non-potable). Enhanced oil recovery (EOR) involves injecting CO₂ to increase oil production from oil fields. Depleted oil or gas fields that are no longer economic for production, but have characteristics suitable for CO₂ injection and storage.

EOR is the dominant form of CO₂ utilisation and is likely to remain so in the short to medium term due to its maturity and large-scale use of CO₂ in commercial operations. Of the 40 Mtpa CO₂ capture capacity of large-scale CCS projects presently in operation or under construction, around 33 Mtpa is associated with CO₂-EOR opportunities and is most evident in North America (30 Mtpa).

The suitability of oil fields for CO₂-EOR is governed by the composition of oil present, and is favoured by the presence of subsurface conditions which allow miscible flooding (efficient mixing of oil and injected CO₂). From a storage perspective, such subsurface conditions typically coincide with depths and settings listed in the section 'Storage Site Characterisation' below.

Depleted gas fields can be broadly divided into: depletion drive fields – where gas production results in lowering of reservoir pressures due to hydraulic isolation from surrounding formations; and water drive fields, where reservoir pressures are partly maintained through encroachment of groundwater from surrounding formations during gas production. Both types are suitable for post-production storage.

Enhanced Coal-bed Methane (ECBM), in which CO₂ is injected into coal-beds to exchange CO₂ with methane (with the CO₂ binding with the coal as permanent storage) is in the research stage. Other emerging CO₂ reuse technologies include mineralisation possibilities (such as carbonate mineralisation, concrete curing, bauxite residue processing) and may ultimately provide a complementary form of 'storage' to beneath-ground storage. However, many of these emerging reuse technologies are at the early stages of development and emphasis must remain on CO₂ storage in deep underground rock formations.

How does storage work?

Once captured, the CO₂ is compressed into a fluid almost as dense as water and pumped down through a well into the storage reservoir(s). Depending on the storage scenario, deep saline formation, EOR or depleted hydrocarbon field, and the specific characteristics of the reservoir, injected CO₂ will migrate away from the well, displacing and/or mixing with the fluids already present in the pore spaces.

As the mass of injected CO₂ (or plume) spreads through the reservoir, a significant proportion will migrate upwards towards the sealing layer. This is especially so in deep saline formation storage where the injected CO₂ will be slightly less dense than native brine occupying the pore space. The presence of the sealing layer provides the primary trapping

mechanism that prevents leakage from the reservoir, in the same way that natural oil, gas and CO₂ accumulations are trapped over geological timescales.

The security of storage can be further enhanced by secondary trapping mechanisms which can immobilise CO₂ within the reservoir, although the degree to which these processes occur and accompanying timescales will be specific to each storage site. Residual trapping results from the isolation of small pockets of CO₂ within pore spaces as the plume migrates through the reservoir; dissolution trapping occurs as CO₂ dissolves into native pore fluids (typically brine). The final trapping process is termed mineral trapping, where chemical reactions cause the CO₂ to be incorporated into solid minerals. Mineral trapping will typically occur over extended timescales and is more difficult to predict than other processes.

Storage characterisation timelines can be significant

The length of time required to prove site-specific storage capacity to support project development is variable. For storage in depleted oil and gas fields or associated with EOR, existing detailed knowledge of the subsurface and available infrastructure may allow rapid formulation of plans and regulatory applications to store CO₂. In contrast, proposals to store CO₂ in deep saline formations where characterisation data is sparse may require up to a decade. This is longer than is generally required to fully develop the capture and transportation elements of a CCS project to final investment decision stage. In the early stages of CCS project development, storage availability can also be the most uncertain element.

The challenge of proving appropriate storage capacity is not inconsiderable. In some cases, projects may need to investigate several storage targets to mitigate the exploration risk that one possible storage site proves unsuitable. To lessen the risk of CCS deployment being slowed by uncertainty over available storage, early selection and characterisation of storage sites is a critical path activity, especially in regions where subsurface data is limited.

NON-EOR CO₂ UTILISATION

From a climate change mitigation perspective, effective CO₂ utilisation concepts are only those that are consistent with long term CO₂ storage (e.g. CO₂-EOR, mineralisation options). As noted earlier, non-EOR utilisation options that allow for permanent CO₂ storage are in early stages of testing and have limited volumetric potential for emissions reductions.

Other CO₂ utilisation options include use of captured CO₂ in food and beverage production, in boosting yields of conventional fertiliser production facilities, in algae cultivation and as feedstock for polymer processing. While these non-EOR utilisation technologies do not represent permanent storage of CO₂, potential benefits include:

- such projects can help drive down costs associated with CO₂ capture, and those cost reductions are transferable,
- such projects can enhance experience with transport infrastructure, and

- such projects may impact the rate of CO₂ additions to the atmosphere.

At present, in the context of the contribution to meeting climate goals, the status of non-EOR technologies is best viewed as providing a ‘supporting role’. CO₂-EOR has a more robust role to play, especially in these early years of CCS deployment (in supporting the business case for CCS projects where opportunities for CO₂-EOR are available). Over the longer term, the majority of the ~95Gt of CO₂ captured and stored to 2050 under the 2°C goal, as shown in Figure 1, is projected to be in deep saline / geological formations. Storage resource assessments are discussed in a later section.

CO₂ USE AND INCIDENTAL STORAGE IN EOR

The oil and natural gas industry has more than 40 years’ experience of injecting almost one billion tonnes of CO₂ (most from naturally occurring sources) into geologic reservoirs to increase oil production. This is called CO₂-EOR. The CO₂ is usually injected into the reservoir under pressure in a liquid or dense phase, allowing it to mix with the oil and make the oil flow more easily, ultimately producing more oil. The CO₂-oil mixture is brought to the surface, where the CO₂ separates from the oil, and is recaptured for re-injection. Through this recycling process, virtually all the CO₂ used will eventually remain in the reservoir indefinitely at the end of the oil field’s life (called incidental storage).

Most of the 22 large-scale carbon capture projects presently in operation or construction are linked to CO₂-EOR systems. By providing partial economic drivers and business models for projects, these CO₂-EOR projects provide an especially important ‘facilitator’ role in the demonstration of CCS in regions with EOR potential. These regions include North America (where most of the CO₂-EOR projects are located), parts of the Middle East and South America (notably Brazil), with significant potential in China.

The amount of incremental oil produced as a result of CO₂-EOR will vary according to individual field characteristics, and the rate of incremental oil recovery will also vary with time in any given field. As an EOR operation progresses, the amount of previously injected CO₂ mixed in with the produced oil increases, resulting in larger proportions of recycled CO₂ in the system and lower proportions of newly purchased CO₂. Estimates from experience in the United States suggest that CO₂-EOR operations could boost recovery by 5% to 15% of the original oil in place¹³.

Many oil field operators treat information on purchased quantities of CO₂ as commercially sensitive, so calculation of incremental recovery rates per tonne of CO₂ purchased is often problematic. In 2012 and after 12 years of CO₂-EOR operations, the Weyburn oilfield in Canada was reported as producing 28,000

¹³ IEA Insights Series (2015) Storing CO₂ through Enhanced Oil Recovery: Combining EOR with CO₂ storage (EOR+) for profit, OECD/IEA, 2015.

barrels of oil per day, of which 18,000 could be attributed to CO₂-EOR. CO₂ injection rates at the time were reported as approximately 5 million tonnes of CO₂ per annum, of which around 50% was recycled¹⁴.

¹⁴ Wildgust et al (2013) Introduction to a decade of research by the IEAGHG Weyburn-Midale CO₂ Monitoring and Storage Project. International Journal of Greenhouse Gas Control: Volume 16 Supplement 1.

2. POLICY, ECONOMICS & MARKETS

Total global CO₂ capture capacity of projects in operation or under construction is around 40 Mtpa. This level of capture capacity is dwarfed by the amount of CCS deployment required in the next 20 to 30 years to meet climate targets, estimated at approximately 4,000 million tonnes of CO₂ captured and stored per annum by 2040.

The large-scale projects in operation around the world demonstrate the viability of CCS technology. However, CCS is still to reach full technical maturity, with first and second of a kind capture plants now being constructed and operated in power and new industrial applications. Widespread deployment of CCS will require a reduction in cost compared to unabated plants (which will be enhanced by the positive spill-over effects generated by the new operating projects). In the intervening period there is a pressing need for predictable and enduring policy arrangements that support a positive business case for CCS investment.

COSTS OF CCS IN THE POWER SECTOR

A number of studies have suggested that the exclusion of CCS as a technology option in the electricity sector alone would increase mitigation costs by a very considerable margin.¹⁵ This is because many alternatives to CCS as a low-emissions technology in the electricity sector are more expensive. While it may be possible to reduce emissions in the electricity sector by the amount needed to limit the global temperature increase to below 2°C without using CCS, this would necessarily involve using more expensive technologies.

In 2015, the Global CCS Institute undertook a review of power sector cost studies in the United States.¹⁶ This analysis drew on cost and performance data from a variety of published sources and compared these in a common methodological framework based on the levelised cost of electricity (LCOE). It also combined outputs of the LCOE framework with estimates of CO₂ emissions from various plants to compare technologies in terms of the cost of CO₂ avoided. Comparisons of this type are important when considering policies that lead to a least-cost emissions reduction pathway.

¹⁵ IEA (2012) Energy Technology Perspectives 2012, Paris: OECD/IEA.

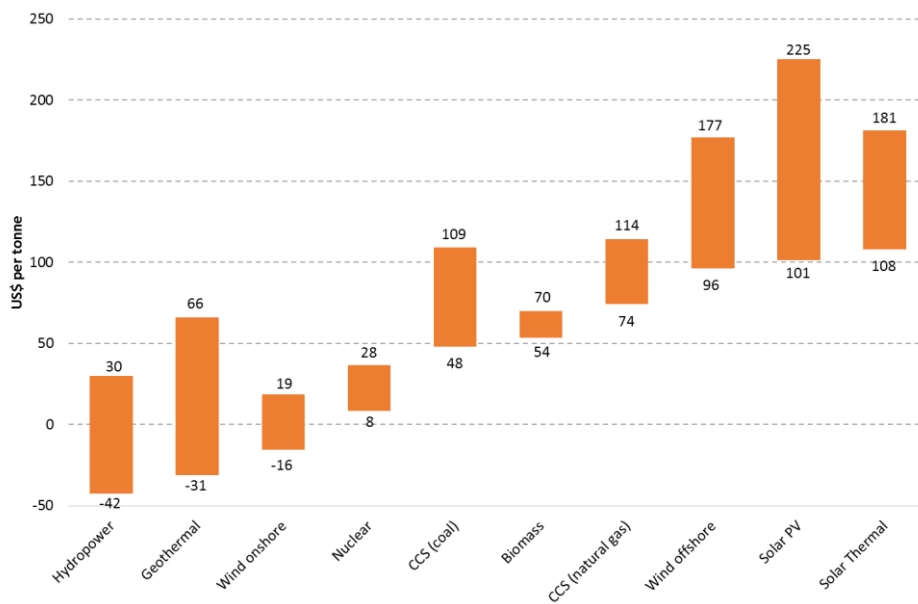
Zero emissions platform (ZEP) (2015) CCS for Industry: modelling the lowest-cost route to decarbonising Europe, European Technology Platform for Zero Emission Fossil Fuel Power Plants.

Energy Technologies Institute (ETI) (2015) Carbon capture and storage, Building the UK carbon capture and storage sector by 2030 - Scenarios and actions. ETI.

¹⁶ Global CCS Institute (2015) The costs of CCS and other low-carbon technologies in the United States: 2015 update, Melbourne.

Overall, the analysis indicates CCS is a mid-range technology in terms of cost of emissions reduction potential (Figure 6). The key cost advantage of CCS-equipped power generators, relative to some renewables like wind and solar, derives from the fact that they are typically used to provide baseload or controllable output, and thus have higher rates of capacity utilisation. For this reason, while CCS currently has a higher investment cost than other low emission technologies, this is spread over a larger amount of clean electricity output.

FIGURE 6: COST OF AVOIDED CO₂ EMISSIONS FOR PLANTS IN THE US (2014 US\$)



Source: Global CCS Institute (2015) The costs of CCS and other low-carbon technologies in the United States: 2015 update, Melbourne.

Generally, these results highlight a commercial and environmental imperative to invest in lower cost, low emission technologies such as traditional forms of hydro generation as well as geothermal and onshore wind. There are, however, natural limits to the ability of each individual low and zero emission technology to deliver the amount of clean generation output required to meet emissions reduction targets. While CCS currently has a higher cost than several forms of renewables technologies, CCS has clear advantages in directly reducing large amounts of emissions from baseload, peaking fossil fuel sources (as well as acting as a back up to the supply of variability of renewables), and can therefore play an important role in meeting climate change targets in a least cost manner.

The integration of two key focus areas will act to drive down capital and operating costs. First, the lessons learned from the portfolio of operating projects will provide valuable information for decreasing the cost of design, construction and operation of future carbon capture facilities. Second, there must be a continuing focus on R&D efforts on 2nd generation and transformational technologies to further reduce costs beyond those that emerge from the learnings of operational projects. This must be accompanied by international collaboration where researchers can leverage each other's knowledge to achieve better, faster results and generate technologies that will speed deployment of capture systems.

POLICY ENVIRONMENT

Strong policy is essential to mitigate CO₂ emissions and hence for CCS deployment at the levels and speed of implementation required to meet global climate targets. The foundation for widespread deployment is based on an equitable level of consideration, recognition and support for CCS alongside other low-carbon technologies – the concept of 'policy parity'. Moreover, enhancements to regulations pertaining to the implementation of CCS are also required.

Policy trends have regional influences and the main ones are discussed below.

North America

EOR helps enable the business case for 13 out of 15 projects in operation or under construction in the United States and Canada but government support initiated five to 10 years ago in the form of various federal and state/provincial incentives, including grants, tax credits, etc. has been essential. Most projects blend a number of different types of incentives but grants have been the most effective to help address higher CCS capital and operating costs.

The three most effective grant programs to date are administered by the US DOE, the Canadian Federal Government and the province of Alberta, Canada. Demonstration funding has tightened in all three programs, resulting in a slowing of early stage projects entering the pipeline. This slowdown also reflects challenging commercial, policy and regulatory environments. Mexico's Secretaria de Energia (SENER) is in the early stages of implementing the country's CCUS roadmap, which includes pilot demonstrations.

While regulatory structures in both the US and Canada now have emission performance standards for coal-fired power plants that may require partial CCS, regulation alone is unlikely to drive CCS projects forward and policy action is needed to address market barriers.¹⁷

¹⁷ On 9 February, 2016, the US Supreme Court voted 5-4 to grant a stay on the Clean Power Plan (to reduce emissions from existing power plants), halting its implementation while the legal challenge brought by 27 states and a number of companies works its way through the courts. At the time of writing, the US Environmental Protection Agency (EPA) rule is on hold and will go before the D.C. Circuit Court of Appeals 'en banc' with oral arguments scheduled for September, 2016.

A number of market factors are disadvantaging CCS, including a low natural gas price that incentivises coal-to-gas fuel switching in the power sector (where CCS is not at present required on natural gas-fired facilities). Also, lower oil prices and growth in shale investments are impacting the short-term outlook for CO₂-EOR, an important enabler for CCS projects throughout the region.

Given current market conditions and limited government funding for large-scale demonstrations, developers are taking a wait-and-see approach to the necessary policy incentives and market shifts to advance new CCS projects into the pipeline.

Also within the US, the issues of long-term storage liability and subsurface property rights are highlighted as requiring further attention from regulators and policymakers.¹⁸ The issue of property rights is largely focused upon the use of the subsurface, and the various rights attaching to the ownership of the pore space and the mineral estate. Long-term liability is a similarly complex topic and one which continues to be raised by project proponents, regulators and policymakers globally. The range of liabilities borne by operators across the project lifecycle, as well as their apportionment upon closure of a storage site are examples of the issues which in some instances have yet to be fully addressed.

These issues have however been addressed by some of the individual states. It is expected that these models or approaches may serve as a guide to others when developing legal and regulatory frameworks.

EMISSION PERFORMANCE STANDARDS IN NORTH AMERICA

In August 2015, the US EPA finalised the Clean Power Plan (CPP), 'Carbon Pollution Emission Guidelines for Existing Stationary Sources: Electric Utility Generating Units', the first-ever US national standards to limit CO₂ emissions from existing power plants. While this rule is undergoing legal challenge at the time of writing (see footnote 16) its main features are as follows.

The CPP also establishes state CO₂ emission reduction goals and gives states flexibility to achieve the goal. States can either select a rate-based or mass-based target:

- Rate-based targets, measured in pounds per Megawatt hour (lb/MWh) for individual units, or
- Mass-based targets, measured in short tonnes of CO₂ that apply to units state-wide.

For states that choose a mass-based target, they have the option whether to include new fossil fuel-fired units, which could require partial CCS.

States must develop implementation plans describing how they will meet their goals and can get extensions from the US EPA to 2018. Emission cuts must start at the latest by 2022, and continue through 2030. If a State fails to submit an acceptable plan, the EPA will require those states to use a 'Federal Plan', the details of which are under draft by the EPA. While CCS is allowed as a compliance option, the EPA's draft Federal Plan does not at time of writing make any mention of CCS.

In August 2015, the US EPA also published the final rule under the Clean Air Act (CAA) on Carbon Pollution Standards (CPS) for new, modified and reconstructed units.

Under the CPS, new units have an emission standard of 1,400 pounds (635 kilograms) CO₂/MWh, which is based on the use of supercritical pulverised coal technology with partial CCS (16% CO₂ capture with bituminous coal and 23% with sub-bituminous or dried lignite). This requirement can also be met with a range of other technology options, including IGCC or by co-firing approximately 40% natural gas.

Reconstructed units must meet an emission standard of either 1,800 or 2,000 pounds (816 or 907 kilograms) CO₂/MWh, depending on size. For modified units, the US EPA adopted a unit-specific emission standard based on 'best demonstrated historical performance' and capped it at the level for reconstructed units.

US EPA (2015) Clean power plan for existing power plants.

US EPA (2015) Carbon pollution standards for new, modified and reconstructed power plants.

In Canada, in July 2015, Canada's CO₂ performance standards, Reduction of Carbon Dioxide Emissions from Coal-fired Generation of Electricity Regulations, came into effect for new coal-fired power plants and units that have reached the end of their useful life. The standard is 420 tonnes of CO₂/gigawatt hour (the emissions intensity of natural gas combined cycle technology) and effectively precludes the construction of any new coal-fired power plants in Canada without CCS. New and end-of-life units that incorporate CCS may apply for an exemption, subject to ministerial approval, until 2025 if there is significant risk of electricity supply disruption. In the rule's cost-benefit statement, there is discussion on the financial benefits of using captured CO₂ for EOR.

Without additional policy incentives, it is unlikely that the regulation alone will drive further CCS deployment in North America.

Europe

The most important recent CCS policy (and regulatory) development in Europe was the review of the Directive 2009/31/EC (CCS Directive) on the geological storage of CO₂. The EC launched an assessment process of the CCS Directive in April 2014. The scope of the review was to assess if the Directive is 'fit for purpose', as well as consider the broader objectives of the Directive related to the EU enabling policy framework for CCS. The final report to the review of Directive 2009/31/EC was released in January 2015.¹⁹ The report's conclusions suggest that there has not been enough experience of the CCS Directive to justify high level changes and that the key issues for the uptake of CCS in Europe are linked to CCS enabling policies rather than the Directive itself. The EC released its own implementation report in November 2015, confirming the findings of the review process.²⁰

STORAGE DIRECTIVE 2009/31/EC REVIEW – THE FINAL REPORT, JANUARY 2015

Conclusions on the Directive assessment:

- The overall need for CCS to decarbonise power production and heavy industry in Europe remains urgent while progress has been slow.
- The CCS Directive is an enabling mechanism for CCS but not the main instrument driving CCS uptake, and it has had little influence on the speed

¹⁹ Triple E Consulting, Ricardo-AEA & TNO (2015) Support to the review of Directive 2009/31/EC on the geological storage of carbon dioxide (CCS Directive), Final deliverable under Contract No 340201/2014/679421/SER/CLIMA.C1, The Netherlands.

²⁰ European Commission (2015) Report on review of Directive 2009/31/EC on the geological storage of carbon dioxide

of technology deployment.

- A revision of the Directive should only occur after more experience is gained with CCS in Europe.
- Effectiveness of Art. 33 of the Directive to retrofit for CO₂ capture could be improved either with limited amendments to only Art. 33 or with a new Guidance Document (GD5).

Conclusions on CCS enabling policy framework:

- Support to promote CCS is emerging from Member States (MSs) and at the EU level;
- To improve governance, suggested actions consist of MSs developing national 2050 low-carbon roadmaps, including the role of CCS for the industrial sector; CCS's role in meeting 2030 abatement reduction targets; and the development of a Storage Atlas.
- Expand the financial support for CCS, including NER type funding; capital grants (i.e., EEPR, Project of Common Interest (PCI) and co-investment by EC and MSs in CCS projects).
- Support to the business case for commercial deployment of CCS, improving coherence of short term (NER and other type of funding) and long-term (EU ETS) policy measures based on a technology neutral principle.

Also of importance for CCS, the structural reform of Europe's emissions trading scheme (ETS) is underway, with changes designed to ensure it sets a price on carbon sufficient enough to support the transition to a low-carbon economy. The European Union's (EU) New Entrants Reserve (NER) financial mechanism has also been renewed, with 400 million emission allowances to be dedicated to establishing an Innovation Fund in the post-2020 period. For the period pre-2020, the market stability reserve (MSR) places 50 million allowances for low-carbon innovation projects to supplement the existing NER300.

Asia Pacific

Much of the recent progress of CCS in the Asia Pacific region has been on technology development through various demonstration projects and research efforts. This progress has been made possible by a mix of pre-existing government commitments and the presence of world-leading technology providers and research institutions.

China has demonstrated support for CCS development, with the technology featuring in government planning documentation, including its INDC submission to the UNFCCC in the lead-up to COP21 in Paris in December 2015²¹. The Chinese Government, in the lead-up to COP20 negotiations in Lima in late 2014, released a joint statement with the US that

²¹ National Development and Reform Commission, People's Republic of China (2015) Enhanced Actions on Climate Change: China's Intended Nationally Determined Contributions

included an undertaking to jointly develop a large-scale CCUS project with water recovery²². In August 2015, the US DOE and China's National Energy Administration further agreed to a memorandum of understanding on clean coal technology at the US-China Coal Industry Forum in Montana²³. The agreement provides for the development of six CCUS pilot projects in China and further demonstrates the importance of the development of such technologies for both countries. The US-China Joint Presidential Statement on Climate Change in September 2015 reaffirmed the Joint Announcement of November 2014²⁴. In November 2015, the Asian Development Bank released a CCS Roadmap for China, including specific actions to implement CCS in a phased approach over the next decade²⁵.

The Japanese Government is supportive of CCS and is collaborating with technology providers in Japanese industry to examine suitable storage sites and the economic feasibility of CCS deployment. Amongst various other government activities, Japan's Ministry of Environment is currently leading studies into an evaluation of the environmental impacts of CO₂ capture processes, shuttle ship transportation and CO₂ injection systems and the design of integrated CCS projects.

The South Korean Government is currently revising its CCS Master Plan, which includes a large-scale CCS demonstration project operating within certain cost parameters by 2020, and commercial CCS deployment thereafter. The Government's policy includes support for a number of testing and pilot plants involving a wide variety of agencies and technology providers in the power generation and steel making industry.

In Australia, considerable project activity continues. The Gorgon Carbon Dioxide Injection Project is expected to be operational in 2017. It will be Australia's first large-scale CO₂ injection project and the largest in the world injecting CO₂ into a deep saline formation. The two hub projects, the South West Hub Project in Western Australia and the CarbonNet Project in Victoria, are both focusing on the transport and storage elements. The Otway CO₂ CRC Project continued a pilot injection program in 2016 while the Callide Oxyfuel Demonstration Project was completed in March 2015.

Middle East

The Middle East has two large-scale CCS projects. Main project efforts are centred in Saudi Arabia and Abu Dhabi, although Qatar is also examining CCS opportunities.

Saudi Arabia is increasing its experience in the research, development and demonstration of CCS. Several institutions in Saudi Arabia are engaged in CCS research, including the King Abdulaziz City for Science and Technology (KACST), King Fahd University of Petroleum &

²² The White House (2014) US-China Joint Announcement on Climate Change

²³ United States Energy Association (2015) 2015 U.S.-China Clean Coal Industry Forum (CCIF)

²⁴ The White House (2015) US-China joint presidential statement on climate change

²⁵ Asian Development Bank (2015) Roadmap for carbon capture and storage demonstration and deployment in the People's Republic of China. Philippines.

Minerals (KFUPM), King Abdullah University of Science and Technology (KAUST), Saudi Aramco, and the King Abdullah Petroleum Studies and Research Center (KAPSARC).

The world's first iron and steel project to apply CCS at large-scale is now under construction in the UAE. The project is being managed by the Al Reyadah: Abu Dhabi Carbon Capture Company, a joint venture between ADNOC and Masdar. Injection of CO₂ is planned to start in 2016. Both joint venture partners consider this a flagship project and its success will be a catalyst for future CCS projects aimed at meeting the growing demand of CO₂ within the UAE for EOR.

Qatar has several CCS-related initiatives, the most significant being the establishment of the Qatar Carbonates and Carbon Storage Research Centre (QCCSRC). This is a US\$70 million, 10-year international research partnership to build Qatar's capacity in CCS and cleaner fossil fuels.

LAW AND REGULATION

Comprehensive legal and regulatory models underpin many national and regional policy commitments and are critical for deploying the technology. These frameworks are not static in nature and continue to evolve in-line with policy priorities and technology developments.





The first edition of the Global CCS Institute's CCS Legal and Regulatory Indicator (Table 1) reveals a clear contrast between the small number of countries that possess relatively advanced models of law and regulation, applicable to most aspects of the project lifecycle, and those with very few or limited CCS-specific legal frameworks.²⁶

Of the countries reviewed, Australia, Canada, Denmark, the UK and the US rated highly.

However, the majority of countries assessed have limited or very few CCS-specific or existing laws applicable across the CCS project lifecycle. Given the nascent stage of CCS project development in many countries, the results are not unexpected and reflect a need and opportunity for further legal and regulatory intervention worldwide. In many instances, even for those jurisdictions with lower assessment scores, there is a foundation within existing national law and regulation upon which further CCS-specific legislation may be based.

²⁶ Global CCS Institute (2015) Global CCS Institute Legal and Regulatory Indicator: a global assessment of national legal and regulatory regimes for carbon capture and storage, Melbourne.

TABLE 1: LEGAL AND REGULATORY INDICATOR RESULTS (IN COUNTRY ALPHABETICAL ORDER)

COUNTRY		TOTAL SCORE (Out of a possible 87)
	Australia	67.0
	Canada	65.5
	Denmark	62.0
	United Kingdom	65.0
BAND A: CCS-specific laws or existing laws that are applicable across most parts of the CCS project cycle		Average score: 65
BAND B: CCS-specific laws or existing laws that are applicable across parts of the CCS project cycle (27 countries)		Average score: 47
BAND C: Very few CCS-specific or existing laws that are applicable across parts of the CCS project cycle (21 countries scored)		Average score: 26

Source: Global CCS Institute (2015) Global CCS Institute Legal and Regulatory Indicator: a global assessment of national legal and regulatory regimes for carbon capture and storage.

3. ENVIRONMENTAL IMPACTS

The principal environmental considerations associated with carbon capture systems revolve around the atmospheric emissions of gas phase and aerosol solvents and solvent degradation products as well as water use. The sections below discuss these considerations and mitigation approaches.

CO₂ CAPTURE

Release of solvents and solvent degradation products

The most widely used technology for industrial scale post-combustion capture is chemical absorption with amine-based solvents. Emission of amines and amine degradation products can have environmental impacts. The main environmental considerations related to amine emissions are the formation of nitrosamines, nitramines, and amides. These compounds can be carcinogenic and largely form through the interaction of amines, atmospheric oxidants (e.g. ozone), nitrogen oxides (NO_x), and sunlight (small quantities have also been observed to form within the absorber unit of a capture system).

However, control measures to minimise emissions are well understood.

- Gas phase emissions of amines can be controlled to acceptable levels through the use of water wash systems.²⁷
- Aerosol emissions can be mitigated through control of the capture process that minimises the formation of aerosol precursors.²⁸

Different regulations for nitrosamines and nitramines have been adopted in North America and Europe. An important risk pathway for nitrosamines is drinking water, and thus several of the existing regulations have focused on that medium.

- The US EPA has set a level of 7 ng/L for N-nitrosodimethylamine (NDMA) in drinking water.
- Canada does not regulate NDMA nationally, but Ontario has established a drinking water quality standard of 9 ng/L for NDMA.

²⁷ Da Silva et al. (2013) Emission studies from a CO₂ capture pilot plant. *Energy Procedia*, vol. 37, 778–783.

²⁸ Dave, Do, Azzi & Feron (2013) *Process Modelling for Amine-based Post-Combustion Capture Plant*, Australia: CSIRO.

- The Norwegian Environment Agency has directly addressed nitrosamines and nitramines related to amine scrubbing, restricting concentrations of total nitrosamine and nitramine to 0.3 ng/m³ in air and 4 ng/L in water.

There are two pathways for solvent-related emissions:

- I. Those resulting from the volatility of the solvent or degradation product (vapour emission)
- II. Those associated with the formation of aerosols - specifically aerosol droplets

Amine gases can be released to the air due to volatilisation losses during the absorption process. There are many factors that determine the quantity of vapour emissions, including the volatility of the solvent (or degradation product), loading of the solvent and the temperature of the gas phase.²⁹ Estimated amine emissions from post-combustion capture are between 0.3 and 0.8 kg/tonne CO₂ captured without water wash.³⁰ However, use of a water wash system at the top of the absorber column effectively reduces vapour emissions.³¹

While a water wash system is an effective control strategy for gas phase emissions, it is not effective for controlling aerosol based emissions in a capture system. The formation of aerosols is associated with contaminants in the gas stream and the way in which the absorption system is operated. Particulate matter and fly ash in flue gas act as nucleation sites that allow for aerosol formation. Similarly, SO₃ present in the flue gas stream at concentrations as low as 1 ppmv can potentially contribute to sulphuric acid mist formation, which also leads to aerosol formation. Sudden quenching of the water-saturated gas within the absorber can lead to condensation and the formation of sub-micron water droplets. Amine vapours can dissolve into these droplets, forming sub-micron size aerosols. Mist eliminator-type candle filters are only 65–90% effective against sub-micron sized aerosols.³²

The most effective approach for managing aerosol emissions is careful control of the absorption process. Removal of flue gas contaminants prior to entering the absorber not only mitigates aerosol formation, but also plays an important role in minimising solvent degradation. In addition, careful temperature control within the absorber minimises the need for rapid cooling and quenching of the water-saturated gas. Process optimisation in the design phase of capture systems can allow for the needed level of process control to minimize aerosol emissions of amines.

²⁹ Da Silva et al. (2013) *ibid*.

Nguyen, Hilliard & Rochelle, (2011) Volatility of aqueous amines in CO₂ capture, *Energy Procedia*, vol. 4, pp.1624–1630.

³⁰ Goff & Rochelle (2004) Monoethanolamine Degradation: O₂ Mass Transfer Effects under CO₂ Capture Conditions. *Industrial & Engineering Chemistry Research*, vol. 43 (20), pp. 6400-6408.

³¹ *Ibid* 29

³² Dave, Do, Azzi & Feron (2013) *ibid*.

Water use in capture systems

Many commodity production processes (e.g. thermoelectric power production, cement manufacturing, steel production, oil refining, and others) require reliable, abundant, and predictable sources of water. Coal-fired power plants, for example, use significant quantities of water for electricity generation - a 500-MW power plant uses more than 45.4 million liters/hour. The largest demand for this water is process cooling. Adding a CO₂ capture system to an existing power station or industrial process has the potential to increase the water demand at the site where it is applied.

There are basically two types of cooling water system designs – once-through (open loop) or recirculating (closed loop). In once-through systems, the cooling water is withdrawn from a local water body such as a lake, river, or ocean and heat is transferred to the cooling water. The warm cooling water is subsequently discharged back to the same water body. In wet recirculating systems, warm cooling water is typically pumped to a cooling tower where the heat is dissipated directly to ambient air by evaporation of the water and heating the air. For a wet recirculating system, only makeup water needs to be withdrawn from the local water body to replace water lost through evaporation.

The two commonly used metrics to measure water use are withdrawal and consumption. Water consumption is used to describe the loss of withdrawn water, typically through evaporation into the air, which is not returned to the source. When evaluated in terms of the two types of cooling water system designs described above, once-through systems have high withdrawal but low consumption, whereas plants equipped with wet recirculating systems have relatively low water withdrawal, but high water consumption, compared to once-through systems.

The water requirements for CO₂ capture systems are widely known and acknowledged, and as such a number of studies have been conducted in which estimates of water use for different types of capture systems and power plants have been calculated. Table 2 provides an overview of relevant studies. A wide variety of capture systems are included in the studies. The Zhai *et al.* and US DOE studies used wet recirculating cooling systems to develop their water consumption estimates, whereas the other studies were based on once-through cooling systems. The results presented here focus on post-combustion capture systems, which are consistent with the results for pre-combustion and oxy-combustion systems as well.

TABLE 2: RELEVANT STUDIES ON WATER REQUIREMENTS FOR CO₂ CAPTURE SYSTEMS³³

Reference	Post-combustion			Pre-combustion	Oxy-combustion		
	SUB PC	SUP PC	USC PC	NGCC	IGCC	SUP PC	USC PC
Zhai, 2010	WR	WR	WR	-	-	-	-
IEAGHG, 2011	-	-	OT	-	OT	-	OT
DOE, 2012	-	-	-	-	-	WR	-
DOE, 2013	-	WR	-	WR	WR	-	-
Hylkema, 2014	-	-	OT	-	-	-	-
DOE, 2015	-	WR	-	WR	WR	-	-

PC = pulverized coal (power plant), SUB = subcritical, SUP = supercritical, USC = ultra-supercritical, NGCC = natural gas combined cycle, IGCC = integrated gasifier combined cycle, WR= wet recirculating cooling, OT= once-through cooling

Source: Please refer to footnote 33.

The earlier studies of water use associated with capture systems using wet recirculating cooling were relatively consistent in their results. Regardless of the power generation platform, the water consumption was estimated to increase by 80% to just over 90% on a volume/MWh basis, as indicated in the blue bars in Figure 7. For each of these early estimates, the capture technology was assumed to be a relatively simple MEA-based system. The magnitude of these estimates has led to the perception that water considerations could be a major factor in decisions regarding the use of CCS as a carbon mitigation technology.

³³ Zhai & Rubin (2010) Carbon capture effect on water use at coal fired power plant, Energy Procedia, vol. 4, pp 1925-1932.

IEAGHG (2011) Water Usage and Loss Analysis of Bituminous Coal Fired Power Plants with CO₂ Capture, Report 2010/05.

US DOE/NETL (2012) Advancing Oxycombustion Technology for Bituminous Coal Power Plants. DOE/NETL 2010/1405.

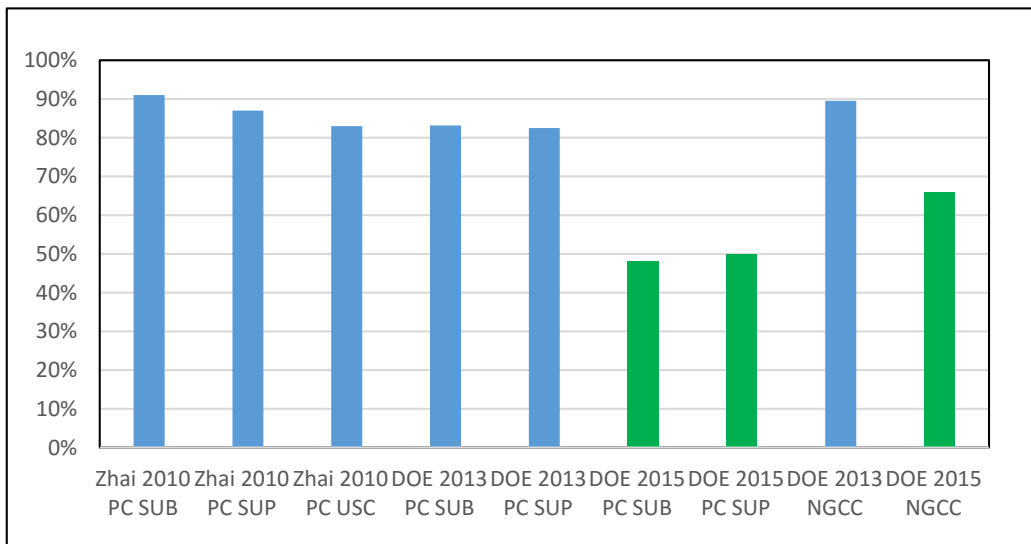
US DOE/NETL (2013) Cost and Performance Baseline for Fossil Energy Plants Volume 1: Bituminous Coal and Natural Gas to Electricity. Revision 2a, September 2013. DOE/NETL-2010/1397.

Hylkema & Read (2014) Reduction of freshwater usage of a coal fired power plant with CCS by applying a high level of integration of all water streams, Energy Procedia, vol, 6, pp 7187-7197.

US DOE/NETL (2015) Cost and Performance Baseline for Fossil Energy Plants Volume 1a: Bituminous Coal (PC) and Natural Gas to Electricity. Revision 3, July 2015. DOE/NETL-2015/1723.

However, for more recent studies, the water use estimates decrease substantially as indicated by the green bars in Figure 7. In these estimates, water use increased by 50% or less for coal-based power systems and by just over 60% for NGCC systems. The principle reason for the decrease is the use of more advanced capture system technology, which employs a more advanced solvent and heat integration that decreases the energy penalty associated with capture operations. Since the water use estimates reported in all of the studies are normalised to power production, a smaller decrease in power production yields a smaller percentage increase in water requirement.

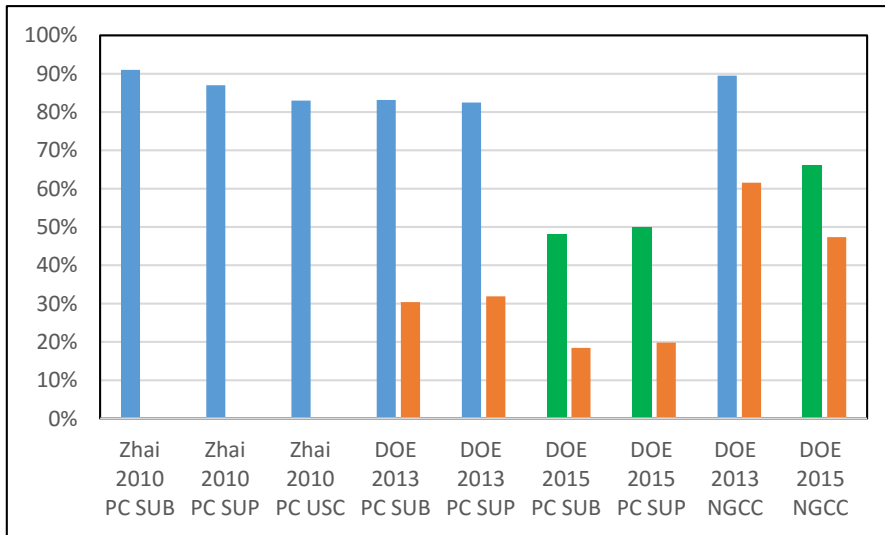
FIGURE 7: INCREASE IN NORMALISED NET WATER CONSUMPTION DUE TO THE ADDITION OF CO₂ CAPTURE



Source: Global CCS Institute (2016) Water use in Thermal Power Plants equipped with CO₂ Capture Systems, Melbourne.

Figure 8 presents the data shown in Figure 7 along with the increases in the total volume of water used (orange bars) as opposed to values normalised to power production. The Zhai *et al.* study did not include data that would allow for calculation of the total volume of water used. However, the US DOE studies did include the necessary data, and as indicated, the percentage increases in total volume of water use are substantially lower than the normalised water use values.

FIGURE 8: INCREASE IN NET NORMALISED WATER CONSUMPTION DUE TO ADDITION OF CO₂ CAPTURE COMPARED TO NON-NORMALISED (ABSOLUTE) INCREASES (ORANGE BARS).



Source: Global CCS Institute (2016) Water use in Thermal Power Plants equipped with CO₂ Capture Systems, Melbourne.

When systems employing once-through cooling are added to the analysis, the picture changes substantially. For these systems, water consumption is minimal, so inclusion of a capture system, which generates liquid water at several points within the process, can actually increase the amount of water leaving the plant.

While studies published prior to 2015 indicated that installation of a capture system would nearly double water consumption for thermoelectric power generation, those studies were based upon an early capture system design that included a relatively inefficient solvent and process design. More recent studies have indicated that the increase in water use in response to addition of a capture system is substantially smaller due to improvements in system performance. In addition, the results of the studies have been presented in terms of water use normalised to power production. While this may be important for broad planning purposes, it overestimates the impact for a particular facility. When an individual facility is evaluating whether to pursue a CCS system in order to achieve GHG reductions, it is more appropriate to consider changes in the total volume of water used as opposed to the normalised value because any impact on local resources will be associated with the total volume of water increase.

CO₂ TRANSPORTATION

The transport of CO₂ by pipeline has been practiced for many decades. These pipelines have been operated with an excellent safety record applying internationally adopted standards and codes for natural gas or other liquids.³⁴ Hence for purposes of risk assessment and management and hazard identification, the designers, constructors and operators of CO₂ pipelines can refer to these pipeline standards. However, there is significantly less industry experience with CO₂ pipelines than there is for hydrocarbon services and current codes and industry standards do not cover all aspects related to CO₂ transportation, especially in the context of large-scale CCS deployment.

To date, almost all the existing onshore CO₂ pipelines have been built in North America, where the CO₂ is predominantly used in EOR operations. These pipelines are typically routed through sparsely populated areas, where the risk to human health from a pipeline failure is very low. In most cases, the CO₂ is transported as a compressed gas, while implementation of large-scale CCS at an acceptable cost will also require transport of CO₂ in dense- or liquid phase, and it may be necessary to route pipeline systems through more densely populated areas. Furthermore, the CO₂ transported in these systems may come from multiple anthropogenic sources, which may have different CO₂ streams in terms of their composition, temperature and pressure. Finally, for transportation of CO₂ to storage sites under the seabed, offshore pipelines may become more common in the future.

For large-scale CCS deployment, the physical and chemical properties of CO₂ present some unique challenges for pipeline designers and operators that are different from handling oil and gas transport systems. These challenges range from selecting the right non-metallic materials that can resist high partial pressure CO₂ streams, to specifying the right toughness requirements for the pipeline steel carrying dense phase CO₂.

Research and development efforts to further enhance know-how on CO₂ pipeline integrity and management in support of large-scale CCS projects, and to provide input into relevant pipeline standards, are ongoing across the globe. A number have recently been completed. Most of these collaborative R&D efforts focus on the design and operational implications of different CO₂ stream compositions, in particular corrosion control, fracture propagation control and CO₂ dispersion modelling for safety analysis and risk assessment.

³⁴ A review of international codes and standards for CO₂ pipelines can be found in Global CCS Institute (2014) Global Status of CCS 2014, Melbourne.

SELECTED R&D PROGRAMS IN CO₂ PIPELINE TRANSPORTATION

COOLTRANS – CO₂ LIQUID PIPELINE TRANSPORTATION

The purpose of COOLTRANS is to provide the technical foundations for the design and operation of dense-phase CO₂ pipelines in the UK. The program includes theoretical studies as well as experimental investigation, including shock tube tests, vent and puncture tests, and large scale crack propagation tests. The results of this research program have been used to develop a comprehensive Quantitative Risk Assessment (QRA) methodology for dense phase CO₂ pipelines, which has been used in routing and design studies for UK CCS projects to ensure that the principles of the UK standards and codes are correctly applied.

COSHER: CARBON DIOXIDE, SAFETY, HEALTH, ENVIRONMENT AND RISKS

The COSHER joint industry project involved a number of large scale experiments to provide CO₂ release and dispersion data under well-defined conditions, studying the full bore rupture of a CO₂ dense-phase high pressure underground pipeline. During the experiments, a ground crater was formed and the CO₂ was allowed to flow freely from both ends of the ruptured section of the pipeline. Measurements of the fluid pressure, temperature and pipeline wall temperature were made together with measurements of the dispersing gas cloud. The data generated are useful for (dispersion) model development and validation as well as for better understanding of the risks involved in underground CO₂ pipeline ruptures.

CO₂ PIPETRANS PHASE2 - DNV JOINT INDUSTRY PROJECT (JIP)

CO₂ PIPETRANS Phase-2 is a JIP led by DNV GL with a main work package dedicated to generating experimental data to assist the development and validation of dense phase CO₂ depressurisation, release and dispersion models. A set of a large scale experiments was conducted where mainly the dispersion characteristics of CO₂ were measured under different conditions (different initial temperature and pressure conditions, different orifice size, release orientation and impact on target). The CO₂ PIPETRANS JIP has also undertaken experimental work to improve knowledge and data availability within the important subject areas of CO₂ pipeline propagating crack prevention and corrosion rates with various CO₂ stream impurities such as O₂, SO_x, NO_x and H₂S.

CO₂ STORAGE

Storage resources to support CCS deployment

Industrial-scale, geological storage of anthropogenic CO₂ has been successfully and securely demonstrated at a number of sites around the world over the last two decades, both in deep saline formations and associated with CO₂-EOR operations. Storage has been undertaken in both onshore and offshore environments. This has built on the knowledge base already derived from over 40 years of CO₂-EOR operations in North America. Large-scale storage in depleted gas fields can also be considered as a mature storage option.

Successful deployment of CCS requires sufficient subsurface storage space to accommodate captured CO₂ emissions. Storage space can be broadly assessed at two contrasting scales – regional and site-specific. Regional surveys and storage resource mapping initiatives, such as the Carbon Utilization and Storage Atlas published by the US DOE, can provide important information to policy makers and other stakeholders on the potential scale of storage resources and can also assist operators in the process of selecting potential sites and reservoirs for further evaluation. Such regional studies and resulting publications do not remove the need for project proponents and operators to conduct site-specific activities where detailed characterisation work results in more confident predictions of storage capacity.

Storage site characterisation

Characterisation is the term used for the process whereby information and data are collected and analysed to improve understanding of subsurface geological conditions. Since the geological characteristics that are either essential or preferable for secure and efficient geological storage are well understood, screening criteria can be developed and used to identify suitable geological formations.

Proven scenarios that fulfil the basic requirements for large scale storage occur within thick sequences of sedimentary rocks referred to as basins. For the purposes of regional resource assessment, basins can be ranked, or in some cases eliminated, from further consideration, based on criteria such as:

- Depth – basins that extend to less than 1,000 metres depth are unlikely to have sufficient reservoir thickness at depths where efficient use of pore space for storage is achieved.
- Stratigraphy – the sedimentary sequence should include suitable reservoir layers and at least one major, extensive, regional-scale sealing layer;
- Pressure regime – storage in basins with over-pressures in potential reservoirs may be problematic.
- Seismicity – basins with low levels of natural seismicity are favourable for storage, whereas basins in highly active seismic zones require more extensive characterisation.
- Geothermal regime – high temperature gradients (>35°C/kilometre) may lead to unsuitable conditions for storage.
- Faulting and fracturing – basins or zones with a high degree of recent faulting and fracturing (for example, transecting sealing rocks) should be avoided due to risks associated with potential leakage.

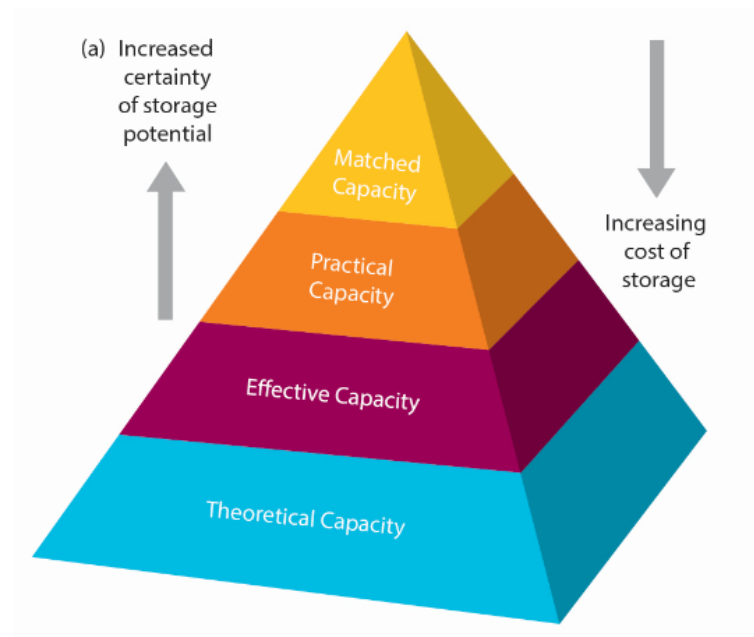
Within basins which present favourable subsurface conditions, potential storage formations or even sites can be identified using further screening criteria (against identified favourable characteristics) for factors such as depth, temperature, pressure and pressure gradient, permeability, seal thickness and porosity.

CO₂ resource classification schemes and assessment methodologies

The Carbon Sequestration Leadership Forum (CSLF) classification scheme and accompanying calculation method is the most widely adopted published scheme for regional surveys, classifying the pore space available for CO₂ storage into a hierarchical pyramid scheme (Figure 9). Each successive higher level of the pyramid reflects a decrease in technical and project uncertainty, and consequently a more realistic estimate of how much CO₂ can be stored.

The two lower layers of the pyramid are most often used in regional storage resource publications. Theoretical capacity estimates are based on relatively simplistic assessments of the total pore space in suitable storage formations, whereas effective capacity calculations represent a subset of the theoretical capacity constrained by technical factors. Effective capacity in the CSLF classification corresponds to the effective storage resources reported in the US DOE Atlas.

FIGURE 9: CSLF TECHNO-ECONOMIC RESOURCE-RESERVE PYRAMID



Source: Carbon Sequestration Leadership Forum (2007) Estimation of CO₂ Storage Capacity in Geological Media – Phase 2 report, Washington DC.

The most accurate method to predict storage resources involves the use of dynamic numerical simulations. These are computer-based modelling techniques which simulate subsurface CO₂ injection, predicting the migration and ultimate fate of injected CO₂ in response to various physical and chemical processes. These assessments are typically

undertaken at the site scale, supported by a detailed knowledge of geology and related subsurface characteristics. Dynamic calculations have computational limits and with increasing spatial and temporal scales, uncertainty increases. However, sub-basin and even basin scale dynamic assessments have been undertaken and modellers are making large advances in this field.

Status of regional and key national CO₂ storage resource assessments

Table 3 summarises selected examples of regional resource assessments. Note that direct comparison between regions should only be considered from a qualitative perspective, since the levels of characterisation data available and methodologies employed across regions are not consistent. Nevertheless, whilst these numbers likely overstate achievable storage capacities by not accounting for economic or regulatory factors, the results indicate that significant storage resources are potentially available in key regions across the world.

TABLE 3: SELECTED KEY ESTIMATES OF EFFECTIVE STORAGE RESOURCES

Nation	Estimated storage resource (Gigatonnes)	
	Deep saline formations	EOR/depleted fields
USA ³⁵	2,379 to 21,633	186 to 232
Europe ³⁶	96	20
China ³⁷	3,000*	2.2
Australia ³⁸	33 to 230	17

Note: the example resource estimates above have been calculated based on geological characteristics and do not account for economic or regulatory factors.

*Resources only calculated at theoretical level

Figure 10 shows the extent to which nations have assessed CO₂ storage resource potential, categorised according to the following criteria:

- Full: comprehensive assessments (including published Atlases) that cover most or all potential storage basins with accompanying effective resource calculations.

³⁵ US DOE/NETL (2015) Carbon Storage Atlas – Fifth Edition (Atlas V). Data refers to the USA plus parts of Canada.

³⁶ Vangklide-Pedersen (2009) EU GeoCapacity Assessing European Capacity for Geological Storage of Carbon Dioxide. Final report: *D16 Storage capacity*.

³⁷ Dahowski et al. (2009) Regional Opportunities for Carbon Dioxide Capture and Storage in China, A Comprehensive CO₂ Storage Cost Curve and Analysis of the Potential for Large Scale Carbon Dioxide Capture and Storage in the People’s Republic of China, Washington: Pacific Northwest National Laboratory (on behalf of the US DOE).

³⁸ Carbon Storage Taskforce (2009) National Carbon Mapping and Infrastructure Plan – Australia: Full Report, Canberra: Department of Resources, Energy and Tourism.

- Moderate: national studies/atlas without widespread effective resource calculations; or, partial coverage by state/province/basin scale atlases or detailed assessments.
- Limited: more restricted studies, consisting of relevant research into selected basins or sites.
- Very limited: minimal or no published research relating to storage potential.

The main restriction on the availability of deep saline formation storage is the time required for capacity to be proved at the project level to support financial investment decisions, and installation of the required infrastructure. For CO₂-EOR, injection of CO₂ has traditionally occurred after primary and secondary (water flood) phases of production. However, recent studies have demonstrated that CO₂ injection could be considered during earlier stages of production. The availability of depleted oil and gas fields for injection and storage is governed by the timescale of extraction of economic reserves, and is usually more straightforward for gas fields. In summary, all of the deep saline formation storage resources and the vast majority of EOR/depleted field resources listed in Table 3 (and in other regions) would be available for use in advance of 2050.

US CARBON STORAGE ATLAS

The fifth version of the US Carbon Storage Atlas³⁹ has been published by the US Department of Energy (DOE) National Energy Technology Laboratory (NETL), detailing a conservative estimate of total onshore storage resources as 2,600 Gigatonnes of CO₂ (GtCO₂) for the US and parts of Canada – up by nearly 10% from the previous 2012 publication. The atlas also details lessons learned to date by the large scale (Phase III) demonstration projects being undertaken across the US by the Regional Carbon Sequestration Partnerships (RCSP) program, which have demonstrated secure geological storage in deep saline formations and in association with CO₂-EOR.

The largest potential storage resources listed by the atlas are associated with deep saline formations, estimated as between 2,379 and 21,633 GtCO₂. The atlas lists potential storage resources associated with oil and gas fields as between 186 and 232 GtCO₂; much of this potential storage could be realised in association with CO₂-EOR.

RCSP Phase III projects (below) are on course to eventually have injected and stored over 10 million tonnes of CO₂, with associated learnings around the advancement of monitoring technologies, predictive modelling capability and risk management procedures.

³⁹ <http://www.netl.doe.gov/research/coal/carbon-storage/atlasv>

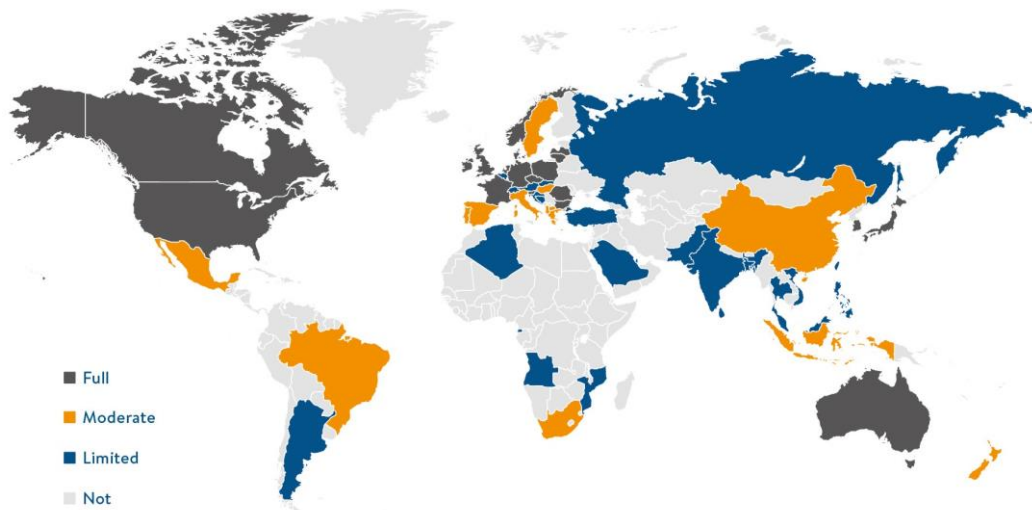
Active Phase III Projects of the US DOE/NETL Regional Carbon Sequestration Partnerships

Project	Regional Partnership	Storage Type	CO ₂ injected* (MtCO ₂)	Storage depth (m)
Cranfield, Mississippi	Southeast (SECARB)	CO ₂ -EOR	>5	>3,000
Bell Creek, Montana	Plains (PCOR)	CO ₂ -EOR	1.1	>1,300
Michigan Basin, Michigan	Midwest (MRCSP)	CO ₂ -EOR	0.3	>1,600
Farnsworth, Texas	Southwest (SWP)	CO ₂ -EOR	0.3	>2,300
Decatur, Illinois	Midwest (MGSC)	DSF	1	>2,100
Citronelle, Alabama	Southeast (SECARB)	DSF	0.1	>3,000

* Injected quantity as reported in Atlas V

The publication of Atlas V builds on previous editions in showing that very large storage resources are present within onshore USA and Canada, capable of supporting CCS deployment for many decades to come. The resource mapping illustrated in Atlas V, as with all such regional studies, is not however a substitute for the detailed site investigations required to characterise commercial storage projects with sufficient confidence for final investment decisions.

FIGURE 10: STATUS OF NATIONAL ASSESSMENTS OF REGIONAL STORAGE RESOURCES



Source: Global CCS Institute (2015) The Global Status of CCS 2015, Summary Report, Melbourne

RISK MANAGEMENT PROCEDURES FOR SECURE GEOLOGICAL STORAGE⁴⁰

Industrial operators have made considerable strides over the past 20 years to minimise risks associated with CO₂ geological storage through the application of established risk management practices. These operators have benefited from the extensive experience derived from oil and gas exploration and operations, by implementing best practices in management of risks and uncertainties.

The primary risk management approach for CO₂ storage is to minimise the possibility of future leakage by selecting sites with the most suitable geological characteristics and to maintain sufficient integrity for all wellbores in contact with the storage formation. The monitoring system is an integral part of the risk management plan and is applicable at: the site selection phase by defining baseline conditions; the operational phase by taking measurements during injection, interpreting signals and forward modelling based on interpretations; and the closure phase when sites are monitored to ensure the CO₂ remains underground.

⁴⁰ A more extensive review of the application of risk management practices as well as an overview of best practice guidance documents for secure and sustainable CO₂ injection and storage is found in Global CCS Institute (2014) Global Status of CCS 2014, Melbourne.

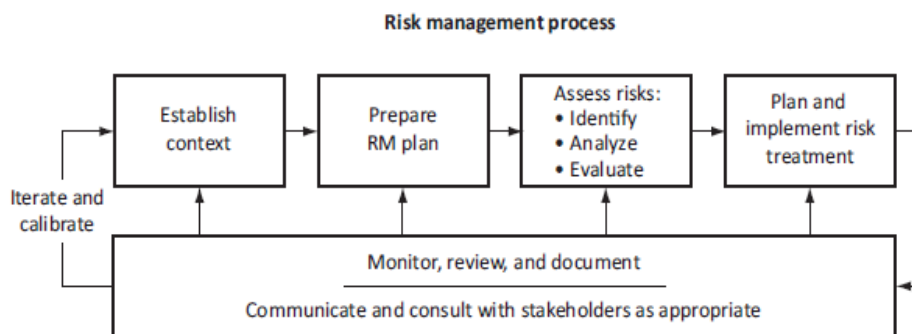
The lessons learned from pilot, demonstration and large scale injection are well documented and publically available. Research and development activities have led to better understanding of storage mechanisms, CO₂ plume behaviour and migration pathways. Application of CCS technology at demonstration sites has improved well design, plume/reservoir modelling capabilities, and monitoring techniques to effectively track the injected CO₂.

The headline risks for CO₂ storage may be addressed by considering the following two questions: Where does the CO₂ go when injected underground, and what ensures that the injected CO₂ remains safely stored?

Risk management is a long established practice across a wide variety of industrial sectors that helps society seize new opportunities without taking undue risks. For CO₂ storage projects, the risk management process starts early during the site screening phase and is relevant throughout the project life cycle.

Best practice within the risk management field has been summarised by the International Standards Organisation (ISO) document ISO-31000, which represents a starting point for applying risk management principles to CO₂ storage. Figure 11 illustrates a risk management work-flow that has been adapted for CO₂ storage by the Canadian Standards Authority (CSA) from the ISO-31000 standard.

FIGURE 11: SCHEMATIC OF RISK MANAGEMENT PROCESS FOR CO₂ GEOLOGICAL STORAGE PROJECTS FROM THE CSA STANDARD (Z741-12)



The first step establishes the context for the opportunities and risks to be managed in a CO₂ storage project, with unwanted consequences arranged into categories that typically would include human safety, environmental impact and groundwater protection.

The second step is preparation of a Risk Management plan that describes how this generic work-flow will be applied in practice, including a description of the organisational procedures

and practices to be used in managing risk. The time scale of interest for CO₂ storage sites span everything from days, weeks and months up to hundreds or even thousands of years.

The third step is risk assessment. This includes three distinct activities around risk identification, analysis (frequency of occurrence and potential impact) and finally the measurement or evaluation of risks identified against agreed acceptance criteria.

Once a CO₂ storage site comes into operation the field operator and the regulatory authorities will monitor site performance through monitoring data such as well pressure and flow rates, or geophysical surveys. Such monitoring results are then compared with predictions made in advance. These activities are represented by the lowermost box in Figure 11 and almost always generate new knowledge and a better understanding of a reservoir in operation. Such learnings should be used to calibrate expectations towards a CO₂ storage site and incorporated into the next iteration of the risk management cycle.

Where does the CO₂ go when injected underground?

CO₂ is stored in the same kind of porous rock that oil or gas flow out of when a well is drilled into a reservoir. The amount of fluid that a rock can hold varies with rock type and depth below the surface of the earth; the pore spaces within a rock that contain fluids are normally too small to be visible to the naked eye, but exist between individual sand grains or within microscopic cracks. In order for CO₂ or any fluid to flow through a particular stratum of rock the pore spaces need to be interlinked, making the rock permeable as well as porous. Rocks that exhibit these dual properties of porosity and permeability are suitable for storing or extracting fluids.

At the depth of a typical storage reservoir CO₂ has a density similar to oil, which means large amounts of CO₂ will occupy a fraction of the space in reservoirs deep underground compared to their gaseous volume on the surface.

The migration of injected CO₂ is controlled by a number of reservoir characteristics including the spatial variation of porosity and permeability, in response to engineered aspects of injection such as the number and orientation of wells, flow rates, etc. Accurate predictive modelling of injection can be undertaken based on characterisation data, experience from injection projects and established knowledge from hydrogeology and reservoir engineering. Monitoring data collected during injection can then be used to calibrate and refine models, to demonstrate confidence in the long term performance and integrity of storage.

What ensures that the injected CO₂ remains safely stored?

Again, we can draw an analogy to hydrocarbons: the same kind of rocks that keep oil and gas underground can be expected to trap CO₂ over geological timescales. These are termed seals or caprocks, overlying reservoir rocks and keeping buoyant fluids in place by virtue of very low permeability characteristics. CO₂ is trapped naturally in this manner in a large number of gas fields, sometimes as a minor associated gas or sometimes as the principal component. Naturally occurring CO₂ reservoirs trapped below seals have been used as the

primary source of CO₂ for enhanced oil recovery in the US, providing many tens of millions of tonnes per year. These fields along with industrial analogues, such as acid gas injection and natural gas storage fields have been extensively studied to learn more about the natural storage integrity that they exhibit.

Monitoring and verification

Monitoring is a key component of the risk management process for a CO₂ storage site, as can be seen from the lowermost box in Figure 11. Monitoring enables a project operator to measure the progress of the CO₂ injection program and provides reassurance to stakeholders that the project is developing as expected.

Certain parameters will be important to monitor for all CO₂ storage projects, such as the rate at which CO₂ is flowing into the ground and at what pressure. Other parameters are selected on a case by case basis to best represent the interests of the project operator or other stakeholders. For example, the Sleipner project in Norway updated the geophysical profile of CO₂ in the reservoir a number of times over the years using 3D seismic surveys. The frequency of repeat seismic surveys for other projects may be more limited during the project lifetime and in some cases, 3D seismic may not be amongst the monitoring techniques employed.

The physical parameters that a project will measure, monitor and verify (MMV) will depend on the monitoring objectives for that project. Monitoring objectives can include for example:

- documenting the quantity of CO₂ injected into a given reservoir;
- demonstrating that CO₂ flows into a reservoir as expected;
- early indication of CO₂ migration to other parts of the reservoir;
- early indication of CO₂ migration to other rock strata or the surface; and
- measurement of flow parameters that may be used to update geological models.

Investment in research on monitoring technologies and their application in planned or operational projects has helped build confidence in the ability to monitor CO₂ behaviour in the reservoir and demonstrate storage integrity. Many of the technologies currently deployed are standard monitoring techniques used in oil and gas field exploration and development. International collaboration through research programs, demonstration and pilot projects has contributed to rapid advancements in effective monitoring techniques for CO₂ storage.

CO₂ STORAGE AND PUBLIC PERCEPTION OF CCS

Among local communities and other impacted stakeholders, CO₂ storage tends to be the least well understood part of the CCS chain. It is therefore the area which benefits the most from focused engagement and outreach activities with project developers in order to build

confidence and trust in the safety and security of CO₂ storage sites⁴¹. Successful stakeholder engagement should be an essential component of all CCS project planning and execution. Several projects, at a variety of scales, have used innovative approaches and established best practices to gain support for CO₂ storage (both onshore and offshore) from local communities and other stakeholders. Successful examples include Decatur (Illinois), Quest (Alberta), Peterhead (UK), Tomakomai (Japan), Aquistore (Saskatchewan), Otway (Australia) and Lacq (France). A common feature of these public engagement 'success stories' was a concerted effort to build a solid understanding and level of trust between the project developers and influential and impacted stakeholders at the very earliest stages of project planning, through the establishment of open, honest communication and engagement.

⁴¹ An overview of the importance of the use of best practice public engagement and communication and education tools in CCS project development is found in Global CCS Institute (2013) Global Status of CCS 2013, Melbourne.

CASE STUDIES IN CO₂ RISK MANAGEMENT PROCEDURES

CASE STUDY 1 – THE QUEST PROJECT

The Quest project in Alberta, Canada, was launched in November 2015. The project involves the capture of approximately 1 Mtpa from an industrial facility and geologic storage in a deep saline formation. Leveraging from decades of risk management experience within the oil and gas industry, the Quest project developed a fully integrated risk management process as part of its storage development plan. The plan takes into consideration all the necessary decision gates for the project lifecycle that are critical in determining if the project will move forward. The holistic risk management plan includes the perceived risks in the eyes of the public, financial risks and technical and safety risks related to a CO₂ storage site.

The Quest team held extensive risk assessment workshops with relevant experts to identify and manage risks. The fully integrated risk management plan allowed early identification of gaps and sufficient time to manage risks before regulatory submissions were made. The organised and structured approach allowed for transparency that has been tremendously effective in stakeholder communication.

In 2011, Quest received the world's first certificate of fitness for its storage development plan from DNV GL. This included an expert panel review over a two-week period with CCS experts from academia and research institutions. The summary of the review sessions was included in regulatory submissions.

The risk management process for the Quest CO₂ storage project is well documented on the project website along with future monitoring plans, engineering studies and stakeholder engagement material. The procedures that have been followed and the way in which they have been made publicly available set a new standard for transparency in CCS project development.

CASE STUDY 2 – THE WEYBURN-MIDALE CO₂ MONITORING AND STORAGE PROJECT

Anthropogenic CO₂ sourced from a gasification plant in North Dakota has been used for CO₂-EOR operations in the Weyburn oilfield of southern Saskatchewan, Canada since 2000, and in the neighbouring Midale oilfield since 2005. Well in excess of 25 million tonnes of CO₂ has been stored in these oilfields as a result of CO₂-EOR operations. The Weyburn field is also receiving additional CO₂ supplies from the capture facility at the nearby Boundary Dam Power Station.

The large scale injection of CO₂ at the Weyburn field provided the basis for the IEAGHG Weyburn-Midale CO₂ Monitoring and Storage Project, which yielded over a decade of detailed research under the management of the Petroleum Technology Research Centre. Storage research included geological characterisation, predictive modelling, geochemical and geophysical monitoring, wellbore integrity and risk

assessment.

Highlights of the research program included the successful demonstration of 3D surface seismic surveys as an effective monitoring tool to track CO₂ distribution within the storage reservoir, and the use of extensive geochemical monitoring to demonstrate the integrity of the CO₂-EOR operations. The project also established strong outreach links with the local community and other stakeholders. The Monitoring and Storage Project culminated in the publication of a Best Practices Manual in 2012 and provided the basis for a number of public outreach publications.

Source:

Hitchon, Brian (editor) (2012) Best practices for validating CO₂ geological storage: Observations and guidance from the IEA GHG Weyburn-Midale CO₂ monitoring project, Sherwood Park: Geoscience Publishing.

Global CCS Institute (2014) What Happens When CO₂ is Stored Underground? Q&A taken from the IEAGHG Weyburn-Midale CO₂ Monitoring and Storage Project. Melbourne.

4. GLOBAL TABLE

The Global Table and Country Notes overleaf have been compiled based on data held by the Global CCS Institute on large-scale CCS projects and, where relevant, on lesser-scale CCS projects. Large-scale CCS projects are generally defined as projects involving the capture, transport, and storage of CO₂ at a scale of:

- at least 800,000 tonnes of CO₂ annually for a coal-based power plant, or
- at least 400,000 tonnes of CO₂ annually for other emissions-intensive industrial facilities (including natural gas-based power generation).

The thresholds listed above correspond to the minimum amounts of CO₂ typically emitted by commercial-scale power plants and other industrial facilities. Projects at this scale must inject anthropogenic CO₂ into either dedicated geological storage sites and/or enhanced oil recovery (CO₂-EOR) operations, to be categorised by the institute as large-scale projects. EOR may result in partial (incidental) or complete storage of injected CO₂ in oil reservoirs, subject to technical and economic factors. The Institute acknowledges that in some cases and jurisdictions, CO₂-EOR operators and/or regulatory authorities may not operate or permit CO₂-EOR sites specifically for GHG mitigation purposes; though there are regulatory pathways in the US to report CO₂ containment in an EOR reservoir. EOR projects can demonstrate both the successful operation of full-chain CCS projects and the secure underground injection of CO₂ at industrial scale.

This analysis also includes discussion of lesser scale CCS projects of 100,000 tonnes CO₂ capture or more which are evident in a number of countries (e.g. China and Japan). Overall, the global data is dominated by the large-scale projects.

The analysis is focused on CCS projects in operation or under construction.

TABLE 4: CO₂ CAPTURE CAPACITY OF CCS PROJECTS IN OPERATION OR UNDER CONSTRUCTION BY KEY REGION (MTPA)

Region	CO ₂ capture capacity of CCS
North America	Approximately 32 Mtpa
Asia Pacific	Approximately 4.5 Mtpa
Europe	Approximately 1.5 Mtpa
Middle East	Approximately 1.5 Mtpa
Rest of World	Approximately 0.5-1.0 Mtpa
TOTAL	Approximately 40 Mtpa

Note: A comprehensive listing and descriptions of large and lesser-scale CCS projects at various stages of development (and other notable CCS initiatives) can be found at the Global CCS Institute's website:

<http://www.globalccsinstitute.com/>

Data in this chapter is current as of mid 2016.

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REFERENCES

- Da Silva, E. F., et al (2013),
- European Commission (2015), Report on review of Directive 2009/31/EC on the geological storage of carbon dioxide,
http://ec.europa.eu/clima/policies/strategies/progress/docs/com_2015_576_annex_2_en.pdf
[Accessed 12 March 2016].
- Global CCS Institute (GCCSI)
www.globalccsinstitute.com/sites/www.globalccsinstitute.com/files/publications/25916/ccs-developing-countries.pdf
- Goff GS & Rochelle GT (2004)
- IPCC (2005), Carbon Dioxide Capture and Storage, New York: Cambridge University Press.
- IPCC (2014), Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III To the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, Geneva.
- Monoethanolamine Degradation: O₂ Mass Transfer Effects under CO₂ Capture Conditions. Industrial & Engineering Chemistry Research, vol. 43 (20), pp. 6400-6408.
- National Development and Reform Commission (2015), People's Republic of China: Enhanced Actions on Climate Change: China's Intended Nationally Determined Contributions, Available at:
www4.unfccc.int/submissions/INDC/Published%20Documents/China/1/China's%20INDC%20-%20on%2030%20June%202015.pdf [Accessed 12 March 2016]
- Nguyen T, Hilliard M, & Rochelle G, (2011), Volatility of aqueous amines in CO₂ capture, Energy Procedia, vol. 4, pp.1624–1630
- Ricardo-AEA, & TNO (2015), Triple E Consulting
- Support to the review of Directive 2009/31/EC
On the geological storage of carbon dioxide (CCS Directive)
- The White House (2014), US-China Joint Announcement on Climate Change, Available at:
www.whitehouse.gov/the-press-office/2014/11/11/us-china-joint-announcement-climate-change [Accessed 12 March 2016]
- The White House (2015), US-China joint Presidential statement on Climate Change, Available at:
www.whitehouse.gov/the-press-office/2015/09/25/us-china-joint-presidential-statement-climate-change [Accessed 12 March 2016]
- The White House (2015), US-China joint presidential statement on climate change. Available at:
www.whitehouse.gov/the-press-office/2015/09/25/us-china-joint-presidential-statement-climate-change [Accessed 12 March 2016]
- United States Energy Association (2015), 2015 U.S.-China Clean Coal Industry Forum (CCIF)
Available at: www.usea.org/event/2015-us-china-clean-coal-industry-forum-ccif [Accessed 12 March 2016]

US DOE Regional Partnerships, Available at: <http://energy.gov/fe/science-innovation/carbon-capture-and-storage-research/regional-partnerships> [Accessed 12 March 2016]

US DOE (2012), Washington DC United States carbon utilization and storage atlas – fourth edition (atlas IV)

US EPA (2015), Clean power plan for existing power plants. Available at: www.gpo.gov/fdsys/pkg/FR-2015-10-23/pdf/2015-22842.pdf

US EPA (2015), Carbon pollution standards for new, modified and reconstructed power plants Available at: www.gpo.gov/fdsys/pkg/FR-2015-10-23/pdf/2015-22837.pdf

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KEY FINDINGS

1. Energy storage is a very varied subject area with multiple technologies and multiples applications.
2. Pumped hydro energy storage has dominated energy storage for over a century, but the growth of electric vehicles and the need to integrate renewable power technologies, such as solar and wind, are driving huge investments in the development of battery technologies.
3. Most commercial interest is in battery storage.
4. The costs of several storage technologies will fall as production volumes increase.
5. The future outlook for energy storage markets is good due to an increasing need.
6. Regulatory and legal framework failing to keep pace.

INTRODUCTION

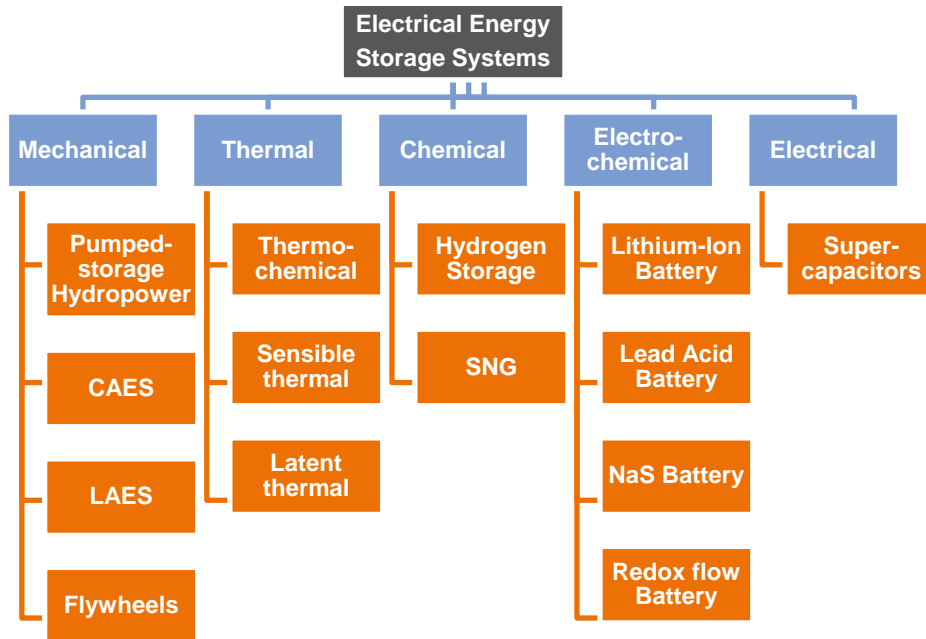
The big picture

Energy storage is a very varied subject area: from very small (e.g. battery storage for domestic PV installations of a few kW) to very large (e.g. pumped hydro of several hundred MW), and from very short-duration (frequency response services for grid operators) to very long (seasonal storage in hydro reservoirs). Currently, applications are emerging where specific technologies fit specific applications. These applications may achieve sufficient volume to drive down costs, reduce market barriers, and increase investor confidence. Many of the new applications use batteries.

This Chapter covers all forms of storage¹ for energy systems. Most of the chapter deals with storage of electricity, as currently there is a great deal of innovation and interest in this area. However, thermal storage is also covered where relevant.

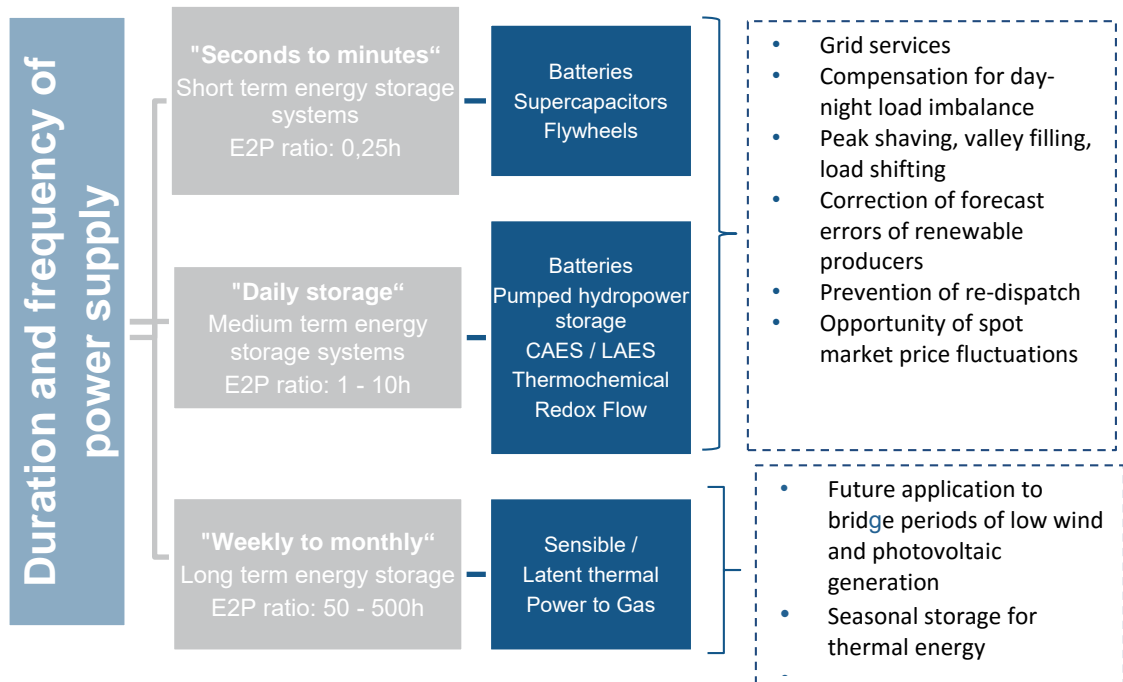
¹ Pumped hydro storage is covered, as it is by far the main component of electricity storage globally. It is noted that there is also very large storage capacity in conventional hydro reservoirs; however, this is covered in the chapter on hydro, and under some definitions does not qualify as 'electricity storage', as it does not use electricity as an input. In this respect, conventional hydro can be considered to be similar to natural reservoirs of gas or oil, or coal in a stockpile.

FIGURE 1: SCIENTIFIC CATEGORISATION OF STORAGE



Source: PwC (2015) CAES is Compressed Air Energy Storage; LAES is Liquid Air Energy Storage; SNG is Synthetic Natural Gas

FIGURE 2: DURATION AND FREQUENCY OF POWER SUPPLY



Source: PwC (2015) following ISEA Aachen, 2012²; E2P stands for Energy to Power Ratio

Some typical energy storage applications are:

- **Arbitrage:** storing energy during off-peak (low-priced) periods, and selling it during peak (high-priced) periods on the same market.
- **Frequency regulation:** the operator of the power system continuously has to keep the balance between supply and demand, in order to regulate the frequency of the system (nominally 50 or 60 Hz). Suitable technologies for such application are batteries with fast response, and flywheels.
- **Demand shifting and peak shaving:** similar to arbitrage, energy storage can be used to 'shift' or delay the demand for energy, typically by several hours. Such shifting can be directly used to reduce ("shave") peak demand, which can reduce the total generation capacity required.

² Institut für Stromrichtertechnik und Elektrische Antriebe RWTH Aachen (2012) "Technology Overview on Electricity Storage"

- **Integration of variable renewables**, typically wind and solar: the use of energy storage is viewed as one potential means to support the integration of variable renewable energy sources into the system, by bridging both rapid and longer-term output changes.
- **E-mobility**: electric vehicles play an important part in future power system visions, as presenting a possible zero-emission transport solution, particularly when integrated with renewable energy sources. These vehicles can also serve as distributed energy storage units, used to balance fluctuations of the power system.
- **Seasonal storage**: storage of energy for longer time periods (e.g. months) to compensate for seasonal variability on the supply or demand side of the power system. The reservoirs of conventional hydro stations are often used in this way.

GLOBAL AND REGIONAL CURRENT RESOURCE POTENTIAL

For similarity to the other chapters on specific energy resources, this section is entitled ‘resource potential’. However, for energy storage the concept of ‘resource potential’ is complex. Clearly for some technologies, such as pumped-hydro and CAES, there is in principle some ‘resource’ limit on the storage capacity which can economically be achieved in a region. However, for other technologies there is no such limit.

Many factors affect the global and regional availability, need for and use of energy storage technologies. For example, in regions where there is a substantial need for heating or cooling, there are opportunities to use thermal storage. On isolated or island electricity systems, energy storage can reduce the total generating capacity required, especially if there is also a significant wind or PV resource. Where there are large differences in electricity prices over time, for example over a day, electricity storage may be attractive.

Some of these issues are discussed further in “Global, regional and domestic markets”.

GEOGRAPHICAL DISTRIBUTION FOR MOST RECENT AVAILABLE PERIOD

Energy storage installations are very widely distributed, depending on the application: for example, battery storage with PV installations. See “Global, regional and domestic markets”.

COMMENTARY ON HISTORICAL BACKGROUND

The concept of energy storage is not new, though development has been mainly restricted to one technology until recently. Currently, pumped hydro storage accounts for well over 95% of global installed energy storage capacity. Compressed air energy storage currently has only two commercial plants (in Germany and the US), in total 400 MW, with a third under development in the UK. Battery storage capacity is increasing: for example, there are around 25,000 domestic installations in Germany alone in conjunction with PV installations, with total capacity of 160 MWh. The total battery capacity in electric vehicles

is also growing rapidly. Millions of water heaters have been operated in France for decades; they provide a massive benefit in reducing peak demand, by shifting 5% i.e. 20 TWh from peak periods to low-demand periods. These small-scale energy storage installations are not necessarily well represented in global statistics.

Large batteries are also being developed with installed capacity amounting to almost 750 MW worldwide. Sodium-sulphur became the dominant technology in the 2000s, accounting for nearly 60% of stationary battery projects (441 MW). In recent years, lithium-ion technology has become more popular. Flow batteries, if developed further, could be a game changer in the medium term.

In terms of installed capacity, all other electricity storage technologies remain marginal³. Despite recent commissioning of a MW scale plant in the United States, flywheels struggle to find their value proposition, while supercapacitors are still at an early phase. Interest is high in chemical energy storage, especially in Europe, but the primary aim of these large-scale demonstration projects is predominantly not to inject electricity back to the grid, but to produce fuels.

³ Note that electricity transmission and distribution systems contain, by their very nature, stored energy in the electrical capacitance and inductance of the system components, and in the inertia of synchronously rotating generators, pumps and motors. These characteristics are intrinsic to the stable operation of the power system. However, in practice, these are not relevant for the purposes of this document.

1. TECHNOLOGIES

CURRENT AND EMERGING TECHNOLOGIES

Energy storage is not a single technology, but rather refers to a suite of diverse technologies. This section serves as a summary of the key differences between technologies. Due to the wide range of technologies, it is important to begin by outlining the types of technologies which can be deployed. Technologies are further compared in the table and figure below. Due to space limitations, it is not possible to provide technical details of specific technologies: this information is available in other sources⁴.

This section focusses on the hardware, rather than SCADA or other control and management systems.

The different roles that they can play within the energy system, or applications, are covered in the next section.

Pumped hydro energy storage (PHS)

Pumped hydro energy storage has dominated energy storage for over a century. The vast majority of current installed energy storage capacity comprises PHS technologies. The operating principle is simple and efficient. PHS stores and generates electricity by moving water between two reservoirs at different elevations. During off-peak periods an electric motor drives a pump or pump turbine, which pumps water from a lower reservoir to a higher storage basin. When electricity is needed, the water is directed downwards through turbines.

(Conventional hydro stations are not covered in this chapter).

Compressed air energy storage (CAES)⁵

This technology shares some characteristics with PHS in that it is mature, commercially viable, can provide significant energy storage at relatively low cost, and also has topographical constraints. However, compared to PHS, its contribution to large-scale

⁴ For example, IRENA (2015) Renewables and Electricity Storage

⁵ Martens (ed.) (2013) Joint EASE/EERA recommendations for a European Energy Storage Technology Development Roadmap towards 2030. European Association for Storage of Energy and European Energy Research Alliance (EASE/EERA) Core Working Group, March, 2013.

energy storage is less significant: the only commercial plants are a 321 MW plant in Huntorf, Germany, and a 110 MW plant located in McIntosh, USA. A new 330 MW project is being developed in Northern Ireland⁶. CAES utilises off-peak electricity to compress air, usually at high pressures, for storage in geological structures such as mines or aquifers, salt caverns, and aboveground pressure vessels. The compressed air is then released, preheated and used to drive a turbine-generator system, to produce electricity when required.

Liquid air energy storage (LAES)

Sometimes referred to as Cryogenic Energy Storage (CES), LAES is a promising storage alternative, currently at the demonstration stage. It is not prone to geological constraints or public resistance. Air is compressed and cooled in a refrigeration plant, using cheap, off-peak energy, and stored in a relatively large insulated tank or vessel. This liquid air is then converted back to gas, expanded in volume, heated and used to drive a turbine to generate electricity on demand. It can be particularly suited to locations where there is a source of low-grade heat or cooling, such as an industrial process.

Flywheels

Though flywheels have been in existence for decades, they have only recently gained attention for large-scale stationary energy storage. They store kinetic energy in rotating discs or cylinders, suspended on magnetic bearings. They are suited for applications requiring high power for short periods, and require little maintenance, compared to other storage technologies.

Batteries⁷

These depend on chemical reactions that occur between the electrodes and generate a flow of electrons through an electrical circuit. Whilst these electrochemical devices have been used for energy storage since the 19th century, they have mostly found use in small-scale applications, such as mobile power sources, and in the automotive industry. However, the growth of electric vehicles and the need to integrate renewable power technologies such as solar and wind are driving huge investments in the development of battery technologies.

Currently the leading technologies in service are lead-acid and lithium-ion, but many other possible battery chemistries are in development or in the research phase, and could well supersede these for specific applications. For example, flow batteries store the electrolytes separately from the electrodes, and therefore storage capacity can be increased by increasing the volume of the storage tanks.

Batteries from electric vehicles which no longer meet the requirements of this application may well still have a 'second-use' in static applications.

⁶ <http://www.gaelectric.ie/energy-storage-projects/>

⁷ IRENA (2015) Battery Storage for Renewables: Market Status and Technology Outlook,

Superconducting magnetic energy storage (SMES)⁸

SMES stores energy in the magnetic field of a coil. The coil is superconducting in order to reduce the electrical losses, and therefore requires a cryogenic cooling system. The response time is extremely fast, and the technology is suited for short-term power applications such as improving power quality.

Supercapacitors

Supercapacitors are an established technology which stores much more energy per unit volume or mass than traditional capacitors. The response time is extremely fast. The costs per unit of energy storage capacity are higher than for batteries, though supercapacitors can withstand much higher numbers of charge/discharge cycles. Supercapacitors therefore are suitable for very short-term power applications.

Hydrogen

Power to Gas (PtG or P2G) uses electricity to create hydrogen by electrolysis. Hydrogen can be stored as gas under pressure or liquid at low temperatures. It can then be used to create electricity in conventional reciprocating engines, gas turbines or in fuel cells, though in many cases it may be better to use the gas for industrial uses, space heating or transport. A further area of application is that the hydrogen may be injected into existing natural-gas networks, which not only provides substantial storage capacity, but also makes use of existing gas transmission capacity, and may avoid the need for substantial new electricity transmission capacity.

'Storage' is therefore only a part of the picture for Power to Gas.

The conversion efficiency from electricity to hydrogen is such that low carbon electricity must be used, if reduction of emissions is the objective.

Synthetic Natural Gas (SNG)

Hydrogen can be converted into methane (SNG). The main advantage in the context of energy storage is that the amount of hydrogen that can be tolerated in existing natural gas infrastructure is limited (of the order of 10% depending on technical characteristics of the infrastructure). There is no such restriction on the amount of SNG that can be injected into existing gas infrastructure

Thermal Energy Storage (TES)

There are three fundamental forms of thermal energy storage:

- **Sensible** thermal storage – increase or decrease of temperature of a storage medium, such as water, oil, rocks or concrete. For example, residential water

⁸ Zakeri & Syri (2015) Electrical energy storage systems: A comparative life cycle cost analysis. *Renewable and Sustainable Energy Reviews*, 42 (0), 569-596

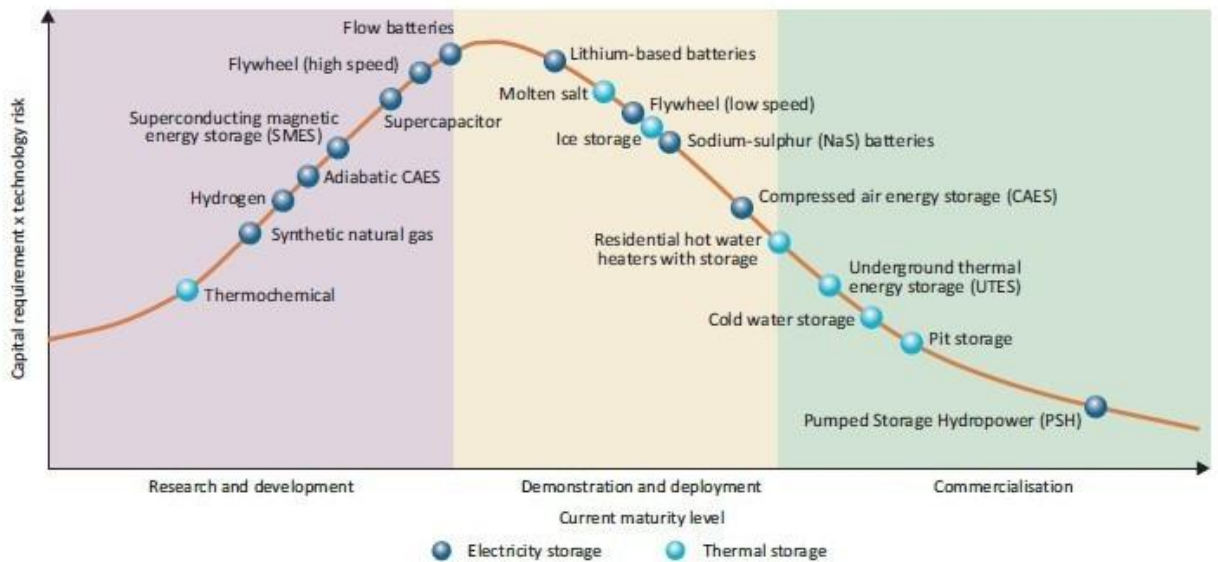
heaters are a mature energy storage technology, which is currently commercialised in some countries; hot water storage is also used on district-heating networks. Also, building materials with very high thermal capacity can provide substantial energy storage on timescales of months.

- **Latent** thermal storage – phase transformation, e.g. molten salt, paraffin, or water/ice;
- **Thermochemical** storage – a reversible chemical reaction, which is energy demanding in one direction and energy yielding in the reverse direction (sorption and thermochemical), such as silica gel, zeolite, metal hybrids, or zinc.

Thermal storage can be used to produce electricity, by producing steam for a conventional thermal power plant. However, the heat can also be used directly in industrial process or for space or water heating; this clearly requires less plant and avoids conversion losses, though the value of heat is substantially lower than the value of electricity.

Note that thermal storage can also be used to provide ‘cold’, and this is currently a growing market for energy storage in the form of ice, for deferring air-conditioning loads.

FIGURE 3: MATURITY OF ENERGY STORAGE TECHNOLOGIES



Source: IEA (2014) Technology Roadmap; Decourt and Debarre (2013), “Electricity storage”, Factbook, Schlumberger Business Consulting Energy Institute, Paris, France; and Paksoy (2013), “Thermal Energy Storage Today” presented at the IEA Energy Storage Technology Roadmap Stakeholder Engagement Workshop, Paris, France, 14 February

Figure 3 above indicates the commercial maturity of several storage technologies. Pumped hydro and compressed air energy storage are the most advanced electricity storage technologies; others bring a cost and risk premium due to their lower levels of commercial maturity. As technologies move from demonstration and deployment stage to commercialisation, the cost of the technology reduces and the technical characteristics are often enhanced. For example, in certain technologies, technical progress to date has seen the overall round trip efficiency increase and lifetime of the storage system improve. The time in which technologies mature is driven by many factors such as market incentives, installation volumes, technical constraints and geographical restrictions.

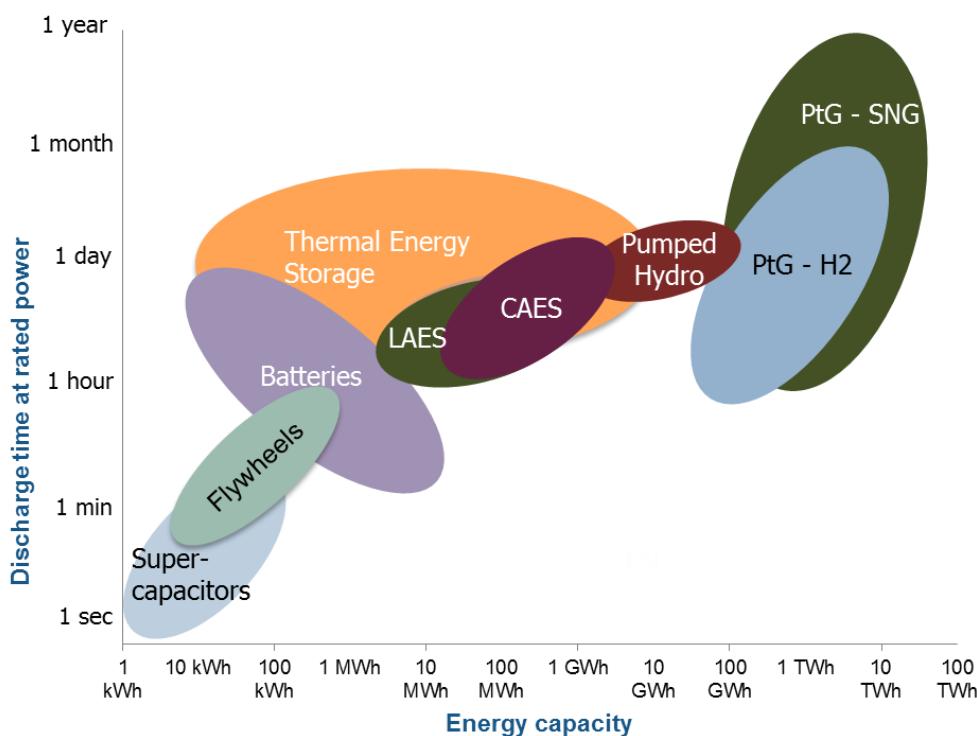
TABLE 1: COMPARISON OF MAJOR ENERGY STORAGE TECHNOLOGIES BY TECHNICAL CHARACTERISTICS

WORLD ENERGY COUNCIL | E-STORAGE

	Power rating (MW)	Discharge time	Cycles, or lifetime	Self-discharge	Energy density (Wh/l)	Power density (W/l)	Efficiency	Response time
Pumped Hydro	100 – 2500	4 – 16h	30 – 60 years	~ 0	0.2 – 2	0.1 – 0.2	70 – 85%	10 s – min
Compressed Air	10 – 1000	2 – 30h	20 – 40 years	~ 0	2 – 6	0.2 – 0.6	40 – 70%	min
Flywheels	0.001 – 20	sec – min	20000 – 100000	1.3 – 100%	20 – 80	5000	70 – 95%	< sec
Li-ion battery	0.05 – 100	1 min – 8h	1000 – 10000	0.1 – 0.3%	200 – 400	1300 – 10000	85 – 95%	< sec
Lead-acid battery	0.001-100	1 min – 8h	6 – 40 years	0.1 – 0.3%	50 – 80	90 - 700	80 – 90%	< sec
Sodium-sulphur battery	10 – 100	1 min – 8h	2500 – 4500	0.05 – 20%	150 – 300	120 – 160	70 – 90%	< sec
Flow battery	0.1 – 100	hours	12000 – 14000	0.2%	20 – 70	0.5 – 2	60 – 85%	< sec
Superconducting Magnetic	0.1 – 1	ms – sec	100000	10 – 15%	~ 6	~ 2600	80 – 95%	< sec
Supercapacitor	0.01 – 1	ms – min	10000 – 100000	20 – 40%	10 – 20	40000 - 120000	80 – 95%	< sec
Hydrogen	0.01 – 100	min – week	5 – 30 years	0 – 4%	600 (200bar)	0.2 – 20	25 – 45%	sec - min
Synthetic Natural Gas	1 – 100	hour – week	30 years	Negligible	1800 (200bar)	0.2 – 2	25 – 50%	sec - min
Molten Salt (latent thermal)	1 – 150	hours	30 years	n/a	70 – 210	n/a	80 – 90%	min

Excludes technologies with limited experience to date from multiple sources. Sources: Bradbury, K. (2010), “Energy Storage Technology Review”; IEC (2011), “Electrical Energy Storage. A White Paper”; Schlumberger Business Consulting (2013), “Leading the Energy Transition: Electricity Storage.” Schlumberger Business Consulting Energy Institute, FactBook Series, World Bank ESMAP Technical Report 006/15 ‘Bringing variable renewable energy up to scale: Options for grid integration using natural gas and energy storage’, and contributions from WEC Energy Storage Knowledge Network participants.

FIGURE 4: MAPPING STORAGE TECHNOLOGIES ACCORDING TO PERFORMANCE CHARACTERISTICS



Source: PwC (2015) following Sterner et al. (2014)
 CAES: Compressed Air, LAES: Liquid Air, PtG: Power to Gas.

TECHNOLOGIES: APPLICATION AND POTENTIAL

The application of energy storage can roughly be placed on a continuum of power and energy. In general, energy applications are defined as those that need a continuous supply of energy over a considerable length of time. In this case, the total energy flow is more important than the magnitude of the charged or discharged power. Typical energy applications include peak shifting, energy arbitrage, etc.

In contrast, power applications require fast injection and absorption of energy, but durations for such operation are usually shorter. Power applications include frequency control, and ramp rate control for intermittent renewable generation.

Electricity storage applications can usually be viewed as either primarily energy or primarily power applications, and this categorisation can be applied to technologies as well, using the E2P ratio, also known as Discharge Time. If the E2P ratio is about 0.5 h or less, the technology can deliver or absorb significant power over a short time, such as flywheels, supercapacitors or some types of batteries. If the E2P ration is about 2h or greater, the technology can sustain energy delivery for a much longer period, like certain batteries, especially flow batteries. In addition, two large-scale technologies (pumped hydro and compressed air energy storage) are capable of providing significant levels of both power

and energy, however they usually should be categorised as technologies suiting energy applications. Since each storage technology can serve a range of applications, other factors should also be considered for a detailed classification, like round trip efficiency, cycle and shelf life, and other physical limitations.

Possible thermal storage applications are very diverse, as much energy supplied ends up as heat. However, in practice, thermal storage applications are currently relatively limited. District heating systems can use storage of hot water to match electricity and heat production and demand, and there is a developing market for thermal storage to defer air-conditioning loads from peak periods. This shows that thermal storage often overlaps with demand management.

As discussed in “Global and regional current resource potential”, the ‘potential’ of energy storage technologies is less limited by geographical or resource constraints than other energy sources. ‘Potential’ in many cases is governed by the possible applications: for example, the market for electric vehicles.

EL HIERRO - PUMPED STORAGE IN CONJUNCTION WITH VARIABLE RENEWABLES ON AN ISLAND POWER SYSTEM

A wind/pumped hydro system was installed on the island of El Hierro (Canary Islands) in 2015. The plant is intended to reduce diesel fuel consumption for electricity generation, and also to provide some water for irrigation.

The plant is intended to be capable of providing satisfactory stability of the island electricity system even when no diesel generators are in operation. This has been successfully demonstrated, for periods of hours, in early 2016⁹. Both wind/hydro and wind-only generation have been achieved. When the diesel generators are not running, the pump/motor sets of the pumped-hydro system provide inertia and other functions to achieve stable operation of the grid.

Stable operation of a grid supplied only by variable renewable generation (wind) is technically achievable, with stability functions provided by pumped-hydro generators. However, there is still frequent use of at least one diesel generator and the storage capacity provided by the reservoirs is not of sufficient scale to provide seasonal storage of renewable energy.

TECHNOLOGIES: CAPITAL INVESTMENT AND OPERATIONAL COSTS

This section presents the results of two widely used metrics to present the cost development of different storage technologies, both based on recent studies and projections out to 2030.

⁹ https://demanda.ree.es/movil/canarias/el_hierro/total

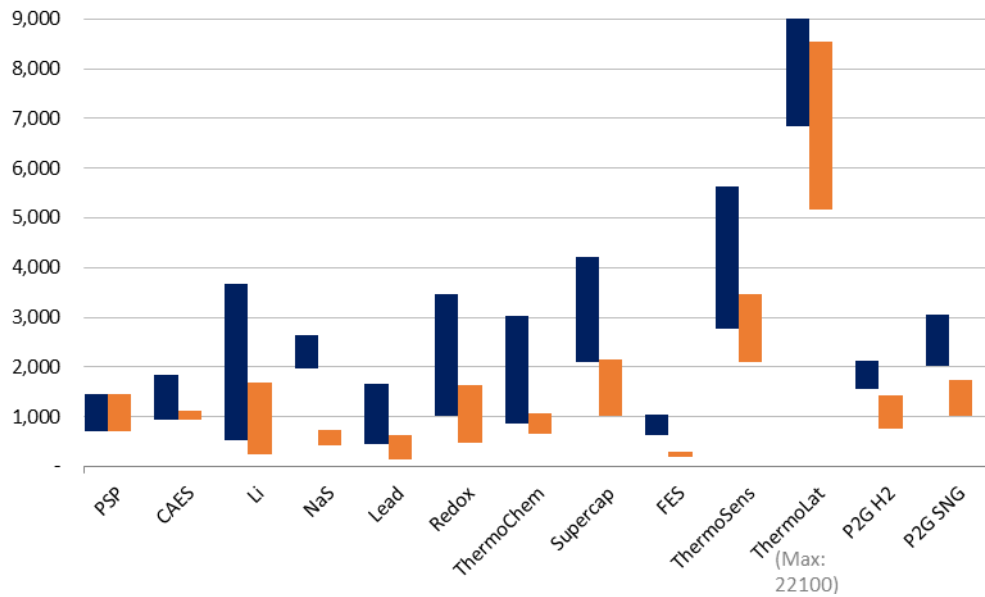
Understanding the economics and costs of energy storage is challenging due to the different technologies and applications. In general, energy storage systems are rated by power capacity (kW or MW) and potential energy output (kWh or MWh). Energy storage systems can be applied in a wide range of fields. This adds a further dimension to the problem of a meaningful comparison. In practice, two common metrics are used to compare and analyse the costs of energy storage systems, specific investment costs (SIC) and levelised cost of storage (LCOS).

Specific Investment Costs

The metric of SIC describes the installation costs for power and energy storage capacity. In the following, we refer to the SIC in terms of €/kW i.e. the investment costs per installed discharging capacity. Using the SIC for a comparison implies that the comparison is independent of the specific application of the storage system. Hence, it is independent of the amount of energy generated each year by the storage system and it highlights the cost intensity regarding the capacity a storage technology can provide.

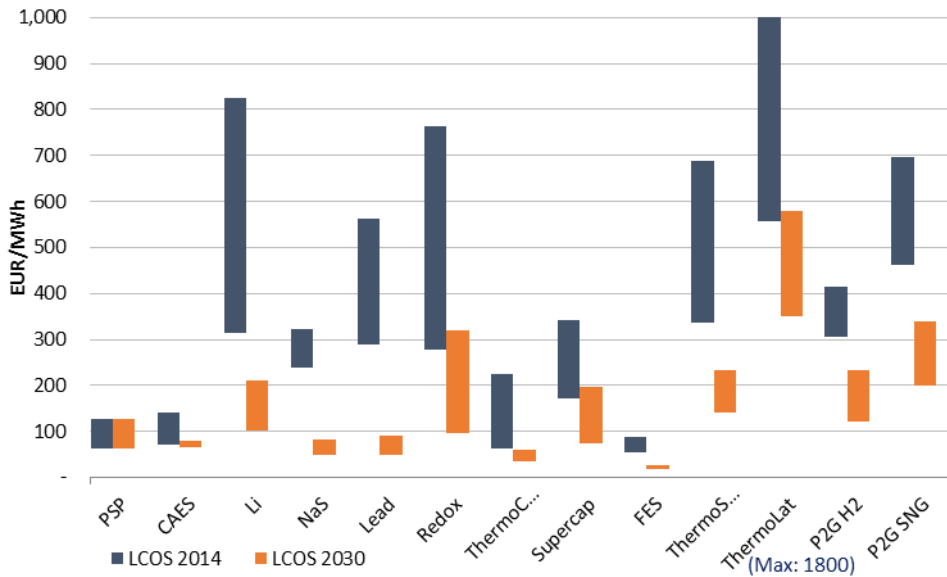
The results of the SIC can be seen in Figure 4 and Figure 5. The columns refer to the year 2014 and 2030 (predicted), respectively. The range of the bars in the graphs represents both uncertainty, and the effect of location, project size and other variables. As can be seen in the figures, pumped hydropower storage, CAES, batteries and flywheels have the lowest SICs and the smallest ranges. For 2030, regarding these storage systems, further cost reductions are expected. In particular, lithium-ion batteries, sodium–sulfur batteries and power-to-gas technologies are expected to reduce their costs clearly. These changes are likely to have an impact on storages deployed by 2030. The degree of cost reduction is mostly driven by maturity and synergy effects, stemming from cross-industry application. This is why technologies such as lithium-ion batteries are expected to show a significant cost reduction in the future (due to an expected wide-spread use in the mobility sector).

FIGURE 5: SPECIFIC INVESTMENT COSTS, STUDY PERIOD 2015 AND 2030 (€2014/KW)



Source: PwC (2016) (PSP = pumped storage hydro, FES = flywheel)

FIGURE 6: LEVELISED COST OF STORAGE STUDY PERIOD 2015 AND 2030 (€ 2014)



Source: PwC (2016)

Levelised Cost of Storage

The metric of LCOS uses the metric of levelised costs of electricity (LCOE), which is typically used to assess the cost of electricity production from different power plant types. In this analysis the formula has been transferred to storage technologies, as an economic exploration of the discharging side of energy storage. Because a storage plant does not generate power and depends on a different generating technology, the formula is referred to as LCOS. It still enables comparison between different types of storage technologies in terms of average cost per generated kWh. The LCOS is calculated as follows.

$$LCOS = \frac{I_0 + \sum_{t=1}^n \frac{A_t}{(1+i)^t}}{\sum_{t=1}^n \frac{M_{el}}{(1+i)^t}}$$

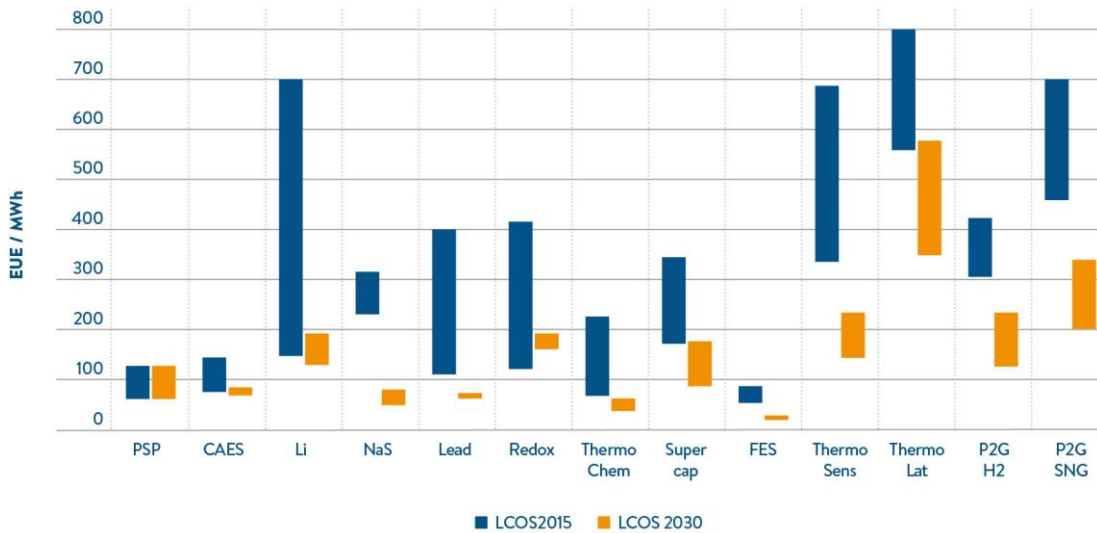
<i>LCOS</i>	<i>Levelized cost of energy [€/kWh]</i>
<i>I₀</i>	<i>Investment costs [€]</i>
<i>A_t</i>	<i>Annual total costs in year t [€]</i>
<i>M_{el}</i>	<i>Generated electricity in each year [kWh]</i>
<i>n</i>	<i>Technical lifetime [years]</i>
<i>t</i>	<i>Year of technical lifetime (1, ..., n)</i>
<i>i</i>	<i>Discounted rate (WACC)[%]</i>

As the LCOS includes the amount of electricity generated each year, it is important to note that *M_{el}* is strongly dependent on the assumed application (linked with the cycles per year). *A_t* includes both fixed and variable operational costs. For the LCOS formula, it is crucial to note that the cost of the input energy is not included.

The results of the calculations regarding the LCOS can be seen in Figure 7. It displays the general LCOS of each technology, i.e. it is assumed that a suitable application is used. The analysis assumes that the technical lifetime, which the technology is capable of, is fully utilised. Additionally, a general number of cycles per year and a general E2P ratio is applied.¹⁰ Thereby a specific optimum application for each storage technology is assumed, which should reflect the general cost level for a suitable application for each storage technology.

¹⁰ <http://www.worldenergy.org/publications/2016/e-storage-shifting-from-cost-to-value-2016/>

FIGURE 7: LEVELISED COST OF STORAGE IN 2015 STUDY PERIOD AND 2030 (€ 2014)

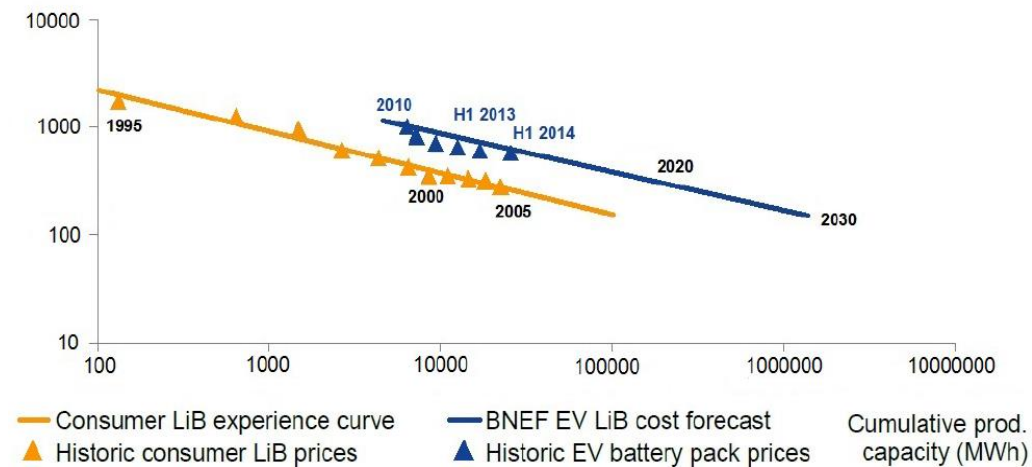


Source: PwC (2015)

Cost reduction expectations

Energy storage is often regarded in terms of high capital costs, but the results of the analyses reported above indicate a clear trend in the cost development. For several storage technologies, there is reason to believe that costs will fall as production volumes increase. This belief is supported by historical cost developments such as the one for Lithium-ion batteries. Figure 7 shows cost development of Lithium-ion batteries both for electrical vehicles and for consumer purposes. The so-called experience curve, which can be seen in Figure 7 is based on the observation that for manufactured products the cost decreases as production output increases. This correlation can be attributed to economies of scale, as well as manufacturing and engineering improvements.

FIGURE 8: COST DEVELOPMENT FOR LITHIUM-ION BATTERIES (USD/KWH)



Source: Bloomberg New Energy Finance, Maycock, Battery University, MIT

However, the cost development and the experience curve depend strongly on the application case of the energy storage system. A further illustration of a specific application case can be found in “Investments: long term ROI”.

DOMESTIC ENERGY STORAGE APPLICATION WITH PV, FOR ENERGY INDEPENDENCE AND BALANCING POWER

Small battery storage applications mainly serve two purposes. First, to increase the ‘energy independence’ of a household given for example a PV plant on the roof, and second, to provide balancing power to the grid infrastructure. Caterva GmbH, a spin-off company of Siemens AG founded in 2013, invented a business model that serves both purposes and generates synergy benefits. Caterva operates a ‘swarm-project’ together with the energy supplier N-ERGIE AG in the southern region of Germany. The cooperation is further accompanied by three chairs of the Friedrich-Alexander-Universität Erlangen-Nürnberg. The cooperation is divided as follows: N-ERGIE provides the customer contact and grid infrastructure, and Caterva provides the storage technology and the operating technology. The cooperation started off as a pilot project with the name SWARM (“Storage with Amply Redundant Megawatt “), which is financially supported by the Bavarian state government.

Caterva has developed a system that connects local storage systems (connected to a photovoltaic plant) in a swarm-system, currently consisting of 65 plants. The swarm is operated via the UMTS-system. The stored electricity in the energy storage system of a household is both used for electricity consumption of the household, and for balancing power for grid stabilization.

To fulfil both tasks, the Caterva energy storage system (ESS) is equipped with batteries from SAFT Batterien GmbH. The ESS provides a potential energy output of 21 kWh and a power capacity of 20 kW. The 65 plants in the swarm-system add up to a virtual capacity greater than 1 MW and thus fulfil one of the

requirements of the pre-qualification procedure of the German balancing power market. In July 2015, Caterva passed the pre-qualification procedure and became one of 22 suppliers of primary balancing power in Germany.

Due to the dual economic use of the ESS, Caterva is able to achieve a better economic feasibility for an energy storage system. The ESS of Caterva provides each household energy independence or “autarky degree” of up to 80%. All electricity which is withdrawn from the ESS for power balancing actions is recharged to the ESS at a later point in time. Hence, the customer is not affected by these actions.

The operating system of the Caterva ESS is programmed to discharge the battery benignly, to provide a long life span. Based on test results of Siemens, SAFT and Caterva, the battery is expected to last for 20 years. During this time the battery is maintained by Caterva according to the maintenance contract. The entire system has a system efficiency of 85% and is recommended for photovoltaic plants between 3 and 15 kWp.

ÉVORA SITE

Évora, a city 130 km from Lisbon, is been chosen as the first smart city in the InovGrid project led by EDP Distribuição, the main Portuguese Distribution System Operator (DSO). The pilot project is based on an electro-chemical energy storage system connected to the distribution grid, with also the Islanding capacity to self-supply the University campus for 30 minutes, at nominal load.

Field results demonstrate that a Li-Ion BESS can significantly improve energy quality and enhance renewable integration at distribution level, while providing an “online” lab to understand the new possibilities and challenges of batteries interconnection with electric systems and also off-grid applications.

FRADES II, A MILESTONE IN HYDROPOWER

Frades, in the northeast of Portugal, is facing a test phase for the biggest variable speed PHS plant in Europe and one of the biggest in the world. It will be commercially operated in 2016 and consists of 2 units with pump capacity of 390 MW each, installed upon the completion of a repowering project conducted by EDP – Energias de Portugal, SA. A consortium between Voith Hydro GmbH&Co KG (Germany) and Siemens S.A. (Portugal) has designed, installed and tested the necessary equipment. The variable speed technology allows the pumped storage units to adapt their rotational speed and import power from the grid in the

range between 319 and 383 MW. During peak hours the plant will work in turbine mode returning the stored power to the grid.

Doubly fed induction machines have shown to be a good choice for variable speed applications of significant power. The power electronics converters and corresponding control system, based on IEGT's, are able to inject three-phase currents in the rotor of the above mentioned machines. Those active and reactive currents are fully controlled by the VLSI (Very Large Scale Integration) devices to guarantee the compliance to the very stringent conditions imposed by the Portuguese grid code.

Simulations of the behavior of the whole system, including the impact of symmetrical and asymmetrical faults on the national grid were performed and evaluated, and finally approved by the Portuguese TSO.

2. ECONOMICS & MARKETS

HISTORIC AND CURRENT TRENDS

The historic trend is dominated by pumped hydro storage, which is now a mature technology, with costs largely governed by the location.

All other energy storage technologies have not reached the same level of maturity, and indeed some are still very much at the development stage. Costs are therefore seen to reduce with experience and volume, as shown in “Technologies: capital investment and operational costs”.

Market trends are also very disparate, depending on many local factors. It can be argued that historically, widespread electrification has led to a reduction in energy storage, as users have become accustomed to reliable energy at the flick of a switch, and no longer need substantial fuel stores close to the point of use. That trend is now reversing, as centralised electricity generation becomes more expensive, further development of electricity transmission systems becomes harder in some economies, and as localised renewable resources become more significant.

GLOBAL, REGIONAL AND DOMESTIC MARKETS

The US Dept. of Energy Global Energy Storage Database¹¹ provides a project-by-project perspective on both past and future storage growth. Due to its bottom-up approach, if anything the database provides a conservative view on the energy storage market. The database has been used below to summarise both historic and projected storage growth, in magnitude and location. Other reviews of storage capacity reach similar conclusions¹².

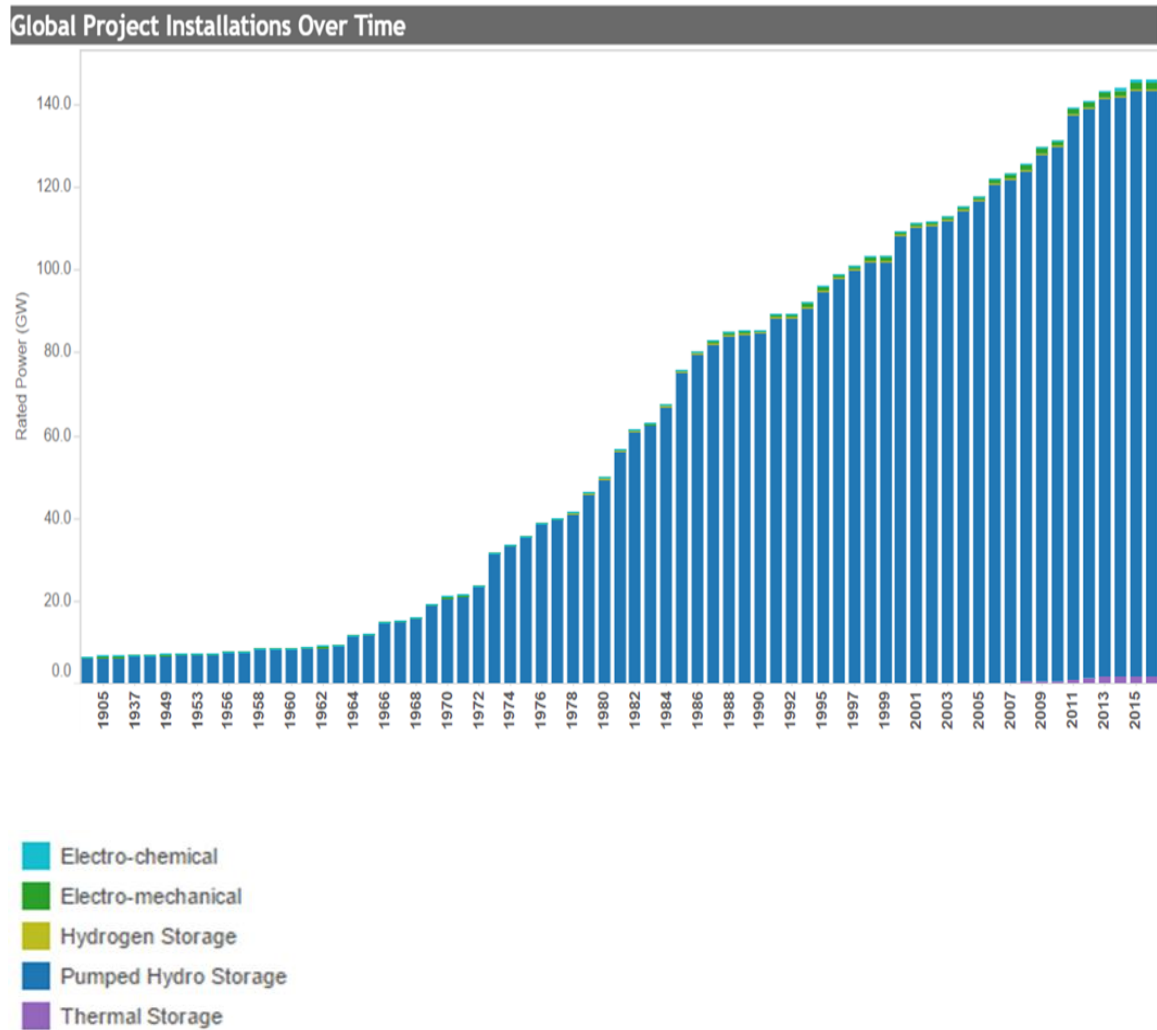
STORAGE GROWTH TO DATE

As of end-2015, the global installed storage capacity was 146 GW, consisting of 944 projects. Pumped hydro clearly dominates the storage portfolio (Figure 9). When pumped hydro is stripped out (Figure 9), it is apparent that there has been growth in a range of storage technologies, but particularly from thermal storage, in part due to the large project size.

¹¹ DOE Global Energy Storage Database, Office of Electricity Delivery & Energy Reliability

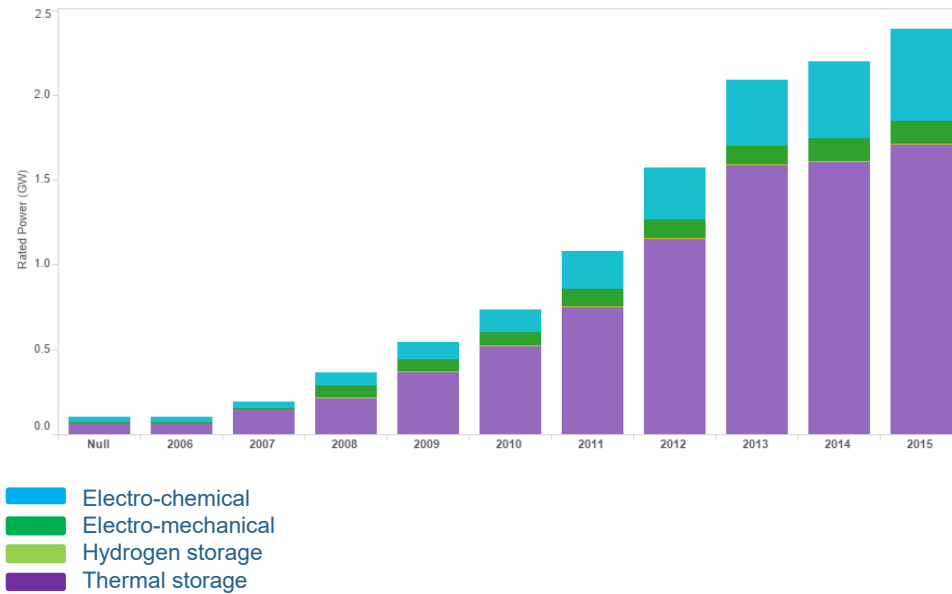
¹² For example, IRENA (2015) Battery Storage for Renewables: Market Status and Technology Outlook

FIGURE 9: HISTORIC GROWTH IN GLOBAL STORAGE INSTALLATIONS, BY RATED POWER (GW)



Source: DOE Global Energy Storage Database (2016)

FIGURE 10: HISTORIC GROWTH IN GLOBAL STORAGE INSTALLATIONS, EXCLUDING PUMPED HYDRO, BY RATED POWER (GW)



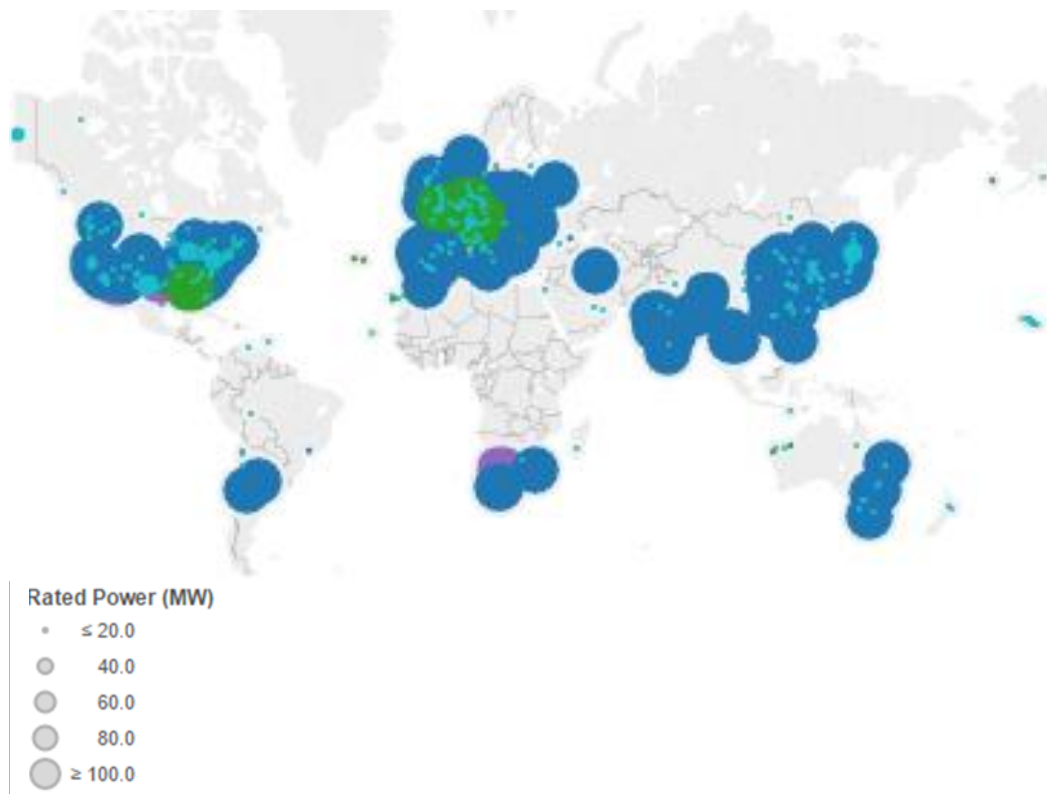
Source: DOE Global Energy Storage Database (2016)

STORAGE LOCATION TO DATE

Operational storage projects to date have been widely distributed globally, albeit with a bias towards developed markets (Figure 10). Once pumped hydro is stripped out (Figure 11), it is clear that electrochemical technology deployment is similarly fairly dispersed, albeit with hubs in the US, Europe, South-East Asia and Australia.

Thermal projects are more constrained by the solar irradiance requirements of Concentrated Solar Power technology, being clustered in Spain, the US and South Africa.

FIGURE 11: LOCATION OF OPERATIONAL STORAGE PROJECTS



Source: DOE Global Energy Storage Database (2016)

FIGURE 12: LOCATION OF OPERATIONAL STORAGE PROJECTS, EXCLUDING PUMPED HYDRO

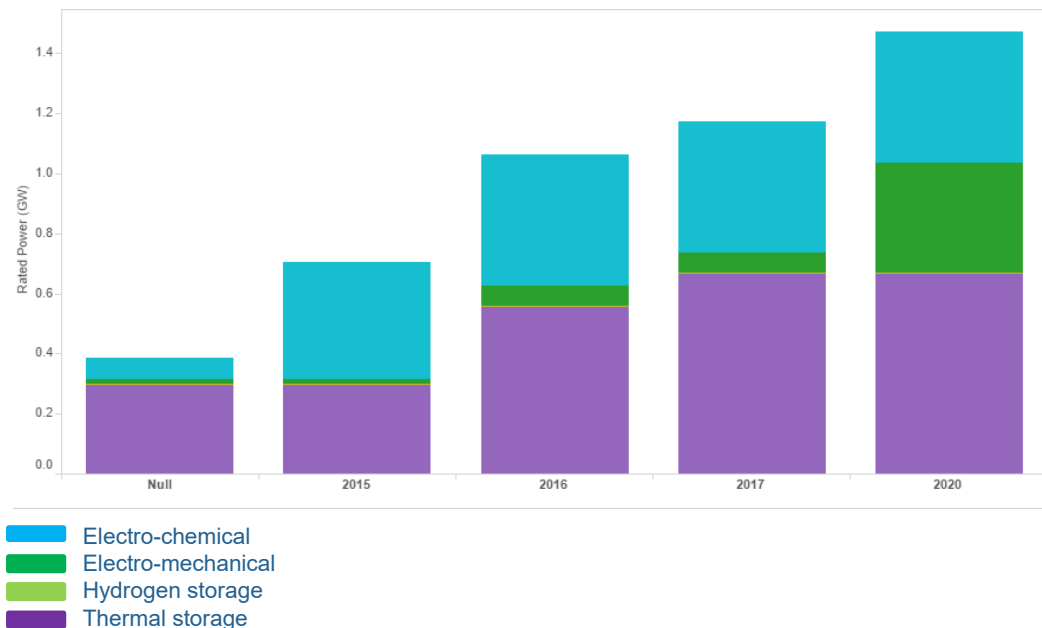


Source: DOE Global Energy Storage Database (2016)

FUTURE STORAGE GROWTH

Bottom-up projections suggest a global storage market of 1.4 GW/y by 2020, with strong growth in electro-mechanical technologies in particular (Figure 12). However, note that this is likely to be an underestimate, since the fast rate of build-out means that projects will be constructed during this period which have not yet been announced. Also, as noted earlier, residential and small commercial-scale battery installations in conjunction with PV may not be well recorded¹³.

¹³ The Energy Storage Association in the US expects these 'behind-the-meter' installations to surpass the 'utility' sector by 2020.

FIGURE 13: FUTURE GLOBAL DEPLOYMENT OF STORAGE TECHNOLOGIES, TO 2020

Source: DOE Global Energy Storage Database (2016)

APPLICATIONS

The applications for storage with the greatest near-term commercial momentum are as follows:

- Solar and storage:** In some locations, there is a strong market for battery storage in conjunction with small-scale PV, for example Germany, Australia and some parts of the US. Currently this is driven by pricing mechanisms for electricity imported and exported, and network charges.
- Electric vehicles:** The EV market is driving very substantial development effort for batteries.
- Islands and other isolated electricity systems:** Storage is being used for smoothing renewables generation, for instance in Hawaii. Islands are amongst the storage pioneers out of necessity – they tend to have comparatively high renewables penetration, limited flexibility options, and diesel generators can prove expensive to run due to the cost of transporting fuel to remote locations.
- Primary frequency response:** Storage projects for primary frequency response have been or are being deployed in a range of markets, including US, Korea, Germany and the UK. The technology of choice at present is typically lithium-ion batteries. The reason for the momentum behind this application is that this is a relatively clearly defined service, with a clearly defined revenue stream, and the requirement is increasing as wind and solar replace conventional synchronous generation. The application is well suited to battery technology, and enables developers to benefit from scale, leading to 10+MW plants.

- **Pumped-storage hydro:** development of pumped-hydro projects will continue, particularly in south-east Asia, Africa and Latin America, as developing economies continue to exploit the resources available to them.

A different perspective on the potential applications is obtained by considering from the viewpoint of ownership. Potential owners of storage capacity can be subdivided as:

- Domestic and small commercial building owners or occupiers, where applications are often concerned with optimising use of energy within the building. Examples are PV plus storage, management of demand (especially heating and cooling), and charging of electric vehicles. This type of owner may well 'subcontract' their participation to aggregators or to their energy supplier.
- Large demand customers: again, management of energy within the establishment is important, but the organisation may have the skills to handle the contracts and operation in-house.
- 'Merchant' storage owners, possibly in conjunction with ownership and operation of generation.
- Distribution and transmission system owners and operators; in these cases, the benefits will include provision of ancillary services, and deferral or avoidance of network reinforcement. In some jurisdictions, electricity system operators are not allowed to own generation resources, which can be taken to include storage.

DRIVERS AND KEY DYNAMICS, SUPPLY AND DEMAND DYNAMICS

Drivers

Energy storage technologies are becoming a valuable component in several power systems, and they are also expected to play an important role in reaching low-carbon future scenarios. However, some technologies are still too expensive, compared to traditional solutions, and the competition is also slowed by inefficient regulatory and market conditions. In the near future it is of utmost importance to properly define and analyse the multiple services that storage can provide in large-scale, small-scale and other (e.g. off-grid) applications.

Ongoing research and development work focusses on realising technology cost reductions and improving the performance of existing and emerging technologies. Also, non-technical barriers are addressed by an increasing number of stakeholders. The most important drivers for energy storage can be identified as follows:

- enhanced performance and reduced costs as a result of ongoing R&D;
- growing emphasis on the quality of power supply (reliability, resilience, stability), smart grid infrastructure developments;

- improving the overall efficiency of the electricity supply chain (generation, transmission and distribution, consumption);
- increasing use of variable renewable energy sources, primarily wind and solar;
- definition of new energy market services;
- increasing self-production of electricity and providing access to electricity via off-grid applications;
- electrification of the transport sector (hybrid and full electric vehicles and vessels).

Availability of resources, IP and skills are not seen as major constraints. Some storage technologies rely on specific materials, particularly batteries, but this will not constrain all technologies.

Competition

Demand-side management and demand response technologies could be a competitor to energy storage technologies in several cases, especially for heating and cooling applications, or if rollout of electric vehicles is able to reach a significant level. The batteries of EVs can be operated as distributed storage units, capable of providing services on distribution and residential level.

Greater interconnection between and within transmission systems also provides substantial benefits for coping with variation in electricity demand and in variable renewable generation.

Conventional thermal generation, in particular gas turbines, can also be made more flexible and can therefore compete for some of the services that energy storage can provide.

Incentivisation of investments in energy storage

Given cost reduction, direct incentivisation is not necessarily a prerequisite for energy storage to flourish. Instead, what is needed is a transparent and level playing-field that fairly values the services that energy storage can provide, enabling it to compete.

The following principles in policy and market design are likely to encourage investments in energy storage:

1. **Ensuring clear signals:** Clearly articulate the value of flexibility at a policy level, to create confidence in future growth.
2. **Technology agnosticism:** Frame markets based on what system operators need, rather than what conventional technologies can offer. Historically, the technical specification of ancillary services has been framed by what conventional power generation can provide, which makes it hard for storage to compete. However, there may be other reasons (e.g. protecting or establishing an industry) which would justify a country focusing on specific technologies. Note that a true

technology-agnostic approach will also allow flexible generation, demand management and greater interconnection to compete against storage.

- 3. Revenue compensation for services:** Fairly value the full range of services that storage can provide. This is often not the case at present. For instance, the opportunity to help network operators to defer investment in transmission or distribution assets is not always clearly priced, or even available. Similarly, intervention in some wholesale energy markets has reduced the “spikiness” or volatility in energy prices, meaning that price arbitrage services are not fairly compensated.
- 4. Removing regulatory anomalies:** Ensure that regulation is storage-ready. Address outdated regulatory barriers, such as double fees for storage assets for both charging and discharging, and clarification of storage’s functional classification. Ensure that storage located on the distribution network is not unfairly prevented from providing value to the transmission network.
- 5. Supporting innovation:** Storage technologies with low Technology Readiness Levels, and startups with innovative business models, may justify capital grant support to test their higher-risk propositions. In Canada (Ontario), innovative storage projects are being supported by contracts for 10 years, as short-term market arrangements are seen as difficult for projects with high capex.
- 6. Promoting data transparency from system and network operators:** Ensure that network and system operators make data publicly available and transparent, to inform storage siting and system sizing decisions.

The following case studies provide examples of incentivizing a range of storage business models.

ENHANCED FREQUENCY RESPONSE (EFR) IN THE UK

The UK’s transmission system operator National Grid issued its first tender for Enhanced Frequency Response (EFR) in 2016. The goal is to procure services that address the challenge of reducing system inertia (due to increasing penetration of non-synchronous sources such as PV and wind), improving management of the system frequency.

Contract duration is 4 years. EFR providers must offer a solution which can activate within 1 second, and provide this service for at least 15 minutes at a time. Projects can be between 1 MW and 50 MW.

This revenue stream comes in the context of a wider National Grid campaign, “Power Responsive”, which has helped ensure stakeholder engagement early on.

To ensure cost-effective procurement on behalf of consumers, National Grid has

chosen to define its scheme in terms of system value, rather than tailor it to a particular technology. Whilst the new service is well suited to batteries, National Grid has been clear that submissions are invited from any technology type that can meet the required parameters, and 35% of the prequalified capacity was from non-battery technologies. However, all winning bids used battery technologies.

RESIDENTIAL BATTERY INSTALLATIONS IN GERMANY

Germany has introduced a storage program to incentivise distributed battery storage in combination with PV. The initial programme started in March 2013 and finished by end of 2015. It has aimed at pushing market development of stationary battery storage systems, accelerating technology development and reducing costs.

The scheme has provided loan support – low interest rates and a repayment bonus - via KfW bank, a national development bank, for homeowners looking to install a battery in combination with their rooftop PV. The installed capacity of the PV plant has been limited to 30 kWp. Due to this specific dedication to PV panels the program has also promoted the country's solar industry market that has faced a number of shrinking years. According to the Germany Federal Ministry of Economic Affairs and Energy roughly 19,000 storage systems have received funding with a total of €60 million. The program induced investments of nearly €450 million.

In March 2016 a new revised programme was launched. Distributed battery storage in combination with PV plants will be supported until the end of 2018 by attractive loans, including a repayment bonus of up to 25% for the eligible costs. The repayment bonus will be gradually reduced depending on the year of application. The programme is funded with in total €30 million. The conditions have become tighter than in the previous programme. Only a maximum of 50% of the electricity produced with the PV facility can be fed into the grid.

The main result of this programme has been the establishment of a supply chain in Germany for domestic-scale battery storage in conjunction with PV. The programme has been criticised, since the financial rewards are available only to those households which can afford the initial capital costs. Lower-income households are unlikely to be able to participate, which potentially can lead to eroding solidarity in society with respect to electricity supply.

MOLTEN SALT STORAGE FOR CONCENTRATING SOLAR POWER PLANT IN SOUTH AFRICA

The 50 MW Bokpoort Concentrated Solar Power plant in South Africa started generation early in 2016. It uses parabolic mirrors to focus sunlight on a working fluid, which is then used to generate electricity. The plant includes energy storage in molten salt, equivalent to over 9 hours of generation.

Using the molten salt storage, the plant has already demonstrated continuous generation for a period of 161 hours and continuous electricity production for periods of days is feasible.

Electricity purchase contracts that reflect the value or price of electricity in the evening strongly affect the economic optimisation of the design and operation of the energy store.

INTEGRATION OF STATION BATTERY IN ROMANIA

Due to the increase of the energy market pressure on renewable energy tariffs, promoters are now being challenged to evaluate integration of stationary battery energy storage systems. In Romania, a pilot project delivered by Siemens S.A. (Portugal), will serve as proof of concept for the integration of a Li-Ion batteries system. In 2016 it will be connected with an Energy Management System to an extending wind farm near the city of Cobadin. The development of new algorithms will allow an intelligent real-time storage system, capable of minimising the error (and contract penalisation) between day-ahead energy production forecasts and real-time measurements, while ensuring the expected life span of the system and compliance with existing grid codes.

INVESTMENTS: LONG TERM ROI

The typical approach to calculate the profitability of an investment is to calculate its long term return on investment (ROI) and to compare it to the long term costs. However, this approach is quite difficult to implement when conducting a general (not country-specific) comparison of energy storage systems. Whereas the cost side can be modelled with some assumptions being made, the potential earnings of energy storage vary significantly across countries and markets. This is due to differences in regulation schemes such as balancing markets and power markets. Additionally, revenues depend crucially on the development of electricity prices and country-specific market design, which again show geographical differences caused by differences in generation mix and the demand side. This is why we focus on the long term costs, which should be compensated by revenues in order to make the investment in an energy storage system profitable.

As already stated in “Technologies: capital investment and operational costs”, costs vary significantly depending on the application case. Hence, in the rest of this section we will

concentrate on the application case of a storage system together with a photovoltaics plant. This illustrative example should provide a meaningful first impression of the cost development and consequently the revenues required to achieve a profitable business case.

The electricity storage systems presented in “Current and emerging technologies” represent existing technologies in the market. However, it is important to group the electricity storage systems according to the purpose and application (e.g. short term vs. long term storage). In addition, it is important to differ between different levels of scale or capacity: e.g. household, industry and power grid (low, medium, high voltage). Although we will not address differences between these scales here, it is important to keep this in mind.

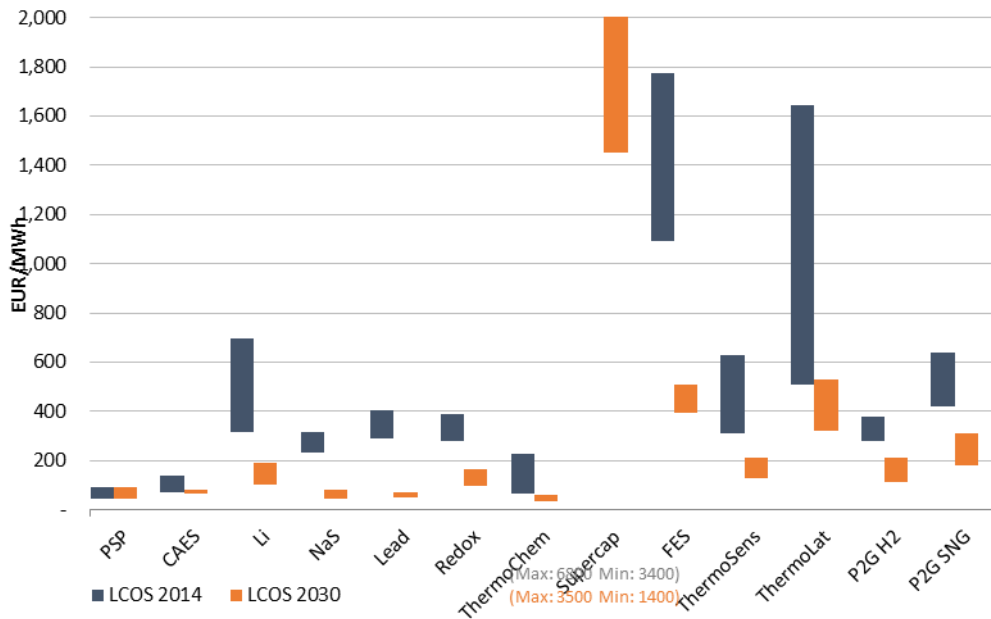
The application case with PV is based on the following parameters:

- 365 cycles/year [daily structuring]
- 6 hours discharge time at rated power

Out of a strict economic perspective, pumped hydropower, compressed air and thermochemical storage technologies are most competitive for this particular solar or daily storage application. These technologies achieve storage costs at around 50-200 €/MWh. This is followed by battery technologies, and these also show substantial cost reductions by 2030.

However, the installed capacities of the generating unit and the corresponding storage unit need to match. This is why battery technologies are still suitable to a solar-storage system of e.g. households with PV and storage capacities of below 10 kW.

FIGURE 14: LEVELISED COST OF STORAGE FOR PV APPLICATION CASE IN THE 2015 STUDY PERIOD AND IN 2030



Source: PwC (2016)

It is important to note a number of limitations of the cost modelling. The projections of the technology pathway to 2030 and its implications for cost reduction are clearly indicative. They are still subject to substantial uncertainty given the fast pace of change in this sector, and are subject to regional differences. Addressing these differences would require a local perspective rather than a global one. Yet, the most crucial limitation of this analysis is that a broad range of storage technologies are compared under one framework. The energy storage systems addressed in this report do all have specific application purposes. Some of the technologies might even be infeasible to deploy in real life due to geographic limitations. Therefore, an accurate analysis needs to consider the specific application case, because the profitability of a storage system is crucially dependent on it. Hence, the application case presented above should be seen as only one specific example.

The economic feasibility of energy storage systems depends not only on geographical location and differences in regulations, but also on the specific service the energy storage systems provides. This brings us to the conclusion that an accurate analysis at this point in time should focus on the cost side. After specifying the playing field, potential earnings can be derived and the business case can be analysed accurately.

The LCOE approach can make sense for an investor's perspective. From a policy maker's or from a social welfare perspective, the LCOE approach is incomplete: the key cost is the cost of electricity for the consumer, for the complete energy supply system. A systems approach is more relevant in these cases.

COST IMPLICATION OF EMISSIONS OR AVOIDED EMISSIONS

The impact of energy storage installations on emissions depends strongly on the application, and the other generation supplying the network to which the energy store is connected. It is therefore not possible to provide generic guidance.

The production, construction and installation of most energy storage technologies are predominantly machinery manufacture and civil construction works, and therefore not particularly emissions-intensive. Emissions due to creation of hydro reservoirs are discussed in the chapter on hydro-electric generation.

However, it is noted that in several applications, energy storage acts to 'smooth' the power demand to be met by other generators, thereby providing an opportunity to operate thermal generation closer to maximum efficiency. Storage also facilitates the use of variable renewables such as wind and solar. For these reasons, storage may act to reduce emissions from electricity generation. On the other hand, energy storage devices have losses, which act to increase the emissions intensity of an electricity system, i.e. the emissions per unit of electricity usefully consumed.

UNITED NATIONS FRAMEWORK CONVENTION ON CLIMATE CHANGE

The UNFCCC and related agreements including the Paris Agreement have no specific treatment of energy storage. However, as discussed above, energy storage can aid in decarbonisation of electricity generation, and therefore is relevant to the aims. For example, the spread of 'microgrids' of PV and battery storage in areas beyond conventional electricity distribution systems contributes to emissions reduction from the entire energy system, as well as substantial other benefits of improved quality of life and cost savings, and therefore contributes to the economic development and technology transfer aspects of the UNFCCC.

ENERGY SECURITY

Energy storage provides 'energy security' on two levels. Firstly, storage provides similar 'security' benefits as fuel storage, i.e. resilience against supply disruptions. This applies on all scales, from individual households to national energy systems. At large scale, most energy storage technologies except perhaps hydro reservoirs will struggle to compete for this function on cost alone against conventional storage of coal, oil or gas.

Secondly, energy storage can facilitate the integration of variable renewables such as wind and PV, and also electricity generating technologies such as nuclear which for economic or technical reasons are best operated at near-constant output. Therefore, reliance on imported fossil fuels or electricity can be reduced, increasing energy security at a national level. In particular, for small islands, indigenous renewables plus storage can greatly reduce reliance on imported fossil fuels.

RISK ANALYSIS

Major risks identified for energy storage applications are as follows.

Securing a bankable revenue stream

Securing a bankable revenue stream from storage assets can be challenging for two reasons. Firstly, under conditions where no one source of revenue is sufficient, multiple revenue streams must be 'stacked', and modelling the interactions between multiple revenue streams brings complexity and uncertainty about compatibility. Secondly, contracts can either be too short (e.g. the UK's Enhanced Frequency Response contract is just 4 years long) or non-existent (for instance, price arbitrage strategies mean taking a bet on the volatility of future wholesale energy markets). Due to this revenue uncertainty, a key risk for projects is that they cannot secure cost-effective financing, particularly project financing.

Impact of commodity costs and availability

Some energy storage technologies, especially batteries, rely on specific materials with limited sources of supply and limited other markets. These are vulnerable to impacts of political tension or conflict, or market manipulation. However, this is a risk only for that particular technology.

The greater risk for energy storage technologies generally is changes in fuel costs, such as gas or oil, which change the costs of competing forms of energy supply.

Diminishing returns

Some of the revenue streams have diminishing marginal value, i.e. the more storage is installed, the less the marginal revenue.

Regulatory and political risk

Many applications for energy storage currently rely on legislation or regulation; for example, electricity-generating renewables in most countries are still supported through some form of favourable tariff, traded emissions permits, or similar. Changes in priorities for regulators or politicians can rapidly affect storage applications for renewables integration, though usually not in many markets at the same time.

Further, regulatory frameworks may not allow the full value provided by energy storage to be realised: a form of market failure.

There is also 'regulatory risk' for electricity storage applications very similar to those borne by electricity generators, i.e. increasing demands on technical performance, as electricity systems become more complex.

Changes to the principles for charging for use of the electricity system can also have a major impact on energy storage applications. For example, an electricity system operator may recover some fraction of network capital and operating costs through charges related to customers' maximum demand. This creates a cost incentive for customers to install energy storage 'behind the meter', to reduce their maximum demand, but not their total electricity consumption. If the electricity system operator responds by moving to recover costs across all electricity consumed (i.e. per kWh), the economic case for storage behind the meter can be radically changed.

Volume or development risk

This risk applies to most new technologies which are reliant on volume or 'learning by experience' to achieve the required cost reductions. Achieving the necessary volumes requires confidence in the long-term market, which in turn requires a stable regulatory environment and clear policy aims from governments.

FUTURE OUTLOOK

The future outlook for energy storage markets, particularly for electricity storage, is good. This is principally driven by:

- increasing need: for example, electric vehicle batteries, and integration of renewables;
- falling costs, especially for batteries.

However, the future outlook for individual energy storage technologies is riskier, because they are competing against each other in specific applications, and also against other solutions such as demand response, greater interconnection of electricity systems, and flexible forms of electricity generation. As the storage market matures, it is expected that the market will focus on a smaller number of 'winning solutions', benefiting from mass production and supply-chain scale.

Substantial progress is expected in particular applications, and in particular locations where there is a supportive regulatory framework. These 'niches' (for example, electric vehicles in some countries) will create sufficient volume to reduce costs and improve performance of particular technologies, which is then anticipated to allow those technologies to spread into other areas.

'Second-use' electric vehicle batteries may find use in static applications, as the number and age of EVs grows. It is also feasible that electric vehicles may provide some value in 'vehicle to grid' services when the vehicles are grid-connected – this would most likely be provided via 'aggregator' companies which can combine the capabilities in a portfolio of services to offer to grid operators and others.

3. SOCIO-ECONOMICS

SOCIO-ECONOMIC IMPACTS

The socio-economic impact of different storage devices will vary substantially. For socio-economic impacts of pumped hydro, see the Hydropower Chapter.

Most commercial interest is in battery storage. Battery technologies are likely to have a more positive socio-economic impact than the conventional alternatives that they displace. Compared with some other energy technologies considered in this report, the visual and noise impact of a battery is minimal, and some developers even propose to place their battery systems within agricultural-style buildings to minimise this impact further.

SOCIO-ECONOMIC BENEFITS

The primary benefits are likely to include:

- Reduced greenhouse gas emissions (decarbonisation), for applications which result in increased use of renewables in place of conventional generation, or which allow conventional generation to run more efficiently.
- Improved local air quality, for the same applications.
- Improved local resilience and energy security, if the overall cost of energy is competitive from the customer's point of view
- Electrification of rural areas earlier than would occur using conventional network design practices and large centralised generators.
- Local job creation opportunities, for instance around installation and maintenance, particularly if storage is used in conjunction with renewables to reduce imported fuel.
- Reduced system balancing costs for integration of variable renewables.
- Reduced system balancing costs and network capital costs, if storage costs reduce sufficiently in the long term.
- Empowerment for residential homeowners, with even the potential option to go off-grid, which may lead to alternative business models and more diverse energy supply.

As an example, in comparison with investments required to build the "traditional" power grid infrastructure or at the least to extend an existing grid, to facilitate energy access for the less privileged in rural Africa, energy storage may make better economic sense, particularly in conjunction with local renewable energy sources such as PV. It offers

immense economic and social benefits, which in turn contribute to sustainable development.

SAFETY

PHS produces the same risks as hydro reservoirs, which are covered in the Hydropower Chapter.

CAES has risks which apply to all pressure vessels, and standard mitigation methods can be applied. Similarly, thermal stores have risks of uncontrolled release of thermal energy, which are similar to all industrial processes which store or transfer hot or cold fluids.

For some battery technologies, there are risks of faults leading to emissions, fire or even explosions. Some of these risks are specific to the battery industry, but are well understood¹⁴ and can be adequately mitigated at the design, installation and operational stages.

Flywheels have the possibility for mechanical failure, leading to destruction of the spinning mass. However, adequate containment can be incorporated.

The Power to Gas technologies have the risk of gas fire or explosion. The mitigation measures required are no different from other industrial processes handling these gases in bulk.

INTERNATIONAL IMPACTS

The main international impacts of energy storage are likely to be unrelated to technology – there are no major issues which are technology-specific. Some of the battery technologies use uncommon or rare materials, where supply may be concentrated in a few countries, but restrictions in supply are likely only to lead to other battery technologies being preferred, or new sources being exploited. The issue is a risk for technology developers, but not directly for purchasers or users of energy storage.

Battery production is characterised by very large volumes of standard units, and therefore cost competition is driven by volume (including local market size) and manufacturing costs. A similar situation applies to PV module production, and recent years have seen major growth in PV manufacturing in Asia, at the expense of production in Western countries – the same may well happen with battery manufacturing.

Other impacts are related to the applications of energy storage. Energy storage which facilitates greater use of variable renewables, or nuclear, will affect markets for fossil fuels, which are internationally traded. This also improves energy security for some countries.

The growth of electric vehicles driven by battery cost reduction and performance improvements may, on some projections, have a radical impact on oil consumption.

¹⁴ IEC standards are under development, and other guidance and good-practice documents are available, for example at <https://www.dnvgl.com/energy/brochures/download/gridstor.html>

Energy storage which provides flexibility in operating national power systems competes directly against greater international interconnection capacity, which provides similar flexibility benefits.

4. ENVIRONMENTAL IMPACTS

LAND USE

Land use is only an issue for PHS. The impacts are similar to hydro reservoirs, which are covered in the Hydropower Chapter.

ECOSYSTEM MODIFICATION

Only PHS and CAES are likely to produce significant ecosystem modification. Experience shows that the impacts depend very significantly on the specifics of the installation¹⁵.

WATER USE

PHS is the only energy storage technology for which water use may be an issue. PHS projects which create new or expanded water bodies may be subject to evaporation losses, and will influence hydrology.

EMISSIONS

Some battery technologies can produce harmful emissions in the event of a serious failure.

The Power to Gas technologies have the potential for emissions of hydrogen or methane, which are safety risks. Methane in particular is also an important greenhouse gas, though of course if it is used to replace naturally-occurring methane, net emissions are not increased.

The emissions benefits of some energy storage applications are noted in “Socio-economic benefits”.

Storage technologies which have substantial conversion losses (for example, electrolysis of hydrogen) could lead to net increases in emissions if used to store electricity from electricity systems with a high fraction of coal or gas-fired generation. Hydrogen appears to be a possible energy vector for storage only when low carbon electricity is used for its production.

ENERGY USE IN MANUFACTURE OR CONSTRUCTION

Battery technologies use substantially more energy in their manufacture than other forms of energy storage¹⁶. Lithium-ion appears to be the best of the technologies studied, with the ability to store over its lifetime around 10 times the energy used in its manufacture,

¹⁵ University College Cork and Malachy Walsh & Partners (2012) Environmental performance of existing energy storage installations, StoRE project, www.store-project.eu, Deliverable D.3.1 Feb

¹⁶ Barnhart (2013) On the importance of reducing the energetic and material demands of electrical energy storage.

whereas PHS and CAES reach over 200 times. Improved cycle life and recycling of materials are necessary to improve this.

MATERIALS REQUIREMENTS

Materials required for batteries are obtained by mining, which can have substantial local environmental impacts. The same of course applies to steel and concrete.

Materials used in some battery technologies are toxic or have other harmful effects, and therefore good practice in handling and controlling materials is required. As an example, the most significant drawback of Ni-Cd batteries is the highly toxic cadmium used within them. Although this metal is highly recyclable it is exceedingly toxic. Most nickel is recovered from end-of-life batteries, since the metal is reasonably easy to retrieve from scrap and can be used in corrosion resistant alloys such as stainless steel. EU legislation is in part responsible for Ni-Cd batteries being superseded by Ni-MH batteries, and represents a significant issue to any future development of Ni-Cd battery technologies.

Another example is flow batteries. The potential size and scale of these systems are likely to determine the extent to which environmental impacts are significant. Significant quantities of space may be required for holding tanks containing the electrolytes and although these substances may not be specifically toxic, this obviously requires care at the design stage. A major advantage of the technology is the ability to perform discharge cycles indefinitely so there are no significant waste products associated with operation.

DECOMMISSIONING

Decommissioning activities and environmental impacts vary greatly between energy storage technologies. For some, it may be more attractive to renovate or 'repower' the existing installation, such as for pumped storage hydro.

For the battery storage technologies, decommissioning and recycling pathways already exist, and there can be substantial value in the materials. However, 'second use' of batteries is also feasible, particularly electric vehicle batteries.

5. OUTLOOK

SHORT TERM

In the short-term (up to 5 years), the storage industry is focused on the basics of how to put storage projects together: Project developers are working out the components of battery projects (PCS, BMS etc), the different supply chain options for procurement, and the associated contractual risk interfaces. Early storage projects generally seek to stack 1-3 services only.

There will be two main drivers.

Technical development and cost reduction

Rapid technical development of specific technologies will continue, particularly batteries, but also other technologies (see case study below). This is expected to be aimed principally at cost reduction, by technical improvements such as increased cycle life, and by manufacturing (volume production, and learning). This will be affected by the growth of the electric vehicle market.

True costs will not be determined for most applications in the short term, but the cost trends and forecasts will become clearer.

Some consolidation of suppliers and technologies will occur, but not extensively.

Regulatory and commercial change

Regulation and legislation are currently impediments to several potential markets for energy storage, and it is expected that governments with a need to decarbonise electricity, heat and transport will make changes.

This will be particularly important for the complex area of utility-scale electricity storage: for example, in some applications energy storage capacity has value as a capital investment like other network assets, and in others energy storage competes in markets for energy, reserve and other forms of flexibility. Decisions in this area will influence which organisations are the best owners of storage. It is particularly important that clear policy frameworks are established by national governments and energy regulators.

For this reason, the true value available from storage applications will start to become clearer.

Energy storage will increasingly become 'bankable'. To date most storage projects have been funded 'off balance sheet'. This will change as new equity players enter, and lenders become comfortable with the risk. Gearing ratios will increase.

The main areas of growth in the next five years are likely to be:

- Small-scale battery storage in conjunction with PV. There are already around 25,000 residential-scale units in Germany alone, and this could grow to 150,000 by 2020.
- Utility-scale electricity storage, for multiple purposes, especially frequency response.
- Electric vehicles.
- Commercial, communications and software capabilities to allow multiple small distributed storage, demand response and distributed generation sources to be aggregated, in a 'virtual powerplant' or 'swarm'.
- Pumped storage hydro, especially in south-east Asia, Africa and Latin America.
- Isolated electricity systems such as islands, to aid integration of renewables in order to save fuel costs.

MEDIUM TERM

In the medium term (5-8 years), the storage industry will place greater emphasis on optimisation: storage operators will seek to stack more revenue streams together, refining their algorithms both to enable the provision of multiple services, and to optimise battery condition and lifetime.

Looking to the medium term, we expect to see the following:

- **Business models:** There will be continued innovation in business models for storage, similar to the array of entrepreneurial approaches seen in the solar sector (leasing, private wire etc). Costs and value will become well-established. As energy storage projects generally have lower capital costs than most renewables and conventional generation projects, financing of portfolios is likely to become more important, to attract a wide range of investors.
- **Further substantial technical development**, for example as shown in the case study below of hydrogen storage at high energy density without pressure tanks, or PHS using underground reservoirs.
- **Increased emphasis on software:** As storage technology becomes proven, the emphasis will increasingly move away from the hardware and towards the software. In other words, there will be increased emphasis on the algorithms and control systems which determine how storage plant will operate. Research and commercial activity will focus on optimising the role of storage within the wider system, such as within virtual power plants.
- **Synergies with electric vehicle market:** The EV market will help drive down lithium-ion battery costs, and there will be continued synergies with stationary storage – for instance, some market players will continue to pursue both markets,

and increased effort will be invested in capitalising on the storage potential of EV batteries. This may include second-use of EV batteries.

- The importance of **longer-term storage** will grow, since structuring of electricity production with time frames of several days or more will be necessary.
- Links to **mobility and heating sectors** via Power to Gas and heat technologies provide an alternative to electricity storage, which take advantage of inherent storage capacity and existing infrastructure.
- **Consolidation** of technologies ('winning solutions') and technology providers in the largest markets will occur.

The 'big picture' in the medium term is the emergence of several substantial energy storage markets, with very different technical, economic and regional characteristics, such that eventually the field will be as diverse as, for example, electricity generation and end use are today.

PROS AND CONS OF ENERGY STORAGE COMPARED TO ALTERNATIVES

Energy storage is a diverse field, but for the purposes of this section it can be considered in three areas.

For electricity, storage is one form of providing flexibility. Flexibility is becoming more important, as decarbonisation of electricity networks increases. However, flexibility can also be provided by demand management, flexible generation, and greater interconnection of networks.

These options are compared in the table below.

TABLE 2: COMPARISON OF ELECTRICITY STORAGE AGAINST OTHER FLEXIBILITY OPTIONS

Issue or need	Demand management	Flexible generation	Greater interconnection	Electricity storage
Matching supply and demand (variable renewables, reducing curtailment, arbitrage etc)	Low cost. Co-ordination of multiple small loads required. Limited volumes	Low cost (e.g open-cycle gas turbines, diesels). May need capacity market	High capex, low opex. Needs strong stable market signals	Wide range of technology options. High capex, low opex
Provision of reserve, frequency response and	Low cost. Co-ordination of multiple small loads required.	Low cost	High capex, low opex. Complex contractual	High capex, low opex. Validation or certification.

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similar services	Limited volumes		arrangements	
Energy security	Only useful in short term	Strong benefits if fuel storage is included in costs, or fuel source is secure.	Strong benefits if the other networks have high energy security.	Only useful in short term
Assists with network operation (if regulatory framework permits)	Very limited	High	High	High (for some applications)
Reduces network capital investment (if regulatory framework permits)	High benefit in some locations	High benefit, depending on location	Low benefit, except in specific locations	High benefit for most applications
Program	Very short lead times	Long lead times	Very long lead times	Short lead times
Familiar technology	Simple, but communications and control need demonstration and validation	Familiar technology	Familiar technology (though HVDC is a developing technology)	Some technologies very established, others new. Communications and control need demonstration and validation
Emissions and decarbonisation when used with variable renewables	High: very little new equipment or construction needed. Limited volumes	Fair: on large electricity systems, may only need to burn fuel for a few hundred hours per year	Large carbon footprint. Benefits depend on fuel mix of interconnected systems	High: though carbon footprint is significant for some technologies, and losses need to be considered

Electricity storage gets much of the attention, but thermal storage is also important, because much of our energy is used as heat or cooling. For direct heating or cooling applications, thermal storage provides advantages in reducing the nominal rating of the heating or cooling plant, and allowing energy to be stored from low-price periods. A prime example is the use of ice to shift electricity demand for air conditioners from peak price periods to off-peak¹⁷.

It is arguable that thermal storage used in this context is more accurately considered as demand management.

The third area is Power to Gas. Hydrogen, methane or other gaseous fuels can be stored more easily than electricity, though conversion losses from electricity are substantially higher than for electricity storage. The gas has multiple potential markets: industrial gases,

¹⁷ See for example <http://www.ice-energy.com/>

transport fuels, injection into existing gas grids, and reconversion to electricity by conventional engines, gas turbines, or by fuel cells. Conversion losses and equipment costs mean that the latter option is currently an expensive form of electricity storage.

The main advantage is that the gas is 'green', i.e. very low net carbon emissions compared to natural gas.

In most countries existing transport fuels and natural gas are substantially cheaper by energy content than electricity, before tax is applied. Therefore, this becomes part of broader political decisions on the need to decarbonise transport and heating. However, in the context of storage for high penetrations of variable renewables, the very high storage capacity potentially available in existing gas networks could be an important factor in some countries.

STORAGE OF HYDROGEN

The "Smart Grid Solar" project in Arzberg, Germany aims to investigate the integration of PV into the low voltage grid by testing different short- and long-term storage technologies. Within the project, a complete hydrogen system has been installed by AREVA.

A proton exchange membrane (PEM) electrolyzer (75 kW) transforms the electricity of a solar farm into hydrogen; a fuel cell (5 kW) reconverts hydrogen into electricity. Both components have already proven their readiness for industrial scale use. In an innovative approach a so-called LOHC technology is used to optimise the hydrogen storage by charging in and discharging from a Liquid Organic Hydrogen Carrier.

The LOHC technology enables safe storage of large amounts of hydrogen in a small space, compared to conventional pressure tanks. The volume per energy unit is reduced, and the fluid can be safely stored in normal tanks without pressure. Compared to the industrial hydrogen tanks with a pressure of 35 bars, the storage in LOHC requires less volume by a factor of 15. LOHC can be easily transported in existing infrastructures such as tanks, trucks and ships. There are no losses as hydrogen is chemically bound in the LOHC.

The LOHC-module consists of a hydration and dehydration unit and two tanks. One of the tanks contains the LOHC liquid carrier in its initial state. The hydration unit inserts hydrogen into the fluid in a chemical reaction. The loaded LOHC is then stored inside the second tank. When required, the dehydration unit discharges the hydrogen from the LOHC by an endothermic reaction. The fluid returns to the initial tank.

The hydrogen can be converted to electricity in the fuel cell (though the economics of electricity storage via hydrogen and fuel cells are currently challenging), injected into an existing gas grid, or provided for transport or for industrial uses.

6. GLOBAL TABLE

PROJECTS AND NOMINAL POWER BY COUNTRY AND STORAGE TECHNOLOGY

Sources of data for energy storage installations worldwide are scarce. The data presented here are all taken from the US DOE energy storage project database¹⁸, as it is a comprehensive and self-consistent source, readily available to all. This database is used to produce the Figures in the “Technology” section. The database is regularly updated, and the figures presented here were obtained in June 2016. The only exception to this is for Pumped Storage, where the figures have been checked and if necessary modified to agree with the Hydropower Status Report 2016¹⁹. In this case, the total number of Pumped Storage projects in a country may not be defined.

The database covers around 80 countries; the table below covers only those countries with projects in operation. The database also includes data for projects which are in construction, or proposed, or not in operation, but these are not included in this table.

The table shows the numbers of projects and total nominal power (‘nameplate capacity’) by the five categories of storage technology used in the US DOE database. The database is easily searchable for substantial additional information, such as storage duration, use cases or sources of value, and ownership. The database concentrates on ‘projects’, and is therefore likely to under-represent small-scale installations, particularly residential-scale storage for PV, the total battery capacity of electric vehicles, and domestic hot water storage. Therefore, where known, estimates for these are included in the final column.

¹⁸ DOE Global Energy Storage Database, Office of Electricity Delivery & Energy Reliability
<http://www.energystorageexchange.org/>

¹⁹ International Hydropower Association (2016) Hydropower Status Report 2016

TABLE 3: NOMINAL POWER (MW), BY TECHNOLOGY GROUP AND LOCATION

Note: The World Energy Council is aware that there are other e-storage projects in operation or underway and therefore, we do not consider this table as exhaustive, but more as an indication of the variety of e-storage projects in existence in some of the countries.

Nation	Electro-chemical storage	Electro-mechanical storage	Hydrogen storage	Pumped hydro storage	Thermal storage	Comments
Antigua and Barbuda	1 project, 3 MW flow battery	0	0	0	0	
Argentina	0	0	0	2 projects, 974 MW	0	
Australia	19 projects, 7 MW	2 projects, 1 MW (both flywheels on micro grids with high wind or solar fraction)	0	740 MW	1 project, 3 MW (thermal storage for concentrating solar plant)	Growing numbers of domestic-scale battery systems associated with PV
Austria	1 project, 0.064 MW	0	0	5200 MW	0	
Belgium	0	0	0	2 projects, 1307 MW	0	
Bolivia	1 project, 2.2 MW	0	0	0	0	
Bosnia and Herzegovina	0	0	0	1 project, 420 MW	0	

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Nation	Electro-chemical storage	Electro-mechanical storage	Hydrogen storage	Pumped hydro storage	Thermal storage	Comments
Brazil	0	0	0	1 project, 20 MW	0	
Bulgaria	0	0	0	864 MW	0	
Canada	10 projects, 10 MW	2 projects, 2.7 MW (flywheel and compressed air)	0	1 project, 174 MW	2 projects, 2 MW	
Cape Verde	1 project, 0.03 MW	0	0	0	0	
Chile	2 projects, 32 MW	0	0	1 project, 31 MW	1 project, 11 MW (concentrated solar)	
China	54 projects, 50 MW	0	0	23060 MW	1 project, 2 MW (concentrated solar)	Substantial growth in electric vehicles
Croatia	0	0	0	3 Projects, 282 MW	0	
Czech Republic	2 Projects, 0.04 MW	1 Projects, 70 MW (Institute of Plasma Physics)	0	3 Projects, 1145 MW	0	
Denmark	3 Projects, 2 MW	0	0	1 Project, <0 MW	1 project, 49 MW	Substantial thermal storage exists in district heating network. Vojens Fjernvarme has installed the world's largest underground thermal

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Nation	Electro-chemical storage	Electro-mechanical storage	Hydrogen storage	Pumped hydro storage	Thermal storage	Comments
						pit storage (200,000 m ³) in the city of Vojens. The plant was put into operation in May 2015.
Equatorial Guinea	1 Project, 5 MW	0	0	0	0	
France	10 Projects, 9 MW	0	1 Project, 0 MW (university)	10 Projects, 5812 MW	1 Project, 3 MW	Around 20 TWh of storage provided in domestic hot water tanks, for peak-shaving.
Germany	35 Projects, 251 MW	3 Projects, 708 MW	4 Projects, 3 MW	6806 MW	1 Project, 2 MW	Many further pilot projects for hydrogen or methane as storage or as fuel sources are listed at http://www.powertogas.info/power-to-gas/pilotprojekte-im-ueberblick/?no_cache=1
Greece	0	0	0	2 Projects, 699 MW	0	
Haiti	1 Project, 0 MW	0	0	0	0	
Hungary	1 Project, 1 MW	0	0	0	0	
India	3 projects, 0.1 MW	0	0	4786 MW	1 project, 0.2 MW, chilled water storage for air conditioning	

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Nation	Electro-chemical storage	Electro-mechanical storage	Hydrogen storage	Pumped hydro storage	Thermal storage	Comments
Indonesia	1 Project, 0.4 MW	0	0	0	0	
Iran	0	0	0	1 project, 1040 MW	0	
Iraq	0	0	0	240 MW		Information only from Hydropower Status report 2016
Ireland	4 Projects, 0.5 MW	2 Projects, 2.3 MW flywheels	0	1 Projects, 292 MW	1 Project, 4.6 MW Ice thermal storage	High wind penetration, relatively isolated grid, therefore interest in flywheels to provide inertia.
Israel	1 Project, 0 MW	0	0	0	0	
Italy	18 Projects, 42 MW	0	0	22 Projects, 7669 MW	2 Projects, 5 MW	
Japan	47 Projects, 255 MW	0	0	27637 MW	0	
Korea, South	44 Projects, 206 MW	0	0	7 Projects, 4700 MW	0	
Lithuania	0	0	0	1 Project, 760 MW	0	
Luxembourg	0	0	0	1 Project, 1096 MW	0	

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Nation	Electro-chemical storage	Electro-mechanical storage	Hydrogen storage	Pumped hydro storage	Thermal storage	Comments
Madagascar	1 Project, 0 MW	0	0	0	0	
Maldives	1 Project, 1MW	0	0	0	0	
Martinique	2 Projects, 3 MW	0	0	0	0	
Morocco	0	0	0	1 Project, 465 MW	1 Project, 160 MW (molten salt storage)	
Netherlands	7 Projects, 14 MW	0	0	0	0	
New Zealand	2 Projects, 0 MW	0	0	0	0	
Norway	0	0	0	1351 MW	0	
Philippines	0	0	0	685 MW	0	
Poland	0	0	0	6 Projects, 1745 MW	0	
Portugal	1 Project, 0 MW	2 Projects, 1 MW flywheels (Azores island systems)	0	1343 MW	0	
Puerto Rico	1 Project, 0MW	0	0	0	0	
Qatar	1 Project, 0 MW	0	0	0	0	

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Nation	Electro-chemical storage	Electro-mechanical storage	Hydrogen storage	Pumped hydro storage	Thermal storage	Comments
Romania	0	1 Project, 0 MW	0	92 MW	0	
Russia	2 Projects, 3 MW	0	0	1360 MW	0	
Serbia	0	0	0	1 Projects, 614 MW	0	
Slovakia	0	0	0	916 MW	0	
Slovenia	0	0	0	1 Project, 185 MW	0	
South Africa	1 Project, 0 MW	0	0	3 Projects, 1580 MW	2 Projects, 150 MW	
Spain	14 Projects, 8 MW	2 Projects, 2 MW	0	5268 MW	26 Projects, 1132 MW (molten salt, associated with solar plants)	
Sweden	1 Project, 0 MW	0	0	99 MW	1 Projects, 8 MW	
Switzerland	5 Projects, 2 MW	0	0	1817 MW	0	
Taiwan	1 Project, 0 MW	0	0	2 Projects, 2608 MW	0	
Thailand	0	0	0	1000 MW	0	
Ukraine	0	0	0	1315 MW	0	

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Nation	Electro-chemical storage	Electro-mechanical storage	Hydrogen storage	Pumped hydro storage	Thermal storage	Comments
UAE	1 Project, 8 MW	0	0	0	1 Project, 0 MW	
UK	23 projects, 24 MW	400 MW flywheel at nuclear fusion laboratory	Small research or demonstration plants only	4 projects, 2828 MW	Small: demonstration cryogenic and LAES plants	The storage market is being catalysed by the TSO's pilot tender for Enhanced Frequency Response, expected to be 200MW. The Government (DECC) is conducting a consultation on energy storage; direct project subsidies are unlikely, though there may be innovation funds available for pioneering new business models. The UK has a long history of substantial electricity storage radiator capacity, operated overnight by timeclock or by direct radio signal. This was intended to fill in the overnight trough, in part to allow greater penetration of baseload plant, especially nuclear. Domestic electric heating has to compete against relatively cheap gas central heating for most of the UK housing stock.
US	227 Projects, 473 MW	21 Projects, 171 MW	0	38 Projects, 22561 MW	135 Projects, 664 MW	

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- Agora Energiewende (2014)
- Barnhart CJ (2013), On the importance of reducing the energetic and material demands of electrical energy storage, Stanford news
- Bloomberg New Energy Finance, Maycock, Battery University, MIT
- Department of Energy, DOE, Global Energy Storage Database, Office of Electricity Delivery & Energy Reliability, <http://www.energystorageexchange.org/>
- DNVGL, GRIDSTOR Recommended Practice for grid-connected energy storage, www.dnvgl.com/energy/brochures/download/gridstor.html
- Energy Research Alliance (EASE/EERA) (2013), Core Working Group, March
- European Association for Storage of Energy and European, Development Roadmap towards 2030
- Fraunhofer Institute for Wind Energy and Energy System Technology, IWES https://demanda.ree.es/movil/canarias/el_hierro/total
- Institut für Elektrische Anlagen und Energiewirtschaft der RWTH (2014), IAEW Aachen, Stiftung Umweltenergierecht
- Institut für Stromrichtertechnik und Elektrische Antriebe RWTH Aachen (ISEA), (2012), Technology Overview on Electricity Storage
- IRENA (2015), Battery Storage for Renewables: Market Status and Technology Outlook
- IRENA (2015), Battery Storage for Renewables: Market Status and Technology Outlook www.irena.org/menu/index.aspx?mnu=Subcat&PriMenuID=36&CatID=141&SubcatID=495
- IRENA (2015), Renewables and Electricity Storage www.irena.org/menu/index.aspx?mnu=Subcat&PriMenuID=36&CatID=141&SubcatID=600
- International Hydropower Association (2016), Hydropower Status Report, www.hydropower.org/2016-hydropower-status-report
- Martens D (ed.) (2013), Joint EASE/EERA recommendations for a European Energy Storage Technology
- PwC (2015) PwC research
- Renewable and Sustainable Energy Reviews, 42 (0), 569-596
- University College Cork and Malachy Walsh & Partners (2012), Environmental performance of existing energy storage installations, StoRE project, Deliverable D.3.1, www.store-project.eu, Deliverable D.3.1 Feb 2012
- World Energy Council (2016), World Energy Resources, E-storage: Shifting from cost to value 2016, www.energystorageexchange.org
- www.gaelectric.ie/energy-storage-projects/

www.ice-energy.com

www.worldenergy.org/publications/2016/e-storage-shifting-from-cost-to-value-2016/

Zakeri B, & Syri S (2015), Electrical energy storage systems: A comparative life cycle cost analysis

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COUNTRY NOTES

ALBANIA

Albania is almost completely dependent on **hydropower** and imports for its power supply. New hydropower capacity additions are focused in the southern region of the country, and include the two projects on the Devoll River totalling 256 MW, expected to be completed in 2016 and 2017.

ALGERIA

The In Salah CO₂ Storage Project in central Algeria is a pioneer **CCS** project and built up a wealth of experience highly relevant to subsequent geologic CO₂ storage projects worldwide. Injection commenced in 2004 and over 3.8Mt of CO₂ has been stored in the subsurface. The storage performance has been monitored using a unique and diverse portfolio of geophysical and geochemical methods. It also identified key lessons learned from actual storage operations and data review that was an important case study for knowledge transfer to other major CCS projects in the planning and execution phases. Carbon dioxide injection was suspended in 2011. The future injection strategy is currently under review and the comprehensive site monitoring programme continues. The project also presents an excellent project closure study opportunity (the world's first).
CO₂ capture capacity: N.C.

Algeria is one of the most notable countries in Africa in terms of **natural gas** due to their high level of proved reserves and production. As of 2014, Algeria had ~4,504 bcm of proved natural gas reserves, which represented the tenth largest amount globally. Furthermore, this total gave them the second most proved natural gas reserves in Africa behind only Nigeria. Algeria produced 83.3 bcm of natural gas in 2014, which made them the ninth largest producer of natural gas in the world. Additionally, Algeria only consumed 37.5 bcm in 2014. Therefore, this significant difference between natural gas production and consumption in Algeria allows them to be an exporter of natural gas. Algeria has the opportunity to further grow their natural gas production in the future if they are able to take advantage of their shale gas potential. Algeria is an important exporter of natural gas and they have effectively been able to export it both through pipeline and via LNG throughout the years. Algeria exported 40.8 bcm of natural gas total in 2014. Of this 40.8 bcm, 23.5 bcm was exported as pipeline gas. The large majority of these pipeline exports (19.5 bcm) were sent to Europe with Spain and Italy being the two largest importers at 11.1 bcm and 6.2 bcm respectively. In addition to these pipeline natural gas exports, Algeria has also been able to take advantage of LNG exportation. In fact, Algeria became the world's first exporter of LNG in 1964 when their LNG plant at Arzew shipped LNG to the UK. LNG exportation still plays a large role in Algeria as they exported 17.3 bcm of natural gas via LNG in 2014 with the large majority of this total being shipped to Europe and Asia.

Nearly US\$200 billion in foreign reserves offer Algeria some short-term protection from the pain of low **oil** prices. Spending on social programmes could, however, be reduced if prices stay low for a prolonged period. Regardless of oil's sharp decline, state oil company Sonatrach intends to invest US\$90 billion in the oil and gas sector from 2015-19. Despite this ambitious plan, Algeria's production capacity is expected to decline by 220 kb/d to 950 kb/d in 2020 due to a long period with no projects and very little commerciality. Prospects

for growth have also been set back by security concerns after the kidnapping and execution of a French tourist in September 2014 as well as bureaucratic inertia. There is lingering unease following the deadly 2013 attack on the 'Amenas' gas facility, and the free-flow of weapons and Islamist militants from neighbouring Libya since the fall of Gaddafi is a growing concern for IOCs.

A long period with no projects on its books has, however, spurred Algiers, heavily reliant on oil and gas revenues for its state budget, to improve its fiscal regime post in Amenas. Exploration and development of new fields is at a standstill despite an impressive resource base and Algiers' last licensing round in September 2014 failed to drum up much interest as the sweeter commercial terms apparently did not offer adequate incentives. The North African country is seeking to exploit its shale gas resources.

ANGOLA

Oil's collapse has dimmed the outlook for growth in Angola, Africa's second biggest producer. Capacity is expected to edge up to 1.9 mb/d by 2020 for a gain of 90 kb/d versus an estimated 360 kb/d in MTOMR 2014. Angola and fellow West African producer Nigeria are under severe budgetary pressure that will impact their ability to fund costly deep-water projects with foreign partners. Even before oil began to drop, Angola's official 2 mb/d target looked elusive given myriad technical problems afflicting its deep-water projects. Further delays are likely as lower oil prices lead some foreign oil companies to review these expensive developments. Regulatory uncertainty and hold ups in contract approvals are also likely to set back projects. It is crucial for Angola, which relies on oil exports for 80% of state revenue, to start up new oil fields in order to offset steep decline rates that are as high as 15% at some of its deep-water reservoirs. The country has a number of deep-water projects on the drawing board, but the challenges posed by low oil prices as well as water injection systems and floating production, storage and offloading (FPSO) facilities are likely to postpone some start-ups. Chevron's 110 kb/d Mafumeira Sul is due to come online in 2015. Total's 160 kb/d deep-water Cravo, Lirio, Orquidea and Violetta (CLOV) project started up in July and the French oil major's US\$16 billion, 200 kb/d ultra-deepwater Kaombo project is due to start up in 2017. The first sub-salt development, the 100 kb/d Cameia field, is unlikely to take place during the forecast period as the outlook for Angola's sub-salt acreage looks uncertain due to declining oil prices and disappointing drilling results.

Algeria has adopted, in voluntary manner, an ambitious national programme for renewable energy development with targets to install by 2030 a capacity of 22 GW, most of which from **solar** energy (13,575 MW PV – 62% and 2,000 MW CSP – 10%). Algeria's renewable energy plans show the willingness to diversify gradually its energy resources and explore its huge solar potential. The deployment of CSP is due to start in 2021 in south, highlands and coastal regions. For coastal areas, due to land scarcity, rooftop installations will be encouraged. Pilot projects include 150 MW parabolic through CSP power plant with gas-solar combined cycle in which 25 MW from solar, being installed in 2011 in Hassi R'mel in the south of Algeria, a platform with capacity of 1.1 MW PV with multi-technology installed in Ghardaïa, in operation since June 2014; and 20 solar PV power plants with capacity of 343 MW to be commissioned by July 2016 in the High Plateaus and South regions.

ARGENTINA

Argentina has 10,118 MW installed **hydropower** capacity. Construction began recently on the Nestor Kirchner and Jorge Cepernic projects in 2016. The two stations, with a combined capacity of 1,740 MW will be the largest hydropower project in Argentina and also the largest electric power project undertaken by the Chinese in the international market.

Argentina's **natural gas** reserves overall may not be one of the world's largest, however Argentina's reserves are noteworthy as a significant portion of them are unconventional based. It is estimated that Argentina has the world's second largest total of shale gas reserves. Therefore, Argentina has the potential to significantly increase their natural gas production as they further develop their shale gas capabilities.

Within Argentina, the Neuquén Basin is responsible for a large portion of the country's natural gas. More specifically, the Vaca Muerta formation in the Neuquén Basin is current Argentina's largest shale gas play. Certain key features of the Vaca Muerta formation set it up to potentially have very large and rapid success. It has a lot of similarities to the Eagle Ford basin in the US, which will allow US operators to efficiently apply their expertise gained from that basin. Additionally, the Vaca Muerta formation already has established road and pipeline infrastructure combined with a developed service sector. The combination of these advantages should allow Argentina to effectively capitalise on the shale gas potential in the Vaca Muerta formation.

Even though Argentina produces a respectable total of natural gas, their natural gas consumption still outweighs their production levels currently. As a result, Argentina is a net importer of natural gas. They currently import natural gas via both pipeline and LNG. In 2014, they imported 5.4 bcm of pipeline natural gas from Bolivia. Additionally, they imported 6.5 bcm of natural gas as LNG, including 3.4 bcm from Trinidad and Tobago.

Natural gas plays a significant role in Argentina's energy mix as it was responsible for 49% of Argentina's primary energy consumption in 2014. Argentina's heavily reliance on natural gas for their energy mix is a major reason that they remain a natural gas net importer.

Argentina has three **nuclear** reactors Atucha-I (335 MWe PHWR), Atucha-II (692 MWe PHWR) and Embalse (600 MW_e PHWR) generating nearly one-tenth of the country's electricity demand. Construction of a small locally-designed reactor started in Feb 2014. Plans for a fourth and a fifth NPP progress forward construction following agreement with China to build a further PHWR and an ACP1000 which is a PWR. The Member Committee foresees that by the end of 2030 four reactors will be in operation in Argentina, with an aggregate net capacity of 3 GWe.

The government of Argentina is currently taking the first steps to develop a **Waste-to-Energy** market. The construction of a WtE plant was announced in 2014 in Santiago del Estero province, and is expected to start generating 50kW/h and increase to 250kW/h that will be injected in the national grid. There is great potential in terms of resource, but also because the energy demand is increasing. The nature of the MSW with high organic

content makes favourable the development of bio-chemical conversion processes for production of biogas.¹

ARMENIA

Armenia has relied much on **nuclear** power since 1976 when the first of the two original VVER units was commissioned. The nuclear power plant is built close to the capital of Armenia Yerevan (64 km), and one of the two reactors was shut down in 1989 following an earthquake which occurred in the previous year. The second of the two original VVER units (Medzamor-2) has been upgraded and refurbished, returning to commercial operation in 1996 with a capacity of 376 MWe. This unit supplies about a third of the total electricity produced in the country (2.3 bil-lion kWh). Medzamor-2 has had its life extended to at least 2026 and is expected to be replaced by a new reactor.

AUSTRALIA

The Gorgon Carbon Dioxide Injection Project continues through the construction stage, with the Global **CCS** Institute expecting CO₂ injection to commence around the middle of 2017. It will be Australia's first large-scale CO₂ injection project (at around 3.4-4.0 Mtpa) and the largest in the world injecting CO₂ into a deep saline formation. It is anticipated that over 100 million tonnes of CO₂ will be injected over the life-time of the project.

The Callide Oxyfuel Project in Central Queensland completed its demonstration in March 2015. At 30 MWe, this was the world's largest demonstration of oxyfuel and CO₂ capture applied to coal-fired power generation during its operational tenure. The project recorded over 10,000 hours of oxy-combustion and more than 5,500 hours of CO₂ capture.

The Otway CO₂ CRC Project in Victoria is one of the largest storage laboratories in the world. Approximately 15,000 tonnes of CO₂ will be injected into a deep saline rock formation in the first half of 2016 for a three-year study program. This follows an injection and monitoring program that began in 2008, with approximately 65,000 tonnes of CO₂ injected in 2008 and 2009.

CO₂ capture capacity: Up to 4 Mtpa

Atlantis Resources originated from Australia and is deploying a 1.5MW AR1500 **marine** energy device at the commercial MeyGen site in the UK (see UK). Australia has also seen BioPower Systems, OceanLinx, Wave Energy Rider and Bombora Wave Power all deliver small scale demonstrators, however Carnegie Wave Energy has been the most active testing three of its 240kW CETO 5 devices off Garden Island, Australia. They plan to demonstrate its 1 MW CETO 6 device off Garden Island in 2016/17 before deploying an array at WaveHub, UK.

Australia currently has the 11th largest total of proved **natural gas** reserves globally. While this large reserve base has led to increased natural gas production (4.6% average annual

¹ Electric Light & Power, (2014)

production growth from 2004-2014), their overall production level of 55.3 bcm in 2014 still has room for growth relative to countries with a similar amount of proved reserves.

Unconventional gas production is an area that Australia has utilised in order to increase their domestic production. In particular, CBM has played a large role in this unconventional gas production growth. In 2014-2015, ~12.2 bcm of CBM was produced by Queensland Australia, which represented a noteworthy share of the region's overall natural gas production.

Furthermore, Australia has taken actions in order to further improve their status as a major natural gas exporter via LNG due to producing significantly more natural gas than they consume. In 2014, Australia exported 31.6 bcm of LNG, of which 25 bcm went to Japan. However, Australia has been constructing LNG export terminals for a few years now and as of 2015 their current LNG export capacity increased to 50.5 bcm. Furthermore, this total capacity is expected to grow to 119.3 bcm by 2020 based on the projects currently under construction.

In the development of their LNG export capability, Australia revolutionised the process when they introduced the world's first CBM to LNG export terminal in late 2014. During 2014 and 2015, three CBM to LNG projects were brought online or were in final construction. These projects represent 29.5 bcm of LNG export capacity. By 2020, CBM to LNG export terminals are expected to be responsible for almost 40% of Australia's total LNG export capacity.

Australia is one of the most significant uranium producer and there is an adequate infrastructure to support **nuclear** development. However, there is no power generation from nuclear. In February 2015, a Royal Commission to report on nuclear options (fuel cycle, high-level waste disposal, power generation) was established by the Labor state government of South Australia which might lead to a change of nuclear policy.

Australia's **oil** shale deposits contain an estimated 24 billion barrels of shale oil. In recent years a new oil plant project has been running in Australia but it has not reached the industrial production phase yet. One of the notable developments is that Queensland Energy Resources (QER) successfully completed the operation of its demonstration plant near Gladstone in early 2014. In addition, OilCorp holds a site-specific license for using EcoShale® technology in Queensland.

Australia added more **solar** capacity in 2015 than any other power generation source. Installed capacity is around 5 GW contributing around 2.5% of country's overall electricity generation. Residential PV penetration is quite high in Australia with more than 1.5 million homes generating their own power.

The **Waste-to-Energy** market has a long history in Australia, yet it is under developed. The country generates each year around 50 million tonnes of urban waste and 20% ends up in landfills. The Clean Energy Finance Corporation estimates a potential investment

opportunity in urban energy from waste of between US\$2.2 billion and US\$3.3 billion². Future progress in the sector will be around building commercial-scale WtE plants to process the roughly 20 million tonnes of waste that is disposed in landfills every year³.

AUSTRIA

Austria's Andritz Hydro purchased Norway's tidal stream developer Hammerfest Strom in 2012. In 2016 it will fabricate and deploy three HS1500 1.5 MW **marine** turbines at the MeyGen site in Scotland (see UK).

Austria has set a target of reaching 1,200 MW of **solar** PV capacity by 2020 as per National Green Electricity Act (GEA) issued in 2002. Around 140 MW capacity was added in FY 2015 adding up to cumulative capacity of 925 MW. Both feed-in-tariff and capital subsidies scheme (for selected categories) are available in the country.

In 2013, Austria produced 50.8 million tonnes of waste. According to the Austrian Federal Environment Agency database, there are roughly 2,400 plants in the country that treat various types of waste. Around 70 plants use thermal treatment of various specific types of waste, and approximately 8% of the total waste volume is thermally treated or incinerated every year. In 2014, there were 11 **Waste-to-Energy** plants with a capacity of 2.4 million tonnes of waste. The total capacity of WtE facilities for various mixed commercial and municipal wastes exceeds a thermal capacity of 800 MW.⁴

'Spittelau' is one of the largest WtE plants in Austria, treating 250,000 tonnes of waste per year. It produces approximately 40,000 MWh of electricity, 470,000 MWh of district heating, 6000 tonnes of scrap iron and 60,000 tonnes of clinker, ash and filter cake⁵. The plant has been in operation in Vienna for over 40 years, and it has been fully renovated in 2015 with an investment of €130 million. It is considered to be among the most modern WtE plants in the world, with an efficiency of 76%, and over 50,000 households are supplied with remote heat and power⁶.

AZERBAIJAN

Azerbaijan's **natural gas** production and consumption has been continuously growing in recent years. In 2014, Azerbaijan's natural gas production reached 16.9 bcm, which marked the third consecutive year that their natural gas production had grown. Over this three-year span, production growth has occurred at an annual average of 4.6%. Furthermore, Azerbaijan's natural gas consumption reached 9.2 bcm in 2014, which marked the fourth consecutive year that their natural gas consumption had grown and occurred at a 5.5% average annual rate.

² Clean Energy Finance Corporation, (2015)

³ Lokuge, (2016)

⁴ www.iswa.org/uploads/tx_iswaknowledgebase/Scheffl.pdf

⁵ Wien Energie, Spittelau waste incineration plant

⁶ Condair, Humidification in the incineration plant Spittelau, Austria

Azerbaijan has been able to be a net exporter of natural gas due to the fact that their production outweighs their consumption. Azerbaijan utilises their natural gas pipeline network in order to export their natural gas. Azerbaijan exported 7.7 bcm of natural gas via pipeline in 2014, which represented ~45.6% of their total natural gas production. A majority of this natural gas was imported by Turkey as they received 5.3 bcm of pipeline natural gas from Azerbaijan in 2014.

Municipal solid **waste** (MSW) in the capital region of Baku is about 0.8 kg per capita per day, while in the rest of the country 5.3 million people generate approximately 0.3 kg per capita per day⁷. The country is investing in developing the waste management sector, and one notable addition is the MSW incineration plant with energy recovery from the region of Baku. The plant is equipped with fourth generation technologies and an annual capacity to process 500,000 tonnes of solid waste and up to 10,000 tonnes of medical waste. The plant's annual output potential is of 231.5 million kW/hours. In 2015, the country produced 182 million kilowatt/hours of electricity from MSW, of which 28.5 million kW/hours was used for the operation of the plant, and the rest of 153.5 million kW/hours were exported to the electricity grid.

BANGLADESH

In 2014, Bangladesh only had 253.2 bcm of proved **natural gas** reserves. However, Bangladesh has not been extensively explored currently and there is some belief that their overall potential natural gas reserves could be significant. Bangladesh would be a country to pay attention to in regards to natural gas once more extensive exploration takes place. Furthermore, all of Bangladesh's natural gas production came from onshore reserves as of 2014 and they are looking to expand investment in natural gas to offshore exploration.

Petrobangla is Bangladesh's prominent player in their natural gas industry and the company is owned by the country. Petrobangla is responsible for corporate planning of Bangladesh's natural gas sector and it is the supplier of Bangladesh's national energy.

Currently, Bangladesh is self-sufficient in terms of their natural gas use. In 2014, Bangladesh both produced and consumed 23.6 bcm of natural gas. As a result, they are neither major importers nor exporters of natural gas.

Bangladesh plans to operate two Russian 1000 MWe **nuclear** power reactors, with the first expected to be commissioned by 2026. This is to meet increasing demand and reduce ratio of natural gas. Today, about 88% of electricity is produced by natural gas, and electricity demand is rising rapidly, with peak demand of 7.5 GWe.

BELARUS

Belarus currently, imports 90% of its gas from Russia (estimate of 22.5 billion m³ in 2012) - much of it for electricity - and is seeking to reduce this dependence by achieving 25-30% energy independence. Two VVER-1200 **nuclear** reactors have been financed by Russian

⁷ Asia Development Bank, (2014)

sources and are under construction in Belarus. It is expected that they will both be commissioned in the early-2020s.

BELGIUM

A Belgian 100 kW oscillating wave surge convertor device called Laminaria will be tested at the UK's EMEC in 2017, following testing of a smaller prototype in 2014/15 in the Harbour of Ostend, Belgium. The FLANSEA project for **marine** energy also took place in 2013 to test the Wave Pioneer, a 1:2 scale 100 kW point absorber.

Belgium has seven **nuclear** reactors producing about half of its electricity. Belgium's first commercial nuclear power reactor began operation in 1974 and currently constitutes four units at Doel and three at Tihange all of the same PWR type, with a current aggregate net generating capacity of 5 943 MW_e. There has been little government support for nuclear power generation, which incurs a EUR 0.5 cent/kWh tax. In January 2003, Belgium's Senate voted for a nuclear phase-out law which stipulates that all seven units shall be closed after completing 40 years of operation. The first reactors were expected to be shut down in 2015, the last in 2025. However, in October 2009 the Belgian Government announced that its plans for phasing out nuclear power would be put back for ten years. The oldest reactors, Doel 1 and 2 were due to be closed in February 2015 and March 2016 respectively. In December 2015 the country's Council of Ministers agree to permit their operation for a further ten years.

Recently **solar** PV capacity addition market development has been sluggish with country adding only around 100 MW in year 2015 reaching total installed capacity of around 3227 MW. This installed capacity provided around 4% of electricity demand due to high solar radiation in the country. Small systems (<10 KW) are charged with a 'prosumer fees' to pay for grid use by system owners.

The country has a total of 20 **Waste-to-Energy** plants with a summed capacity of 2.77 million tonnes. In 2013, the plants treated 2.68 million tonnes of waste and produced over 1.26 million MWh of electricity, enough for about 290,000 households, and 320,000 MWh of heat⁸. Some of the WtE plants include Biosteam, Doel-Bevren, IVM, Oostende, Pont-du-Loup and Virginal.

BOLIVIA

Although Bolivia only had 297.3 bcm of proved **natural gas** reserves as of 2014, they have been steadily increasing their production over the years. Bolivia's natural gas production has been growing each year since 2009 and their 2014 natural gas production of 21.4 bcm represented a growth of 74% over 2009 levels.

Bolivia is also an important exporter of natural gas via pipeline to their fellow South American countries, Brazil and Argentina. In 2014, Bolivia exported approximately 16.4 bcm of natural gas, all of which occurred via pipeline trade. These natural gas pipeline

⁸ Belgian Waste to Energy

exports were sent exclusively to Brazil and Argentina with Brazil being responsible for the larger total at 11.1 bcm.

BRAZIL

The Petrobras Lula Oil Field **CCS** Project is the first operational offshore CO₂-EOR project in the world. The floating production, storage and offloading facilities are located approximately 300 kilometres off the coast of Rio de Janeiro. The facilities have a CO₂ capture capacity of around 0.7 Mtpa. By 2020, Petrobras expects to install 20 new floating production systems in the area of the Santos Basin, many of them to include CO₂/gas re-injection for EOR purposes. This suggests that Brazil will continue to play an important role in the CCS landscape.

CO₂ capture capacity: Approximately 0.5-1 Mtpa

Brazil's current installed hydropower capacity has reached 91.7 GW and is second only to China. Domestic hydropower capacity has increased by almost 47% since 2001, and the country commissioned 2.4 GW in 2015, including partially the 3,750 MW Jirau and 3,568 MW Santo Antonio projects along the Madeira River.

For **marine** energy, Brazil has deployed a 5ckW point absorber COPPE wave device that was tested between 2009 and 2012 at Rio Grande do Norte, Brazil by state department ANEEL.

Brazil still has a lot of potential for growth in regards to their **natural gas** industry. Brazil's proved natural gas reserves as of 2014 were 464.1 bcm and their natural gas reserves are currently spread throughout the country. This total amount of proved natural gas reserves gives Brazil the second most proved natural gas reserves in South America behind only Venezuela. However, there is potential for significantly more natural gas to be discovered in Brazil. Among other areas, the Tupi field in Brazil has a large amount of estimated recoverable natural gas. If proved, these areas of recoverable natural gas could add a substantial amount of proved natural gas reserves to Brazil and dramatically impact their potential natural gas production.

Brazil is not a global-leading in regards to natural gas producer, as evidenced by their natural gas production of 20 bcm in 2014. Furthermore, Brazil consumes significantly more natural gas than they produce. In 2014, Brazil consumed 39.6 bcm of natural gas. However, even though Brazil's consumption significantly outweighs their production, natural gas's role in Brazil overall is still relatively small as natural gas only made up ~12% of their primary energy consumption in 2014.

As a result of their natural gas production being significantly less than their consumption, Brazil is a major natural gas importer. Brazil has been able to successfully leverage natural gas imports via both pipeline natural gas and LNG. Brazil imported 19 bcm of natural gas in 2014, which represented ~48% of their total natural gas consumption. Of this 19 bcm, 11.1 bcm came in the form of pipeline natural gas. Nearly all of Brazil's pipeline natural gas imports come from Bolivia. Although their share of Brazil's natural gas imports has been

declining in recent years, Bolivia was still responsible for ~58.4% of Brazil's total natural gas imports in 2014.

The reason for Bolivia's declining share of Brazil's natural gas imports is Brazil's increasing reliance on LNG for natural gas imports. Brazil has expanded on their number of LNG imports in order to improve their energy security of supply through diversification. In 2014, Brazil imported a total of 7.9 bcm of natural gas via LNG from nine different countries. Additionally, none of those countries were responsible for more than 2 bcm of imports, which further illustrates a large amount of diversification in regards to Brazil's natural gas supply.

Brazil has two **nuclear** reactors: Angra-1 (491 MW_e net PWR) and Angra-2 (1 275 MW_e net). generating 3% of Brazil's electricity. Its first commercial nuclear power reactor began operating in 1982. Work on the construction of a third unit at Angra, of similar size to Angra-2, was started in 1983, but suspended in 1986. Construction restarted in 2010 with the start of operations expected in 2018.

Brazil started using **oil** shale in 1881. The government supported this and in 1954 the oil company Petrobras was founded. The company developed the Petrosix technology for producing oil and commenced industrial production with it in the 1990s. There are at least nine oil shale deposits in Brazil, and they contain an estimated 80 billion barrels of shale oil.

Petrobras continues mining and retorting Irati oil shale, producing about 4,000 BOPD using the Petrosix technology, with no expansion plans. Sartuprati Energy Limited, owned by Forbes & Manhattan, is based in Southern Brazil and controls >3,100 km², with over 2 billion barrels of potential oil shale resources. It plans an 8,000-10,000 BOPD shale oil plant based on the PRIX technology, which is an incremental improvement over the Petrosix technology.

The country with about 144,500,000 urban residents does not have a **Waste-to-Energy** market yet. MSW generation is predicted to be around 330,960 tonnes per day by 2025. There is huge potential for market development of bio-chemical technologies due to high organic content from MSW.⁹

BHUTAN

Bhutan currently has 23,000 MW of economically feasible **hydropower** potential. While it currently only has 1,615 MW of hydropower in operation, India's targets for clean energy are driving hydropower development. Currently, hydropower contributes over 14% towards Bhutan's GDP through exports to India, including the 126 MW Dagachhu project, completed in 2015, which is exporting power exclusively to India.

BRUNEI

Although Brunei does not have a significant level of proved **natural gas** reserves nor a

⁹ The World Bank, (2012)

large total of natural gas production, they have established themselves as important natural gas players due to their role as an LNG exporter to countries within the Asia Pacific. Brunei's natural gas production in 2014 was only 11.9 bcm, of which a majority was exported as LNG.

In 2014, Brunei exported 8.3 bcm of natural gas and all of this exported natural gas was shipped to the Asia Pacific in the form of LNG. Therefore, Brunei exported ~70% of their natural gas production in 2014. The largest importer of LNG from Brunei historically has been Japan and they imported 5.9 bcm from Brunei in 2014.

BULGARIA

Bulgaria has two **nuclear** reactors generating over 34% of its electricity. Originally, six VVER units have been constructed at Kozloduy, in the north-west of the country, close to the border with Romania. Four units (each of 408 MW_e net capacity) were brought into operation between 1974 and 1982, and two other (each of 953 MW_e capacity) were commissioned in 1987 and 1989, respectively.

Kozloduy-1 and -2 were shut down in December 2002, followed by Kozloduy-3 and -4 at the end of 2006, in accordance with the terms of Bulgaria's accession to the European Union. The government actively supports future nuclear energy, although financing construction of the new units will not be easy. Construction of a new nuclear plant was planned, but instead it was decided to add a third 1200 MWe unit to the existing plant and Westinghouse is currently negotiating to build the reactor. The country has been a significant exporter of power, however, with the closure of the two older nuclear units at the end of 2006, electricity exports have dropped somewhat.

CAMEROON

The **hydropower** industry in Cameroon is continuing to expand. The 210 MW Memve'ele hydropower plant is expected to be completed at the end of 2016. In addition, the filling of the Lom-Pangar reservoir began in 2015 with power production expected to begin in June 2016. Taking advantage of the new reservoir, a small fishing village has already been formed in the region around the dam.

CANADA

Canada has three operational large-scale **CCS** projects and two under construction, for a total CO₂ capture capacity of approximately 7 Mtpa. The western provinces of Alberta and Saskatchewan contain most of the project activity. Almost all of these projects have CO₂-EOR as the primary storage type. The Boundary Dam CCS Project, the world's first power plant equipped with carbon capture technology at scale (1 Mtpa CO₂ capture capacity), became operational in October 2014 in Saskatchewan. Carbon dioxide supplied to the Weyburn oil field for EOR is the primary storage option, although some amount will be injected into a deep saline formation as part of the Aquistore project. The Quest Project in Alberta (CO₂ capture capacity of more than 1 Mtpa) was launched in November 2015 and will be storing CO₂ in a deep saline formation. Two projects in the fertiliser and refining

sectors in the Alberta Heartland will supply approximately 2 Mtpa of captured CO₂ into the new Alberta Carbon Trunk Line (ACTL) in 2017 for use in EOR operations in central Alberta.

The Weyburn-Midale oil fields have been injecting CO₂ for EOR purposes since 2000 and 2005 respectively and was subject of an extensive storage monitoring program that ended in 2012. Injection capacity of (new) CO₂ is between 2.5-3 Mtpa. Total CO₂ storage to date is over 25 million tonnes.

Canada also has a considerable history of research and pilot programs in both CO₂ storage and carbon capture. The test facility at the Shand power station in Saskatchewan was opened in June 2015. It has a CO₂ capture capacity of 120 tonnes per day (tpd) and allows capture technologies to be tested in a commercial setting.

Canada continues to be among the world's leading countries in terms of installed hydropower capacity, with 79.2 GW (including pumped storage). In 2015, 700 MW of new capacity was added in Canada in 2015. In addition, new transmission lines are under construction for the purpose of exporting surplus power to the USA.

CO₂ capture capacity: Approximately 7 Mtpa

Since 1984 Canada has operated in 20 MW Annapolis Royal tidal range plant for **marine** energy in the Bay of Fundy. Canada has been very active in developing run-of-the-water devices applicable to both tidal stream and river environments. Leading developers include Jupiter Hydro, New Energy Corp and Instream Energy Systems. Accumulated Ocean Energy Inc. There are also a number of Canadian wave energy developers including Accumulated Ocean Energy Inc., Grey Island Energy and Mermaid Power. The grid-connected Fundy Ocean Research Center for Energy (FORCE) is an international centre for tidal development with four berths for testing.

Canada has established themselves as a major global producer of **natural gas**. Although they had the 16th largest global amount of proved natural gas reserves as of 2014, they currently utilise their reserves effectively as they were the fifth largest natural gas producer in the world in 2014 at 162 bcm. Canada managed to reach this level of production through effectively utilising both conventional and unconventional means.

While Canada is a major natural gas producer, they also are a significant consumer of natural gas. In 2014, Canada consumed 104.2 bcm of natural gas. This level of consumption made them the world's sixth largest consumer of natural gas. Although Canada is a major natural gas consumer, natural gas only made up ~28.2% of the country's primary energy consumption in 2014.

Furthermore, Canada produces significantly more natural gas than they consume and therefore they have been able to become a large natural gas exporter via pipeline. In 2014, Canada exported 74.6 bcm of pipeline natural gas, all of which went to the US. However, this pipeline natural gas trade was not only one-way as Canada imported 21.8 bcm of pipeline natural gas from the US in 2014. Canada has relied on the US importing their natural gas in the past and are still reliant on this currently.

However, Canada's natural gas exports to the US decreased by 7% from 2010 to 2014, largely due to the success of the US shale gas revolution. US production of natural gas is expected to continue to grow in the coming years, which is expected to lead to even less US natural gas imports. This is a major concern for Canada and therefore they have begun exploring the possibility of exportation via LNG. A majority of their current LNG export proposals would result in Canada exporting natural gas to Asia in efforts to reduce the detriment of decreased US pipeline natural gas imports.

Canada's **nuclear** power generate about 17% of its electricity with 19 reactors, highest share is Ontario province that provide about 13.5 GWe of power capacity. Canada has cancelled plans for new reactors but is planning to maintain its existing nuclear capacity by a programme of refurbishment that will extend the life of some current reactors into the 2050s, which will allow a phase out of the use of coal. For many years Canada has been leader in nuclear research and technology exporting reactor system as well as a high proportion of the world supply radioisotopes used in medical diagnosis and cancer therapy. In 2013, Canada generated 652 billion kWh, of which about 16% was from nuclear generation compared with 60% of hydro, 10% from coal and C\$1.4 billion in government revenue.

Canada's price sensitivity differs greatly from that of the United States. Canadian **oil** sands, which account for most of the country's oil output growth, require comparatively high upfront capital costs and have long pay-back periods. Projects that have already been invested in will not be stopped by lower prices. Producers will instead be incentivised to maximise output in a bid to recoup investment costs. New projects, on the other hand, are unlikely to be sanctioned and will likely be delayed.

Canadian E&P capital spending on liquids is forecast to decline in 2015 to US\$79 billion, before increasing in each of the following years through 2020, according to Rystad Energy data published in mid-January 2015. Planned investments in oil sands projects are expected to drop sharply to US\$37 billion before reaching US\$88 billion by the end of the forecast period. The drop in investments in the near term is price driven as companies cope with oil prices around US\$50 per barrel. However, it is believed that a rebound in prices in 2016 and beyond, is likely leading to an increase in capex.

Solar PV power capacity in Canada grew at an annual rate of 25 % between 1994 and 2008. In recent years this growth was 98% in 2011, 48% in 2012, 54% in 2013 and 52% in 2014 due to the Ontario incentive programs. The Province of Ontario, Canada's most populous and second largest province, leads the country in photovoltaic (PV) investments. As of September 2015, the cumulative PV installed capacity stood at 1,766 MW embedded within the distribution network and 240 MW connected directly to the transmission grid for a total of 2,006 MW.

Canada disposes of around 33 million tonnes of waste annually, and the vast majority ends up in landfills¹⁰. The **Waste-to-Energy** market has developed significantly, from just 4

¹⁰ Albrecht, (2015)

operating plants in 2006 to 12 facilities in 2014¹¹. Rising population will increase the amount MSW available, so very likely there will be a rise in WtE adoption for both waste management and energy production.

CHILE

Owing to government supportive policies, **solar** has embarked a remarkable growth of any new energy source in Chile over the last three years. Renewable Energy Law set by Chilean Government, enabled the country in 2015 to achieve highest PV installed capacity of 1 GW in Latin America. This law sets a target of 20% non-conventional renewable energy in electricity mix to be realised in 2025. Absence of subsidies for fossil fuelled electricity and the growing demand for solar energy driven by mining industry (copper, gold, silver) in the top half of the country also resulted in a very competitive market electricity prices. Some major steps taken to realise solar development include: i) tendering more than 3,000 hectares of land for renewable projects in multiple locations in the country in an energy auctions; ii) approval of a road map to an aspiring target of 70% renewables by 2050; iii) pledge of the government to reduce CO₂ emissions, making Chile the first country in Latin America to establish a green tax on carbon emissions of US\$5 per tonne of CO₂; and iiiii) creation of a government-funded Strategic Solar Plan, which aims to bring costs down through R&D by looking into areas of improvement and efficiency of solar technologies.

The country is predicted to have around 19 million residents by 2025, producing 26,493 tonnes of MSW per day. There is a great potential for **Waste-to-Energy** market development as most of the waste is disposed in landfills.¹²

CHINA

China is especially important for **CCS** development in view of its large carbon emissions footprint. China is making significant strides in progressing both 'pilot' and 'demonstration' projects, R&D activities and CCS has been included in several national strategic plans. CCS was included in China's INDC submission to the UNFCCC in the lead-up to COP 21 in Paris in December 2015.

While (at the time of writing) China is yet to have a large-scale CCS project move into operation, it has more large-scale CCS projects in development planning than any other country. A number of companies have undertaken 'pilot' or 'demonstration' projects as a precursor to moving to large-scale project development. China has a number of CCS projects of lesser scale, some in the range up to 200,000 tonnes of CO₂ capture capacity per annum. In total, these lesser scale CCS projects, either in operation or under construction, have between 0.5-1 Mtpa of CO₂ capture capacity per annum. The use of CO₂ for EOR is the dominant storage type for these lesser projects, as it is for the most advanced large-scale projects in development planning.

¹¹ Canadian Resource Recovery Council

¹² The World Bank, (2012)

For the tenth consecutive year, China added more new installed hydropower capacity than the rest of the world combined. In 2015, China added 19,370 MW of new hydropower capacity, including the final 4,620 MW of the 13,860 MW Xiluodu project – the third-largest hydropower plant in the world. China's installed hydropower capacity now totals 319.4 GW. **CO₂** capture capacity: Approximately 0.5-1 Mtpa

Between 1972 and 1980 China delivered approximately 5.5 MW **marine** energy from tidal barrage capacity but has since focused on tidal stream, wave energy and OTEC, delivering 31 demonstration projects. Flagship projects include the deployment of two 300 kW Haineng III vertical axis turbine, 4x300 kW modular LHD L-1000 turbine and its 300 kW Eagle 2 as part of its Dawanshan Island hybrid power station.

China's **natural gas** consumption and production has been growing in recent years. China's increased demand for natural gas has led to them becoming the third largest global consumer of natural gas. In 2014, China consumed 185.5 bcm of natural gas, which represented an 8.6% year-over-year growth.

Their natural gas production is also expected to continue to grow as the Chinese government has emphasised a desire to increase domestic natural gas production going forward. In 2014, China was the world's sixth largest natural gas producer at 134.5 bcm. In September 2015, CNPC discovered an additional 163.53 bcm of proved natural gas reserves in the Sichuan Basin, which is already China's top producing basin and now has further potential after this discovery.

Unconventional gas production is one of the main natural gas growth areas that China is pursuing. In 2014, China produced 1.3 bcm of shale gas and 15.2 bcm of CBM. However, the Chinese government set a target of 30 bcm/year for both shale gas and CBM by 2020. By increasing domestic production, China has been able to improve their energy security, which will continue to be improved through domestic production growth.

In addition to domestic production, China has also made efforts to improve their energy security through diversifying their natural gas imports. In 2014, China imported ~27.6 bcm of natural gas through LNG, making them the third largest global importer of LNG. Additionally, the Power of Siberia pipeline from Russia to China is currently under construction and will be able to provide China up to 38 bcm/year of natural gas through the pipeline once it is fully operational.

Mainland China has 31 **nuclear** power reactors in operation, 21 under construction, and more about to start construction. Additional reactors are planned, including some of the world's most advanced, to give more than three-fold increase in nuclear capacity to at least 58 GWe by 2020-21, then some 150 GWe by 2030. The impetus for increasing nuclear power share in China is increasingly due to air pollution from coal-fired plants. China has become largely self-sufficient in reactor design and construction, as well as other aspects of the fuel cycle, but is making full use of western technology while adapting and improving it. China's policy is to export nuclear technology including heavy components in the supply chain. Nuclear power plays an important role in China, especially in the coastal areas located far from the coal mines and where the economy is developing most rapidly.

Development of nuclear power in China commenced in 1970 and from about 2005 the industry moved into a rapid development phase. Technology has been drawn from France, Canada, Russia and the USA, with local development based largely on the French element. The latest technology acquisition has been from the USA (via Westinghouse, owned by Japan's Toshiba) and France. The Westinghouse AP1000 reactor is the main basis of technology development in the immediate future, particularly evident in the local development of the CAP1400 reactor based on it. By around 2040, PWR capacity is expected to level off at 200 GWe and fast reactors progressively increase from 2020. At the same time, CNNC and CGN co-operated and designed a new reactor, called Hualong One or HPR1000. In July 2013 the National Development and Reform Commission set a wholesale power price of CNY 0.43 per kWh (7 US cents/kWh) for all new nuclear power projects, to promote the healthy development of nuclear power and guide investment into the sector. Nuclear power is already competitive, and wholesale price to grid has been less than power from coal plants with flue gas desulfurization, though the basic coal-fired cost is put at CNY 0.3/kWh. In March 2015 a new round of electricity market reform was launched, which allowed nuclear power companies to negotiate prices with customers. This is expected to help get the currently deferred inland projects moving ahead.

China's fast-growing economy has made it the largest energy consumer and producer in the world. The country is one of the biggest shale **oil** producers in the world. China's oil shale deposits contain around 328 billion barrels of shale oil. There are a total of 80 known oil shale mines in China, and two of the most important are called Fushun and Moaming. China's Fushun Mining Group also owns one of the largest shale oil producing factories, which produces around 350,000 tonnes of oil per year. Various companies in China are running several shale oil or electricity production projects. China currently produces shale oil and electric power from oil shale mined in the Fushun, Huadian, Huangxian, Junggar, Maoming, and Luozigou Basins, and from the Dalianhu and Haishiwan areas. Operating oil shale retorting plants are located in Beipiao, Chaoyang, Dongning, Fushun, Huadian, Jimsar, Longkou, Luozigou, Wangqing and Yaojie. Evaluation is continuing in four other basins and a number of other areas, with a billion-tonne resource recently discovered in Heilongjiang Province. The major producing and developing companies are the Fushun Mining Group, the Maoming Petrochemical Co. (owned by SINOPEC), Longkou Coal Mining Co, Longteng Energy Company, Gansu and Saniang Coal Companies, Julin Energy & Communication Corp., and Petrochina. The gas-combustion Fushun retort is the dominant technology, and the Fushun district is responsible for about half of Chinese production. A new open pit mine opened in 2014 in Fushun. New retorts are being built rapidly in China—about 130 in 2014. Most of them use lump oil shale, but some retorts are now being built to process fines. In 2015, Fushun Mining Group reported that the ATP retort in Fushun had been in operation more than 90-days in a row and running at over 80% availability. Oil shale fines are also burned in fluidised beds for power production.

China now is world's largest producer of **solar** PV power with installed capacity reaching around 43 GW at the end of 2015. Country added more than 15 GW of PV power in year 2015. Target is to reach 150 GW solar PV installations by 2020. Generous FiT along with self-consumption policies have been able to facilitate high level penetration of small projects along with large utility scale projects.

China is one of the fastest growing countries in the world, with increasing economic growth and urbanisation. These trends will exacerbate China's waste problem of about 189 million tonnes annually, which is expected to increase by 2030. While most of the MSW is still landfilled, there is a noticeable growing interest to treat waste in **Waste-to-Energy** plants. For example, in 2008 there were 85 WtE plants in the country, and now the government plans to build 300 facilities in the next two to three years. One of these will be the largest WtE plant in the world located on the outskirts of Shenzhen. The plant will open in 2020, will measure a mile in circumference and will process around 5,000 tonnes of MSW per day – approximately a third of the waste generated by the city's inhabitants. The plant will be equipped with the most advanced technology, the roof will be covered in solar panels, and the facility will have a visitors centre to show the different processes utilised to convert waste into energy¹³. Overall, China aims to convert 30% of its waste to electricity by 2030, up from current <5%.

In 2015, China broke a new record of **wind** installations by adding 30,500 MW of new grid-connected wind capacity, increasing the accumulated capacity in the country to 145,104 MW. These additions were equivalent to 22% of all new power capacity added in the country, and installed wind capacity is now twice as high the level in 2012. In 2015, wind power generated approximately 210 TWh of electricity, representing 3.8% of total generation. It now ranks as the third largest source of electricity supply following thermal power plants and hydropower.

End of 2015, nearly all installed capacity was onshore wind with a total capacity of 144 GW. In the next years, if China can maintain its annual capacity additions at these levels, it can easily overpass its new target of 250 GW by 2020 according to the 13th Five Year Plan. Total installed offshore wind capacity has reached 1,018 MW by end 2015 up from 658 MW in 2014. For a total capacity of around 11 GW, pre-feasibility studies are being prepared, however, at these annual installation rates, it is highly unlikely that the 2020 target of 30 GW will also be missed.

COLOMBIA

Hydropower makes up roughly 70% of Colombia's installed power generating capacity, totalling 11,392 MW. Driven by increasing demand and an integrated power grid with neighbouring countries, the hydropower sector is continuing to expand. In 2015, 599 MW of new hydropower was commissioned, including the 400 MW El Quimbo station, the first private sector hydropower project to be built in Colombia.

Colombia overall has seen their proved **natural gas** reserves increase in recent years, however their total amount of proved reserves is still modest relatively. As of 2014, Colombia had 162.2 bcm of proved natural gas reserves. Furthermore, Colombia only produced 11.8 bcm of natural gas in 2014 and consumed a majority of this production at 10.9 bcm. Due to producing more natural gas than they consume, Colombia has achieved self-sufficiency and a high level of energy security of supply in regards to natural gas.

¹³ Messenger, (2016)

Currently in Colombia, there is a separation between where a majority of the proved natural gas reserves are located and where the largest production of natural gas is occurring. The largest amount of natural gas reserves in Colombia can be found in the Llanos basin. However, the largest amount of natural gas production occurs in the Guajira basin at the moment.

Oil drilling plays an important role in Colombia. Natural gas can help aid in the production of oil through a reinjection process. As a result, approximately half of Colombia's natural gas production has been reinjected in efforts to improve oil recovery in recent years.

Colombia has an extensive natural gas pipeline network that allows them to successfully transport natural gas throughout the country. There are approximately 3,100 miles of natural gas pipelines currently in Colombia.

COSTA RICA

Costa Rica was able to operate on 100% renewable energy for 285 days. Normally relying on **hydropower** for approximately 80% of power supply, the 1,800 MW existing hydropower capacity played a significant role in this achievement. Costa Rica commissioned the 50 MW Torito hydropower station in 2015.

CZECH REPUBLIC

The Czech Republic has insignificant domestic sources of **natural gas**, total reserves amount to about 1 bill. m³.

The volume of domestic production of natural gas is around 100 mill. m³ a year, this means ca. 1% of the annual natural gas consumption in the Czech Republic. Therefore, nearly all supply is covered by imports.

The natural gas imports had been growing dynamically in early 1990's, in consequence of rapid substitution of coal in the heat supply industry and for the direct final consumption. Maximum natural gas imports (level of 9 to 10 bill. m³ per year) have been historically reached in the years before 2005. Since then, natural gas consumption, and also imports have been slowly decreasing due to a step-by-step appliance` efficiency and building thermal insulation improvement.

Natural gas is being supplied to the Czech Republic in two principal directions (from West via Nord Stream and OPAL pipelines and from East via Eustream pipelines). Long-term contracts on natural gas supply to the Czech Republic have been concluded with suppliers from the Russian Federation and from Norway, in addition, significant volumes are bought on the stock market.

Fluctuation of natural gas consumption in the Czech Republic is subject to balancing by a well-developed system of underground gas storages. The main operator of gas storage installations is RWE Gas Storage. For the needs of the Czech Republic, gas storage capacity of a volume exceeding 3.5 bill. m³ is used. That shows – with regard to the current

annual consumption of about 8 bill. m³ of gas – a very high figure of storage capacity for the Czech Republic in comparison with other European countries.

The Czech Republic has six **nuclear** reactors generating about one-third of its electricity. The first commercial nuclear power reactor began operating in 1985. Government commitment to the future of nuclear energy is strong. Electricity generation in the Czech Republic has been growing since 1994 and in 2013 87.1 billion kWh was generated from 20 GWe of plant, of which 51% (44.2 billion kWh) was from coal, 35% (30.7 billion kWh) from nuclear. More than 80% of the country's gas comes from Russia. A draft national energy policy to 2060 issued in 2011 indicated a major increase in nuclear power, to reach 13.9 GWe or up to 18.9 GWe in the case of major adoption of electric vehicles. In June 2015, the cabinet approved a long-term plan for the nuclear industry, which mentioned one new unit at Dukovany, and possibly three more units. The current four units at Dukovany will get 20-year life extensions, to 2045-47. Nuclear plants should furnish district heating to Brno and other cities by 2030. The plan envisages nuclear providing 50% of the country's electricity by 2040.

DENMARK

Denmark has no commercial **marine** projects but some test facilities. The largest project - Wavestar - was close to its final step before commercialisation in 2016, but was closed down in June 2016 due to lack of investors. Ongoing projects include WavePiston's testing of its 1:3 scale attenuator and LEANCON Wave Energy test its 1:10 scale Oscillating water column at the Nissum Bredning part of its DanWEC test site. Crestwing is also testing its 1:2 scale attenuator at in the Kattegat area in 2016.

Denmark is not a major holder of proved **natural gas** reserves. Additionally, they are not currently a major producer or consumer of natural gas. However, they are a noteworthy country in terms of natural gas due to the fact that they are a natural gas exporter.

As of 2014, Denmark only held 35 bcm of proved natural gas reserves. Denmark's fields in the North Sea are mainly responsible for the country's proved natural gas reserves and have allowed them to become a natural gas producer. Denmark's natural gas production was only 4.6 bcm in 2014. However, their production level still plays an important role as it is sufficient to not only cover their domestic demand, but also allows for exportation as well. Denmark is self-sufficient in regards to natural gas as evidenced by their consumption level of 3.2 bcm in 2014. This self-sufficiency has aided Denmark's energy security of supply.

Denmark also is a net exporter of natural gas. The country currently exports natural gas through pipeline trade. In 2014, Denmark exported 2.1 bcm of pipeline natural gas to other European countries.

The total **solar** installed capacity at the end of 2015 was 791 MW. The Danish Energy Agency forecasted PV to reach 1,75 GW by 2020, accounting for 5% of power consumption, and over 3 GW by 2025, achieving 8% of power consumption.

The country has a remarkable history of energy recovery from waste and an advanced waste management system. Denmark has one of the highest amounts of waste generated per capita from the EU, with 759 kg per year¹⁴. In 2014 there were 26 **Waste-to-Energy** plants processing 3.5 million tonnes of MSW.

ECUADOR

Ecuador has taken the decision of exploiting its huge **hydropower** potential resource that in fact is more than 20,000 MW from feasibility studies. This huge hydroelectric potential will be able to ensure meeting the growing energy demand for the upcoming 40 years. Currently, Ecuador has eight hydroelectric projects under construction, with direct management of the Ecuadorian State and progressing as planned. One of them started operation in 2015 and the others will follow in 2016 and 2017, incorporating 2,832.4 MW additional hydropower. With this large investment, in the upcoming years, it is expected that around 90% of the electrical energy consumed in Ecuador will come from hydropower and the remaining 10% from thermoelectric generation and interconnections.

Oil

Ecuador - OPEC's smallest producer - has cut some low-priority projects in its oil sector. By 2020, production capacity in the Andean nation is forecast at 590 kb/d, up by 20 kb/d from 2014. Oil is one of the primary sources of export revenue for Ecuador's 15 million people and if prices continue to fall, public spending may be cut. Quito has looked increasingly to China as a major source of funding – including some loans that are supported by crude oil deliveries. In early January, Ecuador secured more than US\$7 billion in credit lines and loans from Beijing.

EGYPT

Egypt is an important country in regards to **natural gas** as they are within the top 20 countries globally for proved natural gas reserves, natural gas production, and natural gas consumption. More specifically, Egypt had 1,846.3 bcm of proved natural gas reserves as of 2014. Egypt's natural gas reserves have been aided by discoveries in the Mediterranean Sea, the Nile Delta, and the Western Desert.

Egypt's natural gas production has been steadily declining in recent years. In fact, 2014 marked the third consecutive year of falling natural gas production in Egypt and the drop has been substantial. Egypt produced 48.7 bcm of natural gas in 2014, which represented approximately a 13% drop from 2013 levels. As domestic production has been falling, it has started to converge with Egypt's natural gas consumption. This is evidenced by the country's 2014 natural gas consumption total of 48 bcm.

Egypt was once a significant exporter of natural gas via both pipeline natural gas and LNG. However, the country's falling production and the sequential convergence of Egypt's gap between domestic production and consumption has impacted their potential for exporting natural gas. In 2014, Egypt only exported 0.4 bcm of LNG, all of which was sent to

¹⁴ Eurostat, (2016)

countries in Asia Pacific. In fact, Egypt even began importing LNG in 2015 in order to fulfil domestic natural gas demand.

Natural gas plays an important role in Egypt's energy mix, particularly when it comes to the country's electricity production. Natural gas is the fuel responsible for approximately 70% of Egypt's electricity currently.

ESTONIA

Estonia has the most advanced **oil** shale industry in the world. Currently oil shale is mostly used for electricity production, and increasingly more for oil production. Oil shale continues to play an important role in the Estonian future energy mix. Oil shale is currently the dominant factor why Estonia is the least energy dependent in the European Union and provides 4-5% of the Estonian GDP.

There are three producers, EestiEnergia (internationally known as Enefit), ViruKeemiaGrupp (VKG), and KiviõliKeemiatööstus. Enefit produces 80% of Estonia's electricity from oil shale and operates two Enefit140 retorts and one Enefit280 retort producing shale oil at a rate of about 8,000 BOPD. In 2015, Enefit's oil production grew to 2,15 million barrels, despite the market slump. Enefit is planning to gradually increase production, as the company has a new production facility reaching design capacity and maximum load - the Enefit280, which has proven to have very low air emissions and significantly increased efficiency. In addition, Enefit is developing capacities to purify heavy fuel oil and extract gasoline from retort gas, both developments will have a positive impact on the production volumes. In 2015, Enefit has doubled its shale oil production, whereas about 40% of its total volumes coming from the new Enefit280 oil plant. The most important challenges of energy production in Estonia are reducing CO₂-intensity and meeting the challenges of the competitive markets.

Enefit has invested heavily over the past years into increase the efficiency and lower the environmental impacts of energy production and our production facilities are in full compliance with the stringent EU emission directives. Enefit has lowered air emissions of oil shale utilisation dramatically during the last years. Enefit has modified some of their existing power production facilities to use up to 50% of woodchips, a renewable resource and see that it is a viable solution to gradually and affordably increase the renewable energy production in Estonia.

VKG commissioned a second and a third Petroter plant in August 2014, and third in November 2015 with efficiency over 75% and lower environmental impacts. This rose their capacity to about 12,000 BOPD. In the beginning of 2016, VKG conserved the oil plants using Kiviter technology due to the decrease in oil prices. VKG also opened a new power generation complex increasing their electricity production capacity to 95 MW.

Estimations of MSW generation per capita point in the region of 1.47 kg/day, but projected to increase by 2025 to 1.7 kg/day, leading to a total generation of 1,535 tonnes/ day. In 2014, Estonia had 1 **Waste-to-Energy** facility processing 0.22 million tonnes of waste.

ETHIOPIA

Ethiopia boasts one of the highest **hydropower** potentials in the region, estimated at 45 GW. Hydropower already accounts for 80% of current power supply and the country has ambitious plans to quadruple hydropower capacity in order to meet growing domestic demand and to take advantage of opportunities to export power to neighbouring countries in the East African Power Pool. Future additions include the Gibe III (1,870 MW) project, which began operation in 2015, and the Grand Ethiopian Renaissance Dam (6,000 MW) which is scheduled to be completed over the next year.

FINLAND

Finland has no commercial **marine** projects but like Denmark is active in wave energy demonstration via Wello Oy and its testing of three 1MW Penguin rotating mass converter devices at WaveHub, UK in 2016. The second is via WaveRoller's testing of three 100kW oscillating wave surge convertors at Peniche, Portugal.

Finland has four **nuclear** reactors providing over 30% of its electricity. Four nuclear reactors were brought into operation between 1977 and 1980: two 488 MWe VVERs at Loviisa, east of Helsinki, and two 840 (now 860) MWe BWRs at Olkiluoto. Construction was started in 2005 on an EPR and commercial operation is anticipated at Dec 2018. In 2011 electricity production in the country was 73.5 TWh, with nuclear providing 23.6 TWh. Finland has made great progress with developing a geological repository, for which the construction license was granted in November 2015 electricity by 2040.

Finland's **solar** market used to be dominated by PV off-grid systems however, there are now more PV systems connected to the grid. It was estimated that at the end of 2015 the installed PV capacity amounted to 11 MW.

Finland generates a significant amount of waste, with 482 kg per person/year in 2014. In 2014 there were 9 operational **Waste-to-Energy** plants that managed 1.2 million tonnes of waste. The largest WtE facility was opened in 2014, and combusts around 320,000 tonnes of MSW to produce 920 GWh of heat and 600 GWh of electricity. The plant will produce half of the district heating demand and 30% of the electricity needed for the municipality of Vantaa¹⁵.

FRANCE

Hydropower accounts for almost 20% of installed capacity in France, second only to its nuclear capacity. With 25,397 MW of hydropower capacity currently installed, France is seeking to increase hydropower capacity by at least 3,000 MW by 2020. Hydropower in France plays an essential role in balancing the nation's nuclear baseload; more than half of the current hydropower supply in France is flexible and allows for adjustment of production to meet fluctuating demand.

¹⁵ Uutiset, (2014)

Regarding **marine** energy, La Rance, a 240 MW tidal barrage in Brittany, remains one of the world's largest commercial ocean energy schemes but a single 500 kW D10 horizontal-axis tidal stream device is now operational in Brittany, led by Sabella. France's DCNS acquired Ireland's OpenHydro in 2012 which is demonstrating two 0.5 MW turbines in Paimpol Bréhat, France and installing two 2 MW turbines at FORCE, Canada. In 2013 Alstom acquired TGL and was testing its 1 MW DeepGen device at EMEC, UK until 2015. GEPS Techno are also testing their 30 kW Octopusea 36 device.

France has 58 **nuclear** reactors operated by Electricite de France (EdF). Total capacity is over 63 GWe supplying 416 billion kWh per year, i.e. 77% of the total generated electricity that year. About 17% of France's electricity is from recycled nuclear fuel. France has pursued a vigorous policy of nuclear power development since the mid-1970s and now has by far the largest nuclear generating capacity of any country in Europe, and is second only to the USA in the world. PWRs account for the whole of current nuclear capacity. The present setup of the electricity industry in France is a result of the government decision in 1974, just after the first oil shock, to expand rapidly the country's nuclear power capacity using Westinghouse technology. Referring to the 1974 decision and the following actions, France now claims a substantial level of energy independence and almost the lowest cost of electricity in Europe. It also has an extremely low level of CO₂ emissions per capita from electricity generation, as 90% of its electricity is generated by nuclear or hydro. France is the world's largest net exporter of electricity with very low generation cost. In 2014, EDF exported to Belgium, Italy, Spain, Switzerland and UK, with total net exports of 65.1 TWh. France has been very active in developing nuclear technology. Reactors and fuel products and services are a major export. In 2014, the National Assembly approved an Energy Transition for Green Growth bill which mandates a 50% share of nuclear generation by 2025 and limits total capacity to the current level. In accordance with this law, EDF will have to close some of its current operating nuclear capacity when the Flamanville 3 EPR starts commercial operation in 2017.

Solar installed capacity at the end on 2015 was estimated at 6,549 MW with around 364,830 PV installations. The sector has developed in a context of national policy support and feed-in tariffs. For instance, in 2015 the new measures that favour the photovoltaic sector raised 2020 National target volume of PV installations from 5,400 MW to 8,000 MW. Also, the Energy Regulatory Commission launched two calls for tenders, one for rooftop systems totalling 240 MW, and one for the installation of 50 MW of PV plants with storage in non-interconnected territories. It was recently released a calendar of new calls for tenders totalling 4,350 MW between 2016 and 2017.

France generates around 511 kg of waste per capita/year, with treatment methods representing incineration 35%, compost 17% and landfilled 20%. France has 126 **Waste-to-Energy** plants processing 14.7 million tonnes of waste. An important new project is a 12 MW Plasma Gasification plant built in Morcenx that took 17 months for construction with an investment of 40 million Euros.¹⁶

¹⁶ Waste Management World, (2014)

GEORGIA

Hydropower accounts for more than 80% of Georgia's generating capacity and between 75% and 90% of overall power generation. Georgia commissioned the 87 MW Paravani station in 2015, with the objective of increasing energy security through interconnections with neighbouring countries.

GERMANY

The country does not have natural **geothermal** steam reservoirs, so technologies such as binary systems or Organic Rankine Cycle are utilised to allow efficient electricity production at temperatures below 100°C. In 2014, there were 180 installations for direct use of geothermal energy. Some of the installations include district heating, space heating, greenhouses and thermal spas. At the end of 2015, a new binary plant in Bavaria was completed, which supplied 5.5 MW of power generating capacity as well as 12 MW of thermal output. Geothermal development has been supported by government policy by allocating funding to R&D projects with generous feed-in tariffs of 0.25 €/kWh (in 2014).¹⁷

Germany's Voith Hydro deployed its HyTide 1000 1 MW tidal stream demonstration device in 2013 at EMEC (UK) but has since scaled back their activities. Voith also delivered a 300 kW commercial OWC wave energy device at Mutriku harbour, Spain in 2011. Schottel is a leading turbine developer whose technology will be incorporated in the Sustainable Marine Energy's PLAT-O and Tidal Stream's TRITON horizontal axis multi-turbine devices, whilst Siemens sold its shares in **Marine** Current Turbines to Atlantis in 2015. Some small German wave developers are also testing devices such as NEMOS and SINN Power.

Although Germany's total remaining proved **natural gas** reserves are low as is their current level of domestic natural gas production, Germany is important to the natural gas market due to being the eighth largest consumer of natural gas globally. In 2014, Germany's natural gas consumption of 70.9 bcm substantially outweighed their natural gas production of 7.7 bcm and even was significantly more than their total amount of proved natural gas reserves (43 bcm).

Due to this significant gap between domestic natural gas production and consumption, Germany is a major importer of natural gas, particularly through pipeline natural gas trade. Germany was the world's largest importer of pipeline natural gas in 2014 at 85 bcm. Russia, Norway, and the Netherlands were the three main suppliers of Germany's imported pipeline natural gas at 38.5 bcm, 27.7 bcm, and 18.1 bcm respectively. Furthermore, Germany has an extensive natural gas pipeline network, which allows them to act as a transport centre and exports natural gas to their surrounding countries when needed.

Germany has 8 **nuclear** reactors which supply almost one sixth of its electricity demand. Germany's electricity production in 2014 was 635 billion kWh (TWh) gross with coal providing 299 TWh (47%, more than half being lignite), nuclear 97 TWh (15%), gas 67 TWh (10.6%), biofuels & waste 54.6TWh (8.6%), wind 53.4 TWh (8.4%), hydro 26.3 TWh (4.1%),

¹⁷ Weber et al, (2015)

solar 30 TWh (4.7%). Following the Fukushima accident, the German government decided to shut down 8 nuclear reactors immediately in 2011 and close the remaining reactors by 2022. Currently, the shutdown of the eight nuclear reactors has been estimated to have resulted in additional emissions of 165 million tonnes of CO₂ per year.

The country reached at the end of 2015 nearly 40 GW of total installed **solar** capacity. The German government has set down an annual target of 2.5 GW for PV capacity additions, but in 2015 were added only about 1.3 GW. The country needs approximately 200 GW of added PV capacity by 2050 in order to meet the energy demand with renewables. It is estimated that in 2015 PV-generated power amounted to 38.5 TWh and covered about 7.5% of Germany's net electricity consumption. Solar energy is supporting the energy transition in the country and its share in the electricity mix is predicted to increase.¹⁸

The country has an evolved infrastructure for recovery of energy from MSW. Every person here produces on average 618 kg of **waste** per year. Around 1% of MSW goes to landfill, to incineration around 35% and composting 17%. 99 WtE plants were registered in 2014 that processed a staggering 25 million tonnes of MSW. The waste management sector produced around 3% of the country's electricity (around 19 TWh) and a significant amount of heat as well (14 TWh a year)¹⁹. With growing recycling rates among other factors, there is not enough waste available for combustion plants, so it is imported from countries such as Italy, Britain, Ireland and Switzerland.

The share of renewable energy sources in Germany's gross electricity consumption rose significantly in 2015 to reach 32.6%, representing a total of 196 TWh per year. This share is up from 27.4% recorded in 2014. Today, **wind** power is by far the most important renewable energy source in Germany with a total output of 88 TWh (thereof 79.3 TWh onshore and 8.7 TWh offshore in 2015). The high share of renewables in 2015 was also thanks to the increase in wind power capacity and the high wind speeds.

Onshore wind is a predictable industry that has been growing with an annual capacity installation rate of 1.5-2 GW per year. 2014 was a record year, however, where the annual installation has reached 4.4 GW. Although the annual installation has dropped down to 3.5 GW in 2015, it still remained higher than what the industry has seen in the past decade. One reason for high investments was repowering. Today, onshore wind industry in Germany is a mature sector with high public acceptance and there is a strong institutional and economic basis around it thanks to the years of experience, financing, infrastructure and professional training.

Germany has made a record offshore wind installation of 2,283 MW in 2015 overtaking the annual installation of the United Kingdom that has the largest installed capacity today. The record installation in 2015 also represents two-thirds of all capacity that was installed worldwide in the same year. With total installed capacity standing at 3,295 MW today, Germany is progressing well to meet its 2020 and 2030 targets of 6,500 MW and 15,000 MW, respectively. Recently, there were concerns around planning for offshore wind in order

¹⁸ Fraunhofer Institute for Solar Energy Systems, (2016)

¹⁹ Gellenbeck, (2014)

to transmit the electricity to the southern parts of the country. Potential areas for onshore wind with lower wind speeds and onshore wind turbines with higher hub heights were proposed as alternatives. The main challenge around wind power in Germany is related to transmission grids, and this challenge may become more prominent in the years ahead with variable renewable energy shares increasing. Today, with curtailment rates of wind power rising, network expansion needs to speed up to overcome the delays, otherwise there may be important consequences for Germany to meet its renewable energy targets. Further integration of European power markets and as flexibility measures, sector coupling and demand side management will be essential to accommodate higher shares of wind and for Germany to realise its renewable electricity targets.

GUINEA

Guinea commissioned the 240 MW Kaleta dam and power station in 2015, effectively tripling the country's installed **hydropower** capacity to 368 MW. The generation from this project will supply the domestic grid and mining sector, and will also contribute to the shared grid through regional interconnections with neighbouring Gambia, Guinea-Bissau and Senegal.

HUNGARY

Hungary has four **nuclear** reactors generating more than one-third of its electricity. Its first commercial nuclear power reactor began operating in 1982. In 2013, total electricity generation in Hungary by 9.4 GWe of installed capacity was 30.3 billion kWh (gross), of which nuclear's share was 15.4 billion kWh (51%). Four VVER reactors, with a current aggregate net capacity of 1 859 MWe, came into commercial operation at Paks in central Hungary. The Hungarian Parliament has expressed overwhelming support for new nuclear and a contract with Rosatom has been signed for the construction of two 1.2GW VVERs.

Hungary generates 12,904 tonnes of MSW per day, and projections to 2025 show an increase to 14,022 tonnes per day. The country has only one operational **Waste-to-Energy** facility in the capital of Budapest with a capacity of 420,000 tonnes per year, processing around 52% of the total waste generated in the capital region.²⁰

ICELAND

Being located in the Mid-Atlantic Ridge, the country has an abundant supply of **geothermal** resources. Installed power generating capacity at the end of 2015 totalled 665 MW, and in 2014 the share of geothermal in the primary energy supply was about 68%. The annual power generation is now 5,238 GWh, accounting for roughly 29% of the total electricity generation in the country. Geothermal utilisation in 2014 included: electricity generation (41.1%), space heating (42.6%), fish farming (4.9%), snow melting (4.2%) swimming pools (3.5%), industrial process heat (2%) and greenhouses (1.4%). Geothermal power plants for electricity generation include: Hellisheiði 303 MW, Nesjavellir 120 MW, Reykjanes 100 MW, Svartsengi 74.4 MW, Krafla 60 MW, Bjarnarflag 3.2 MW, Húsavík 2 MW. The most

²⁰ European Environment Agency, (2013)

developed project at the end of 2014 was in the Theistareykir geothermal field in North Iceland, not far from the Krafla geothermal field. Overall, geothermal energy utilisation is expected to increase in the coming years.²¹

Hydropower accounts for more than 70% of domestic electricity production in Iceland. In assessing impacts of climate change on its existing hydropower infrastructure, Iceland is already implementing climate change adaptation measures by adding a 100 MW expansion to the Búrfell hydropower project, to take advantage of increased glacial run-off attributable to increasing average temperatures.

INDIA

India commissioned 1,909 MW of new **hydropower** projects in 2015, continuing the strong growth trend in the country's hydropower sector and bringing total installed hydropower capacity to 51.5 GW, with a potential to develop a further 100 GW.

India is projected to be one of the fastest growing **natural gas** markets in the world going forward, however in the short-term India has seen their domestic natural gas consumption drop. This drop in natural gas consumption was a result of both falling domestic production and the high price environment of LNG from 2011 to 2014. India was the world's 12th largest consumer of natural gas in 2014 at 50.6 bcm, however that represented the third consecutive year that India's natural gas consumption had fallen. More specifically, this 50.6 bcm represented a ~20% consumption drop from India's 2011 total.

As previously mentioned, India's falling domestic natural gas consumption was partly due to their falling domestic production. In 2014, India's natural gas production was 31.7 bcm and it marked the fourth consecutive year of decreasing domestic natural gas production. In fact, India's natural gas production in 2014 was ~37.7% lower than the total natural gas production seen in 2010.

As a result of India's natural gas consumption significantly outweighing their domestic production, India has been a large importer of natural gas. However, India has focused on importing natural gas via LNG given that they do not have the extensive pipeline system necessary to be able to import natural gas via pipeline trade currently. Due partly to their large focus on LNG for natural gas imports, India was the world's fourth largest LNG importer in 2014 at 18.9 bcm. India received their LNG imports from a multitude of countries, however Qatar was responsible for the large majority of India's LNG supply as they provided 16.2 bcm in 2014.

Natural gas currently struggles to compete with coal and oil when it comes to India's primary energy demand. As a result, natural gas was only responsible for approximately 7% of India's primary energy demand in 2014.

India has 21 **nuclear** reactor units in operation, with an aggregate net generating capacity of 5302 MWe, nearly all of which are relatively small PHWRs that have been built using a

²¹ Ragnarsson, (2015)

domestically developed supply chain. Output from India's nuclear plants accounts for about 3.5% of its net electricity generation. According to the IAEA, six reactor units were under construction at the end of 2015, with an aggregate net generating capacity of 3907 MWe. Four 630 MWe PHWRs were under construction at end-2015: Kakrapar 3-4, Rajasthan 7-8, as well as a 917 MWe VVER (Kudankulam2) and a 470 MWe fast breeder reactor (PFBR). India has an active nuclear power programme and expects to have 14,600 MWe nuclear capacity on line by 2024. In July 2014 the new Prime Minister urged the nuclear sector to raise capacity to 17 GWe by 2024. The objective is to supply 25% of electricity from nuclear power by 2050. The success of the sector in meeting these objectives depends on a degree of foreign participation, however, since 2010, a fundamental incompatibility between India's civil liability law and international nuclear liability conventions limits foreign technology provision. In addition to a conventional uranium-based nuclear programme, India has been developing uniquely a nuclear fuel cycle to exploit its reserves of thorium.

India has set a target of reaching 100 GW PV capacity by end of FY 22. Decentralised small PV projects, large utility scale projects and vary large **solar** parks (> 500 MW) have been planned in the country. The country added a decent capacity in 2015-16 to reach a cumulative capacity of little more than 6 GW by March 2016.

India is a developing country that is experiencing increasing population and urbanisation levels. This situation is favouring growing production of MSW, which requires better waste management models. One of the strategies employed by the Indian Government is to increase **Waste-to-Energy** capacity, with targets to generate 700 MW energy from waste by 2019. There is a great potential for market development as it is projected that 265,834 tonnes of MSW will be generated per day by 2017²².

INDONESIA

Being situated at the convergence of several tectonic plates in Southeast Asia, the country has a significant **geothermal** potential estimated to be around 29 GW, with only 5% currently being utilised. The current generating capacity of roughly 1.4 GW is located in Java, Bali, North Sumatra and North Sulawesi. Currently, less than 3% of total electricity generation capacity is sourced from geothermal, with plans from central government to further increase the share by adding new 5 GW of geothermal capacity by 2022²³. Some of the projects include a 330 MW Sarulla geothermal facility in Tapanuli Utara, North Sumatra, with completion in 2018; and a 150 MW project for Sumatra and Sulawesi, with funding of US\$300 million from the World Bank and Clean Technology Fund. In addition, the Indonesian government is accepting bids since December 2015 for the development of geothermal projects in Way Ratai (55 MW planned unit), Lampung, Marana (20 MW planned unit), Central Sulawesi and Gunung Talang (20 MW planned unit), Bukit Kili and West Sumatra.²⁴

²² Messenger, (2016)

²³ EIA, (2015)

²⁴ Delony, (2016)

Indonesia has an estimated 8,000 MW of undeveloped hydropower potential and currently has over 5,000 MW in the planning phase or already under construction to add to the current installed capacity of 5,258 MW. Most notably, Indonesia is constructing the 1,040 MW Upper Cisokan pumped storage project which will provide peaking capacity for the Java-Bali Grid.

Indonesia has established themselves as an important supplier of **natural gas** both globally and particularly in the Asia Pacific throughout the years. Additionally, Indonesia still has a large base of proved natural gas reserves. This is evidenced by the fact that they held the world's 14th largest total of proved natural gas reserves at 2,908 bcm as of 2014.

Indonesia has been able to successfully turn their proved natural gas reserves into natural gas production throughout the years. In 2014, Indonesia was the world's tenth largest producer of natural gas and was the second largest natural gas producer in the Asia Pacific. Historically, a large amount of Indonesia's natural gas production has been exported, however domestic consumption's share of their natural gas production has also been on the rise.

Indonesia consumed 38.4 bcm of natural gas in 2014, which represented approximately half of their 2014 domestic natural gas production. Furthermore, this 38.4 bcm of natural gas consumption in Indonesia represented a 5.1% increase from the previous year's consumption. Natural gas's role in Indonesia's primary energy consumption has grown in combination with the overall natural gas demand growth witnessed in the country. Natural gas was responsible for ~19.8% of Indonesia's primary energy consumption in 2014. Although Indonesia's natural gas consumption has been growing, the country is still a major exporter of natural gas and an important global energy supplier. Indonesia has established their ability to export natural gas both through pipeline trade and via LNG. A substantial majority of Indonesia's natural gas exports supply other Asia Pacific countries. Indonesia exported a total of 31.2 bcm of natural gas in 2014 with 30.9 bcm of that total being exported to the Asia Pacific. A majority of the natural gas that Indonesia exports is via LNG. More specifically, Indonesia exported 21.7 bcm of natural gas as LNG in 2014, which made them the world's fifth largest LNG exporter. The large majority of that LNG was exported to the Asia Pacific with Japan and South Korea receiving 7.8 bcm and 7.1 bcm respectively. While LNG makes up a majority of Indonesia's natural gas exports, they also export natural gas via pipelines. In 2014, Indonesia exported 9.5 bcm of pipeline natural gas, of which 6.6 bcm was exported to Singapore. Although Indonesia is a significant natural gas exporter, the country has taken the necessary steps to be able to import natural gas in the future. Indonesia currently has contracts signed with the US that will result in natural gas being imported into Indonesia as LNG in 2018. This illustrates the struggle that Indonesia has been facing due to the combination of their declining domestic production and increasing domestic consumption.

IRAN

Seeking to reduce its dependency on power generation from fossil fuels, Iran finalised the 1,040 MW Siah Bishe pumped storage project in 2015, the first of its kind in the region. Current **hydropower** capacity total 11,196 and there are some 14 projects totalling over

5,800 MW in the pipeline.

Iran is one of the global leaders in terms of proved **natural gas** reserves, natural gas production, and natural gas consumption. In 2014, Iran had the largest total of proved natural gas reserves globally at 34,020 bcm, slightly edging out Russia's total proved reserves. Iran has been able to successfully take advantage of their large level of natural gas reserves as they were the world's third largest producer of natural gas in 2014 at 212.8 bcm. Additionally, Iran utilises a significant amount of their domestic natural gas production as they were the fourth largest consumer of natural gas globally as well in 2014 at 170.2 bcm. Although Iran produces a good amount more natural gas than they consume, they have not currently established themselves as a major global natural gas supplier. In 2014, Iran only exported a net total of 2.7 bcm. This is because Iran only exported 9.6 bcm of pipeline natural gas in 2014, of which 8.9 bcm was exported to Turkey. Conversely, Iran imported 6.9 bcm of natural gas in 2014 with 6.5 bcm coming from Turkmenistan. All of Iran's natural gas trade in 2014 occurred via pipeline. However, Iran could become a significant natural gas supplier in the coming years as a result of the recent Iran Nuclear Deal, which led to the removal of major Western sanctions. After the lifting of these sanctions, Iran has looked into potential ways to increase their natural gas exportation, including utilising LNG. The European Commission (EC) has projected that Europe could import 25-35 bcm/year of LNG from Iran by 2030.

Construction of two 1,200 MWe PWRs started at Bushehr in the mid-1970s was suspended following the 1979 revolution. In April 2006, the IAEA reported that Iran had one unit under construction: Bushehr-1 (1,000 MWe gross, 915 MWe net). Iran announced an international tender in April 2007 for the design and construction of two light-water reactors, each of up to 1 600 MWe, for installation near Bushehr. A large **nuclear** power plant constructed by Rosatom, Bushehr-1, is operating after many years' construction. The country also has a major programme for developing uranium enrichment that was concealed from IAEA inspectors for many years. In July 2015, a Joint Comprehensive Plan of Action was finalized between six countries (China, France, Germany, Italy, UK, and US) and Iran, in accordance with which, Iran's enrichment facilities are being downsized.

A major Middle East supply boost could arrive courtesy of Iran, where production capacity is currently estimated at 3.6 mb/d. Stringent international sanctions have reduced Tehran's output to roughly 2.8 mb/d for the past several years. Yet, people familiar with the Iranian **oil** industry, including Iranian oil industry representatives and third-party foreign experts with direct knowledge of the sector, indicate that Tehran has the ability to raise output by around 800 kb/d within months.

IRAQ

Iraq has a large base of proved **natural gas** reserves. As of 2014, Iraq was the world's 13th largest holder of proved natural gas reserves at 3,158 bcm. Approximately three-quarters of Iraq's proved natural gas reserves are associated with oil and a majority of these reserves are in the southern part of Iraq, which is home to multiple massive fields.

Although Iraq has a large total amount of proved natural gas reserves, this has not resulted in noteworthy amount of marketed production yet as a majority of their natural gas is reinjected to aid oil production. This is evidenced by the fact that Iraq only produced 0.9 bcm of marketed natural gas in 2014. Therefore, there is still a significant amount of potential natural gas production yet to be unlocked by Iraq given the country's current level of proved natural gas reserves compared to their natural gas production.

Additionally, Iraq currently utilises the natural gas they produce for domestic means. A majority of the natural gas that is commercially consumed in Iraq is used by the electricity sector.

IRELAND

OpenHydro originated in Ireland before acquisition by DCNS and are delivering some large-scale demonstration of **marine** energy outside Ireland (see France). ESB International are leading the delivering of the 1 MW WestWave project for 2018 and a floating OWC is set for installation in the US by Ocean Energy in 2017. Finally, GKinetic's demonstration of its 1:10 scale 15 kW vertical axis turbine at Limerick Docks. To complement its 1:4 scale Galway Bay test facilities Ireland is developing a full scale test grid connected facility, Atlantic Marine Energy Test Site (AMETS).

Ireland's estimated population is about 4.6 million in 2015, and has one of the largest proportions of people living in rural areas from the European Union, with 42%, while 35% of the population lives in urban areas²⁵. The MSW generated per person in 2013 averaged at 586 kg per year. A large percent is sent to landfills – 42%, while 18% is incinerated and 6% is composted. In 2014 there was only 1 **Waste-to-Energy** plant treating 0.22 million tonnes of waste per year. A new modern WtE facility with combustion technology is expected to come online in 2017 in Dublin, and will generate 58 MW of electricity from processing 600,000 tonnes of waste per year.²⁶

ISRAEL

EcoWavePower demonstrated its 100 kW **marine** energy point absorber off Gibraltar in 2015.

The total **solar** installed capacity at end of 2015 was 772 MW, with most of the installations being PV systems. Two large scale plants were commissioned, Halutziot with 55 MW and Ketura Solar with 40 MW. The country has a target of 13% Renewable Energy electricity production by 2030, and it is expected that more than 50% of the renewable energy in Israel will come from the solar energy. In 2015, electricity production from renewables was around 3%.

²⁵ McMahon, (2016)

²⁶ Messenger, (2016)

ITALY

Geothermal resources are mainly utilised for electricity production, and all plants are located in the region of Tuscany, specifically Larderello-Travale and Mount Amiata. In 2013, Enel Green Power installed the first binary power plant in Italy, Gruppo Binario Bangore 3 of 1 MW. In 2015, Cornia 2 power plant has been upgraded with the integration of biomass fired boiler (using local forest biomass) to raise geothermal steam temperatures from about 150°C to 380°C. This hybridisation added 5 MW of capacity to the plant and output is expected to increase by 30 GWh per year.²⁷

For **marine** energy, since 2000 Ponte di Archimede has operated a vertical axis Kobold 1 tidal stream device in the Strait of Messina, Italy whilst FRI-EL continue to demonstrate their horizontal axis Messina 3 device. The ISWEC project is also testing a 100 kW rotating mass converter wave energy device off Pantelleria island, Italy in 2016. The UK company 40South Energy deployed its R115 wave energy in 2013 and its joint wave and tidal H24 device in 2015 for demonstration, both in Italy.

Italy has had four operating **nuclear** power reactors but shut the last two down following the Chernobyl accident. Nearly 15% of its electricity comes today from nuclear power – all of which is imported. The government intended to have 25% of electricity supplied by nuclear power by 2030, but this prospect was rejected at a referendum in June 2011.

In 2013, Italy generated 288 billion kWh of electricity. Of this, 110 billion kWh was from gas-fired generation; 50 billion kWh from coal; 18 billion kWh from oil; 53 billion kWh hydro, 22 billion kWh from solar and 15 billion kWh from wind. Italy imported 42 TWh, mostly from France and Switzerland.

The total **solar** capacity at the end of 2015 was close to 19 GW, and PV energy production reached 25,2 TWh representing 8,5% of the total Italian electricity production and 9% of total gross production. In 2015, 55% of total energy production from new renewable sources was from PV. The sector has been supported by policy and financial support through feed-in tariffs.

MSW is generated in Italy at a rate of 488 kg per capita/year. From the total production of MSW, 21% is incinerated, 18% is composted and 34% is landfilled. There were 44 **Waste-to-Energy** plants in 2014 treating 6.3 million tonnes of waste. There are ongoing plans for the construction of a dry AD plant, the largest of its kind in Europe, in Bologna. The plant will process 100,000 tonnes of organic waste per year, yielding over 14 million cubic meters of biogas.²⁸

In Italy the construction of new **wind** capacity has significantly slowed down with merely 295 MW of added capacity in 2015, taking the total installed wind energy to 9,126 MW. Heavy delay on the Ministerial Decree on Renewables – originally scheduled for approval in

²⁷ Razzano & Cei, (2015)

²⁸ www.endswasteandbioenergy.com/article/1396415/italy-deal-europes-largest-dry-ad-facility

December of 2014 – has had a serious impact on the wind industry, keeping it close to stationary for a year and a half.

Wind energy contributed with 14,589 GWh of electric energy output in 2015, down 3,3% from 2014, adding up to 5,3% of total net production. This is despite the demand rising 1,5% from 310 TWh to 315 TWh. Wind energy is thus one of only two renewable energy sources – hydro being the other – that experienced a decrease in output from 2014 to 2015.

The main concern among many Italian wind providers at the moment is the End of Life (EOL) of the wind parks. EOL covers the different opportunities that arise when a wind park reaches the end of the incentivised period and/or the moment when the guarantee on the wind turbines runs out. Given the geographical limitations of the Italian peninsula, the majority of locations adapt for wind energy production are already built up. The EOL of many parks therefore represents an important opportunity for providers to increase the efficiency and capacity of their parks, while decreasing the environmental impact, by replacing the old turbines with new, more efficient ones.

JAPAN

Although Japan does not have any large-scale **CCS** projects under development, a very active program of projects of lesser scale is being established. The most notable development is the Tomakomai CCS Demonstration Project, the purpose of which is to demonstrate an overall CCS system as a foundation for commercialising CCS from 2020. The capture plant (using emissions from a hydrogen production unit at Tomakomai port) will process CO₂ at a rate of at least 100,000 tonnes per annum, to be injected into two near shore reservoirs. The project commenced operations in the first half of 2016.

CO₂ capture capacity: Approximately 0.1 Mtpa

Japan has a substantial **geothermal** potential, but a significant portion is unutilised. For more than a decade, geothermal development stalled mainly because it was not economically competitive and lacked social support. However, a resurgence happened after the Fukushima nuclear accident in 2011, with government support leading the development of over 40 projects in 2014. Several units of 6.8 MWe altogether have been commissioned in 2015, bringing the total installed power generating capacity to 533 MW. The new plants included 3 binary units, a 5 MW plant constructed by Turboden and Mitsubishi, a 1.4 MW plant installed in the Kagoshima prefecture, and a 400 kW unit installed in the Fukushima prefecture²⁹. Regarding direct use geothermal, new additions concentrated around heat pumps, which are used for heating and cooling, domestic hot water and snow melting. Bathing, being very popular at Japanese-style inns, accounts for 90% of direct-use applications.³⁰

Japan is currently managing two demonstration OTEC projects. The first is a 30 kW of **marine** energy delivered by the Institute of Ocean Energy at Saga University, Imari city

²⁹ REN21, (2016)

³⁰ Yasukawa & Sasada, (2015)

launched in 2007. The second is a 100 kW delivered by the Okinawa Deep Seawater Research Institute on Kume Island, Okinawa.

Japan has to import about 81% of its energy requirements. Its first commercial **nuclear** power reactor began operating in 1966, and nuclear energy has been a national strategic priority since 1973. This is now under review following the 2011 Fukushima accident and government has stated an indicative share of nuclear of 20-22% by 2030 which implies a significant number of closures of existing plants. There is a programme of reactor restarts underway that has seen the first two restarts, Sendai 1 in September 2015, and Sendai 2 in November 2015. Despite being the only country to have suffered the devastating effects of nuclear weapons in wartime, with over 100,000 deaths, Japan embraced the peaceful use of nuclear technology to provide a substantial portion of its electricity. However, following the tsunami which killed 19,000 people and which triggered the Fukushima nuclear accident, public sentiment shifted markedly and there were public protests calling for nuclear power to be abandoned. The balance between this populist sentiment and the continuation of reliable and affordable electricity supplies is being worked out politically. At the beginning of 2010, total net nuclear generating capacity was 46,823 MWe in 54 reactors, which provided about 29% of Japan's net generation of electricity during the year. 11 nuclear reactors were decommissioned in the years following the Fukushima accident and the total number of restarts remains uncertain.

Japan established in the 'Long-term Energy Supply-demand Outlook' how should the energy mix look like in 2030. Accordingly, the target for renewable energy ranges between 22-24%, out of which 7% is expected to come from **solar** PV installations. At the end of 2015, Japan had just over 33 GW of installed solar capacity. Japan will see the commissioning of the largest floating solar power plant in 2018 that will have the capacity of 13.7 MW and will include 51,000 solar modules located over the Yamakura Dam reservoir, and covering an area of 180,000 m².³¹

Japan is one of the leading countries in **Waste-to-Energy** implementation and technology. In 2013 the country generated around 65 million tonnes of MSW, of which 40 million tonnes were treated thermally. Grate combustion plants dominate the market; however, the country is the largest user of MSW gasification in the world. There were 310 WtE plants in 2012, which processed about 115 tonnes of MSW per day. The recent trend has been to increase capacity of existing plants, rather than investment in the construction of new facilities.³²

JORDAN

Jordan has the world's fifth largest **oil** shale deposit, which contains about 102 billion barrels of oil. Oil shale can be found on more than 60% of the territory of Jordan and research shows that the oil shale layers in some deposits can be a hundred metres or more thick. Jordan's oil shale is easily excavated and can be mined in opencast mines. Jordan suffers from a large shortage of energy, which is why it imports more than 90% of its energy from other countries. There is no oil or gas in Jordan, meaning the country is dependent on

³¹ Boyd, (2016)

³² Yolin, (2015)

gas supplies from Egypt. Unfortunately, these gas supplies have stopped on several occasions, and so Jordan is looking for ways to use local resources so that they could produce their own energy at lower costs. In 2006 the Jordanian government signed memoranda with three oil shale companies who wanted to research Jordan's oil shale in three different deposits. Those companies were Royal Dutch Shell, Enefit, and Jordan Energy and Mining. In 2007 the Jordanian government signed memoranda with Brazil's Petrobras and with several other companies.

In Jordan, development schedules have been adjusted due to economic conditions, but development projects continue. JOSCO, a wholly owned Shell subsidiary, has drilled and characterised 340 wells to support the selection of its final 1000 km² lease hold. It activated a small-scale in-situ pilot in September 2015 to calibrate its subsurface models. Oil was pumped to the surface after a few months, and heating will continue until summer 2016. Another approved project by Saudi Arabian Corporation for Oil Shale had intended to start producing shale oil in five years and increase to 30,000 BOPD by 2025, but no current schedule is available. The venture will use the Russian UTT-3000 technology, a version of a hot-burned-shale process.

Jordan imports over 95% of its energy needs, at a cost of about one fifth of its GDP. It generates 16.6 billion kWh, mostly from oil, and imports 0.7 billion kWh of electricity for its six million people. In order to increase its energy security, Jordan is aiming to have a 1,000 MWe **nuclear** power unit in operation by 2024 and a second one later. An agreement with Russia has been signed to supply these reactors.

KAZAKHSTAN

Kazakhstan currently has one of the world's larger bases of proved **natural gas** reserves. More specifically, Kazakhstan had 1506.1 bcm of proved natural gas reserves as of 2014, giving them the world's 20th most proved natural gas reserves. A majority of Kazakhstan's proved natural gas reserves and natural gas production are a result of the Karachaganak field.

Although a majority of the natural gas produced in Kazakhstan is reinjected into oil fields to aid production, Kazakhstan's marketed natural gas production has also been increasing in recent years. Kazakhstan's marketed natural gas production was 19.3 bcm in 2014, which represented the fourth consecutive year that marketed natural gas production increased at an average annual rate of 4.9% during that time span.

Kazakhstan's natural gas consumption was 5.6 bcm in 2014. While natural gas does have a role in Kazakhstan's primary energy consumption, its role is minimal when compared to other fossil fuels such as coal and oil. More specifically, natural gas was only responsible for 9.4% of Kazakhstan's primary energy consumption in 2014.

As Kazakhstan's natural gas production is significantly more than their natural gas consumption, Kazakhstan has taken advantage of their ability to be a net exporter of natural gas. Kazakhstan currently focuses on pipeline natural gas trade and they are both

an importer and exporter of natural gas. Overall, Kazakhstan exported a net total of 4.7 bcm of pipeline natural gas in 2014. Kazakhstan's main partner in their pipeline natural gas trade is Russia and this trade relationship goes both ways. In terms of pipeline natural gas exportation, Kazakhstan exported 11.4 bcm of pipeline natural gas in 2014 with 10.9 bcm of that going to Russia. Conversely, Kazakhstan imported 6.7 bcm of pipeline natural gas in 2014 with Russia providing 4.3 bcm of that total.

Kazakhstan has 12% of the world's uranium resources and is the largest producer of uranium. The current capacity is around 25,000 tU/yr. A single Russian **nuclear** power reactor operated from 1972 to 1999, generating electricity for desalination. Kazakhstan has no national electricity grid, but does export electricity. The government is considering future options for nuclear power. In view of the dispersed demand for electricity, the government considers large NPPs to be inappropriate currently and is planning to install two small VVER-300 nuclear reactors. However, early in 2014 the Mangistau provincial government opposed the choice of Aktau, and Kurchatov is now the most likely site.

KENYA

Geothermal potential in Kenya is large in the Rift Valley area, and exploitation dates back to the 1950s. In 2015, around 20 MW of new capacity were installed, reaching a total of 600 MW³³. Olkaria geothermal field is the largest producing site with total installed capacity in 2014 of 573 MWe from 5 power plants. A 140 MW Akira power plant is planned to be constructed in two phases, with the first 70 MW to be completed by December 2018. The project is the first private sector greenfield geothermal development through power purchase agreement (PPP) in the sub-Saharan Africa. The government of Kenya has ambitious plans to increase geothermal development to reach additional generation of about 1,646 MWe by 2017 and over 5,000 MWe by 2030.³⁴

KOREA (DEMOCRATIC PEOPLE'S REPUBLIC)

A project for the construction of a 1,040 MWe **nuclear** PWR was initiated in 1994 by the Korean Peninsula Energy Development Organisation (KEDO), funded by the USA, the Republic of Korea, Japan and the EU. It was suspended in 2002 and finally abandoned in June 2006.

KUWAIT

Although Kuwait is within the world's top 20 countries in regards to proved **natural gas** reserves, their total amount of reserves is rather low relative to some of the other countries in the Middle East. As of 2014, Kuwait had 1,784 bcm of proved natural gas reserves, which made Kuwait the seventh largest holder of proved natural gas reserves in the Middle East.

³³ REN21, (2016)

³⁴ Omenda & Simiyu, (2015)

Within Kuwait, the Kuwait Petroleum Corporation (KPC) is the country's dominant player when it comes to natural gas. This is because KPC owns all of Kuwait's oil and natural gas resources and executes the country's determined energy policy. KPC is a large national oil and gas company that has many subsidiaries.

Natural gas plays an important role in Kuwait and its role has been growing in recent years. Kuwait's natural gas consumption was 20.1 bcm in 2014 and this represented the fifth consecutive year that their natural gas consumption grew. During this time span, Kuwait's natural gas consumption grew at an average annual rate of 10.1%. As Kuwait's natural gas consumption has grown, so has its importance in their energy mix. In 2014, natural gas was responsible for approximately 45% of Kuwait's primary energy consumption. The majority of this domestic natural gas consumption was utilised for both electricity and water desalination. Kuwait's natural gas production has also grown along with their natural gas consumption. In 2014, Kuwait produced 15 bcm of natural gas.

Although Kuwait's natural gas production has been growing, the country's natural gas demand still currently outweighs their domestic production. As a result, Kuwait has been an importer of natural gas and specifically has focused on importing natural gas via LNG. Kuwait imported 3.7 bcm of natural gas in 2014 in order to aid their gap between natural gas production and consumption.

Kuwait's **oil** capacity is forecast to edge down to 2.8 mb/d by 2020, a decline of 100 kb/d over the forecast period. In the near term, Saudi Arabia's unilateral closure of the jointly shared Neutral Zone oil field of Khafji is expected to put some strain on capacity. Despite oil's rout, Kuwait is pressing ahead with an extensive programme of drilling, well workovers and de-bottlenecking to raise production capacity. The giant Burgan field in southern Kuwait is also expected to benefit from a planned water injection scheme to help keep capacity at a steady 1.7 mb/d beyond this decade.

These combined efforts have led to an upward revision from MTOMR 2014. Kuwait's official target is to reach capacity of 4 mb/d by 2020 through investment of nearly US\$50 billion, but this goal looked ambitious even prior to oil's decline and the Neutral Zone situation.

LATVIA

The country has a large potential for energy production from MSW, and currently the sector is undeveloped. The amount of waste generated per person per year is 281 kg. The country sends the majority of municipal solid waste to landfills – 92%. The **Waste-to-Energy** market is currently developed around anaerobic digestion from agricultural waste. Different kinds of waste, such as oils, tyres and other combustible materials, are incinerated at a cement production facility 'Cemex' with a capacity of 250,000 tonnes per year.³⁵

LIBYA

Libya's importance in regards to **natural gas** is as an exporter. Additionally, although Libya

³⁵ European Commission, (2011)

was the 21st largest holder of proved natural gas reserves in the world in 2014 at 1504.9 bcm, it also was not even within the 30 largest producers in the world. This further illustrates that Libya currently maintains their natural gas importance through exporting natural gas.

Libya is an exporter of natural gas exclusively through pipeline trade currently. Libya is able to be a natural gas exporter due to producing much more natural gas than they consume. In 2014, Libya exported 6 bcm of pipeline natural gas, all of which was imported by Italy. Additionally, Libya was one of the world's first countries to begin exporting LNG when their LNG plant became functional in 1971. However, Libya's LNG plant was damaged during their 2011 civil war and as a result Libya has not exported LNG since.

LITHUANIA

Lithuania shut down its last **nuclear** reactor, which had been generating 70% of its electricity, at the end of 2009. Until then electricity was a major export for Lithuania. A new energy policy in 2012 was cast around the Visaginas nuclear plant, a new LNG terminal, and rebuilding the power grid. Energy reliance on Russia is to drop from 80% in 2012 to 55% by 2016 and 35% in 2020. Gas imports from Russia halved when the new floating LNG terminal started commercial deliveries in January 2015. GE Hitachi plans to build a single 1350 MWe Advanced Boiling Water Reactor, several of which are operating and under construction in Japan and Taiwan.

Lithuania produces around 2,474 tonnes of MSW per day, with predictions of daily increase to 3,290 tonnes. The country has 1 **Waste-to-Energy** plant that treats 0.14 million tonnes of waste per year. A new WtE combined heat and power plant will be constructed in Kaunas and commissioned in 2019. The facility will produce annually around 500 GWh of heat and 170 GWh of electricity from an annual feedstock of 200,000 tonnes of MSW. The plant is expected to reduce the CO₂ emissions by 65,000 tonnes per year.³⁶

LUXEMBOURG

The small country with about 390,000 urban residents produces around 904 tonnes of MSW per day, with projections to 2025 of 1,041 tonnes per day. There is one **Waste-to-Energy** facility that treats 0.13 million tonnes of MSW per year.

LAO PDR

Laos added 599 MW of new **hydropower** capacity in 2015, bringing its total installed capacity to 3,893 MW. The country has commissioned more than 3.5 GW over the past 20 years and is seeking to export power to neighbouring Thailand and Vietnam; and for this reason these countries have supported projects in Laos.

³⁶ Fortum, (2015)

MALAYSIA

Currently Malaysia's total installed **hydropower** capacity is 5,742 MW and makes up about 20% of the country's power supply. However, only around 12% of technically feasible hydropower capacity has been developed in Malaysia. In 2015, the remaining three 236 MW turbines at the 944 MW Murum power station in the state of Sarawak on the island of Borneo were commissioned. The state is also expecting to begin construction on the 1,285 MW Boleh project in 2016.

Malaysia earned their role as a key **natural gas** player globally due to their natural gas production and importance as a global supplier of natural gas. Malaysia has been able to accomplish this without even being one of the top 20 holders of proved natural gas reserves globally. As of 2014, Malaysia had 1078.3 bcm of proved natural gas reserves. A significant portion of these reserves are located within the eastern part of the country.

Malaysia has been able to very successfully turn their proved natural gas reserves into production. Malaysia was the 12th largest producer of natural gas in the world at 66.4 bcm in 2014. Furthermore, although this production level was a slight drop from the previous year, it still represented a growth in natural gas production of approximately 8% versus 2012 levels.

Malaysia's natural gas consumption has also been growing in recent years. Malaysia consumed 41 bcm of natural gas in 2014, which marked the country's fourth consecutive year of natural gas consumption growth. Natural gas also represented the largest share of Malaysia's primary energy consumption in 2014. More specifically, natural gas was responsible for 40.6% of Malaysia's primary energy consumption.

Malaysia has established themselves as a major natural gas exporter throughout the years and has been able to export natural gas both via LNG and pipeline trade. The significant majority of Malaysia's natural gas exports are in the form of LNG. In fact, Malaysia was the world's second largest exporter of LNG at 33.9 bcm in 2014, behind only Qatar. Malaysia's LNG exports to Japan made up a majority of this total at 20.3 bcm. Although Malaysia is a predominant LNG exporter, they also imported a total of 2.4 bcm of LNG from a number of different countries in 2014. In addition to their LNG trade, Malaysia also exports pipeline natural gas to Singapore and imports pipeline natural gas from Indonesia.

Petronas, Malaysia's state-owned oil and gas company, is the country's main player in their natural gas sector. Petronas currently has a monopoly on all of Malaysia's upstream natural gas activity. Furthermore, the company also is a major player in Malaysia's downstream natural gas and LNG trade endeavours.

The country's feed-in tariff mechanism has been the main driver behind the **solar** sector's growth. At the end of 2015, there were recorded around 184 MW of solar installed capacity. In 2015, there were a number of 2,770 PV applications with a total capacity of 72 MW that received approval. Malaysia is an important player on the PV manufacturing market, after China and Taiwan.

MEXICO

While Mexico does not have any large-scale **CCS** projects under development, the country has taken a number of measures since 2008 to implement CCUS, which is guided by Mexico's CCUS Technology Roadmap. Furthermore, the World Bank CCS Trust Funding is supporting activities in Mexico to advance CCUS pilot demonstrations.

CO₂ capture capacity: N.C.

Geothermal energy is mainly developed around electricity production, with 1,069 MWe total installed capacity, and total net increase in 2015 of 43 MW³⁷. Direct use of geothermal energy is underdeveloped, and is mainly utilised for balneology (156 MWh capacity installed in 2014). A new 53 MW unit was commissioned in 2015 in the Los Azufres field, where other 4 units totalling 20 MW were retired. Other two wellhead plants (5 MW each) were installed in the Dorno San Pedro field, being also the first geothermal project to be privatised. The government is setting up the avenues for further geothermal development through new regulatory framework of the power and geothermal markets and the foundation of a national geothermal innovation centre (CEMIE-Geo), which will undertake 30 research and innovation geothermal projects by 2018.³⁸

Mexico has an estimated 27,000 MW of economically feasible **hydropower** potential. Currently the country has 12,028 MW hydropower installed capacity. Reforms to the energy market in 2015 have lifted restrictions of private ownership of hydropower stations, increasing the potential future role of IPPs in hydropower development.

Mexico's role in **natural gas** globally is currently as a key natural gas consumer and importer. This is largely because Mexico's current level of proved natural gas reserves is not within the top thirty globally and their natural gas production does not rank in the top ten globally, which is in contrast to Mexico's natural gas consumption. Mexico was the world's seventh largest consumer of natural gas at 85.8 bcm in 2014.

As Mexico consumes more natural gas than they produce, they have established themselves as a consistent importer of natural gas. In 2014, Mexico imported 29.8 bcm of natural gas. Mexico has been able to successfully import natural gas via both pipeline gas and LNG over the years. Of the 29.8 bcm of natural gas Mexico imported in 2014, 20.5 bcm of that was as pipeline natural gas. It is noteworthy that all of Mexico's pipeline natural gas was imported from the US, illustrating the importance of the US for Mexico's natural gas supply. Additionally, Mexico imported 9.3 bcm of natural gas via LNG in 2014 and nearly half of that import volume came from Peru. Mexico is currently the largest LNG importer in the Americas. By utilising both pipeline gas and LNG imports, Mexico has established multiple ways to acquire their natural gas and in turn increased their energy security of supply. Natural gas plays a crucial role in Mexico's total energy consumption. In 2014, natural gas was responsible for 40% of Mexico's total energy consumption, Mexico's second most used fuel behind petroleum. Although Mexico is not currently a significant shale gas producer, the country does have the potential to utilise shale gas production in

³⁷ REN21, (2016)

³⁸ Gutiérrez-Negrín, (2015)

the future. One of the main reasons for this is that the country's Burgos basin is an extension of the very successful Eagle Ford basin in the US. Additionally, the Burgos basins already has established infrastructure, which aids in the potential development of shale gas in the basin.

Mexico has two **nuclear** reactors which generate almost 4% of its electricity. Its first commercial nuclear power reactor began operating in 1989. There is some government support for expanding nuclear energy to reduce reliance on natural gas, but recent low gas prices have made this less of a priority. Mexico is rich in hydrocarbon resources and is a net energy exporter. The country's interest in nuclear energy is rooted in the need to reduce its reliance on these sources of energy. In the next few years Mexico will increasingly rely on natural gas, and this is central in the new 2012 energy policy. The Federal Electricity Commission (CFE) planned to invest US\$4.9 billion in 2011 and US\$6.7 billion in 2012 in new gas-fired plant and converting coal plants to gas. In addition, it is calling for tenders to build three major natural gas pipelines. In 2013, 298 billion kWh was generated. Gas is playing an increasing role, and in 2013 supplied 166 TWh, oil 48 TWh, coal 32 TWh, hydroelectric 28 TWh and nuclear 11.8 TWh. There is a single nuclear power station with two BWR units of total net capacity 1,300 MWe, located at Laguna Verde in the eastern state of Veracruz. The first unit was brought into operation in April 1989 and the second in November 1994.

The reported installed **solar** capacity at the end of 2015 is of 234 MW. Mexico has an immense untapped solar potential, and so far the market development has been hindered by unclear legislation and lack of financial support. However, Mexico is making efforts to increase investments in the electricity sector, and the country's solar energy association is targeting a total installed capacity of 3 GW by 2025.³⁹

MOZAMBIQUE

Mozambique has a tremendous **hydropower** potential concentrated along the Zambezi River basin. With a current installed hydropower capacity of 2,187 MW, the country is already a net exporter of electricity to neighbouring countries while continuing to develop projects such as the 1,500 Mphanda Nkuwa and 1,245 MW Cahora Bassa north bank expansion.

Mozambique has entered the discussion of potential major **natural gas** players due to large offshore natural gas discoveries recently. Although Mozambique is currently not a major producer or consumer of natural gas, these recent discoveries could change that in the coming years. As a result of the discoveries, Mozambique currently ranked as the world's 15th largest proved natural gas reserve holder with 2831.7 bcm as of 2014. Mozambique's natural gas production is expected to increase drastically in the coming years. In 2014, Mozambique only produced 3.7 bcm of natural gas. However, the IEA projects the country's natural gas production to increase to 60 bcm by 2040 under their New Policies Scenario. This massive increase could result in the country becoming a major natural gas exporter and/or largely increase their domestic consumption in the future. Mozambique has been

³⁹ Critchley, (2015)

looking into potential LNG projects in order to export some of the natural gas production that will be coming online in the future. Between the MZLNG and Coral FLNG projects, Mozambique currently has approximately 20 bcm of annual LNG export capacity proposed. However, these projects are still pre-FID.

MYANMAR

Hydropower currently comprises two-thirds of Myanmar's power supply. New policy frameworks have recently been put into place to encourage international engagement and investment into electricity infrastructure. In 2015, the country commissioned the 140 MW Paunglaung project, raising total hydropower capacity to 3,140.

Myanmar is known for **natural gas** due to their role as an exporter. Myanmar has a very small amount of total proved natural gas reserves relatively at only 283.2 bcm as of 2014. Additionally, Myanmar's level of natural gas production is not drastically large either. In 2014, Myanmar only produced 16.8 bcm of natural gas.

Although Myanmar has a relatively low amount of proved natural gas reserves and production overall, they are still able to play a key role as an exporter of natural gas. Myanmar is the largest pipeline natural gas exporter in the Asia Pacific region. Myanmar exported 12.7 bcm of pipeline natural gas in 2014. This total amount of pipeline natural gas was imported by Thailand and China at 9.7 bcm and 3 bcm respectively.

NAMIBIA

Hydropower forms the backbone of the Namibian power sector, with an estimated 60% of generated power coming from the 332 MW Ruacana run-of-river station. Angola and Namibia are working on a cross-border interconnection project with the objective to supply power from the planned 300 MW Baynes project in Angola.

NEPAL

Like Bhutan, Nepal is also planning to utilise **hydropower** resources to become a net exporter of power to the Indian market; however, Nepal is currently experiencing challenges in meeting its own domestic demand. Nepal was able to bring 45 MW online in 2015, but unfortunately projects experienced construction delays due the earthquakes in April 2015.

NETHERLANDS

In 2015 Tocado installed five T2 horizontal axis bi-directional turbines (total 1.2MW) to produce **marine** energy, at the Oosterschelde Storm Barrier on a commercial basis. This sits alongside other demonstration projects at Afsluitdijk and Den Oever also in the Netherlands, as well as a collaboration with Bluetec to deliver a 200kW floating tidal energy platform. It also is home to a 500kW ECO Park OTEC demonstrator led by Bluerise and commissioned in 2015 on Curacao island, in the Caribbean.

The Netherlands has established their importance to the **natural gas** market due to their crucial role in the EU. The base of proved natural gas reserves in the Netherlands has been declining in recent years due to many years of significant natural gas production.

Specifically, the proved natural gas reserves total in the Netherlands decreased 39.8% from 2004 to 2014. However, the Netherlands still had 799.7 bcm of proved natural gas reserves as of 2014, which gave them the largest total of proved natural gas reserves in the EU.

Natural gas production in the Netherlands has been significantly declining in recent years. There was a particularly large drop off in their production in 2014. In 2014, the Netherlands produced 55.8 bcm of natural gas, which represented a ~18.7% drop in natural gas production compared to the previous year. However, even with this significant drop in production, the Netherlands was still the largest producer of natural gas in the EU and the world's 15th largest producer in 2014.

Natural gas consumption has also been decreasing in the Netherlands in recent years. The Netherlands consumed 32.1 bcm of natural gas in 2014, which represented a ~26.3% drop in natural gas consumption compared to the country's 2010 levels. Even with this drop in production, natural gas still plays a large role in the Netherlands' primary energy consumption. Natural gas was responsible for ~35.6% of the Netherlands' primary energy consumption in 2014, trailing only oil in terms of its overall share.

As a result of producing more natural gas than they consume currently, the Netherlands has been able to be an important natural gas net exporter within Europe. The large majority of the Netherlands' natural gas trade occurs via pipeline trade. In 2014, the Netherlands exported a net total of 20.9 bcm of pipeline natural gas. This includes 44.1 bcm of pipeline natural gas exports to other European countries, of which Germany was the largest importer at 18.1 bcm, and also includes 23.2 bcm of pipeline natural gas imports. Additionally, the Netherlands has incorporated the ability to be a transport hub for LNG.

Nuclear power has a small role in the Dutch electricity supply, with the Borssele reactor providing about 4% of total generation – 2.9 billion kWh in 2013. It began operating in 1973. Borssele it was designed and built by Germany's Kraftwerk Union (Siemens). It is operated by Electricity Generating Company for the Southern Netherlands (EPZ). In 2006, following an extension of its operating life to 2033, a turbine upgrade boosted its capacity from 452 to 485 MWe. In September 2006 the government submitted to parliament a document entitled, Conditions for New Nuclear Power Plants. Any new reactor must be a Generation III model with levels of safety being equivalent to those of Areva's EPR at a coastal site.

The country generates around 527 kg of waste per person, and from the total MSW 48% is incinerated, 27% is composted and only 1% is sent to landfill. There were 12 **Waste-to-Energy** plants in 2014 processing 7.6 million tonnes of MSW. The sector and infrastructure are well developed, and WtE provides 12% of all sustainable energy in Netherlands⁴⁰. In 2012, the plants produced 4,014 GWh of electricity and 14.1 petajoule (PJ) of heat.⁴¹

⁴⁰ Dutch Waste Management Association

⁴¹ www.legco.gov.hk/yr13-14/english/sec/library/1314in10-e.pdf

NEW ZEALAND

Geothermal energy utilisation has increased in New Zealand with about 20% per annum in the level of generation from 2010 to 2014, totalling in 2015 to almost 1,000 MW, which account for 16% of national electricity generation – from 13% in 2013. The country has a target of 90% electricity generation from renewables by 2025, being already on track as it currently stands at 75% generation from low-carbon sources. Direct geothermal energy use is increasing, especially from heat-pumps, with other uses dominated by the Norske Skog Tasman pulp and paper mill at Kawerau.⁴²

With 5,254 MW of installed capacity, **hydropower** is the primary source of renewable generation in NZ and provides approximately 57% of NZ's power needs. The total renewables share of NZ generation is 80% with the balance of this renewables component largely supplied by geothermal and wind. It is likely that further investment in wind and geothermal will be required to achieve New Zealand's target of 90% of electricity production from renewable sources by 2025.

Callaghan Innovation in collaboration with the US's Northwest Energy Innovations is demonstrating its 20kW Azura device at the US Navy's Wave Energy Test Site at the **Marine** Corps Base Hawaii. It presents a hybrid between a point absorber and oscillating wave surge convertor.

NICARAGUA

Nicaragua commissioned its first **hydropower** project in 40 years as it connected the 17 MW Larreynaga project, raising total hydropower capacity in 2015 to 123 MW.

NIGERIA

Nigeria's role as a major **natural gas** player is due to their large base of proved natural gas reserves and importance as a natural gas exporter. As of 2014, Nigeria had 5,111 bcm of proved natural gas reserves. This gave them the ninth most proved natural gas reserves in the world and the most proved reserves in Africa.

However, Nigeria's overall natural gas production is relatively low based on their large amount of proved natural gas reserves. Nigeria produced 43.8 bcm of natural gas in 2014, which only made them the world's 19th largest producer of natural gas globally. However, this natural gas production represented a 6.6% growth compared to the previous year and Nigeria's proved natural gas reserves illustrate that they have the opportunity to further grow production in the future.

Nigeria is also one of the world's largest exporter of natural gas via LNG. Nigeria exported 25.3 bcm of natural gas as LNG in 2014, which made them the fourth largest LNG exporter in the world and the largest LNG exporter in Africa. Nigeria exported this LNG to a multitude of countries and regions. However, the Asia Pacific region overall was the main importer of

⁴² Carey et al., (2015)

Nigeria's LNG in 2014 having imported 13.3 bcm, while Japan specifically was the largest importing country at 6.5 bcm. Additionally, Nigeria also exports a small amount of pipeline natural gas through the West African Gas Pipeline.

In Nigeria, Africa's top **oil** producer, capacity is expected to contract by about 90 kb/d over the forecast period and sink to 1.9 mb/d as the oil sector is plagued by an array of daunting above-ground challenges and finds it ever harder to market its oil. Investment in high-cost deep-water projects had already slowed due to the long-running deadlock over the Petroleum Industry Bill (PIB) - and the sharp decline in oil prices will lead to further delays. Nigeria's inability to pass the controversial reform legislation to reorganise the state oil company and adjust fiscal contract terms has postponed final investment decisions and created a climate of uncertainty, now heightened by a drop in oil revenues and the presidential election in February. The PIB is unlikely to be passed into law before the expiry of the National Assembly's term in May. Plans for capacity growth are also being threatened by large-scale oil theft and pipeline sabotage in the restive Niger Delta oil heartland and rising violence by Islamic extremists Boko Haram.

NORWAY

Norway was an early pioneer in establishing **CCS** projects. The Sleipner and Snøhvit projects offshore Norway have been operational since 1996 and 2008 respectively. Since 1996, around 20 million tonnes of CO₂ has been stored deep undersea by the two projects. Norway is also home to the Technology Centre Mongstad, located at an industrial complex adjacent to the Mongstad Refinery near Bergen. This demonstration test facility, operating since 2012 and comprising two capture units, is the world's largest facility for testing CO₂ capture technologies.

CO₂ capture capacity: Approximately 1.5 Mtpa

Regarding **marine** energy, Norway's Hammerfest Stromare now owned by Austria's Andritz Hydro (see Austria). Norwegian tidal stream developers include Flumill, Havkraft, Hydra Tidal Energy Technology and Tidal Sails, with Flumill expecting to deploy its 2 MW Archimedes screw device at EMEC in 2017. Fred Olsen also continues to test its Bolt Lifesaver point absorber wave energy device, with a 240 kW demonstration at the US's WETS site. Developers like Seabased and Waves4Power have also been tested at the grid-connected Norwegian Runde test site.

Norway plays an important role globally in regards to **natural gas** and a large reason for that is their ability to produce a significant amount of natural gas, even without having one of the largest proved natural gas reserve bases globally. This was illustrated by the fact that Norway was the world's seventh largest producer of natural gas at 108.8 bcm in 2014, even without being within the top 15 countries globally for proved natural gas reserves.

Although Norway is the seventh largest producer of natural gas globally, they only consumed 4.7 bcm of natural gas domestically in 2014. The combination of their massive production levels and minimal consumption levels allows Norway to be one of the world's most important natural gas suppliers. Norway has established themselves as significant natural gas exporters via both pipeline gas and LNG.

In 2014, Norway exported 106.4 bcm of natural gas, which represented just under 98% of their total natural gas production. This dedication to being a global supplier of natural gas was mainly executed through pipeline natural gas exports, however Norway also capitalises on their ability to export LNG. Norway exported 101.1 bcm of pipeline natural gas and 5.3 bcm of LNG in 2014. As a result, Norway was the world's third largest natural gas exporter overall behind only Russia and Qatar, while being the second largest exporter of pipeline natural gas behind only Russia.

Norway is a crucial supplier of natural gas to Europe as 97.6% of their natural gas exports in 2014 were to Europe. This 97.6% represented 103.8 bcm of natural gas exports, which made Norway Europe's second largest supplier of natural gas behind only Russia. Additionally, in efforts to accommodate the demands of their natural gas importers, Norway has begun increasing the amount of spot pricing used in their sale of natural gas.

The country generates 423 kg of MSW per capital/year. In 2014, there were 17 **Waste-to-Energy** plants treating 1.58 million tonnes of waste. Norway has high levels of waste incineration – 54%, fermentation – 17% and very low landfilling rate of only 3%. The capital, Oslo has a well-developed infrastructure for district heating, making the plants in the region more efficient. A new project at the largest WtE plant in Oslo caught international attention, as the technology of Carbon Capture and Storage (CCS) is going to be utilised to deal with the carbon emissions from the plant. The facility burns over 310,000 tonnes of waste per year and produces 300,000 tonnes of CO₂. The experiment is expected to result in a 90% reduction in carbon emissions from the plant.⁴³

OMAN

Oman has one of the Middle East's smaller proved **natural gas** reserves totals relative to the rest of the region. As of 2014, Oman only had 705.4 bcm of proved natural gas reserves. In turn, Oman is also one of the Middle East's smaller producers of natural gas relatively. Although Oman's natural gas production is small by Middle East standards, they have seen their production grow in recent years. Oman produced 29 bcm of natural gas in 2014, which represented approximately a 17% increase in production compared to their 2009 natural gas production.

Oman consumes a noteworthy amount of natural gas and natural gas plays an important role in Oman's energy supply. Oman consumed 20.4 bcm of natural gas in 2014, which represented about 70% of the country's total production. Furthermore, natural gas is the primary fuel utilised by Oman in order to generate their electricity.

Due to Oman producing more natural gas than they currently consume, Oman has been able to establish themselves as an important net exporter of natural gas. Oman is an interesting country when it comes to natural gas trade because they export natural gas via LNG, however they also import a smaller total of natural gas via pipeline trade. In 2014, Oman exported a net total of 8.3 bcm of natural gas. LNG is responsible for the country's natural gas exports and in 2014 Oman exported 10.4 bcm of natural gas via LNG. These

⁴³ Cuff, (2016)

LNG exports mainly are sent to South Korea and Japan as those countries imported 5.1 bcm and 4.7 bcm respectively in 2014. While Oman is currently a large LNG exporter, they also import natural gas through pipeline trade with Qatar. Oman imported 2.1 bcm of pipeline natural gas in 2014 from Qatar. Although Oman is currently a net exporter of natural gas, rising domestic consumption prompted Oman to announce that they would divert their exports back towards domestic consumption by 2024.

PAKISTAN

Although Pakistan does not have a particularly large proved **natural gas** reserves base, they are able to effectively turn out good production in relation to their total proved reserves. Pakistan's proved natural gas reserves were 578.7 bcm as of 2014.

Furthermore, although Pakistan's proved natural gas reserves have been falling in recent years (27.5% drop from 2004 to 2014), the country's natural gas production has remained fairly consistent. Pakistan produced 42 bcm of natural gas in 2014, which was only a drop of 0.7 bcm compared to the country's natural gas production in the previous year.

Pakistan also consumed 42 bcm of natural gas in 2014, which illustrates that the country is domestically consuming all of the natural gas that they produce. Pakistan's sole reliance on their domestic production to meet their natural gas consumption needs has allowed Pakistan to improve their energy security of supply in regards to natural gas. Furthermore, natural gas has been heavily integrated into Pakistan's energy mix and is responsible for the largest share of the country's primary energy consumption. In 2014, natural gas represented ~51.4% of Pakistan's primary energy consumption.

Pakistan has a small **nuclear** power programme, with 690 MWe capacity, but plans to increase this substantially. In 2005 an Energy Security Plan was adopted by the government, calling for a huge increase in generating capacity to more than 160 GWe by 2030. Significant power shortages are reported, and load shedding is common. Since Pakistan is outside the Nuclear Non-Proliferation Treaty due to its weapons programme, it is largely excluded from trade in nuclear plant or materials, which hinders its development of civil nuclear energy. However, China is positive about nuclear cooperation with Pakistan and is developing civil nuclear power in that country. Chasma 3-4 are under construction and Karachi Coastal 1-2 are expected to start construction soon.

PAPUA NEW GUINEA

Papua New Guinea is a noteworthy country in regards to **natural gas** mainly due to their large LNG project, PNG LNG. Papua New Guinea continued to move ahead on this project even though the country has a very small base of proved natural gas reserves. More specifically, Papua New Guinea had 151.3 bcm of proved natural gas reserves as of 2014.

The PNG LNG project has seen success and became operational in mid-2014. The project was a very significant undertaking as it required an initial investment of US\$19bn. The PNG LNG project currently has a capacity of approximately 9.5 bcm/year. This project also has secured long-term supply contracts of LNG with China Petroleum and Chemical

Corporation (Sinopec), Osaka Gas, Tokyo Electric Power Company (TEPCO), and CPC Corporation. Even though the PNG LNG project did not become operational until mid-2014, the project was still able to export 4.7 bcm of LNG in 2014, of which 3 bcm went to Japan.

PERU

In Peru, the 172 MW Cheves **hydropower** station commenced operations and is the first South American project to be entirely developed and constructed by SN Power.

Although Peru's proved **natural gas** reserves are relatively small based on a global scale, they are still one of the largest natural gas reserve holders in South America. Peru had 426.1 bcm of proved natural gas reserves as of 2014, which gave them the third largest total in South America. The majority of Peru's proved natural gas reserves and natural gas production are a result of their Camisea field.

Peru has achieved substantial and sustained natural gas production growth in recent years. Peru produced 12.9 bcm of natural gas in 2014. This marked the country's 14th consecutive year of natural gas production growth. Additionally, this 2014 level of natural gas production was drastically higher than Peru's production level of 3.5 bcm just five years prior in 2009.

Peru's consumption of natural gas has also seen significant increases in recent years as well. Peru consumed 7.2 bcm of natural gas in 2014, which was more than double the country's natural gas consumption as recently as 2009. Furthermore, natural gas's importance in Peru's primary energy mix has also increased. Natural gas was responsible for 28.2% of Peru's primary energy mix in 2014.

Peru has also established themselves as an important natural gas exporter via LNG. Peru first became an exporter of LNG when their Melchorita plant became operational in 2010. Peru exported 5.7 bcm of LNG in 2014. Of this total, 4.3 bcm went to Mexico, which made them the largest importer of Peruvian natural gas.

PHILIPPINES

The country is the world's second largest producer of **geothermal** energy, with 1,930 MWe installed capacity at the end of 2015. The geothermal power plants (as of December 2014) include: 722.68 MW Leyte, 458.53 MW MakBan, 234 MW Tiwi, 172.5 MW Palinpinon, 130 MW Bacman, 108.48 MW Mindanao, 49 MW Nasulo and 20 MW Maibarara. The government is planning to continue the geothermal capacity addition trend realised since the enactment of Renewable Energy Act 2008, to add a total of 1,465 MWe new generation capacity by 2030. These plans will have to be supported through harmonised government policies and regulations for the exploration and utilisation of geothermal resources in particular in protected areas, but also for the appropriate development of projects varying in size and output.⁴⁴

⁴⁴ Fonda, Marasigan & Lazaro, (2015)

POLAND

Although Poland does not currently have a large total of proved **natural gas** reserves or significant natural gas production, the country's shale gas potential could lead to increases in both categories in the coming years. As of 2014, Poland only had 98.3 bcm of proved natural gas reserves. Additionally, the country only produced 4.2 bcm of natural gas in 2014.

Poland is currently the predominant shale gas player in Europe. Overall, Poland has 4.1 tcm of technically recoverable shale gas reserves. The Baltic basin is responsible for a majority of that total at approximately 3 tcm. Poland's shale gas potential is also aided by favourable pipeline infrastructure and access to skilled workers. Although Poland's shale gas infrastructure overall is advantageous, they still need to make progress in regards to water treatment and disposal infrastructure before they can fully take advantage of their large resource base.

While Poland's production may increase in the coming years due to their shale gas potential, currently the country is a large natural gas importer due to not being able to meet demand purely with domestic production. The country consumed 16.3 bcm of natural gas consumption in 2014. As a result, Poland had to import 10.6 bcm of natural gas via pipeline in 2014. Russia supplies a large majority of Poland's pipeline natural gas imports. Specifically, Poland imported 8.9 bcm of pipeline natural gas from Russia in 2014.

Poland plans to have **nuclear** power from about 2027 as part of its energy portfolio diversification, moving it away from heavy dependence on coal and imported gas. The nuclear plant will be a joint venture of three utilities and a mining company all state-owned. In 2013, Poland produced some 164 billion kWh gross from 34 GWe of mostly coal plant. Coal provided 140 TWh of the electricity, gas 5.1 TWh, biofuels 8.7 TWh (mostly co-fired in coal plants) and wind 6.0 TWh. In August 2014 a draft energy policy for Poland described two scenarios, both with nuclear power playing a key role. One had nuclear power supplying 50 TWh/yr by 2035, with renewables 60 TWh. The other had stronger growth in nuclear to 74 TWh/yr, and 49 TWh renewables. Both involve a major shift from lignite and black coal which currently provide about 84% of electricity and most of the air pollution.

In 2014, the average generation rate of MSW was 272 kg/capita per year, and is expected to grow to 377 kg⁴⁵. Landfilling is the dominant waste disposal method, with incineration and composting representing only a small percentage. There is a great untapped potential for **Waste-to-Energy** as incineration with energy recovery, pyrolysis and gasification are basically non-existent. Pyrolysis in particular would benefit Poland, as it has an estimate of 110,000 tonnes of waste tires produced annually that could be turned into oil⁴⁶. A new WtE facility has been proposed in the Polish capital that would have five times the capacity of Warsaw's existing facility. The plant has an estimated investment cost of €143-199 million,

⁴⁵ Swiss Business Hub, APAX Consulting Group, (2015)

⁴⁶ Alwaeli, (2015)

a capacity to process 100,000 tonnes of waste per year, produce 50 MW of electricity and 25 MW of heat.⁴⁷

PORTUGAL

Portugal operates its 400 kW Pico OWC in the Azores for **marine** energy. It has also hosted a 300 kW wave energy array at Peniche delivered by WaveRoller (see Finland).

The country generates per capita around 453 kg of waste yearly, and incinerates 21%, composts 14% and sends to landfill 49% of the total MSW treated. There are 3 **Waste-to-Energy** plants located in Porto, Lisbon and Madeira, that treat 0.97 million tonnes of MSW⁴⁸. Grate combustion technology is present in all three WtE facilities.

QATAR

Qatar plays a significant role in the global market of **natural gas**. One of the key reasons that they have this position globally is their massive amount of proved natural gas reserves. Globally, Qatar has the third largest total of proved natural gas reserves. This large base of proved natural gas reserves sets Qatar up to be a major global natural gas player for many years to come. A majority of Qatar's current natural gas reserves are located in the North Field.

Qatar has also been successful at capitalising on their proved natural gas reserves as they are currently the fourth largest natural gas producer in the world. Furthermore, Qatar produces significantly more natural gas than they consume. This was evident in 2014 as their production level was nearly four times their consumption level. This large disparity between production and consumption allows for Qatar to export a significant amount of natural gas and therefore has helped establish them as an important global energy supplier.

In 2014, Qatar was the world's second largest natural gas exporter at 123.5 bcm, trailing only Russia. Qatar has established their ability to export natural gas both as pipeline natural gas and as LNG, however they are a much more prominent LNG exporter. Qatar is by far the world's largest LNG exporter. In 2014, Qatar exported 103.4 bcm of natural gas via LNG, which was over three times more than Malaysia, the world's second largest LNG exporter. This LNG margin alone would be enough to make them one of the top natural gas exporters globally, however Qatar also exports a significant amount of natural gas through pipeline trade. Qatar exported 20.1 bcm of natural gas via pipeline in 2014.

Qatar's crude **oil** production capacity recovers to 730 kb/d by 2020 after slipping in the early years of the forecast period. It is relatively costly to develop Qatar's oil fields due to their complex geology, so raising capacity beyond 730 kb/d may prove prohibitively expensive in the current low price environment. Keen to breathe new life into its declining oil fields, Qatar Petroleum has been planning to redevelop the onshore Dukhan field and

⁴⁷ Kość, (2014)

⁴⁸ Blanco, (2014)

double the 45 kb/d, offshore Bul Hanine field to 90 kb/d at an estimated cost of US\$11 billion. A core component of the costs is the redevelopment of the ageing infrastructure and installation of new offshore central processing facilities.

ROMANIA

Romania has a relatively small total of proved **natural gas** reserves compared to some of the other significant global players and their level of reserves has been dropping over the years. As of 2014, Romania only had 110 bcm of proved natural gas reserves, which represents a large drop from their total of 295 bcm in 2004.

There has been a major drop in Romania's natural gas production over the years. Romania's peak production of natural gas occurred in the 1980s, however their production has significantly dropped from those levels and has plateaued in recent years. Romania's natural gas production was only 11.4 bcm of natural gas in 2014.

Similar to the country's natural gas production, Romania's natural gas consumption peaked in the 1980s and has dropped significantly since then. In 2014, Romania's natural gas consumption was only 11.7 bcm, which also marked the third consecutive year of falling natural gas consumption. Although Romania's natural gas production and consumption has drastically decreased from their peak levels, natural gas was still responsible for the largest share of Romania's primary energy consumption in 2014 at ~31.4%.

Romania also used to be a significant importer of natural gas through pipeline trade. However, Romania's natural gas imports have drastically shrunk in recent years and Romania is projected to no longer import natural gas by 2016.

Romania has two **nuclear** reactors generating more than 18% of its electricity. Romania's first commercial nuclear power reactor began operating in 1996. Its second started up in May 2007. Romanian government support for nuclear energy is strong and in November 2013 two nuclear cooperation agreements were signed by Nuclearelectrica (SNN) with China General Nuclear Power (CGN), one a letter of intent relating to construction of units 3&4. In May 2014 a further agreement with CGN was signed, and in mid-2014 the Industrial and Commercial Bank of China agreed to finance the €6.5 billion project, with CNPEC building the two reactors. CGN would hold a major share in the project, with Nuclearelectrica (SNN) a minor shareholder holding 49% in a new joint venture.

RUSSIA

As for **marine** energy, Russia has 1.7 MW of tidal range capacity installed at Kislaya Guba, on the coast of the Adriatic Sea. It was originally built in 2004 and upgraded in 2007.

Over the years, Russia has firmly established themselves as one of the largest and most important **natural gas** players in the world. They are the only country globally that falls within the top two countries in natural gas proved reserves, natural gas production, and natural gas consumption. Although they are a significant yearly producer of natural gas,

their massive amount of proved reserves will allow them to continue production at the same level for decades if they desire.

Russia's natural gas operations are significantly dominated by Gazprom. Gazprom is one of the world's predominant natural gas companies and Russia owns a majority share of the company. According to the company, they are responsible for 72% of Russia's total natural gas reserves and 17% of global natural gas reserves. Additionally, they are responsible for 72% of Russia's natural gas output and 12% of global natural gas output. These significant figures illustrate how important Gazprom is in both Russia specifically and the world in regards to natural gas.

In addition to consuming a significant amount of natural gas, Russia is also a major global supplier of natural gas through export. Russia has effectively established the ability to export natural gas through both pipeline and LNG. In 2014, Russia exported 187.4 bcm of natural gas via pipeline. A majority of this pipeline natural gas, 147.7 bcm, was exported to Europe (not including Former Soviet Union). Additionally, 14.5 bcm of natural gas was exported via LNG to the Asia Pacific in 2014, of which 11.5 bcm went to Japan. Therefore, due to the combination of their pipeline natural gas and LNG exports, Russia is the world's largest natural gas exporter and a crucial natural gas supplier to both Europe and Asia.

Furthermore, Russia has the potential to be a major supplier of natural gas to China in the future. The Power of Siberia pipeline, an extensive pipeline that runs from Russia to China, is currently under construction and will provide Russia with the ability to supply China with 38 bcm of pipeline natural gas yearly when it is fully operational.

Russia is moving steadily forward with plans for an expanded domestic role for **nuclear** energy. In February 2010 the government approved the federal target program designed to bring a new technology platform for the nuclear power industry based on fast reactors. Rosatom's long-term strategy up to 2050 involves moving into inherently safe nuclear plants using fast reactors with a closed fuel cycle. It envisages nuclear providing 45-50% of electricity at that time, with the share rising to 70-80% by the end of the century. Exports of nuclear goods and services are a major Russian policy and economic objective. Technologically, Russian reactor designs are well advanced and the country is a world leader in fast neutron reactor technology. Over 20 nuclear power reactors are confirmed or planned for export construction. Rosenergoatom is the only Russian utility operating nuclear power plants. There are 34 nuclear units installed at ten different sites at the end of 2015, with an aggregate net generating capacity of 25,264 MWe. In all, NPPs provided almost 19% of the Russian Federation's electricity output in 2015. Utilisation of existing plants has improved markedly; in the 1990s capacity factors averaged around 60%, but they have steadily improved since and in 2010, 2011 and 2014 were above 81%.

SAUDI ARABIA

Saudi Arabia is evaluating the use of CO₂ injection as part of a longer-term Carbon Management Roadmap and has planned a series of programs at various scales in mature hydrocarbon fields. The largest project became operational in mid-2015 and involves the capture of 0.8 million tonnes of CO₂ per annum from a natural gas liquids recovery plant for

use in EOR. The project has a number of research objectives and includes a comprehensive monitoring and surveillance plan. Several institutions in Saudi Arabia are engaged in **CCS** research. Saudi Arabia is also home to a large CO₂ capture and purification plant as feedstock for non-EOR utilisation purposes. While this type of utilisation is not the same as permanent beneath ground storage options, it can help drive down costs associated with capture (and those cost reductions are transferrable), it can enhance experience with transport infrastructure, and it can impact the rate of CO₂ additions to the atmosphere.

CO₂ capture capacity: Approximately 0.5-1 Mtpa

Saudi Arabia is a noteworthy country in terms of **natural gas** due to both their significant natural gas potential and current natural gas utilisation. As of 2014, Saudi Arabia's total proved natural gas reserves were 8,488.9 bcm, which gave them the sixth most proved natural gas reserves globally and the third most in the Middle East specifically. This huge base of proved natural gas reserves has allowed Saudi Arabia to be a large natural gas producer throughout the years.

Saudi Arabia produced 102.4 bcm of natural gas in 2014, which made them the eighth largest natural gas producer in the world. Additionally, it marked the fifth consecutive year of increasing natural gas production in Saudi Arabia, illustrating that Saudi Arabia has emphasised growing their domestic production in order to continue to meet their energy demand.

Furthermore, Saudi Arabia was the world's fifth largest consumer of natural gas in 2014 as they consumed 108.2 bcm. The country's natural gas consumption has continued to grow as has natural gas's role in Saudi Arabia's current energy mix. In 2014, natural gas made up ~40.7% of Saudi Arabia's primary energy consumption.

Currently, Saudi Arabia does not import or export natural gas and therefore they have not established themselves as a global natural gas supplier even though they produce significant amounts of it. Additionally, Saudi Arabia has been able to achieve important energy security of supply due to the fact that they only rely on themselves to meet their natural gas consumption. However, this also means that Saudi Arabia will have to continue to produce at a high levels going forward to meet their domestic demand.

Saudi Arabia has also pursued becoming a shale gas producer in the coming years and is now expected to produce shale gas by 2020. Furthermore, Saudi Aramco plans to invest an additional US\$7bn into developing Saudi Arabia's shale gas resources. In order to fully take advantage of their shale gas potential, Saudi Arabia will need to address permeability, water scarcity, and workforce concerns.

Saudi Arabia plans to construct 16 **nuclear** power reactors over the next 20 years at a cost of more than US\$80 billion, with the first reactor on line in 2022. It projects 17 GWe of nuclear capacity by 2040 to provide 15% of the power then, along with over 40 GWe of solar capacity. In March 2015, the Argentinian state-owned INVAP (Investigacion Aplicada) and Saudi state-owned technology innovation company Taqnia set up a joint venture company, Invania, to develop nuclear technology for Saudi Arabia's nuclear power

program, apparently focusing on small reactors such as CAREM (100 MWt, 27 MWe) for desalination.

Saudi Arabia is expected to sustain its **oil** production capacity near its official 12.5 mb/d target throughout the forecast period. With an estimated US\$750 billion in foreign exchange reserves, Riyadh has a hefty cash cushion that could see it through several years of low oil prices. Saudi Aramco's Chief Executive Khalid al-Falih has, however, said that the low oil price environment has created an opportunity for the state oil company, and the industry as a whole, to sharpen fiscal discipline.

SINGAPORE

Atlantis Resources is headquartered in Singapore but originates from Australia and operates mainly through its UK **marine** energy subsidiary (see Australia and UK). A 4k W OWC wave energy device was tested in 2013 by Hann-Ocean Energy.

SLOVAKIA

Slovakia has four **nuclear** reactors generating half of its electricity and two more under construction. Slovakia's first commercial nuclear power reactor began operating in 1972. Government commitment to the future of nuclear energy is strong. In November 2014 the government approved a long-term energy plan based on greater use of nuclear power, some renewables, and reducing the use of coal. Electricity consumption in Slovakia has been fairly steady since 1990a. In 2013, 28.5 billion kWh gross was produced, 15.7 TWh (55%) of this from nuclear power, with hydro 5.1 TWh, coal 3.3 TWh, gas 2.4 TWh and solar 0.6 TWh. Net imports were zero. Slovakia has gone from being a net exporter of electricity – of some 1 billion kWh/yr – to being a net importer following the shutdown of the Bohunice 1-2 reactors. The remaining four reactors are reported to have a current net capacity of 1 816 MWe and to have provided 56.8% of the republic's electricity output in 2014. All of the country's gas comes from Russia.

The country generates 4,164 tonnes of MSW per day, and projections to 2025 identify that this trend will increase, reaching 5,280 tonnes/day. There are only 2 operational **Waste-to-Energy** plants, treating 0.19 million tonnes of MSW per year. The largest plant can process up to 150,000 tonnes of waste per year and can produce around 48,000 MWh of electricity. The facility in Bratislava is slightly smaller and can process 135,000 tonnes of MSW per year. However, both plants have not been working at full potential, the first one taking only 75,000-80,000 tonnes/year, while the second one around 90,000 tonnes/year.⁴⁹

SLOVENIA

Slovenia has shared a **nuclear** power reactor with Croatia since 1981. A bi-national PWR (current capacity 666 MWe net) has been in operation at Krsko, near the border with Croatia since 1981. According to the Slovenian WEC Member Committee, Krsko will operate till 2023, with possible extension. A further Krsko unit is under consideration, of 1,100 to 1,600

⁴⁹ Walsh, (2015)

MWe. An application towards a second reactor at the Krsko nuclear power plant was submitted to the country's ministry of economy by GEN Energija in January 2010. Parliament was expected to decide on this in 2011, and it remains an objective as JEK2 project. The cost is estimated at up to €5 billion, and it would be fully owned by Slovenia. Electricity production in Slovenia in 2012 was 15.7 billion kWh gross, with net exports ranging from 0.9 to 2.1 billion kWh over 2010-12. Most trade is two-way with Croatia, and most exports are to Italy. Nuclear power supplied 5.5 TWh, coal provided 5.1 TWh and hydro 5.5 TWh.

SOUTH AFRICA

South Africa has the largest CO₂ capture plant in the world as part of the process to produce synthetic fuels and operated by Sasol and PetroSA. Currently that CO₂ is released into the atmosphere. There is also a smaller capture plant in one industrial installation where the CO₂ captured is used as part of their production process. Under the South African Centre for **CCS** (a division of the South African National Energy Development Institute) a pilot CO₂ storage project is underway with first injection scheduled for 2019. Planning and stakeholder engagement are well advanced with exploration scheduled to start in 2016. Regulatory development has commenced and a carbon tax is scheduled to be introduced soon.

CO₂ capture capacity: N.C.

Despite having limited **hydropower** potential, South Africa is pursuing further development to support its ongoing struggle with meeting power demand. The first two units at the 1,332 MW Ingula pumped storage project came online in early 2016. Unserved electricity demand in the Southern African Development Community (SADC) is driving regional cooperation in hydropower development.

South Africa is currently not a major producer or consumer of **natural gas** on a global scale. However, the country has large shale gas potential, which could lead to increased production down the road. It is estimated that South Africa has 11 tcm of technically recoverable shale gas reserves. The Karoo shale basin is the most significant potential shale gas play for South Africa. The Karoo shale basin could play a large role in improving the country's existing electricity networks. However, in order to fully capitalise on the basin's shale gas potential, South Africa will need to solve their current workforce, infrastructure, and water availability concerns near the basin. South Africa is currently a minor natural gas producer and only produced 3 bcm of natural gas in 2014. However, the IEA projects that South Africa will up domestic production to 12 bcm by 2040 under their New Policies Scenario. The country's shale gas potential is a major factor in this projected production increase. In regards to natural gas consumption, South Africa consumed 4.1 bcm of natural gas in 2014. However, coal is still responsible for a significant majority of the country's primary energy consumption, while natural gas plays a much smaller role. In 2014, natural gas only represented 2.9% of South Africa's primary energy consumption. South Africa also imports natural gas via pipeline to meet domestic demand. South Africa imported 4 bcm of pipeline natural gas exclusively from other African countries in 2014.

South Africa has two **nuclear** reactors generating 5% of its electricity. Government has

plans for a further 9,600 MWe in the next decade, but financial constraints are severe. There is a single nuclear power station at Koeberg, about 40 km north of Cape Town, which began operating in 1984. The plant has two 900 MWe PWR, is owned and operated by Eskom, the national utility, and provided nearly 5% of South Africa's electricity in 2009. In September 2014 Rosatom signed an agreement with South Africa's energy minister to advance the prospect of building up to 9.6 GWe of nuclear capacity by 2030. Agreements are also in place with France, China, the USA and South Korea and a further agreement is pending with Japan.

SOUTH KOREA

The South Korean Government is revising its **CCS** Master Plan, which includes a large-scale CCS demonstration project operating within certain cost parameters by 2020, and commercial CCS deployment thereafter. The Government's policy includes support for a number of testing and pilot plants, involving a wide variety of agencies and companies in the power generation and steel making industry. This includes the testing of post combustion capture technologies at its Boryeong and Hadon Power Stations.

CO₂ capture capacity: N.C.

In regard to **marine** energy, South Korea's 254 MW Sihwa-Lake tidal range plant is the world's largest ocean energy installation but will soon be trumped by its 1.32 GW Incheon Tidal Power Plant and 400 MW Saemangeum tidal plant, both currently under construction. Its 1.5 MW Uldolmok Tidal Power Station is also operating commercially. It has numerous ongoing demonstration projects including such as its 1 MW OTEC plant on the island of Kiribati and its active-controlled 225kW Korean Shark 200 tidal stream device. Korea is a leading user and developer of **nuclear** energy. It also exports nuclear technology and is currently building four nuclear reactors in the UAE under a US\$20 billion contract. Korea has 24 nuclear reactors (20 PWRs and 4 PHWRs) in operation, with a reported aggregate net capacity of 22.4 GWe and which provide about one-third of South Korea's electricity. Nuclear energy is a strategic priority for South Korea, and capacity is planned to increase by 70% to 37 GWe by 2029 which it is projected would reduce greenhouse gas emissions by 37% below business as usual levels. Three reactors are currently under construction. Korea is seeking relief from treaty commitments with the USA which currently constrain its fuel cycle options.

The country reached at the end of 2015 over 3 GW of **solar** installed capacity. Korea has a target of 11% that represents the share of renewable energy in 2035, while at the moment the total primary energy consumption from renewable energy stands at around 3,6%. The government's 'New and Renewable Energy' plan will further boost the solar sector, and in 2015 around 1 GW was installed under this programme.

SPAIN

Voith Hydro operates the commercial Mutriku Wave Energy Plant in Spain (see Germany). Magallanes Renovables are currently testing a 2 MW horizontal axis floating device, whilst Wedge Global have recently tested their 200 kW W200 point absorber and OCEANTEC are currently testing a small 40 kW floating OWC. Spain's test sites include the Oceanic

Platform of the Canary Islands (PLOCAN) and the grid-connected Biscay **Marine** Energy Platform (BIMEP).

According to 2014 data, the country generated around 435 kg of waste per person/year. Around 12% of the MSW was incinerated, 17% composted and 55% was sent to landfill. Spain has 12 **Waste-to-Energy** plants processing 2.5 million tonnes of waste. It is believed that the country needs around 17 facilities in total to effectively process 22 million tonnes of waste. The additional plants would require an investment of approximately €4 billion. Landfill gas is successfully extracted in 71 out of 134 municipal landfills, generating in 2012 a total of 331 GWh.⁵⁰

SWEDEN

As for **marine** energy, Seabased are delivering the world's largest wave energy array; a 42 device 1 MW array of point absorbers at Sotenas in western Sweden. They have also delivered a six device 400 kW array near Ada Foah in Ghana. Three ongoing non-commercial demonstration projects include the Lysekil project led by Uppsala University with two 20 kW point absorbers, Waves4Power testing their own point absorber at Runde in Norway and Minesto's Deep Green 3 kW tidal kite being tested in Stangford Lough in Northern Ireland. Uppsala University manages two test sites: The Lysekil wave power site and the Söderfors tidal current site.

Sweden has nine operating **nuclear** power reactors providing about 40% of its electricity. About 40% of domestic production is nuclear, and up to half hydro, depending on the season (affecting hydro potential). In 2013, Sweden generated 152.5 TWh, of which 65.8 TWh (43%) was from nuclear and 61.3 TWh (40%) from hydro. Wind provided 10 TWh and various fossil fuels 5 TWh and biofuels & waste 10.6 TWh. In 1980, the government decided to phase out nuclear power. In June 2010, Parliament voted to repeal this policy. The country's 1997 energy policy allowed 10 reactors to operate longer than envisaged by the 1980 phase-out policy, but also resulted in the premature closure of a two-unit plant (1,200 MWe). Some 1600 MWe was subsequently added in upgrades to the remaining ten reactors. In 2015 decisions were made to close four older reactors by 2020, removing 2.7 GWe net. Sweden has a tax discriminating against nuclear power – now about 0.75 Euro cents/kWh - which makes up about one-third of the operating cost of nuclear power. Wind and biomass are subsidised by about three times that. In June 2016, the main Swedish political parties agreed to phase out the tax over a two-year period starting in 2017; the agreement also permits new reactors to be built to replace units being permanently shut. Four reactors will be decommissioned by 2020 and nuclear power will bear the cost of disposal of spent fuel and nuclear waste. Moreover, the state will not pay for neither decommissioning nor final disposal.

It was announced in June 2009 that the world's first permanent disposal site for used nuclear fuel would be constructed at Forsmark in eastern Sweden. with construction site works possibly beginning in early 2020 and it is hoped that the Spent Fuel Repository can be ready to start operations about ten years later.

⁵⁰ European Biogas Association, (2015)

Sweden is one of the world leaders in recovering energy from waste. Here, generation of MSW per capita is around 438 kg per year. Incineration of waste is highly utilised for waste management and energy recovery – representing 50% from all MSW treatment, while 16% is used for composting and only 1% is sent to landfills. There were 33 **Waste-to-Energy** plants in 2014 treating 5.7 million tonnes of waste. The country imports around 800,000 tonnes of waste per year for WtE incinerators from Norway, with plans to start bringing waste from Eastern European countries that do not have any recycling and WtE facilities, thus landfill the majority of the waste produced⁵¹. The imported waste was used to heat almost 1 million homes and provide electricity to around 260,000.

SWITZERLAND

Switzerland has 15,635 MW of installed **hydropower** capacity accounting for nearly 60% of domestic electricity production. While there are limited hydropower resources available to be developed, most projects are utilising existing infrastructure and reservoirs. 1,000 MW is currently under construction and is expected to be achieved in 2018.

Switzerland has five **nuclear** reactors generating almost 38% of its electricity. A national vote had confirmed nuclear energy as part of Switzerland's electricity mix. However, in June 2011 parliament resolved not to replace any reactors, and hence to phase out nuclear power by 2034, despite continuing strong public support for nuclear power. In December 2014, the National Council decided that after 40 years' licences could be renewed for ten years followed by possibly another ten years. The Council of States (cantons) voted on the matter in September 2015, and agreed to avoid putting legal limits on the operating lives of reactors. In 2013 electricity production was 70 billion kWh gross, mostly from nuclear and hydro. A lot of electricity is imported from France, Austria and Germany and up to 26 TWh/yr exported to Italy, with exports and imports largely balanced. In 2013 nuclear power contributed 26 TWh, 40.6% of Swiss total production, with hydro supplying 57%. Closure of the Muhleberg reactor is expected by 2020 which along with the expiration of drawing rights for some 2,500 MWe of French nuclear capacity in the second half of the next decade will increase pressure on the Swiss electricity supply system. Replacement of this capacity will provide a major challenge for Swiss energy policy in the coming years.

Switzerland introduced a landfill ban in 2000. All the MSW is either recycled (glass, metal, PET, paper) or incinerated. The organic fraction is mostly used to produce biogas. Separate **waste** collection systems for organic waste are installed in certain municipalities. Energy was recovered in 2014 from 30 plants that treated 3.8 million tonnes of MSW. From 45 PJ waste input were produced 8.8 PJ electricity and 17 PJ thermal energy for distant heating systems.

TANZANIA

Similar to Mozambique, Tanzania is another country whose **natural gas** production could drastically increase in the upcoming years due to significant offshore discoveries. As of

⁵¹ Burgess, (2013)

2014, Tanzania had a very large proved natural gas reserve base of 1316.7 bcm as a result of these major offshore natural gas discoveries.

Although Tanzania is currently a relatively small producer of natural gas, their production is expected to see a large increase in the future due to their large offshore natural gas discoveries. The IEA projects that Tanzania's natural gas production will increase to 20 bcm by 2040 under their New Policies Scenario. This production increase will provide Tanzania with the opportunity to increase their domestic consumption and/or natural gas exports.

Tanzania LNG is a major potential LNG project in Tanzania. If Tanzania LNG is completed, it could provide Tanzania with approximately 13.8 bcm of annual export capacity, however FID on the project is not planned until 2018.

THAILAND

Although Thailand has a relatively small total of proved **natural gas** reserves, they have been able to produce a significant amount of natural gas given their level of reserves. Thailand only had 238.3 bcm of proved natural gas reserves as of 2014, however Thailand was still able to produce 42.1 bcm of natural gas in 2014. Furthermore, Thailand has been able to continuously increase their natural gas production over the years. Thailand's increased natural gas production total in 2014 marked the 13th consecutive year that their natural gas production has grown.

Along with producing natural gas, Thailand is also a major consumer of natural gas. In 2014, Thailand consumed 52.7 bcm of natural gas, which made them the 11th largest consumer of natural gas globally. Furthermore, 2014 marked the 25th consecutive year that Thailand has increased their domestic natural gas consumption.

Thailand's main use of natural gas is in electricity generation. Overall, natural gas plays an important role in Thailand's energy mix and natural gas is responsible for 39% of Thailand's primary energy consumption.

While Thailand's natural gas production has been consistently growing over time, domestic production alone is not able to satisfy the country's natural gas demand. Therefore, Thailand has historically been an importer of natural gas. Thailand imported a total of 11.6 bcm of natural gas both via pipeline and LNG trade in 2014. The large majority of Thailand's natural gas imports are a result of pipeline trade with Myanmar. In 2014, Thailand imported 9.7 bcm of pipeline natural gas, all of which came from Myanmar. Thailand imported an additional 1.9 bcm of natural gas via LNG in 2014. Qatar was Thailand's largest LNG supplier at 1.3 bcm.

Total **solar** installed capacity at the end of 2015 was estimated to be 1,605 MW, making Thailand a significant solar power producer in the Southeast Asia region. Thailand's long-term 'Alternative Energy Development Plan' is proposing a target of solar power of 6,000 MW by 2035, representing 9% of total energy generation that will meet the electricity need of about 3 million households. The government introduced in 2013 a feed-in tariff

programme designed to support deployment of residential and commercial PV systems.⁵²

TRINIDAD AND TOBAGO

Trinidad and Tobago has seen their total proved **natural gas** reserves decline in recent years. Trinidad and Tobago had 346.6 bcm of proved natural gas reserves as of 2014, which represented a decline of about 28% from the country's 2007 level. Even though Trinidad and Tobago has a limited amount of proved natural gas reserves remaining, they continue to be a relatively large natural gas producer. However, their production of natural gas has begun to slightly decline in recent years. In 2014, Trinidad and Tobago produced 42.1 bcm of natural gas, which represented a 6% drop from their peak production in 2010. Trinidad and Tobago's natural gas consumption had been increasing until its peak in 2011. Now, similar to the country's natural gas production, there has been a slight decrease in domestic consumption in recent years. Trinidad and Tobago consumed 22 bcm of natural gas in 2014. Even with the slight decline in domestic natural gas consumption recently, natural gas still makes up the large majority of Trinidad and Tobago's primary energy consumption. In 2014, natural gas was responsible for ~92.3% of the country's primary energy consumption. Trinidad and Tobago has also established themselves as an important global energy supplier due to their significant level of natural gas exportation via LNG. Trinidad and Tobago exported 19.3 bcm of LNG in 2014, which made them the world's sixth largest LNG exporter. Trinidad and Tobago exported their LNG across the globe and the country was the largest LNG supplier to the US, Canada, and the South American region overall.

TURKEY

Turkey has significantly increased the exploitation of **geothermal** energy in the past few years owing the geothermal law with favouring regulations, feed-in tariffs, and a target of 1 GW of geothermal power capacity to be installed by 2023. Around 225 geothermal fields have been discovered, and 10 new power capacity unites have been completed in 2015 totalling 159 MW, and rising the total installed power capacity to 624 MW (excluding the final energy output of ground-source heat pumps, which was estimated at 99 TWh). Electricity generation increased in 2015 by 50% from the previous year to achieve 3.37 TWh. One project in particular attracted attention, as the 4 MW binary Organic Rankine Cycle (ORC) plant is considered to be the world's first to operate at two pressure levels, which not only increases energy recovery, but also the overall efficiency from low-temperature resources⁵³. In 2014, there were 16 geothermal district heating systems in operation serving 77,453 residences. For the other direct-use applications, the total for the country is 2,886.3 MWt of installed capacity and 45,126 TJ/year for annual energy use.

Turkey has an ambitious target of 34 GW of installed **hydropower** capacity by 2023. Currently, the country has 25.9 GW currently operational and by adding 2,225 MW in 2015, remaining on pace to meet the ambitious target.

⁵² Jittapong, (2015)

⁵³ Ren21, (2016)

Turkey plays an important role in the **natural gas** market currently due to the country's significant level of natural gas imports. Additionally, Turkey has the potential to increase their domestic natural gas production in the future due to their shale gas potential.

Turkey's natural gas demand has been increasing rapidly in recent years. In 2014, Turkey consumed 48.6 bcm of natural gas. Furthermore, the country only produced 0.5 bcm of natural gas in that same year. Natural gas plays a crucial role in Turkey's primary energy consumption. In 2014, natural gas accounted for the largest share of Turkey's primary energy consumption at 34.9%, slightly edging out both coal and oil.

As a result of the country's natural gas consumption significantly outweighing their production, Turkey has become a major importer of natural gas. Turkey has been able to leverage both pipeline and LNG in order to import their natural gas. Turkey imported 48.4 bcm of natural gas in 2014. A large majority of this natural gas was imported via pipeline. Turkey imported 41.1 bcm of pipeline natural gas in 2014, of which Russia was by the largest supplier at 26.9 bcm. Turkey also imported natural gas in the form of LNG. In 2014, Turkey imported 7.3 bcm of LNG, of which 4.1 bcm came from Algeria. Although the majority of Turkey's natural gas imports come from Russia, their expansion into LNG and pipeline imports from other countries illustrates their desire to improve their energy security of supply.

Another way that Turkey could go about improving their energy security of supply for natural gas would be to capitalise on their shale gas potential. Between the Dadas Shale in the South East Anatolian basin and the Hamitabat Shale in the Thrace basin, the EIA estimates that Turkey has 0.7 tcm of technically recoverable shale gas reserves. However, in order to fully take advantage of this opportunity, the country will need to further evaluate their exact shale gas potential and improve upon policy and infrastructure concerns.

Turkey has had plans for establishing **nuclear** power generation since 1970. Plans for nuclear power are a key aspect of the country's aim for economic growth, and it aims to cut back its reliance on Russian and Iranian gas for electricity. The Ministry of Energy and Natural Resources (ETKB) projects 2020 electricity production as possibly 499 TWh in a high scenario of 8% growth, or 406 TWh with a low one with 6.1% growth. Recent developments have seen Russia take a leading role in offering to finance and build 4800 MWe of nuclear capacity. Application has been made for construction and operating licences for the first plant, at Akkuyu, and these are expected in 2016. A Franco-Japanese consortium is to build the second nuclear plant, at Sinop and China is in line to build a third plant, with US-derived technology.

TURKMENISTAN

Turkmenistan had the fourth largest proved **natural gas** reserves base globally at ~17,479 bcm as of 2014. Additionally, Turkmenistan was the world's 11th largest producer of natural gas in 2014 at 69.3 bcm. However, this large amount of proved natural gas reserves and production has not currently translated into major natural gas consumption relatively. This is evidenced by the fact that Turkmenistan is not currently one of the world's 25 largest natural gas consumers.

Although Turkmenistan's natural gas consumption does not appear to be very significant based on a global scale, natural gas actually does play a large role in Turkmenistan relative to their size. This is illustrated by the fact that natural gas was responsible for ~80% of Turkmenistan's primary energy consumption in 2014.

Additionally, Turkmenistan is able to play a role as a global energy supplier due to the fact that they produce significantly more natural gas than they consume. Currently, Turkmenistan is able to export a notable amount of natural gas via pipelines. In 2014, 41.6 bcm of natural gas was exported by Turkmenistan, exclusively as pipeline natural gas. The vast majority of this natural gas was exported to China, Russia, and Iran at 25.5 bcm, 9 bcm, and 6.5 bcm respectively. In 2014, Turkmenistan was the world's largest exporter of natural gas to China, which conveys the important role they play in helping supply China's growing energy demand.

UKRAINE

Ukraine does not currently hold a substantial amount of proved **natural gas** reserves relatively and does not produce a large amount of natural gas either. As of 2014, Ukraine had 637.5 bcm of proved natural gas reserves. The level of natural gas production in Ukraine has remained consistent for the most part in recent years. Ukraine produced 18.6 bcm of natural gas in 2014.

Unlike the country's relatively consistent natural gas production, Ukraine's consumption of natural gas has been drastically decreasing. In 2014, Ukraine consumed 38.4 bcm of natural gas, which represented a ~28.4% drop from the country's 2011 level of natural gas consumption. Additionally, 2014 marked the third consecutive year of declining natural gas consumption in Ukraine. However, even with the significant decline in consumption, natural gas still plays the largest role in the country's primary energy consumption. In 2014, natural gas made up 34.6% of Ukraine's primary energy consumption.

Ukraine is both a significant natural gas importer themselves and an important transit centre for Russian pipeline natural gas exports to Europe. Ukraine imported 17.5 bcm of pipeline natural gas in 2014 in order to fill the gap between their natural gas production and consumption. Russian natural gas was responsible for a majority of this total at 12.9 bcm. In addition to utilising Russian pipeline natural gas domestically, Ukraine is also a key partner to Russia as Ukraine's pipeline network and location aids Russia in transporting their pipeline natural gas to various European countries.

Ukraine is heavily dependent on **nuclear** energy – it has reactors generating about half of its electricity. Ukraine receives most of its nuclear services and fuel from Russia, but is reducing this dependence by buying fuel from Westinghouse. In 2004 Ukraine commissioned two large new reactors. The government plans to maintain nuclear share in electricity production to 2030, which will involve substantial new build. After initially contracting with Rosatom to build the new reactors, the government is now looking to the West for both technology and investment in its nuclear plants. A large share of primary energy supply in Ukraine comes from the country's uranium and substantial coal resources. The remainder is oil and gas, mostly imported from Russia. In mid-2012 the Ukraine energy

strategy to 2030 was updated, and 5,000 to 7,000 MWe of new nuclear capacity was proposed by 2030, costing some US\$25 billion. A major increase in electricity demand to 307 TWh per year by 2020 and 420 TWh by 2030 is envisaged, and government policy was to continue supplying half of this from nuclear power. This would have required 29.5 GWe of nuclear capacity in 2030, up from 13.8 GWe (13.1 GWe net) now. The new government formed in 2014 has confirmed these targets, and said that Ukraine aims to integrate with the European power grid and gas network to make the country part of the European energy market by 2017. However, finance will be a major challenge and currently there are no concrete plans in place that that would deliver the 2030 targets.

UNITED ARAB EMIRATES

Abu Dhabi, as the major oil producing emirate of the United Arab Emirates (UAE), is making major progress on **CCUS** beyond carbon capture with Masdar's development of a domestic CCUS network. Following the completion of a two year CO₂-EOR pilot project in November 2011 at an onshore field, Masdar is implementing a CO₂-EOR project that brings 800,000 tonnes of CO₂ annually from a steel plant to an oil field of the Abu Dhabi National Oil Company.

CO₂capture capacity: Approximately 0.5-1 Mtpa

The United Arab Emirates (UAE) is an important nation in regards to **natural gas** due to their large total of proved natural gas reserves and natural gas consumption. The UAE had a substantial 6,091 bcm of proved natural gas reserves as of 2014. Abu Dhabi is currently responsible for a large majority of the country's total proved reserves. This level of proved natural gas reserves gave the UAE the seventh largest total in the world, yet only the fourth largest total in the Middle East.

The UAE's natural gas production has been growing in recent years and the country produced 54.2 bcm of natural gas in 2014, which represented 5.8% growth year-over-year. Although the UAE's natural gas production has been growing, their 2014 production level only made them the world's 17th largest natural gas producer, which is low relative to their global status for total proved reserves.

One of the key reasons that the country does not produce more natural gas is that a majority of their natural gas contains high sulphur. Therefore, this leads to large increases in both technical difficulty and economic cost in order to develop and process these natural gas reserves. The process is still very challenging and expensive, however recent technological developments have led to some improvement in the process.

The UAE is a significant consumer of natural gas and their consumption has been consistently growing in recent years. In 2014, the country consumed 69.3 bcm of natural gas, which made them the ninth largest natural gas consumer in the world. Additionally, this marked the fifth straight year of growth in terms of natural gas consumption. Natural gas is responsible for a majority of the UAE's primary energy consumption. More specifically, natural gas represented 60.4% of the country's primary energy consumption in 2014. A significant portion of the UAE's natural gas use is for electricity generation and desalination.

Even with the UAE's massive total of proved natural gas reserves, the country still must import natural gas in order to meet their natural gas demand. The UAE is a major importer of pipeline natural gas, however they also both import and export natural gas via LNG. In 2014, the UAE imported 18 bcm of pipeline natural gas, which came exclusively from Qatar. Additionally, the country exported 8 bcm of natural gas via LNG, of which 7.7 bcm went to Japan, while also importing 1.9 bcm of LNG. Therefore, the UAE has the unique title of being a pipeline natural gas net importer and LNG net exporter. In summary, the UAE imported a net total of 11.9 bcm of natural gas in 2014.

The UAE is embarking on a major **nuclear** power program in close consultation with the International Atomic Energy Agency. In 2009, it accepted a US\$20 billion bid from a South Korean consortium to build four commercial nuclear power reactors, total 5.6 GWe, by 2020 at Barakah. All four units are now under construction, the first two units envisaged for 2017-2018, followed by units 3 and 4 in 2019-2020.

The country is focusing on increasing **solar** power share in the energy mix. In the near term, Solar PV is a favoured technology owing to resource availability and low cost, while CSP is expected to scale up slower due to higher costs. Total solar installed capacity reached in 2015 133 MW. The largest renewable energy project commissioned in the Middle East is the 100 MW Shams 1 CSP plant in Abu Dhabi. In Dubai were commissioned 13 MW of solar PV as the first phase of the eventually 1000 MW Mohammed Bin Rashid Al-Maktoum Solar Park in Dubai. Other 10+ MW of rooftop solar PV have been installed across the country with expectations for this trend to continue. UAE is also looking at solar power for desalination, and in 2014 were approved 4 pilot projects that use highly energy-efficient membrane technologies to produce around 1,500 m³ of water per day. Water heating from solar thermal collectors is commercially available, but at the moment is mainly used in large installations such as hotels and new buildings in Dubai⁵⁴.

UNITED KINGDOM

The UK continues to be one of the leading **marine** energy developers. Its flagship scheme is MeyGen, the world's first multi-turbine tidal stream array in the Pentland Firth, Scotland. Phase 1A with incorporate 4 turbines providing 6 MW and is the first phase of a potential 398 MW project. Another commercial projects include Nova Innovation's 3 turbine 300kW Shetland Tidal Array in Scotland. Tidal Energy Ltd has deployed a 400kW tidal stream turbine off Ramsey Sound in Wales with a view to install a 9 turbine 10 MW commercial scheme. Numerous pre-commercial demonstration schemes are also planned by developers such as Carnegie and Wello Oy for 2016 and 2017.

Significant RD&D and deployment support has been offered by Scottish Government of late via the Renewable Energy Investment Fund (REIF) and Wave Energy Scotland (WES). The UK also offers two grid-connected ocean energy test sites (EMEC and WaveHub) offering testing in a range of conditions. This is in addition to the non-grid connected FABTEST in

⁵⁴ IRENA, (2015) www.irena.org/remap/irena_remap_uae_report_2015.pdf

England, FloWave test tank in Edinburgh and the forthcoming Perpetuus tidal test facility on the Isle of Wight.

Natural gas plays an important role in the UK and they are one of the world's largest consumers of natural gas. In 2014, the UK consumed 66.7 bcm of natural gas, which made them the tenth largest natural gas consumer globally. However, although the UK consumes a significant amount of natural gas, they do not currently produce a large amount and their total proved natural gas reserves are not substantial either.

One of the new ways that the UK has looked into meeting their natural gas demand, while simultaneously increasing their energy security of supply, is by exploring their shale gas production potential. Although the sentiment in Europe overall has been mostly negative on the shale process, the UK feels that shale gas could provide them with the opportunity to drastically increase their domestic production. However, while the UK would like to potentially move forward on shale gas drilling domestically, the process already has been banned in Scotland and Wales, which clearly limits its potential in the UK.

As the domestic production of natural gas is currently well below the natural gas consumption in the UK, natural gas trade is one key way that the UK is able to maintain their consumption levels. The UK has historically utilised both pipeline natural gas trade and LNG trade in order to meet their domestic demand. In 2014, the UK imported 44.2 bcm of natural gas between both pipeline natural gas imports and LNG imports.

The UK plays an important role in Europe's natural gas pipeline trade as they not only import a significant amount of pipeline natural gas for their own consumption, but they also export a smaller amount of natural gas to other European countries. The UK imported 32.9 bcm of natural gas through pipeline in 2014, of which 25.9 bcm came from Norway. Additionally, the UK exported 10.6 bcm of pipeline natural gas in 2014 with the two largest importers being Ireland and Belgium at 4.5 bcm and 4.4 bcm respectively. As evidenced by their pipeline natural gas imports and exports, the UK's advanced natural gas pipeline system has allowed them to play a crucial role in Europe's natural gas trade.

While the UK imports a significant amount of natural gas as pipeline natural gas, they have also successfully utilised LNG imports for many years. In fact, the UK was the world's first importer of LNG in 1964 when they received their first shipment from Algeria's LNG plant at Arzew. LNG imports are still crucial to the UK as they imported 11.3 bcm of natural gas via LNG in 2014 with 10.4 bcm of that total coming from Qatar.

The UK has 16 **nuclear** reactors generating more than 17% of its electricity in 2014, but all of these are to be retired by 2030. The UK has full fuel cycle facilities including major reprocessing plants. The first of some 19 GWe of new-generation plants is expected to be on line by 2025. The government aims to have 16GWe of new capacity operating by 2030, with no restriction on foreign equity. Each of the three major new nuclear projects has a reactor vendor involved – with 10%, 60% and 100% of equity respectively. In the late 1990s, nuclear power plants contributed around 25% of total annual electricity generation in the UK, but this has gradually declined as old plants have been shut down and ageing-related problems affect plant availability. Net electricity imports from France – mostly

nuclear – in 2011 were 6.2 billion kWh, less than 2% of overall supply. EDF and CGN (China General Nuclear Power Group) intends to build four new EPR reactors (each of around 1.6 GWe) by 2025. And in 2015, China CGN said it intended to apply in 2016 for GDA for the 1150 MWe Hualong One reactor design, with a view to building it at Bradwell. GE Hitachi and Westinghouse are undertaking the Generic Design Acceptance process for the ABWRs intended for Wylfa and Oldbury and the AP1000s for Moorside.

Alongside with China and Germany, the United Kingdom's **wind** growth rate has been maintained around, and sometimes even above, the global average. With more than 13,800 MW of wind capacity installed at the end of 2015, almost 1,000 MW were installed last year⁵⁵. Some sources point that United Kingdom has experienced a growth rate of around 9.4% in 2015⁵⁶. In addition, the United Kingdom was considered amongst the top 10 countries with major markets on turbines sales between 0.5 GW and 2.5 GW in 2015⁵⁷.

The country has 8,750 MW of onshore capacity installed. The offshore wind power sector has been mainly dominated by the United Kingdom, which roughly accommodates almost half of the existing offshore wind turbines in British waters. This represents more than 5,105 MW of installed capacity currently, out of which roughly 600 MW were added in 2015. A sequence of policy reforms has been introduced in the United Kingdom in 2015. The reform seems to point towards phasing out support schemes for renewable electricity towards an auction based system. Also in 2015, a tax reform has also been implemented in the United Kingdom. Amongst other results, tax benefits such as the 'Enterprise Investment Scheme' and the 'Seed Enterprise Investment Scheme' were removed.⁵⁸

The amount of MSW generated in 2012 was estimated at 46.5 million tonnes, and projected to reach 48 million tonnes by 2020. The amount of waste treated in **Waste-to-Energy** plants is rather small comparing with the main option of landfilling. There are currently 49 WtE plants operational in the UK, with other 44 facilities either in construction, in procurement or awaiting confirmation⁵⁹. Within the past ten years the local authorities doubled the amount of waste sent for treatment with energy recovery, reaching 5.5 million tonnes in 2012/2013, and is predicted to reach 11.9 million tonnes by 2020⁶⁰. Waste-derived renewable electricity from thermal combustion in England is predicted to grow to 3.6 TWh by 2020⁶¹. Apart from combustion plants, which dominate the WtE market, there will be an increase in Advanced Thermal Treatment facilities. Teesside is the largest advanced plasma gasification plant in the world that was supposed to come online in 2016 and supply renewable energy to 100,000 homes, but the £300 million project was dropped due to technical challenges.⁶²

⁵⁵ IRENA Statistics, (2016)

⁵⁶ WWEA, (2016)

⁵⁷ WWEA, (2015)

⁵⁸ WWEA, (2016)

⁵⁹ www.gov.uk/government/uploads/system/uploads/attachment_data/file/266438/project_list_EIR16Dec.pdf

⁶⁰ Green Investment Bank, (2014)

⁶¹ Defra, (2014)

⁶² Tighe, (2016)

UNITED STATES OF AMERICA

Supported by significant funding from the U.S. DOE, the United States has the most robust portfolio of large-scale **CCS / CCUS** projects of any country in the world. Nearly all projects include CO₂-EOR as the preferred storage type, which has acted to provide added support to the commercial pathway. Of the 22 large-scale CCS projects in operation or under construction around the world, ten are in the United States. The CO₂ capture capacity of these ten projects is approximately 25 Mtpa.

Projects are found in a wide range of industries, including natural gas processing, fertiliser, power generation, chemicals and hydrogen production. Key project data include:

- The Air Products Steam Methane Reformer EOR Project in Texas has been in operation since 2013 and has captured over 2 million tonnes of CO₂ to date. The project is demonstrating a state-of-the-art system to capture CO₂ emissions from two steam methane reformers to produce hydrogen, with the captured CO₂ piped to EOR projects in eastern Texas.
- The Illinois Industrial CCS Project involves the storage of CO₂ already separated in a corn-to-ethanol plant into a deep saline formation adjacent to the plant. This large-scale project builds on the earlier Illinois Basin Decatur Project that injected around one million tonnes of CO₂ over a three-year period to the end of 2014. Larger-scale injection building up to 1 Mtpa may begin in 2016 depending on timing of approval processes.
- Two large-scale CCS projects in the power sector, both of which are targeting operations start in 2016. The Kemper County Energy Facility is a new build 582 MW power plant in Mississippi (using first-of-its-kind coal gasification technology) that will capture around 65% of total CO₂ emissions, or approximately 3 Mtpa. The Petra Nova Carbon Capture Project will retrofit carbon capture facilities to an existing coal-fired power plant in Texas and capture around 1.4 Mtpa.

The United States also has a very extensive research program at laboratory, bench and pilot scale in both carbon capture and storage technologies supported by the US DOE.

A key priority for the U.S. DOE/NETL Carbon Capture R&D Program is pilot-scale testing of second generation technologies. In September 2015, eight projects were selected to receive funding to construct small- and large-scale pilots for reducing the cost of carbon dioxide (CO₂) capture and compression. The projects focus on advancing the development of a suite of post-combustion CO₂ capture and supersonic compression systems for new and existing coal-based electric generating plants.

The U.S. DOE has created a network of seven Regional Carbon Sequestration Partnerships (RCSPs) to help develop the technology, infrastructure, and regulations to implement large-scale CO₂ storage in different regions and geologic formations. The initiative was launched in 2003 and is being completed in phases (I, II, and III). Phase III efforts are underway throughout the partnerships and CO₂ injection has been in progress at

six sites.⁶³

CO₂ capture capacity: Approximately 25 Mtpa

Geothermal is used for both electricity generation and direct-use heating. In 2015, there were 71 MW added from two binary plants commissioned in Nevada, which brought the total operating capacity to around 3.6 GW. Electricity generation in 2015 was 16.8 TWh, with 5.6% higher than in 2014. There is much untapped potential due to regulatory and economic constraints, with 500 MW of projects being delayed⁶⁴. In terms of direct utilisation of geothermal energy, ground-source heat pumps account for 88% of the annual energy use, followed by fish farming and swimming pool heating⁶⁵.

In April, 2016, the US Senate approved the Energy Policy Modernization Act of 2015, part of which amends Section 203 of the Energy Policy Act of 2005 (42 U.S.C. 15852) to include hydropower of all sizes and at all locations. The previous definition only recognized new hydropower capacity achieved from increased efficiency of additions of new capacity at an existing hydroelectric project.

Lockheed Martin co-developed Atlantis's AR1500 deployed at MeyGen (see UK). Ocean Power Technologies are delivering two demonstration projects for variations of their PowerBuoy point absorber device, whilst Columbia Power Technologies are testing their 500kW point absorber device at WEST in Hawaii. In 2015 Makai Ocean Engineering commissioned a 100kW OTEC demonstration facility at the Hawaii National **Marine** Renewable Energy Center (HINMREC). Adjacent to this is HINMREC's Wave Energy Test Site (WETS) co-managed with the US Navy. The US also offers its Southeast National Marine Renewable Energy Center (SNMREC) for tidal stream testing and its north and south Pacific Marine Energy Centres (PMEC) for wave device testing. Many of these National Marine Renewable Energy Centers (NMRECs) are supported via the Water Power Program that budgeted \$41 million for marine and kinetic energy RD&D in 2015.

The US has drastically increased their **natural gas** reserves and production in recent years. Currently, the US is the largest producer of natural gas globally, while also having the fifth largest total of proved natural gas reserves. The large increase in US natural gas production is mainly a result of significant improvements in the unconventional gas process. The US has been a global leader in the development of unconventional gas, which has led to direct cost and efficiency improvements domestically. For the most part, these improvements have been driven by both large and small independents operating in key US basins. Approximately half of the natural gas production in the US comes from their top seven basins. Of these basins, the Marcellus basin plays the largest role. Domestic consumption of natural gas has also increased with domestic production. The US is the world's largest consumer of natural gas. The large increase in domestic production has led to decreased domestic prices, which further encouraged increasing its usage domestically. Natural gas's share of the domestic energy mix has been increasing, largely at the expense of coal's share. The US has also made significant strides towards becoming a major natural

⁶³ US DOE Regional Partnerships. Available at: www.energy.gov/fe/science-innovation/carbon-capture-and-storage-research/regional-partnerships

⁶⁴ Ren21, (2016)

⁶⁵ Lund & Boyd, (2015)

gas exporter via LNG. Based on the LNG export terminals under construction, the US is expected to have five functioning terminals by 2018. Once expected to be a major importer of natural gas, the combination of their increased domestic natural gas production and their LNG export pursuit has caused the EIA to project the US as a net natural gas exporter by 2017.

The USA is the world's largest producer of **nuclear** power, accounting for more than 30% of worldwide nuclear generation of electricity. The country's 100 nuclear reactors produced 797 billion kWh in 2014, over 19% of total electrical output. There are now 99 units operable and 5 under construction with commissioning expected by 2020. However, lower power prices resulting from the availability of low cost gas compounded by the impact of intermittent renewables have put the economic viability of some existing reactors in merchant power markets in doubt and has resulted in the postponement of proposed nuclear projects. The USA has 99 nuclear power reactors in 30 states, operated by 26 different power companies. Since 2001 these plants have achieved an average capacity factor of over 90% (up from 50% in the 1970s), generating up to 807 billion kWh per year and accounting for 20% of total electricity generated. The industry invests about US\$7.5 billion per year in maintenance and upgrades of these reactors. There are 68 pressurized water reactors (PWRs) with combined capacity of about 64 GWe and 35 boiling water reactors (BWRs) with combined capacity of about 34 GWe – for a total capacity of 98,662 MWe. Almost all the US nuclear generating capacity comes from reactors built between 1967 and 1990. Currently, Southern Company in Georgia has two units under construction, Plant Vogtle 3 and 4 (APWRs) and it will be the first nuclear power generator in 30 years. Also Scana Corporation has two units under construction in South Carolina. Tennessee Valley Authority has just completed Watts Bar Unit 2 and is expected to start commercial operation in summer 2016. Watts Bar Unit 2, can produce 1,150 MWe of continuous electricity and combined with Unit 1, who produce the same amount of MWe, this is enough to supply about 1.3 million homes daily.

At the end of 2014, Red Leaf Resources had secured all permits, capital, and contractor relationships, and was under construction of its Early Production System (EPS), a commercial scale demonstration project located on state land in Uintah County, Utah. In early 2015, Red Leaf announced that it would slow construction of the EPS in order to bring forward innovations that were anticipated for the full commercial capsule design, as well as innovations that will make Red Leaf's proprietary **oil** extraction process more efficient and better aligned with current oil market prices. Red Leaf noted that using their first generation capsule technology, a commercial project would be viable at greater than US\$80 per barrel. They estimated that with these new innovations, a commercial project would be viable at US\$60-US\$80 per barrel. This project is a joint venture between Red Leaf and the French oil super major TOTAL, and utilises Red Leaf's patented EcoShale® technology.

In the EcoShale® process, layers of surface-mined oil shale are placed into large capsules which are lined with an impermeable barrier. Once the oil shale is encapsulated, hot gas will be injected until the shale ore reaches approximately 370°C, at which point vapours rich in hydrocarbons are released from the rock. A liquids collection pan at the bottom and slotted vapour collection pipes at the top of each capsule capture the oil products and feed them into a separation and processing facility. The capsule produces a high-quality, liquid

product with no bottoms or fines. Red Leaf and TOTAL are making a significant investment into the innovations being brought forward, which were previously scheduled to take place after the first generation EPS had proven the scalability of the EcoShale® capsule. Once full construction recommences in 1H 2017, Red Leaf believes that the improved EPS will prove both commercial viability and competitive pricing compared to traditional and emerging resources.

London-based TomCo, a Red Leaf licensee with holdings in Uintah County, also has the requisite permits from the Utah Division of Oil, Gas & Mining and Utah Division of Water Quality (contingent on the Red Leaf EPS demonstration), but will wait to commence full-scale commercial operations until Red Leaf completes the commercial demonstration project. Red Leaf has sold 6 EcoShale technology licenses: Total – US & Jordan, Questerre – Canada and Jordan, TOMCO - Utah, Whitehorn - Jordan, TAQA (only country-wide license granted)- Jordan, OilCorp (site specific to project in Queensland) - Australia (license fee + royalty).

Enefit American Oil (EAO) is owned by the Estonian oil shale energy company Enefit. Roughly 2/3 of the company's 3.5 billion in place barrels in place are located on private land, and EAO also holds a Bureau of Land Management (BLM) Research Development and Demonstration (RDD) lease. EAO is planning on continuing development of its Enefit South Project, demonstrating the applicability of its patented and commercially operating (in Estonia) Enefit technology on the Utah oil shale. The company is working with its head office in Estonia on modifying and optimising its technology and associated process engineering and business plan. EAO is also working towards advancing the status of a portion of its property from a measured and indicated oil shale resource to proven and probable oil shale reserve classification. If this ongoing work is successful, EAO will have achieved the first Reserve for a shale oil production project.

The company's main permitting focus has been geared towards bringing industrial scale utilities across federal land to its project, located on private property. These include an oil pipeline, power lines, a water line, a natural gas lines and a road improvement. EAO has been working with the BLM on an Environmental Impact Statement (EIS) for this utility corridor Right of Way (ROW) since early 2012. In April of 2016, the draft EIS was published by the BLM, and the final EIS and grant of the ROW are planned for 2017. EAO also surpassed an environmental obstacle earlier in 2015 when it faced a potential endangered species listing of two types of penstemon, a rare desert flower, previously thought only to grow on oil shale outcrops. The listing was warded off by the development of a cooperative Conservation Agreement arrived at with various local and state agencies and other stakeholders, including Enefit, who has provided the largest amount of private conservation acreage. Nevertheless, several environmental groups have filed lawsuits against the US Fish and Wildlife Service's decision not to list the plants as endangered species.

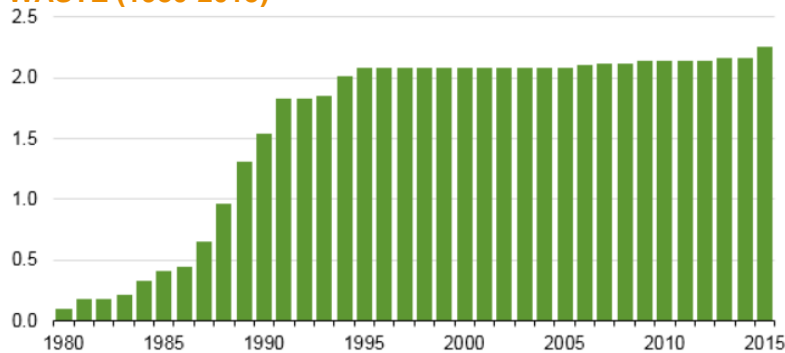
American Shale Oil Corporation (AMSO), a partnership of Total and Genie Energy, is developing a first-round BLM RDD Oil Shale Lease located in the Piceance Basin, Colorado. AMSO is preparing an in-situ pilot retort test that could result, under the terms of the Lease, in an application to the BLM for conversion to a 5120-acre commercial oil shale lease. Various surface and subsurface pilot test facilities have been completed. In-situ

electric heater reliability issues have prevented successful start-up but the company is developing a new in-situ heating system for the pilot who is currently undergoing systematic performance and reliability testing. AMSO will proceed with the in-situ test upon completion of this qualification process.

The total **solar** installed capacity in 2015 was reported to be just over 27 GW. EIA expects that from 2015 to 2017, utility-scale PV capacity will grow by about 14 GW. Planned utility-scale solar additions total 9.5 GW in 2016, more than any other energy source. Distributed solar PV capacity, such as rooftop solar, totalled around 2 GW in 2015. Forecast utility-scale solar power generation averages 1.2% of total U.S. electricity generation in 2017.⁶⁶

United States produced in 2013 about 254 million tons of MSW. In 2015, Waste-to-Energy plants in the United States burned around 29 million tonnes of MSW, of which 26 million were used to generate electricity. Figure 1 below better illustrates the how much electric capacity was added from municipal solid waste from 1980 to 2015.

FIGURE 1: ELECTRIC GENERATING CAPACITY FROM MUNICIPAL SOLID WASTE (1980-2015)



Source: US EIA⁶⁷

At the end of 2015, there were 71 WtE plants in the United States with a total generating capacity of 2.3 gigawatts. The most recent plant came online in Florida, 2015 and is also largest WtE facility. WtE plants provide about 0.4% of total US electricity generation in 2015. Their primary purpose is MSW management, with electricity generation as a second benefit. Most of the WtE electricity generation capacity (roughly 90%) was added between 1908 and 1995 with minor additions after that year. This happened due to the recognition of dioxin and mercury emission levels from waste incineration plants, which created great concerns among the public and hindered the development of further capacity, while also led to the adoption of air pollution control systems to WtE facilities.⁶⁸

In the United States, 61% of all capacity additions were related to renewables, followed by the additions of gas that represented 35% of the total. 7,728 MW of **wind** power capacity came online in 2015, much higher than the additions in 2013 and 2014, but still lower than

⁶⁶ EIA, (2015)

⁶⁷ EIA, (2016)

⁶⁸ EIA *ibid*

the record high year of 2012 that has seen an installation in capacity of 13,399 MW. Wind energy now accounts for nearly 4.7% of the national electricity generation. The key federal incentive for wind energy—the Production Tax Credit (PTC) – has been extended, but support levels will reduce until 2019. An interesting fact from 2015 was that around half of new wind power in the United States was directly bought by large consumers from project developers, thus avoiding traditional power suppliers.

Wind power generation is mainly concentrated in Midwest of the country. There is further potential to grow wind capacity here and in several other parts of the country. The main challenge will be to connect supply with the demand centres. Studies looking into higher shares of wind and solar in total generation in the short-term has concluded that significant long-distance transmission line capacity needs to be built and interconnector capacity between states need to be strengthened. Given the long time required for building such infrastructure, planning needs to start immediately.

UZBEKISTAN

Although Uzbekistan does not have a particularly large total of proved **natural gas** reserves relatively, they still are an important natural gas nation due to their natural gas production and consumption. Uzbekistan had 1085.9 bcm of proved natural gas reserves as of 2014 and the country has been able to turn their reserves into significant production consistently. In 2014, Uzbekistan produced 57.3 bcm of natural gas, which made them the world's 14th largest producer of natural gas.

While Uzbekistan is a large producer of natural gas, they have also established themselves as significant consumers of natural gas. Uzbekistan consumed 48.8 bcm of natural gas in 2014, making them the 13th largest consumer of natural gas in the world. Furthermore, this significant natural gas consumption resulted in natural gas playing a key role in the country's energy mix. In 2014, natural gas was responsible for ~85.5% of Uzbekistan's primary energy consumption.

Although Uzbekistan consumes a significant amount natural gas, their large production still allows them to be an important exporter of natural gas as well. Uzbekistan exports their natural gas through pipeline trade. The country exported 8.5 bcm of pipeline natural gas in 2014 with Russia being the largest importer at 4.1 bcm.

VENEZUELA

Venezuela has the second highest **hydropower** capacity in South America with an installed capacity of 15,393 MW. The country completed the 771 MW Fabricio Ojeda project in 2015, synchronising the third and final 257 MW turbine. The 2,160 MW Manuel Carlos Piar project is also nearing completion on the Caroní River in Venezuela's Bolívar state.

Venezuela has established themselves as an important **natural gas** nation mainly due to their massive total of proved natural gas reserves. Venezuela had 5,617 bcm of proved natural gas reserves as of 2014, which gave them the eighth largest total of proved natural

gas reserves in the world. Additionally, they hold the second largest total of proved natural gas reserves in the Western Hemisphere behind only the US.

Venezuela's significant level of proved reserves has not resulted in major natural gas production as of yet. Throughout the years, Venezuela has focused significantly more attention on domestic oil production as opposed to natural gas production. Additionally, the natural gas that is present in Venezuela is heavily linked with oil. This is evidenced by the fact that approximately 90% of the country's natural gas reserves are associated with oil. Even given their large reserve base, Venezuela only produced 21.9 bcm of natural gas in 2014.

Venezuela is also not a major consumer of natural gas relative to their large natural gas reserve base. Furthermore, their natural gas consumption has begun to slightly slip in recent years. In 2014, Venezuela's natural gas consumption was 29.8 bcm, which represented a 4% decline from the previous year and marked the second consecutive year of falling natural gas consumption.

Natural gas's share of the country's primary energy mix is not the largest, however it still plays an important role. Natural gas is responsible for 31.8% of Venezuela's primary energy consumption. It is estimated that natural gas is responsible for approximately half of the country's electricity generation from fossil fuels. Furthermore, the petroleum industry in Venezuela consumed approximately 35% of the country's gross natural gas production, of which a significant portion was reinjected in efforts to aid oil production.

Venezuela has a massive natural gas pipeline network and has also made efforts to improve the network in recent years. Venezuela has approximately 2,750 miles of natural gas pipelines, which assist in the country's ability to easily transport natural gas domestically. Historically, Venezuela has imported natural gas through pipeline trade with Colombia in order to fulfil the gap between their production and consumption. This natural gas importation was made possible due to the country's established natural gas pipeline network.

Venezuela is perhaps the most vulnerable to the **oil** price slump, which is threatening its financial and social wellbeing and leaving it precious little cash to fund crucial capacity expansions. Oil output capacity in Latin America's biggest producer, now estimated at around 2.6 mb/d, is expected to fall in the early part of the forecast period before recovering by 2020. State oil company PDVSA will reportedly make cuts in its 2015 spending.

VIETNAM

Vietnam commissioned four **hydropower** stations totalling 1,030 MW in 2015, reaffirming the country's commitment to further hydropower development. The government's new strategy to 2030 prioritises renewable energy and plans to increase hydropower generation from 62 TWh in 2015 to 90 TWh by 2020, which corresponds to a total installed hydropower capacity of 21,000 MW by 2020.

YEMEN

Although Yemen is not a significant producer or consumer of **natural gas** and does not have a large base of proved natural gas reserves, the country plays an important role in natural gas due to their LNG exports. As of 2014, Yemen only had 268.9 bcm of proved natural gas reserves.

In addition to their low proved natural gas reserves, Yemen is a very minor natural gas producer and consumer. Yemen only produced 9.6 bcm of natural gas in 2014. This level of natural gas production in 2014 marked a 6.3% drop in production from the previous year.

Although Yemen only produces a small amount of natural gas, they have been able to establish themselves as a natural gas exporter due to exporting almost all of their limited natural gas production. More specifically, Yemen exports their natural gas via LNG. In 2014, Yemen exported 8.9 bcm of natural gas via LNG. Therefore, Yemen exported approximately 93% of their total natural gas production as LNG in 2014. South Korea was the largest importer of Yemen's natural gas at 4.2 bcm.

ZAMBIA

Zambia's 2,272 MW of installed **hydropower** capacity accounts for over 90% of domestic energy supply, and the country still has an estimated 6,000 MW of undeveloped hydropower potential. Plans to add a further 1,100 MW new capacity by 2019 include the 750 MW Lower Kafue Gorge project, which started construction in 2015.

APPENDICES

ABBREVIATIONS AND ACRONYMS

10³ – kilo (k)

10⁶ – mega (M)

10⁹ – giga (G)

10¹² – tera (T)

10¹⁵ – peta (P)

10¹⁸ – exa (E)

10²¹ – zeta (Z)

ABWR – advanced boiling water reactor

AC – alternating current

ACI – activated carbon injection

AD – Anaerobic Digestion

ADS – accelerator driven reactors

AEMFC – African Exploration and Mining Finance Company

AES – Aurora Energy Services

AfDB – African Development Bank

AHWR – advanced heavy water reactor

AMSO – American Shale Oil Corporation

API – American Petroleum Institute

APR – advanced pressurised reactor

APT – The Alberta Taciuk Process

APWR – advanced pressurised water reactor

AVR – automatic voltage regulators

bbi – billion barrels

bcf – billion cubic feet

bcm – billion cubic metres

b/d – barrels per day

BFB – bubbling fluidised bed

BGR – Bundesanstalt für Geowissenschaften und Rohstoffe

BIPV – building integrated PV

bn – billion

BNPP – buoyant nuclear power plant

boe – barrel of oil equivalent

BOO – build, own, operate

BOPD – barrels of oil per day

BoS – balance of system

BOT – build, operate, transfer

bpsd – barrels per stream-day

BRICS – Brazil, Russia, India and China

bscf – billion standard cubic feet

BSEE – US Bureau of Safety and Environmental Enforcement

Btu – British thermal units

BWE – bucket wheel excavator

BWRs – boiling (light) water reactors

C – Celsius

CAA – Clean Air Act

CAES – compressed air energy storage

CAGR – compound annual growth rate

CAPEX – capital expenditure

CBM – coal bed methane

CCGT – combined cycle gas turbines

CCP – coal combustible products

CCS – Carbon Capture and Storage

CCUS – Carbon Capture Utilisation and Storage

CCT – clean coal technologies

CDM – Clean Development Mechanism

CdTe – cadmium telluride	CSP – concentrated solar power
CEDREN – Centre for Environmental Design of Renewable Energy	CTL – coal to liquid
CES – cryogenic energy storage	d – day
Cf – cubic feet	db(A) – A-weighted decibels
CFB – circulating fluidised bed	DC – direct current
CFC – chlorofluorocarbon	DCR – domestic content regulation
CFD – computational fluid dynamics	DECC – UK Department of Energy and Climate Change
CH₄ – methane	DHC – district heating and cooling
CHP – Combined Heat and Power	DHW – domestic hot water
CIL – Coal India Limited	DLE – dendro liquid energy
CIS – Commonwealth of Independent States	DME – dimethyl ether
CIS/CIGS – copper-indium/gallium-diselenide/disulphide	DNI – Direct Normal Irradiance
CLFR – compact linear Fresnel reflector	DoC – Department of Commerce
Cm – centimetre	DOI – US Department of the Interior
CMM – coal mine methane	DOWA – deep ocean water applications
CNG – compressed natural gas	DR – demand response
CNPC – China National Petroleum Corporation	DRE – distributed renewable energy
CO₂ – carbon dioxide	DSO – Distribution System Operator
CO_{2e} – carbon dioxide equivalent	DWH – Deep Water Horizon
Co-Gen – Co-generation	EAO – Enefit American Oil
COP21 – 21 st Conference of Parties	EC – European Commission
COS – Centre for Offshore Safety	ECAs - Emission Control Areas
cP – centipoise	ECBM – enhanced Coal-bed methane
CPP – Clean Power Plan	ECE – Economic Commission for Europe
CPS – Carbon Pollution Standards	ECUs – European Currency Units
CPV – concentrated photovoltaics	EEA – European Economic Area
CRA – Charles River Associate	EEPR - European Energy Programme for Recovery
CRM – Capacity Remuneration Mechanism	EFR – enhanced frequency response
c-Si – crystalline silicon	EGS – engineered geothermal systems

EIA – US Energy Information Administration	FSU – former Soviet Union
EIB – European Investment Bank	Ft – feet
EJ – exajoules	g – gram
EMEC – European Marine Energy Centre	GBEP – Global Bioenergy Partnership
EOR – enhanced oil recovery	gC – grams carbon
E&P – exploration and production	GCR – Gas-cooled reactor
E2P – energy to power ratio	GDP – Gross Domestic Product
EPA – Environmental Protection Agency	GEA – Geothermal Energy Association
EPIA – European Photovoltaic Industry Association	GEF – Global Environment Facility
EPR – European pressurised water reactor	GERD – Grand Ethiopian Renaissance Dam
EPRI – Electric Power Research Institute	GHG – greenhouse gas
ESS – energy storage system	GHI – Global Horizontal Irradiance
ESTIF – European Solar Thermal Industry Federation	GHP – ground-sourced heat pumps
ETBE – ethyl tertiary butyl ether	GIB – Green Investment Bank
ETS – Emissions Trading Scheme	GIP – Global Infrastructure Partners
EU – European Union	GNI – Gross National Income
EV – Electric Vehicles	Gt – gross tonnage
F – Fahrenheit	GTL – gas to liquids
FAO – UN Food and Agriculture Organization	GTW – gas to wire
FBC – fluidised bed combustion	GW – gigawatt
FBR – fast breeder reactor	GW_e – gigawatt electricity
FGD – flue gas desulphurisation	GWh – gigawatt hour
FID – Final investment decision	GWth – gigawatt thermal
FiPs – feed-in premiums	h – hour
FIT – Feed in Tariffs	ha - hectare
FLNG – Floating liquefied natural gas	HAWT – Horizontal-axis wind turbine
FNRs – Fast Neutron Reactors	HCPV – high concentration photovoltaic
FSRU – floating storage and regasification units	HDR – hot dry rocks
	HELE – high-efficiency, low-emissions
	HEMS – home energy management systems

HEFA – hydro-treated ester and fatty acids	IR – inferred resources
HFO – heavy fuel oil	IRR – internal rate of return
HPP – hydro power plant	ISO – International Standards Organisation
HPHT – high-pressure, high-temperature	J – joule
HTC – hydrothermal carbonisation	JNNSM – Jawaharlal Nehru National Solar Mission
HTF – heat transfer fluid	kcal – kilocalorie
HTR – high temperature reactor	kg – kilogram
H₂S – hydrogen sulphide	km – kilometre
HTRs – high-temperature gas-cooled reactors	Km² – square kilometre
HVDC – high-voltage, direct current	kt – kiloton
HVO – hydrogenated vegetable oil	ktoe – thousand tonnes of oil equivalent
Hz - Hertz	kWe – kilowatt electricity
IAEA – The International Atomic Energy Agency	kWh – kilowatt hour
IBRD – International Bank for Reconstruction and Development	kWt – kilowatt thermal
ICE – internal combustion engine	LAC – Latin America and the Caribbean
IEA – International Energy Agency	LAES – liquid air energy storage
IEGT – injection-enhanced gate transistor	lb – pound (weight)
IGCC – integrated gasification combined cycle	LCA – life cycle analysis
IHA – International Hydropower Association	LCOE – levelised cost of electricity
IMF – International Monetary Fund	LCPV – low concentration photovoltaic
IMO – International Maritime Organization	LDC – Least Developed Countries
INDC – Intended Nationally Determined Contributions	LED – light-emitting diode
InP – indium phosphide	LFG – landfill gas
IOC – International Oil Company	LNG – liquefied natural gas
IPCC – Intergovernmental Panel on Climate Change	LOHC – liquid organic hydrogen carrier
IPP – independent power producer	LPG – liquefied petroleum gas
IRENA – International Renewable Energy Agency	LSHFO – low-sulphur heavy fuel oil
	LTCs – long-term contracts
	LTO – light tight oil
	LWGR – light water (cooled) graphite (moderated) reactor

LWR – light water reactor	NETL – National Energy Technology Laboratory
m – metre	NGCC – natural gas-fired combined cycle
m/s – metres per second	NGL – natural gas liquids
m² – squared metre	NGO – non-governmental organisation
m³ - cubic metres	NH₃ – ammonia
MBT – mechanical and biological treatment	NiCd – nickel-cadmium
mcal – megacalorie	Ni-MH – nickel–metal hydride
MDB – Multilateral Development Bank	NLC – Neyveli Lignite Corporation
mb/d – million barrels per day	Nm³ – normal cubic metre
MFC – Microbial Fuel Cell	NOx – nitrogen oxides
MJ – mega joule	NOCs – National Oil Companies
MJ/kg – mega joules per kilogram	NPP – nuclear power plant / net primary productivity
MLR – Ministry of Land and Resources	NREL – National Renewable Energy Laboratory
mm – millimetre	NTPC – National Thermal Power Corporation
MOX – mixed oxide	NWP – numerical weather prediction
MOU – memorandum of understanding	NZD – New Zealand Dollar
m/s – metre per second	OAPEC – Organisation of Arab Petroleum Exporting Countries
MSRs – Molten Salt Reactors	OECD – Organisation for Economic Co-operation and Development
MSs – Member States	OEM – Original Equipment Manufacturer
MSW – Municipal Solid Waste	OGL – open general license
mt – million tonnes	O&M – operations and maintenance
mtoe – million tonnes of oil equivalent	OPEC – Organisation of the Petroleum Exporting Countries
mtpa – million tonnes per annum	OSPRAG – Oil Spill Prevention and Response Advisory Group
MW – megawatt	OTEC – ocean thermal energy conversion
MWh – megawatt hour	OWC – oscillating water columns
MWp – megawatt peak	p.a. – per annum
MWt – megawatt thermal	PBMR – pebble bed modular reactor
NCCC – National Carbon Capture Centre	
NDMA – N-nitrosodimethylamine	
NEA – Nuclear Energy Agency	
NER – new entrants reserve	

PC – pulverised coal	SCADA – Supervisory Control and Data Acquisition
PDO – plan for development and operation	SCCL - Singareni Collieries Company Limited
PFBR – prototype fast breeder reactor	SCR – selective catalytic reduction
PHS – Pumped hydro energy storage	SEC – US Securities and Exchange Commission
PHWR – pressurised heavy water reactor fuel	SEGS – Solar Energy Generating Systems
ppm – parts per million	SHS – solar home system
ppmv – parts per million by volume	SIC – specific investment costs
Pu94 – plutonium	SIPH – solar industrial process heat
PM – particulate matter	SMES – superconducting magnetic energy storage
PPA – power purchase agreements	SMRs – small modular reactors
PTC – parabolic trough collector	SNCR – selective non-catalytic reduction
PtG/P2G – power to gas	SNG – synthetic natural gas
PTO – power take off	SO₂ – sulphur dioxide
PV – photovoltaic	SO_x – sulphur oxides
PWh/yr – Peta watt hour	SSLNG – small scale LNG
PWRs – pressurised (light) water reactors	SWH – solar water heating
RAR – reasonably assured resources	SWT – small wind turbines
RCSP – Regional Carbon Sequestration Partnerships	T – tonne (metric tonne)
R&D – Research & Development	tb/d – thousand barrels per day
RDD – Research Development and Demonstration	tC – tonnes carbon
REIPPPP – Renewable Energy Independent Power Producers Procurement Programme	tce – tonne of coal equivalent
REN21 – Renewable Energy for the 21 st century	tcf – trillion cubic feet
RFS2 – The Renewable Fuels Standard 2	tcm – trillion cubic metres
RO – reverse osmosis	tHM – tonnes of heavy metal
R/P – reserves-to-production ratio	toe – tonnes of oil equivalent
RPS – Renewable Portfolio Standards	tpa – tonnes per annum
RSB – roundtable on sustainable biofuels	TPP – tidal power plant
SAR – South Asian Region	TRLs – Technology Readiness Levels
	TSC – thermosiphon cooling

Ttoe – thousand tonnes of oil equivalent	W – watt
tU – tonnes of uranium	WACC – weighted average cost of capital
TWh – terawatt hour	WANO – World Association of Nuclear Operators
U – uranium	WBA – World Bioenergy Association
U3O8 – uranium oxide concentrate	WCD – World Commission on Dams
UCG – underground coal gasification	WEC – wave energy convertor
UCM – Usibelli Coal Mine	WHO – World Health Organisation
UMPP – Sasan Ultra Mega Power Project	WtE – Waste-to-Energy
UN – United Nations	WTI – West Texas Intermediate
UNDP – United Nations Development Programme	WTO – World Trade Organisation
UNFCCC – United Nations Framework Convention of Climate change	WWER – water-cooled water-moderated power reactor
UNSCEAR – United Nations Scientific Committee on the Effects of Atomic Radiation	W4EF – Water for Energy Framework
US DOE – Department of Energy	yr – year
VAWT – vertical-axis wind turbines	µm – micrometre
VLS – vapour-liquid-solid	~ approximately
VOC – volatile organic compounds	< less than
Vol - volume	> greater than
	≥ greater than or e

GLOSSARY AND DEFINITIONS

Acetic acid

A colourless, pungent, water-miscible liquid, $C_2H_4O_2$, the essential constituent of vinegar, produced by oxidation of acetaldehyde, bacterial action on ethyl alcohol, the reaction of methyl alcohol with carbon monoxide, and other processes: used chiefly in the manufacture of acetate fibres and in the production of numerous esters that are solvents and flavouring agents.

Acid catalyst

In acid catalysis and base catalysis a chemical reaction is catalysed by an acid or a base. The acid is the proton donor and the base is the proton acceptor. Typical reactions catalysed by proton transfer are esterification and aldol reactions.

Aggregation

Bundling several wind energy projects together so that they are treated as one larger project (for example, when purchasing turbines, interconnecting or maintaining a project) to distribute costs among more turbines or projects. This practice can improve project economics.

Alternating current (AC)

Electric current that reverses direction many times per second.

Amino acids

Simple organic compounds containing both a carboxyl ($-COOH$) and an amino ($-NH_2$) group. They are the building blocks of proteins.

Amorphous silicon (a-Si)

Is the non-crystalline form of silicon used for solar cells and thin-film transistors in LCD displays. Used as semiconductor material for a-Si solar cells, or thin-film silicon solar cells, it is deposited in thin films onto a variety of flexible substrates, such as glass, metal and plastic.

Ancillary services

Capacity and energy services provided by power plants that are able to respond on short notice, such as hydropower plants, and are used to ensure stable electricity delivery and optimised grid reliability.

Anemometer

An instrument used to measure the velocity, or speed, of the wind.

Annual production

It is the production output of uranium ore concentrate from indigenous deposits, expressed as tonnes of uranium. Cumulative production is the total cumulative production output of uranium ore concentrate from indigenous deposits, expressed as tonnes of uranium, produced in the period from the initiation of production until the end of the year stated.

Anthropogenic

(chiefly of environmental pollution and pollutants) originating from human activity.

API gravity

API gravity is American Petroleum Institute measure of specific gravity of crude oil or condensate in degrees. It is an arbitrary scale expressing the gravity or density of liquid petroleum products. The measuring scale is calibrated in terms of degrees API. If oil's API gravity is greater than 10, it is lighter and floats on water; if it is less than 10, it is heavier and sinks.

Base load plant

Plant operates at maximum output at all times to provide maximum energy into the grid used to meet some or all of a given region's continuous energy demand.

Battery

Two or more electric cells connected together electrically. In common usage, the term battery is also applied to a single cell, such as a household battery. Battery technologies used for energy storage applications include lithium-ion (Li-ion), sodium-sulphur (NaS) and lead acid (L/A).

Black start capability

The process of restoring a power station to operation without relying on the external electric power transmission network.

Bilateral contract

Is a reciprocal arrangement between two parties where each promises to perform an act in exchange for the other party's act. Each party is an (a person who is bound to another) to its own promise, and an obligee (a person to whom another is obligated or bound) on the other party's promise.

Binary cycle power plant

Binary cycle power plants are closed-loop systems, and virtually nothing (except water vapour) is emitted to the atmosphere. Low to moderately heated (below 400°F) geothermal fluid and a secondary (hence, "binary") fluid with a much lower boiling point that water pass through a heat exchanger. Heat from the geothermal fluid causes the secondary fluid to flash to vapour, which then drives the turbines and subsequently, the generators.

Biodiesel

An alternative fuel similar to conventional or 'fossil' diesel and can be produced from straight vegetable oil, animal oil/fats, tallow and waste cooking oil. The process used to convert these oils to biodiesel is called transesterification.

Bioenergy

Is energy derived from the conversion of biomass where biomass may be used directly as fuel, or processed into liquids and gases.

Biogenic

Produced or brought about by living organisms.

Biomass

Is any organic, i.e. decomposable, matter derived from plants or animals available on a renewable basis. Biomass includes wood and agricultural crops, herbaceous and woody energy crops, municipal organic wastes as well as manure.

Bio-methane

A naturally occurring gas which is produced by the so-called anaerobic digestion of organic matter such as dead animal and plant material, manure, sewage, organic waste, etc. Chemically, it is identical to natural gas which is stored deep in the ground and is also produced from dead animal and plant material.

Bituminous sands (oil sands, tar sands)

Loose sand or partially consolidated sandstone containing naturally occurring mixtures of sand, clay, and, water saturated with a dense and extremely viscous form of petroleum (bitumen). Bitumen is a thick, sticky form of hydrocarbon, so heavy and viscous (thick) that it will not flow unless heated or diluted with lighter hydrocarbons. Bitumen has a viscosity greater than 10,000 centipoises under reservoir conditions and an API gravity of less than 10° API.

Brine

A geothermal solution containing appreciable amounts of sodium chloride or other salts.

Brownfield development

Land is an area of land or premises that has been previously used, but has subsequently become vacant, derelict or contaminated. This term derived from its opposite, undeveloped or 'greenfield' land.

Bulk carrier, bulk freighter, or bulker

Is a merchant ship specially designed to transport unpackaged bulk cargo, such as grains, coal, ore, and cement in its cargo holds.

Cadmium

Is a chemical element with symbol Cd and atomic number 48. This soft, bluish-white metal is chemically similar to the two other stable metals in group 12, zinc and mercury. The main sources of cadmium in the air are the burning of fossil fuels such as coal or oil and the incineration of municipal waste.

Cadmium telluride (CdTe)

Is a photovoltaic (PV) technology based on the use of a thin film of CdTe to absorb and convert sunlight into electricity.

CAES

Compressed Air Energy Storage (CAES) systems use off-peak electricity to compress air, storing it in underground caverns or storage tanks. This air is later released to a combustor in a gas turbine to generate electricity during peak periods.

CAGR

The compound annual growth rate (CAGR) is the mean annual growth rate of an investment over a specified period of time longer than one year.

Calorific value

The energy contained in a fuel or food, determined by measuring the heat produced by the complete combustion of a specified quantity of it. This is now usually expressed in joules per kilogram.

Capacity factor

The ratio of the electrical energy produced by a generating unit for the period of time considered to the electrical energy that could have been produced at continuous full power operation during the same period. A percentage that tells how much of a power plant's capacity is used over time. For example, typical plant capacity factors range as high as 80% for geothermal and 70% for cogeneration.

Capital cost

One-time setup cost of a plant or project, after which there will only be recurring operational or running costs.

Carbon cycle

The combined processes, including photosynthesis, decomposition, and respiration, by which carbon as a component of various compounds cycles between its major reservoirs—the atmosphere, oceans, and living organisms.

Carbon dioxide (CO₂)

A colorless, odorless, non-poisonous gas that is a normal part of Earth's atmosphere. Carbon dioxide is a product of fossil-fuel combustion as well as other processes. It is considered a greenhouse gas as it traps heat (infrared energy) radiated by the Earth into the atmosphere and thereby contributes to the potential for global warming. The global warming potential (GWP) of other greenhouse gases is measured in relation to that of carbon dioxide, which by international scientific convention is assigned a value of one.

Carbon Monoxide

Is a colourless, odourless, tasteless, poisonous gas produced by incomplete burning of carbon-based fuels, including gas, oil, wood and coal.

Capital Expenditures (CapEX)

Are funds used by a company to acquire or upgrade physical assets such as property, industrial buildings or equipment. It is often used to undertake new projects or investments by the firm.

Carbon market

The set of organised and bilateral transactions by which countries trade credits received for greenhouse-gas emission reductions. The market is used to comply with emission goals, or to voluntarily offset a country's own emissions. The carbon market was launched by the creation of three mechanisms under the Kyoto Protocol: emissions trading, across developed countries; the Clean Development Mechanism, based on projects in developing countries; and Joint Implementation, based on projects in developed countries.

Carbon Sequestration

A natural or artificial process by which carbon dioxide is removed from the atmosphere and held in solid or liquid form.

Circular economy

Is an alternative to a traditional linear economy (make, use, dispose) in which we keep resources in use for as long as possible, extract the maximum value from them whilst in use, then recover and regenerate products and materials at the end of each service life.

Circulating Fluidised Bed Combustion (CFBC)

Units that use bed materials (such as silica sand) to support the combustion of coal or any solid fuels around 900°C temperature to generate heat. Steam generated inside the combustor can be used for power generation in steam turbines. CFBCs can tolerate varying particle size (from micron size as in pulverized coal-fired units to coarse feed size around ~10mm), varying fuel quality (from anthracite to lignite, petroleum coke, biomass, and opportunity fuels).

Citric acid

Is a weak organic acid found in citrus fruits. It is a natural preservative and is also used to add an acidic (sour) taste to foods and soft drinks. In biochemistry, it is important as an intermediate in the citric acid cycle and therefore occurs in the metabolism of almost all living things.

Clean Development Mechanism (CDM)

Defined in Article 12 of the Kyoto Protocol, allows a Country with an emission-reduction or emission-limitation commitment under the Kyoto Protocol (Annex B Party) to implement an emission-reduction project in developing countries. Such projects can earn saleable certified emission reduction (CER) credits, each equivalent to one tonne of CO₂, which can be counted towards meeting Kyoto targets.

Cogeneration (cogen)

Through combined heat and power (CHP) is the simultaneous production of electricity with the recovery and utilisation heat.

Commodity

A raw material or primary agricultural product that can be bought and sold, such as copper or coffee.

Comprehensive electrification

Is the process of powering by electricity and is usually associated with changing over from another power source.

Computational fluid dynamics (CFD)

Is the use of applied mathematics, physics and computational software to visualize how a gas or liquid flows -- as well as how the gas or liquid affects objects as it flows past.

Conventional oil

Crude oil that is produced by a well drilled into a geologic formation from which oil flows readily to the wellbore. API gravity greater than 20° (density below 0.934 g/cm³).

Conventional resources

Petroleum which is recovered through wellbores and typically requires minimal processing prior to sale.

Conversion efficiency

This measure gauges the percentage of solar (light) power reaching a module that is converted into electrical power. Conventional cells now range in the high percentage teens. Theoretical and laboratory conversion rates typically are much higher than rates from mass production.

Coking coal

Is an essential ingredient in steel production. It is different to thermal coal which is used to generate power. Coking coal, also known as metallurgic coal, is heated in a coke oven which forces out impurities to produce coke, which is almost pure carbon.

Copper-Indium gallium selenide

Solar cell is a thin-film solar cell used to convert sunlight into electric power.

Cycle life

The number of charge-discharge cycles (one sequence of storage charging and discharging) after which storage becomes inoperable or unusable for a given application. In practice, storage may be inoperable or unusable when it can still deliver a portion of its initial Energy Capacity and/or Nominal Power.

db(A)

A-weighted decibels are an expression of the relative loudness of sounds in air as perceived by the human ear.

Decommission

An individual or series of wind turbines, or an entire wind project, which is taken offline, meaning the turbines no longer deliver electricity to the grid on a permanent basis. Projects or turbines that are decommissioned are commonly removed physically from the project site, but physical removal is not a requirement.

Depth of discharge (DOD)

The portion of energy discharged from a storage system relative to the Nominal Capacity.

Digestate

Is a nutrient-rich substance produced by anaerobic digestion that can be used as a fertiliser. It consists of left over indigestible material and dead micro-organisms - the volume of digestate will be around 90-95% of what was fed into the digester.

Digester

Is a sealed vessel, or series of vessels, in which bacteria act without oxygen.

Dioxins

Are a group of chemically-related compounds that are persistent environmental pollutants (POPs) and are highly toxic. They are formed as a result of combustion processes such as waste incineration (commercial or municipal) or from burning fuels (like wood, coal or oil).

Direct-drive generators

Operate at lower rotational speeds and do not need gear boxes. The rotor shaft is attached directly to the generator, which spins at the same speed as the blades.

Direct Use

Use of geothermal heat without first converting it to electricity, such as for space heating and cooling, food preparation, industrial processes, etc.

Discharge Time

The amount of time over which the energy stored in a storage device can be discharged at the nominal power rating. It is therefore the Energy Capacity divided by the Nominal Power.

Disposal

1. The final placement of MSW that is not salvaged or recycled. 2. The process of finally disposing MSW in a landfill. 3 MSW disposal is an ultimate action by which MSW is disposed on land in acceptable engineering manner with and/or without previous treatment/processing and/or recycling.

Dispatchable power (“Fast Peaking”)

Dispatchable generation refers to sources of electricity that can be dispatched at the request of power grid operators; that is, generating plants that can be quickly turned on or off, or can adjust their power output on demand.

Distributed generation

A small-scale power generation technology that provides electric power at a site closer to customers than central power plant generation. The term is commonly used to indicate non-utility sources of electricity, including facilities for self-generation.

Dragline

Excavator is a piece of heavy equipment used in civil engineering and surface mining. Draglines fall into two broad categories: those that are based on standard, lifting cranes, and the heavy units which have to be built on-site.

Dry steam power plants

Dry steam plants use hydrothermal fluids that are primarily steam. The steam travels directly to a turbine, which drives a generator that produces electricity. The steam eliminates the need to burn fossil fuels to run the turbine (also eliminating the need to transport and store fuels). These plants emit only excess steam and very minor amounts of gases.

Dye-sensitised solar cells

This experimental cell (Graetzel Cell) is made by with a layer of Titanium Dioxide TiO₂ that has absorbed natural dye anthocyanin pigment from a raspberry. Iodide solution provides a means of transferring electrons into the dye.

Efficiency

A percentage obtained by dividing the actual power or energy by the theoretical power or energy. It represents how well the hydropower plant converts the potential energy of water into electrical energy.

Endothermic

Process describes a process or reaction in which the system absorbs energy from its surroundings; usually, but not always, in the form of heat.

Energy capacity (Joules, kWh, MWh, GWh)

The amount of energy that can be stored and recovered from a storage device.

Energy recovery

Obtaining energy from MSW through a variety of processes (e. g. combustion.)

Energy storage

Energy storage is a mechanism to contain useful energy which can then be used at some later time in the future.

Energy to Power ratio, E2P

Energy capacity divided by the nominal power. It is therefore identical to Discharge Time.

Energy-Water nexus

Water is required to produce energy. Energy is required to pump, treat, and transport water. The energy-water nexus examines the interactions between these two inextricably linked sectors.

Engineered geothermal systems or Enhanced Geothermal Systems (EGS)

Are engineered reservoirs created to produce energy from geothermal resources that are otherwise not economical due to lack of water and/or permeability. EGS technology has the potential for accessing the earth's vast resources of heat located at depth. Heat can be extracted by creating a subsurface fracture system to which water can be added through injection wells. Injected water is heated by contact with the rock and returns to the surface through production wells, as in naturally occurring hydrothermal systems.

Enthalpy

It represents a thermodynamic quantity equivalent to the total heat content of a system. It is equal to the internal energy of the system plus the product of pressure and volume. "Enthalpy is the amount of energy in a system capable of doing mechanical work".

Ethanol

Is a renewable, domestically produced alcohol fuel made from plant material, such as corn, sugar cane, or grasses.

Evapotranspiration

Transfer of moisture from the earth to the atmosphere by evaporation of water and transpiration from plants.

Exothermic

Is a chemical reaction that releases energy by light or heat. It is the opposite of an endothermic reaction. Expressed in a chemical equation: reactants → products + energy.

Extra-heavy oil

Extra-heavy oil differs from natural bitumen in the degree by which it has been degraded from the original conventional oils by bacteria. Extra-heavy oil has a gravity of less than 10° API and a reservoir viscosity of no more than 10,000 centipoises (density greater than 1000 kg/m³).

Fatty acids

A carboxylic acid consisting of a hydrocarbon chain and a terminal carboxyl group, especially any of those occurring as esters in fats and oils.

Feed-in premiums

Electricity from renewable energy sources (RES) is typically sold on the electricity spot market and RES producers receive a premium on top of the market price of their electricity production.

Feed-in Tariffs (FiT)

A payment made to households or businesses generating their own electricity through the use of methods that do not contribute to the depletion of natural resources, proportional to the amount of power generated.

Feedstock

Raw material used in a processing plant.

Fish ladder

A transport structure for safe upstream fish passage around hydropower projects.

Flash steam power plant

Flash steam plants are the most common type of geothermal power generation plants in operation today. Fluid at temperatures greater than 182°C is pumped under high pressure into a tank at the surface held at a much lower pressure, causing some of the fluid to rapidly vaporise, or "flash." The vapour then drives a turbine, which drives a generator. If any liquid remains in the tank, it can be flashed again in a second tank to extract even more energy.

Flue gas

Is the gas exiting to the atmosphere via a flue, which is a pipe or channel for conveying exhaust gases from a fireplace, oven, furnace, boiler or steam generator. Quite often, the flue gas refers to the combustion exhaust gas produced at power plants.

Flue gas desulfurisation unit (Scrubber)

Equipment used to remove sulphur oxides from the combustion gases of a boiler plant before discharge to the atmosphere. Chemicals like lime are used.

Fresnel lens

A flat lens made of a number of concentric rings, to reduce spherical aberration.

Furan

Is a clear, colourless, flammable liquid cyclic ether with an ethereal odour. Furan is used as an intermediate in the production of tetrahydrofuran, pyrrole and thiophene. Inhalation exposure to this substance causes eye and skin irritation and central nervous system depression.

Generation efficiency

The electric power plant efficiency η is defined as the ratio between useful electricity output from the generating unit, in a specific time unit, and the energy value of the energy source supplied to the unit, within the same time.

Generator

Device that converts the rotational energy from a turbine to electrical energy.

Geyser

A spring that shoots jets of hot water and steam into the air.

Global warming potential

A measure of the total energy that a gas absorbs over a particular period of time (usually 100 years), compared to carbon dioxide.

Graphene

A form of carbon consisting of planar sheets which are one atom thick, with the atoms arranged in a honeycomb-shaped lattice.

Green bond

Is a fixed-income financial instrument for raising capital through the debt capital market. The key difference between a 'green' bond and a regular bond is that the issuer publicly states it is raising capital to fund 'green' projects, assets or business activities with an environmental benefit, such as renewable energy, low carbon transport or forestry projects.

Greenhouse gas emissions

Any of the atmospheric gases that contribute to the greenhouse effect by absorbing infrared radiation produced by solar warming of the Earth's surface. They include carbon dioxide (CO₂), methane (CH₄), nitrous oxide (NO₂), and water vapour.

Grid parity

The point in time, at which a developing technology will produce electricity for the same cost to ratepayers as traditional technologies. That is, when the new technology can produce electricity for the same cost as the electricity available on a utility's transmission and distribution 'grid'.

Heating value

Is the amount of heat produced by combustion a unit quantity of a fuel. The lower heating value (LHV) or higher heating value (HHV) of a gas is an important consideration when selecting a gas engine or CHP plant.

Heavy oil

Oil with API gravity from 10° to 20° inclusive (density above 1000 kg/m³).

Heliostat

An apparatus containing a movable mirror, used to reflect sunlight in a fixed direction.

HVDC infrastructure

high-voltage, direct current (HVDC) electric power transmission system, also called a power super highway or an electrical super highway, uses direct current for the bulk transmission of electrical power, in contrast with the more common alternating current (AC) systems.

Hydraulic energy

Hydraulic energy pertains to the power related to pressurised fluid, typically hydraulic fluid, used to accomplish machine motion. The pressure can be relatively static (such as reservoirs) or in motion through tubing or hoses.

Hydrocarbon

Any organic compound, gaseous, liquid, or solid, consisting solely of carbon and hydrogen.

Hydroelectricity

Producing electricity by using the force of falling water to turn the turbine blades, usually accomplished by damming a river to create a source of falling water.

Hydrogen sulphide (H₂S)

Is a colourless, flammable, extremely hazardous gas with a “rot-ten egg” smell. Some common names for the gas include sewer gas, stink damp, swamp gas and manure gas. It occurs naturally in crude petroleum, natural gas, and hot springs.

Hydrolytic enzymes

Complex catalytic proteins that use water to break down substrates.

Hydropower

The harnessing of flowing water—using a dam or other type of diversion structure—to create energy that can be captured via a turbine to generate electricity.

Impoundment

A body of water formed by damming a river or stream, commonly known as a reservoir.

Incineration

A treatment technology involving destruction of MSW by controlled burning at high temperatures, such as burning sludge to reduce the remaining residues to a safe, non-combustible ash which can be disposed of safely on land. It is applied in countries where high content of combustible fraction (paper and plastics/synthetics) is present in the MSW and where land for disposal is very limited and scarce. The main objective of this process is in reducing volume of MSW so that landfill life span could be extended. It requires high technological level in the country which is supported by adequate equipment, infrastructure facility and trained personnel.

Inertial response

Is a function of large synchronous generators, which are large synchronous rotating masses, and which acts to balance supply and demand for electric power systems, typically the electrical grid.

Inferred Resources (IR)

It refers to recoverable uranium (in addition to RAR) that is inferred to occur, based on direct geological evidence, in extensions of well-explored deposits and in deposits in which geological continuity has been established, but where specific data and measurements of the deposits and knowledge of their characteristics are considered to be inadequate to classify the resource as RAR.

Injection well

Injection wells inject the brine back into the reservoir after using it in the power production process.

Installed capacity

The amount of power that can be generated at a given moment by a power plant. Usually measured in kilowatts (kW) or megawatts (MW). Actual generation is measured in kilowatt-hours or megawatt-hours.

Intermittent Electricity

Is electrical energy that is not continuously available due to external factors that cannot be controlled, produced by electricity generating sources that vary in their conditions on a fairly short time scale. Sources of intermittent electricity include solar power, wind power, tidal power, and wave power. Although solar and tidal power are fairly predictable (length of days, weather patterns, tidal cycles), they are still intermittent because the time period that electricity can be created is limited. Because of this varying electrical generation these sources are considered non-dispatchable, meaning that their electrical output cannot be used at any given time to meet societies fluctuating electricity demands.

Lactic Acid

Is a compound produced when glucose is broken down and oxidised.

Liquid Air Energy Storage (LAES)

Uses electricity to cool air until it liquefies, stores the liquid air in a tank, brings the liquid air back to a gaseous state (by exposure to ambient air or with waste heat from an industrial process) and uses that gas to turn a turbine and generate electricity.

Lag regression models

In statistics and econometrics, a distributed lag model is a model for time series data in which a regression equation is used to predict current values of a dependent variable based on both the current values of an explanatory variable and the lagged (past period) values of this explanatory variable.

Landfills

Designed, controlled and managed disposal sites for MSW spread in layers, compacted to the smallest practical volume, and covered by material applied at the end of each operating day.

Large hydropower

Although definitions vary, the U.S. Department of Energy defines large hydropower as facilities that have a capacity of more than 30 megawatts.

LCOE

The levelised cost of electricity (LCOE) is the (fictitious) average price that must be received per unit of energy output (effectively kWh or MWh) as payment for producing power in order to reach a specified financial return. In other words, it reflects the average price the project must earn per unit of energy output (sold over the entire lifetime of the technology) in order to break even on the investment and operational costs. The LCOE calculation standardises the units of measuring

the lifecycle costs of producing electricity thereby facilitating the comparison of the cost of producing one megawatt hour by each technology.

LCOS

The levelised cost of storage (LCOS) is the (fictitious) average 'net' price that must be received per unit of energy stored (effectively kWh or MWh) as payment for storing and discharging energy in order to reach a specified financial return. In other words, it reflects the average 'net' price the project must earn per unit of energy stored (sold over the entire lifetime of the technology) in order to break even on the investment and operational costs. The LCOS calculation standardises the units of measuring the lifecycle costs of storing and discharging electricity, thereby facilitating the comparison of the cost of discharging one megawatt-hour of stored electric energy by each technology.

Leachate

Wastewater that collects contaminants as it trickles through MSW disposed in a landfill. Leaching may result in hazardous substances entering surface water, ground water, or soil.

Learning curve

Shows the empirical relationship between costs and accumulated production or capacity.

Life-cycle emissions

A measure of life-cycle greenhouse gas emissions is an attempt to calculate the global-warming potential of electrical energy sources by doing a life-cycle assessment of each energy source and presenting the findings in units of global warming potential per unit of electrical energy generated by that source.

Lignite

A soft brownish coal showing traces of plant structure, intermediate between bituminous coal and peat.

Lignocellulose

It is the most abundantly available raw material on the Earth for the production of biofuels, mainly bio-ethanol. It is composed of carbohydrate polymers (cellulose, hemicellulose), and an aromatic polymer (lignin).

Livestock

Farm animals regarded as an asset.

Load

Something physical or electrical that absorbs energy. A wind generator that is connected to a battery bank is loaded. A disconnected wind generator is not loaded, so the blades are free to spin at very high speed without absorbing any energy from the wind, and it is in danger of destruction from over speeding.

Load factor

Is the ratio of the average load to the peak load during a period of time.

Marginal cost

The increase or decrease in the total cost of a production run for making one additional unit of an item. It is computed in situations where the breakeven point has been reached: the fixed costs have already been absorbed by the already produced items and only the direct (variable) costs have to be accounted for. Marginal costs are variable costs consisting of labour and material costs, plus an estimated portion of fixed costs (such as administration overheads and selling expenses). In companies where average costs are fairly constant, marginal cost is usually equal to average cost.

Micro hydropower

A micro hydropower plant has a capacity of up to 100 kilowatts. A small or micro-hydroelectric power system can produce enough electricity for a home, farm, ranch, or village.

Model output statistics

Is an objective weather forecasting technique which consists of determining a statistical relationship between a predict and variables forecast by a numerical model at some projection time(s). It is, in effect, the determination of the "weather related" statistics of a numerical model.

Module

Describes a unit composed of several solar cells that can be electrically connected, encapsulated in tempered glass and framed. Otherwise known as a solar electric panel, solar panel, or PV panel.

Monocrystalline

Silicon that is pulled as a single crystal. The internal crystalline structure is completely homogenous, which can be recognised by an even external colouring.

Multicrystalline

Also called polycrystalline, a material composed of variously oriented and small individual crystals. A lightly less-efficient material than monocrystalline products.

Nacelle

The structure at the top of the wind turbine tower just behind (or, in some cases, in front of) the wind turbine blades. It houses the key components of the wind turbine, including the rotor shaft, gearbox and generator.

Natural bitumen

Natural bitumen is defined as oil having a viscosity greater than 10,000 centipoises under reservoir conditions and an API gravity of less than 10° API.

N.C.

Not communicated

Net evaporation

Is the evaporation associated with the reservoir minus the evaporation and evapotranspiration that occurred from the natural systems (precipitation).

Nominal Power (kW, MW, GW)

The maximum rate at which energy can be converted (charged or discharged) by an energy storage technology, over an extended time. Higher power may be achievable for short durations.

OEM

The Original Equipment Manufacturer is the turbine vendor of the wind turbines supplied to a wind project.

Oil shale

Solid sedimentary rock that contains kerogen. Oil shale can be used to produce liquid hydrocarbons called shale oil (not tight oil) and oil shale gas (not shale gas). Best deposits of oil shale have more than 40% organic content and 66% conversion ratio into shale oil and gas.

Oil shale gas

Synthetic gas made from oil shale using pyrolysis.

Open-pit, open-cast or open cut mining

Is a surface mining technique of extracting rock or minerals from the earth by their removal from an open pit or borrow.

Organic solar cells

Is a type of photovoltaic that uses organic electronics, a branch of electronics that deals with conductive organic polymers or small organic molecules, for light absorption and charge transport to produce electricity from sunlight by the photovoltaic effect.

Osmosis

Is the spontaneous net movement of solvent molecules through a semi-permeable membrane into a region of higher solute concentration, in the direction that tends to equalise the solute concentrations on the two sides.

P2G, PtG

Power-to-Gas technology converts electricity to various gaseous fuels. A hydrogen-based chemical storage system is a three-step process of converting renewable electricity to hydrogen using electrolysis, storing the chemical energy as hydrogen or synthetic methane in either the natural gas pipeline or local storage tanks, and discharging the stored energy for mobility or power through a gas turbine generator or a fuel cell, or alternatively for direct use in domestic, commercial or industrial applications. The key attributes of Power-to-Gas are the rapid, dynamic response of the electrolyser, and the option of providing a seasonal storage capability.

Parasitic load

At all plants, some of the electricity produced will be used to run the power plant itself – pumps, fans, and controls require a certain amount of electricity. These loads are often referred to as “parasitic loads.”

Particulates

Is a complex mixture of extremely small particles and liquid droplets. Particle pollution is made up of a number of components, including acids (such as nitrates and sulphates), organic chemicals, metals, and soil or dust particles.

Peak wind speed

The maximum instantaneous wind speed (or velocity) that occurs within a specific time period.

Pellets

A small, rounded, compressed mass of a substance.

Perovskite solar cells

Are made of minerals exhibiting a perovskite crystalline structure, such as Methyl ammonium tin halides and methyl ammonium lead halides.

PH

Pumped hydro storage (PH) systems utilise elevation changes to store electricity for later use. Water is pumped from a lower reservoir to a reservoir at a higher elevation, usually during off-peak periods. Subsequently, water is allowed to flow back down to the lower reservoir, generating electricity in a fashion similar to a conventional hydropower plant.

Photovoltaic

Relating to the production of electric current at the junction of two substances exposed to light. A photovoltaic cell (PV cell) is a specialized semiconductor diode that converts visible light into direct current (DC). Some PV cells can also convert infrared (IR) or ultraviolet (UV) radiation into DC electricity.

Piled jackets

Pile jacking technology allows displacement piles to be installed without noise and vibration. The 'press-in' method of pile jacking uses previously-installed piles for reaction, so the piles must be installed at close centres.

Polymers

Are very large molecules made when many smaller molecules join together, end to end. The smaller molecules are called monomers.

Power house

The structure that houses generators and turbines.

Power pool

Is used to balance electrical load over a larger network (electrical grid) than a single utility. It is a mechanism for interchange of power between two and more utilities which provide or generate electricity.

Power Purchase Agreements (PPA)

Is a contract to buy the electricity generated by a power plant. These agreements are a critical part of planning a successful wind project because they secure a long-term stream of revenue for the project through the sale of the electricity generated by the project.

Purchasing Power Parity (PPP)

Is a theory in economics that approximates the total adjustment that must be made on the currency exchange rate between countries that allows the exchange to be equal to the purchasing power of each country's currency.

Pulverised Coal (PC)

It is the most commonly used method in coal-fired power plants, and is based on many decades of experience.

Rate of return

The annual rate of return on an investment, expressed as a percentage of the total amount invested. Also called return.

Reasonably Assured Resources (RAR)

It refers to recoverable uranium that occurs in known mineral deposits of delineated size, grade and configuration such that the quantities which could be recovered within the given production cost ranges with currently proven mining and processing technology can be specified. Estimates of tonnage and grade are based on specific sample data and measurements of the deposits and on knowledge of deposit characteristics. RAR have a high assurance of existence.

Redox

The term redox is a short form of describing reduction-oxidation reactions. Oxidation is the increase in oxidation state by a molecule, atom or ion, while reduction is the decrease in oxidation state. Flow battery technologies utilise redox processes, where ion exchange occurs through a membrane, separating two chemical components.

Refuse-derived fuels (RDF)

Product of a mixed MSW processing system in which certain recyclable and not combustible materials are removed and the remaining combustible material is converted for use as a fuel to generate energy.

Renewable energy credits

A REC verifies that one megawatt hour (MWh) of clean energy was generated by a clean power facility and added to the national electric grid. When the energy is generated, a REC is created simultaneously in a 1:1 ratio. Once clean energy joins the grid, there's no way to accurately track it. Organizations that own RECs in a corresponding volume to the amount of electricity consumed are assured that the equivalent volume of green power was generated.

Renewable heat incentives (RHI)

Is a payment system for the generation of heat from renewable energy sources introduced in the United Kingdom on 28 November 2011 and is similar to feed-in tariffs.

Renewables Obligations (RO)

Provide incentives for large-scale renewable electricity generation by making UK suppliers source a proportion of their electricity from eligible renewable sources.

Reserves

Discovered quantities of hydrocarbons which are economically extractable at prevailing prices and current technologies.

Resources

All quantities of petroleum which are estimated to be initially-in-place.

Response time

The amount of time required for a storage system output to transition from no discharge to full discharge.

Retail grid parity

Is related to an installation whose production is consumed on site and whose LCOE is competitive with traditional energy delivery from the Distribution System Operators Grid.

Round-trip efficiency

The amount of energy that a storage system can deliver relative to the amount of energy injected into the system during the immediately preceding charge.

Sedimentary organic matter

It includes the organic carbon component of sediments and sedimentary rocks. The organic matter is usually a component of sedimentary material even if it is present in low abundance (usually lower than 1%). Petroleum (or oil) and natural gas are particular examples of sedimentary organic matter. Coals and bitumen shales are examples of sedimentary rocks rich in sedimentary organic matter.

Shale oil

Synthetic oil made from oil shale using pyrolysis, hydrogenation, or thermal dissolution.

Shelf life

For a dry cell or battery comprised of dry cells; the amount of time during which the cell/battery can retain a specified percentage of its original energy content, under specified conditions.

Silane gas

An inorganic compound with chemical formula, SiH_4 , which is the principal material used in the production of polysilicon and is an essential material for thin film PV, semiconductors and LCD display manufacturing.

Silicon

The basic material used to make solar cells. It is the second most abundant element in the earth's crust, after oxygen. Silicon is a metal and, therefore, its atoms are organised into a crystalline structure.

Siloxanes

Are a subgroup of silicones containing Si-O bonds with organic radicals. They are widely used for a variety of industrial processes.

Small hydropower

Hydropower projects that generate 10 MW or less of power.

Smart grids

An electricity supply network that uses digital communications technology to detect and react to local changes in usage.

SNG

Synthetic Natural Gas is a fuel gas, produced from either fossil fuels (lignite, black coal, shale-oil, etc.) or biofuels. Production and later use of SNG is a suitable form of storing energy over longer periods.

Socket grid parity

Is related to an installation connected to the Distribution grid and whose LCOE is equal to the long term revenue including (i) self-consumed production valorised at retail power price and (ii) over production sold at wholesale price.

Sodium hydroxide

At room temperature, sodium hydroxide is a white crystalline odourless solid that absorbs moisture from the air. It is a manufactured substance widely used in the manufacture of soaps, paper, rayon, cellophane, mercerized cotton, and many chemicals.

Solar cooling systems

Use concentrating solar collectors and absorption chillers to drive the cooling process.

Spot markets

The spot is a market for financial instruments such as commodities and securities which are traded immediately or on the spot. In spot markets, spot trades are made with spot prices.

Stack losses

Stack losses represent the heat in the flue gas that is lost to the atmosphere upon entering the stack. Stack losses depend on fuel composition, firing conditions and flue gas temperature.

Stoichiometric combustion

In the combustion reaction, oxygen reacts with the fuel, and the point where exactly all oxygen is consumed and all fuel burned is defined as the stoichiometric point.

Strata

In geology and related fields, a stratum (plural: strata) is a layer of sedimentary rock or soil with internally consistent characteristics that distinguish it from other layers.

Suction buckets

Also referred to as suction anchors, suction piles or suction caissons, are a new form of offshore foundation that have a number of advantages over conventional offshore foundations, mainly being quicker to install than piles and being easier to remove during decommissioning.

Syngas

Or synthesis gas, is a fuel gas mixture consisting primarily of hydrogen, carbon monoxide, and very often some carbon dioxide.

Synthetic diesel

Synthetic diesel fuels can be made from carbon containing feedstocks, such as natural gas or coal, in a process developed by Fischer and Tropsch in the 1920s. It is made by reconfiguring another hydrocarbon fuel, natural gas, into liquid diesel fuel.

Synthetic natural gas

Is a fuel gas that can be produced from fossil fuels such as lignite coal, oil shale, or from biofuels (when it is named bio-SNG) or from renewable electrical energy.

The balance of system cost

Encompasses all components of a photovoltaic system other than the photovoltaic panels. This includes wiring, switches, a mounting system, one or many solar inverters, a battery bank and battery charger. Other soft costs include: financing, mechanical installation, electrical installation, system design, customer acquisition, incentive application, permitting, inspection/certification, connection, operation and maintenance.

Thermal coal

In electricity generation, it is ground to a powder and fired into a boiler to produce heat, which in turn converts water into steam. The steam powers a turbine coupled to an alternator, which generates electricity for the power grid.

Thin-film

Denoting a miniature circuit or device consisting of a thin layer of metal or semiconductor on a ceramic or glass substrate.

Tight gas

Natural gas that is found in low-permeability rock (including sandstone, siltstones, and carbonates), and is difficult to access because of the nature of the rock and sand surrounding the deposit. Tight gas is produced using hydraulic fracturing and horizontal drilling. Shale gas is the most commonly known unconventional gas.

Tight oil

Light crude oil that is contained in shales with relatively low porosity and permeability. It is produced using horizontal drilling and hydraulic fracturing, the same technologies used in the production of shale gas. It differs from shale oil by the API gravity and viscosity. Also the method of extraction is different.

Total Petroleum-Initially-in-Place

Quantity of petroleum which is estimated to exist originally in naturally occurring accumulations.

Traditional biomass use

Refers to the use of wood, charcoal, agricultural residues and animal dung for cooking and heating in the residential sector. It tends to have very low conversion efficiency (10% to 20%) and often unsustainable supply.

Turbine

A machine that produces continuous power in which a wheel or rotor revolves by a fast-moving flow of water.

Unconventional oil

Oil that is not produced using conventional methods, includes oil shale, oil sands-based extra heavy oil and bitumen, derivatives such as synthetic crude products, and liquids derived from natural gas – gas-to-liquid (GTL) or coal-to-liquid (CTL).

Unconventional resources

Hydrocarbons that are more difficult to produce. Resources such as shale gas, shale oil, tight gas, and tight oil, coal seam gas/coal bed methane and hydrates.

Undiscovered resources

It refers to uranium in addition to reasonably assured resources and inferred resources and covers the two NEA categories, 'Prognosticated Resources' (PR) and 'Speculative Resources' (SR): PR refer to deposits for which the evidence is mainly indirect and which are believed to exist in well-defined geological trends or areas of mineralisation with known deposits. SR refer to uranium that is thought to exist mostly on the basis of indirect evidence and geological extrapolations in deposits discoverable with existing exploration techniques.

Viability gap funding

A grant one-time or deferred provided to support infrastructure projects that are economically justified but fall short of financial viability. The lack of financial viability usually arises from long gestation periods and the inability to increase user charges to commercial levels.

Vitrification

Is the transformation of a substance into a glass, that is to say a non-crystalline amorphous solid.

Wafer

A sawn silicon disc, used as the starting point for manufacturing a solar cell.

Wake effect

Is the aggregated influence on the energy production of the wind farm, which results from the changes in wind speed caused by the impact of the turbines on each other.

Waste-to-Energy (WtE) or Energy-from-Waste (EfW)

Is the process of generating energy in the form of electricity, heat and transport fuels from the primary treatment of waste. WtE is a form of energy recovery.

Water footprint

The amount of fresh water utilised in the production or supply of the goods and services used by a particular person or group.

Weighted average cost of capital (WACC)

Is the rate that a company is expected to pay on average to all its security holders to finance its assets. The WACC is commonly referred to as the firm's cost of capital. Importantly, it is dictated by the external market and not by management.

Wholesale electricity market

The wholesale market is open to anyone who, after securing the necessary approvals, can generate power, connect to the grid and find counterparty willing to buy their output. These include competitive suppliers and marketers that are affiliated with utilities, independent power producers (IPPs) not affiliated with a utility, as well as some excess generation sold by traditional vertically integrated utilities. All these market participants compete with each other on the wholesale market.

Wholesale grid parity

Is related to an installation connected to the transmission grid and whose LCOE is competitive with wholesale spot market prices.

Wholesale price

Wholesale transactions (bids and offers) in electricity are typically cleared and settled by the market operator or a special-purpose independent entity charged exclusively with that function. Market operators do not clear trades but often require knowledge of the trade in order to maintain generation and load balance. The commodities within an electric market generally consist of two types: power and energy. Power is the metered net electrical transfer rate at any given moment and is measured in megawatts (MW). Energy is electricity that flows through a metered point for a given period and is measured in megawatt hours (MWh).

Wind park (wind farm)

Is a group of wind turbines in the same location used to produce electricity.

Wind vane

Also known as a weather vane, is a tool used to determine the direction the wind is blowing from.

III-V Multi-junction (MJ)

Solar cells with multiple p–n junctions made of different semiconductor materials. Each material's p-n junction will produce electric current in response to different wavelengths of light. The use of multiple semiconducting materials allows the absorbance of a broader range of wavelengths, improving the cell's sunlight to electrical energy conversion efficiency.

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