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Final Report

Security of supply: a pan-European approach

The opportunities and requirements of greater cooperation across European electricity markets

Commissioned by Weltenergierat – Deutschland e.V.

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Table of contents

Figures

Tables

List of abbreviations

ARM	Adequacy Reference Margin
AT	Austria
BE	Belgium
BMWi	Bundesministerium für Wirtschaft und Energie (German Federal Ministry for Economic Affairs and Energy)
CH	Switzerland
CZ	Czech Republic
DE	Germany
DK	Denmark
EEX	European Energy Exchange
ELIX	European Electricity Index
ENTSO-E	European Network of Transmission System Operators for Electricity
EnWG	Energiewirtschaftsgesetz (German Energy Industry Act)
EOM	Energy Only Market
EPEX SPOT SE	European Power Exchange
ES	Spain
FR	France
IE	Republic of Ireland
IT	Italy
LOLE	Loss of Load Expectation
LU	Luxembourg
NASA GES DISC	National Aeronautics and Space Administration Goddard Earth Sciences Data and Information Services Center
NL	Netherlands
PL	Poland
PLEF	Pentalateral Energy Forum: DE, BE, NL, LU, FR, AT, CH
PT	Portugal
RAC	Reliable Available Capacity
RC	Reserve Capacity

RE	Renewable Energy
ROR	Run-Of-the-River (hydroelectricity)
SD	Study Domain: PLEF + PL, IT, UK, ES, DK, CZ, PT, IE
SO&AF	System Outlook and Adequacy Forecast
TSO	Transmission System Operator
TYNDP	Ten-Year Network Development Plan
UK	Great Britain
UTC	Coordinated Universal Time

Glossary

Deterministic approach (generation adequacy assessment)	All events - including future events in particular – are described using particular values and are clearly defined. In this way, using extreme values, a comprehensive representation of results is at-tempted
Copper plate	An expression used to illustrate the concept of a unified (European) power grid without physical bot-tlenecks within the countries or on the countries' borders
Collective assessment scheme	A system that considers cross-border power de-mand and feed-in from intermittent renewables to determine the collective residual load of a group of countries
Correlation	A measure of the relationship between two statisti-cal variables
Excess electricity feed-in situation	A situation where the feed-in from intermittent re-newables exceeds the demand for electricity
Generation adequacy	The ability of the system to meet the aggregate power and energy requirement of all consumers (i.e. the load) at virtually all times
Generation adequacy assessment	An analysis of the ability of the power generation capacities to meet demand for electricity at any point in time
Group peak load	The highest simultaneous load within a group of countries. It thus differs from the sum of national peak loads occurring at different times
Intermittent renewables	Non-controlled generation from wind power, solar power and hydropower (run-of-the-river)
Load duration curve	A representation of the demanded capacity (load) over the course of a year
Load factor	The load factor is defined as the observed/actually fed-in capacity divided by the installed capacity. The load factor can be reported on an hourly or annual basis
Market coupling	The process of creating an integrated domestic electricity market in Europe. Markets for capacity and energy are joined together ("coupled") to form a single, integrated electricity market

National assessment scheme	A system that considers demand and feed-in from intermittent renewables within a country to determine national residual load
Network reserve	The network reserve maintains power plants to overcome bottlenecks in order to ensure secure system operation
Power curve (here: of a wind farm)	A representation of the relationship between power output and wind speed, independent of hub height
Probabilistic approach (generation adequacy assessment)	All events - including future events in particular - are allocated a probability of occurrence. These events (such as different weather data or power plant outages) are combined with each other using the appropriate methods
Reanalysis meteorological data	The results of weather model simulations which, when measured values are taken into account, reproduce the weather activity of the past
Relative availability	Percentage indicating the relationship of feed-in to total installed capacity
Reliable available capacity	The power plant capacity in a power plant fleet which is continuously available with a high level of security
Reserve capacity (reserve power plants)	Power plant capacity which is only made available at the request of the transmission systems operators so as to guarantee security of supply
Residual load	Residual load describes the capacity demanded less the intermittent feed-in from non-controllable power plants. This corresponds to the residual demand which needs to be met by controllable power plants, such as those powered by nuclear power, coal and gas, or storage systems. In short: demand less renewable capacity
Residual load duration curve	See: residual load and load duration curve
Spare capacity (generation adequacy assessment)	Safety margin over the peak load which, together with the peak load, has to be met with secured capacity over a certain period
Strategic reserve	The provision of power plants that are only used in situations where there is low supply of electricity and thus high electricity prices
System adequacy	The ability of a power system to supply the load in all the steady states in which the power system may exist considering standard conditions

System adequacy assessment	An analysis of the ability of a power supply system to meet all demand at any time. In addition to generation adequacy assessment, an assessment of the load situation of the power grid is also conducted
System reserve	Temporary (short-term) operational readiness of certain power plants to stabilise the network
Security of supply	The provision of sufficient quantities of energy to meet demand at all times (various international definitions of security of supply with different levels of detail can be found)
Vertical network load	The total amount of power flowing out of the transmission network to the distribution networks
Volatile feed-in from renewables	See: intermittent renewables
Wind energy availability	The feed-in from wind energy at a particular point in time in relation to total installed capacity

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Summary

In December 2014, Prognos AG (Berlin/Basel) was commissioned by the Weltenergierat – Deutschland e.V to prepare a study on the potential of greater cooperation across European electricity markets. The focus of the analysis was to address the extent to which closer cooperation with respect to **ensuring generation adequacy** could lead to cost reductions. Fifteen countries were studied: the seven countries belonging to the Pentalateral Energy Forum[1] (PLEF) as well as eight additional bordering countries[2].

Today, ensuring generation adequacy takes place at a national level and international effects are not taken into consideration. **Considering cross-border effects** could however unburden adequacy considerations at a national level: load peaks in Europe do not occur simultaneously and the feed-in from renewable energy takes place at different times. Potential savings arise, as less capacity needs to be secured by conventional power plants. An indicator for this in the present study is the so-called residual load.

The study is based on analyses of all existing data relating to **hourly** load and feed-in from renewable energy for the period from **2009 to 2014**. In addition, two **scenarios** (based on Visions V1 and V3 of ENTSO-E's System Outlook and Adequacy Forecast) and numerous sensitivities for **2030** were generated. As the variability of the results is highly dependent on weather conditions, 48 simulations of wind power (sensitivities) established a broad corridor of results. For this reason, ranges are used in the presentation of results. The approach makes this study the **most comprehensive analysis to date** of the potential of closer cooperation with respect to ensuring generation adequacy.

With the assumption of no grid congestion, the study arrived at the following **results**:

- In contrast to a national assessment scheme, under a collective assessment scheme the **residual load** will sink in the PLEF group of countries during peak hours by 2 to 15 gigawatts (most likely between 8 to 10 gigawatts). In the entire study domain of 15 countries the residual load will fall by 15 to 50 gigawatts (most likely between 27 to 34 gigawatts).
- The majority of the potential existing today comes from the time difference between **load peaks**, representing the demand for electricity. In future, the potential will increase largely due to the **expansion of renewable energy**, i.e. the weather-

1 DE, BE, NL, LU, FR, AT & CH
2 PL, IT, UK, ES, DK, CZ, PT & IE

dependent supply of electricity. The contribution presented by load (balancing load peaks) will more or less remain constant.

- The potential increases significantly when considering a **larger study domain**.
- Depending on the scenario, **wind power** will be able to provide reliable available capacity of between at least 1.2 (V1) and 2.2 (V3) gigawatts in the PLEF region by 2030. For the entire study domain, this will total between at least 9 (V1) to 13 (V3) gigawatts. This corresponds to at least 1.3 % of the installed wind capacity in the PLEF, and more than 4 % for the entire study domain. In contrast, only around 1 % of wind capacity is regarded as reliable available capacity today.
- In 2030, with the further expansion of renewables (V1), **excess feed-in situations** would occur in the PLEF in only one in six years. By way of contrast, this would occur every year at the national level. The residual load of the group of countries in the study domain would be negative for barely any hours per year in 2030, even considering the strong expansion of renewables. This means that by 2030, even a **high feed-in from renewables** could be "taken in" without the need for intermediate storage if the networks were to allow such electricity transmission.
- If the potential to reduce residual load could be realised, then less power plant capacity would have to be reserved. Storage to take in excess energy would be necessary only at a later date, if required. Both of these factors can result in **cost reductions**. Potential savings would need to be compared with the network expansion and transaction costs associated with collective generation adequacy assessment. Comprehensive assessment of the costs and benefits should however also take into consideration any gains in the efficiency of electricity generation arising from improved usage of power plants.

The following **requirements** are necessary to achieve this potential:

- In addition to **national** approaches, cross-border methods of generation adequacy assessment need to be further developed.
- **Processes of ensuring generation adequacy** need to be internationally harmonised. This also impacts the legal and organisational aspects of ensuring generation adequacy.
- Parties responsible for security of supply at a national level need reliability with respect to securing domestic demand with cross-border capacity.

- **Grid infrastructure** has to be developed alongside the existing planning (e.g. TYNDP), while giving group effects even more consideration.

In doing so, obstacles as well as transformation and transaction costs need to be considered. These can be difficult to quantify, but play an important role in practice.

We have arrived at the following **recommendations** based on the study:

- **Common definitions** of security of supply, a coordinated process of generation adequacy assessment and ensuring cross-border generation adequacy can in any case contribute to the realisation of a domestic market, even if the actual costs savings and required costs are difficult to determine. We recommend that these factors be taken into account in electricity market design.
- A review of the process of **evaluating wind power capacity** would be advisable, as ensuring cross-border generation adequacy would increase the potential of providing reliable available capacity.
- **Regional cooperation** (e.g. in the PLEF region) can achieve quick wins which would serve to realise some of the reported potential for harmonisation. This cooperation can then be incrementally extended to larger regions.

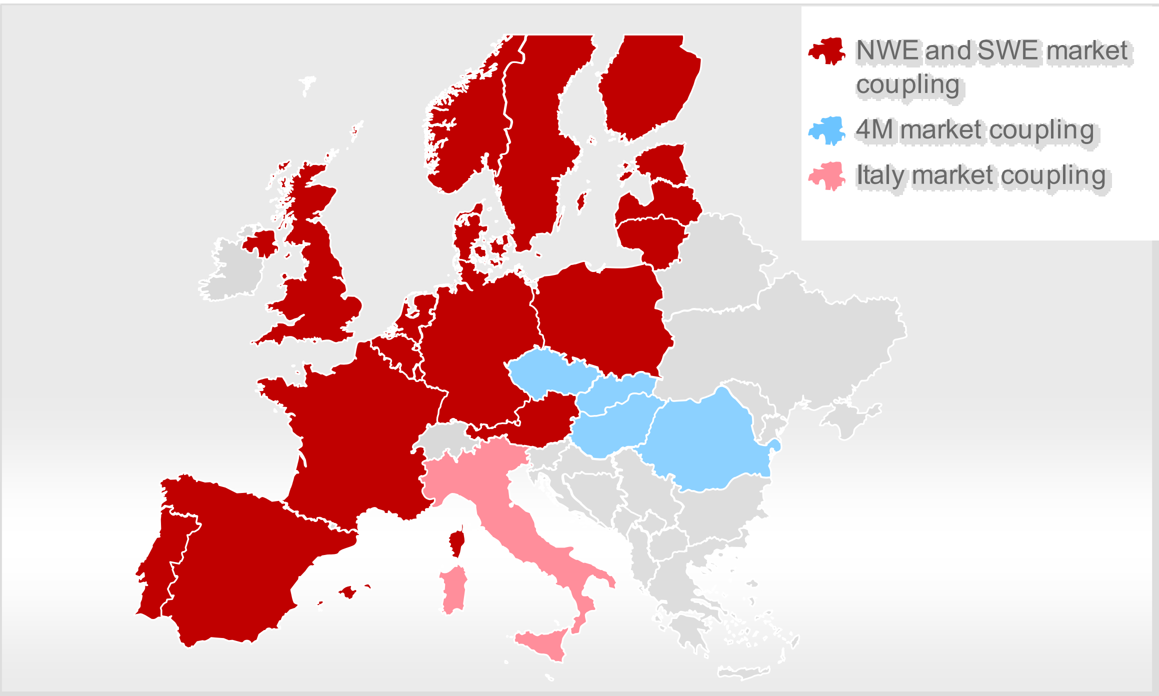
1 Introduction

1.1 Background and assignment

Europe has a long tradition of cooperation with respect to electricity markets, dating back to even before the beginning of electricity market liberalisation. In 2015, the integration of European electricity markets is well advanced. A central component of this integration is the cross-border **trading of electricity** within the **market coupling** framework. The Third Energy Package was incrementally implemented in this manner, allowing cross-border electricity trading.

Fifteen European countries, from Portugal to Finland, have their electricity markets coupled together today. In addition, the Czech Republic, Hungary, Slovakia and Romania have been integrated as part of the 4M Market Coupling. In February 2015, Italy was also integrated into the existing market coupling framework (see Figure 1).

Figure 1: European electricity market integration in 2015: countries involved in market coupling



NWE: North Western Europe, SWE: South Western Europe
Source: swissgrid 2015

Nonetheless, there still remain significant potential welfare effects[3]. An indicator for these is the ELIX (European Electricity Index) electricity price index which is published by both the EEX and EPEX SPOT SE power exchanges. ELIX shows the price given a market situation without bottlenecks at the cross-border interconnectors.

The focus of electricity market integration has always been on increasing economic welfare through enhanced cross-border trading of electricity. Intensified cross-border electricity trading allows efficient usage of available power plant capacities, resulting in a cost-efficient solution for the entire region. An example of this is a mutually beneficial combination of different methods of power generation, such as the hydropower systems in Scandinavia and the mainly thermal electricity generation present in Central Europe today. A harmonisation of prices can generally be seen in integrated markets. The **benefit** of cooperation across electricity markets goes however beyond price-related welfare effects. Cross-border cooperation can increase both short-term and long-term security of supply and improve plannability. The establishment of larger market areas increases electricity market liquidity, and allows consumers of electricity to benefit from a broader range of offerings.

In this respect, the focus up till now on **electricity trading** and the variable costs of electricity generation possibly falls short: the **fixed costs** of power plant fleets represent a major proportion of the total costs for electricity production, and potential efficiencies can also be expected in this area. To realise this potential, the process of ensuring generation adequacy, which takes place primarily at an independent national level today, needs to be internationally harmonised.

The design of the electricity market is also a topic of intense discussion in Germany at the moment. In the autumn of 2014, the German Federal Ministry for Economic Affairs and Energy published the **Green Paper "An Electricity Market for Germany's Energy Transition"** (BMWi 2014a). The Green Paper emphasises both functions of the electricity market: the dispatch function and the reserve function. The maintenance of reserve capacity in particular requires fundamental decisions to be made for the future.

A public consultation was opened with the Green Paper and concluded at the beginning of March 2015. A White Paper with concrete measures will follow the consultation. There will also be a public consultation with the White Paper which will be followed by the drafting of the necessary legislation. In this context, the Wel-

3 See Agency for the Cooperation of Energy Regulators (ACER): Annual Report on the Results of Monitoring the Internal Electricity and Natural Gas Markets in 2013, Ljubljana 2014, p.122, paragraph 288.

tenergierat - Deutschland e.V would like to indicate the **advantages of a further Europeanisation of the electricity market**, and thus commissioned Prognos AG to prepare a study on the opportunities and requirements of an intensified European integration in the electricity and capacity markets. Prognos has examined the cooperation in the area of generation adequacy, as promising potential for synergies is still expected here.

The present study thus analyses if, and to what extent, a **cross-border approach with respect to ensuring generation adequacy** can contribute to reducing the power plant capacities required to be maintained. A central component of the quantitative analysis conducted is considering the (lack of) concurrency in certain supply situations in the power system. If, for example, load peaks do not occur at the same time, less capacity will be required to be maintained in the respective group of countries in total. The resulting additional requirements that need to be established to provide this kind of generation adequacy in a European group of countries are also discussed.

The **objective** of the study is thus to evaluate to what extent cross-border generation adequacy makes sense, and what requirements are necessary to achieve this.

1.2 Study design

The study comprises the following **work packages**:

- The study is introduced with a **stocktake** of the principles of security of supply and ensuring generation adequacy in a cross-European comparison.
- Following this, load, renewable electricity generation and the resulting residual load are examined as part of a **quantitative ex-post analysis**. The objective of the analysis is to determine the potential of a harmonised approach to generation adequacy. The period from 2009/2010 to 2014 is used as a basis for the entire study domain.
- In a **scenario analysis** of load, renewable electricity generation and residual load, the potential of harmonised assessment scheme for 2030 is quantified, based on ENTSO-E scenarios.
- Following this is a description of the **prerequisites** of a cross-border approach to ensuring generation adequacy needed to realise the reported potential.
- **Recommendations** are derived from the analysis of the potential and its prerequisites.

The results of the ex-post analysis (interim report of the project) were submitted as part of the BMWi Green Paper process.

To verify the analyses, members of both the Weltenergierat - Deutschland e.V. and the Swiss Energy Council were involved as **partners** in the discussion of the methodology and results. The following partners also provided financial support for the study:

- 50Hertz Transmission GmbH
- Alpiq Holding AG
- Amprion GmbH
- EnBW Energie Baden-Württemberg AG
- E.ON SE
- EWE AG
- RWE AG
- TenneT TSO GmbH
- PricewaterhouseCoopers AG

as well as representatives of the Weltenergierat - Deutschland e.V.

Two workshops took place with these partners, in which the assumptions and results were intensively checked for plausibility. Nevertheless, Prognos AG bears sole responsibility for content of the results of this study.

2 Security of supply and ensuring adequacy in the European power system – the status quo

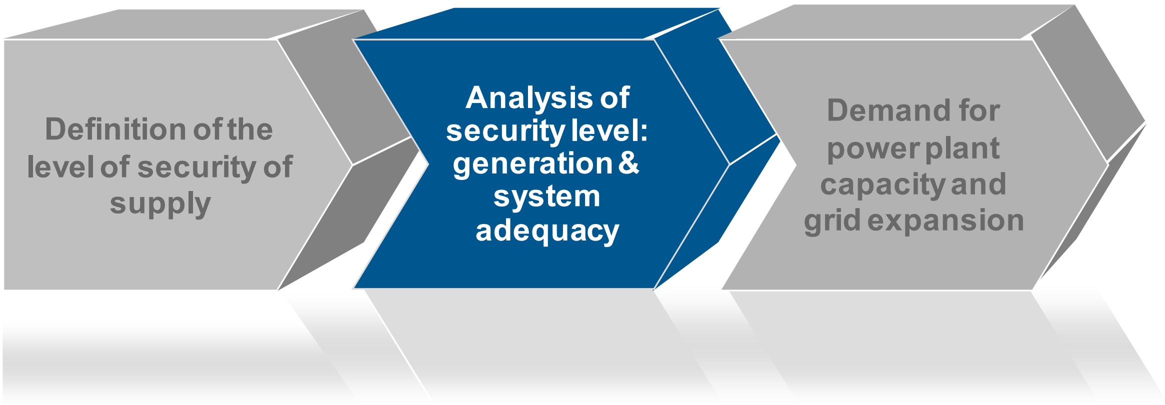
There is currently **no generally accepted definition** of the factors covered by the process of ensuring generation adequacy and the relationship between them, despite the fact that such a process has been implemented in most countries. In the context of this study, we understand generation adequacy as the securing of power plant and grid capacity availability in consideration of the demand for these capacities.

Typically, the process of ensuring generation adequacy comprises the following three elements (see Figure 2):

- **Defining the level of security of supply**
  By defining security of supply for a particular geographic region, a (politically) desired level of security is determined.
- **Performing an adequacy assessment**
  Compliance with this level of security is analysed as part of an adequacy assessment. This compares available power plant capacity with consumer load (this is generally known as generation adequacy assessment) and, in a further step, analyses the grid infrastructure (as part of system adequacy assessment). This process determines the future need for power plant capacity and grid infrastructure.
- **Demand for power plant capacity and grid expansion**
  The induced demand for power plant capacity ultimately covers the need for power plant capacity. The necessary grid expansion is also required to achieve the desired level of security of supply. Incentive mechanisms for power plant capacity (and the flexibilisation of demand for electricity) are currently being intensely discussed in Europe, and could take a number of forms (e.g. EOM with/without strategic reserves, decentralised capacity markets, centralised capacity markets)[4].

[4] e.g. in Germany, a broad public discussion about future electricity market design took place as part of the Green Paper process. The Green Book process leads to a White Paper and the drafting of the necessary legislation in the autumn of 2015. (see Chapter 1.1).

Figure 2: Process of ensuring adequacy



The focus of the analytical part of this study is on an assessment scheme (without considering the power grid) to estimate what potential savings can be expected from harmonising the processes of ensuring generation adequacy. In the analysis of the necessary requirements for this, an examination is conducted of the necessary adjustments to the various elements of the process of ensuring generation adequacy to realise this potential.

A concrete process of ensuring generation adequacy as described here is explicitly established in only a few countries. In practice, individual countries demonstrate significant differences in the design of process for ensuring generation adequacy, the significance and connection between individual factors, and the applied methods and framework. In the following, the individual elements of ensuring generation adequacy are addressed and the fundamental principles and country-specific approaches are very briefly described.

2.1 Security of supply

In addition to efficiency and environmental impact, security of supply is a central criterion of power supply. Security of supply is provided for in Section § 1 of the EnWG (Energiewirtschaftsgesetz - the German Energy Industry Act):

The objective of the Act is to offer a secure, attractively priced, consumer-friendly, efficient and environmentally compatible grid-based supply of electricity and gas to the general public that is increasingly based on renewable energy resources.

Definitions of security of supply vary internationally with respect to their expression. Within the framework of monitoring security of supply by the German Federal Ministry for Economic Affairs and Energy, security of supply is understood as the continuous and sustainable coverage of demand (BMWi 2014b). Other definitions also take into account aspects relating to the price paid by end customers and distinguish between long-term and short-term features of security of supply.

The definition of security of supply with respect to **electricity** usually also includes securing the quality of the supply. This includes factors of securing voltage quality and reliability of supply, as well as the commercial quality. With respect to ensuring generation adequacy, long-term security of supply factors are of primary relevance; i.e. sufficient electricity generation from reliable available power plant capacity and the availability of the requisite grid infrastructure.

The individual Member States of the EU are **responsible for security of supply**. The basis for monitoring security of supply is provided by Article 4 of Directive 2003/54/EC of the European Parliament and of the Council:

Member States shall ensure the monitoring of security of supply issues. Where Member States consider it appropriate they may delegate this task to the regulatory authorities referred to in Article 23(1). This monitoring shall, in particular, cover the supply/demand balance on the national market, the level of expected future demand and envisaged additional capacity being planned or under construction, and the quality and level of maintenance of the networks, as well as measures to cover peak demand and to deal with shortfalls of one or more suppliers.

As a result, both the definition and the monitoring of security of supply are conducted by the individual **Member States**. Due to the national responsibility for security of supply, it is not surprising that a comparison between various European countries reveals significant differences in the desired level of security of supply, as well as the understanding of significance of security of supply in the process of ensuring generation adequacy.

A **comparison of case studies** relating to the level of security of supply in various European countries demonstrates the heterogeneity of approaches to this issue (see Table 1).

Table 1: A comparison of the status quo of the level of security and its relevance to the process of ensuring generation adequacy

	Level of security	Relevance to ensuring generation adequacy
ENTSO-E	Deficits in supply with a probability of occurrence of 1 % should be able to be compensated for	Power plant capacity amounting to a security margin over the peak load should be sufficient to compensate for a deficit in supply
Germany	No explicit formulation	Adequacy assessment provides a general indicator of the supply situation: a security of supply criterion is not considered
France	LOLE[5] < 3 h	LOLE criterion used as a target in ensuring adequacy
Netherlands	LOLE < 4 h	LOLE criterion used as a target in ensuring adequacy
Switzerland	No explicit formulation	Monitoring of security of supply (including adequacy assessment) is conducted by the Swiss Federal Electricity Commission (ElCom). A level of security of supply is not considered
Belgium	LOLE < 3 h (for normal conditions) or LOLE < 20 h (for exceptional circumstances)	LOLE criterion used as a target in ensuring adequacy
Austria	No explicit formulation	Adequacy assessment provides a general indicator of the supply situation: a security of supply criterion is not considered

See ENTSO-E 2014a, 50Hertz et al 2014, RTE 2014, TenneT 2014, SPF Economie 2012

[5] LOLE: Loss of Load Expectation is defined as the number of hours per year in which load cannot be covered.

2.2 Adequacy assessment

The **level of security of the electricity supply** is analysed within the framework of a generation adequacy assessment. This involves comparing, for a specific period, the existing power plant fleets with the consumer load that needs to be met. A system adequacy assessment also takes into account the situation in the power grid.

Conventional approaches to generation adequacy assessment compare the available power plant capacities with the load at a specific determined point in time (usually the time of the expected annual peak load). In principle, these **deterministic approaches** involve deducting various capacity elements from the total installed capacity. These elements include planned and unplanned power plant outages, overhauls, non-usable capacity and system service reserves.

The amount of usable power plant capacity varies especially with respect to intermittent renewables (e.g. wind, PV and hydropower) and can, depending on the time of observation, feature different values. Under a deterministic approach to generation adequacy assessment, these generation systems are allocated a certain value for availability (e.g. 1 % for wind power in the German approach to generation adequacy assessment) which provides a simplified description of the stochastic variability.

The rising share of intermittent renewables, increased electricity market integration and the growing significance of flexible demand and electricity storage has led to conventional methods of generation adequacy assessment being increasingly called into question and to **new approaches to generation adequacy assessment** being developed. The significant options pursued in this respect are the application of probabilistic approaches and the cross-border analysis of adequacy assessments[6].

Figure 3 and Figure 4 illustrate a sample **comparison** of the ENTSO-E (ENTSO-E 2014a) and the German (50Hertz et al. 2014) methodologies for generation adequacy assessment. Both analysis designs in the present study pursue an approach which can generally be characterised as deterministic[7].

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6 An example of this is the study by the transmission system operators for the PLEF region mentioned in Chapter 4.4

7 Probabilities are determined for the individual generation technologies to take into account the stochastics of generation – the description as “deterministic” is somewhat misleading. The methodology presented here for Germany and ENTSO-E describes the status quo. Other parties are currently developing new approaches to generation adequacy assessment, as are ENTSO-E and the Germany TSOs.

Figure 3: ENTSO-E generation adequacy assessment methodology

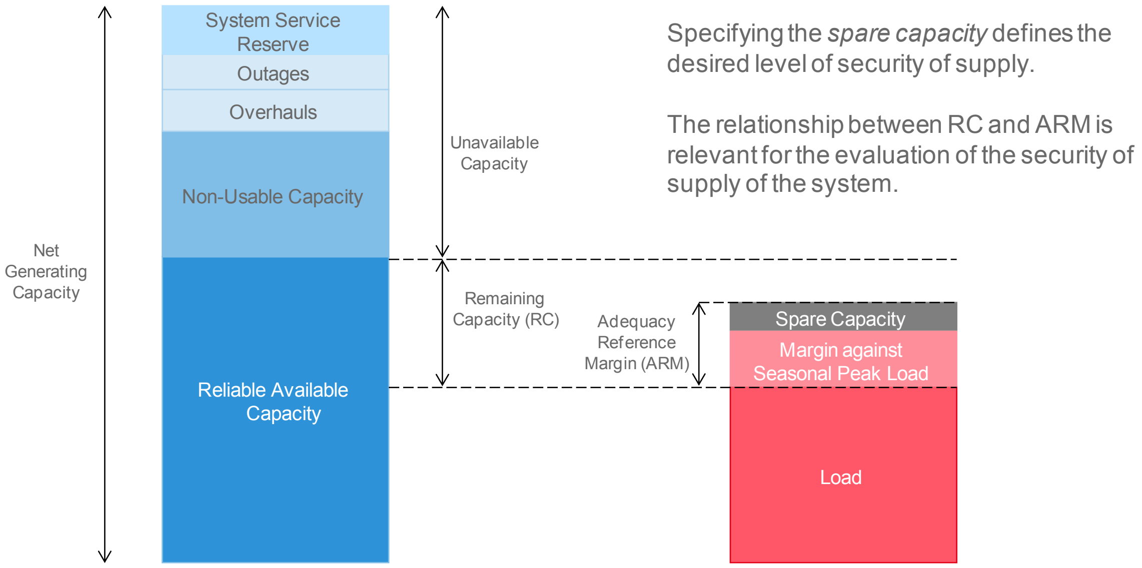
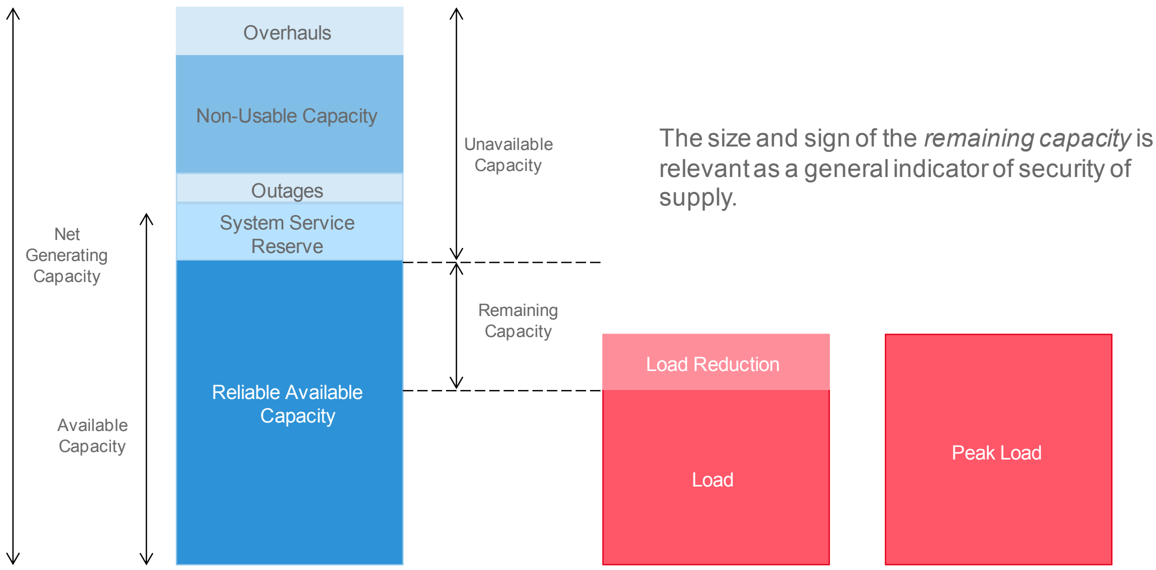


Figure 4: German TSO generation adequacy assessment methodology



Despite the fundamentally similar methodology, the comparison of both approaches illustrates differing **design principles**:

- The ENTSO-E methodology does not classify the **system service reserve** as available capacity, while the Germany methodology does so.
- Along with the margin against seasonal peak load, the ENTSO-E methodology includes **spare capacity** in the adequacy reference margin. This is not the case with the German methodology.
- In principle, both approaches have different **objectives**: while generation adequacy assessment in Germany is only intended to provide a general indicator of the supply situation, the ENTSO-E approach serves as a fundamental analysis of the level of security of supply, and forms the basis of the system adequacy assessment. The latter approach is correspondingly more clearly defined with respect to the security requirements.

Even more significant differences in generation adequacy assessment can be seen by way of **international comparison**:

- While many countries and institutions apply deterministic methods of various designs in generation adequacy assessment (such as Germany, Austria, Switzerland[8] and ENTSO-E), other countries use probabilistic approaches (for example, France, Belgium and the Netherlands).
- The time frame of the analyses ranges from 1 to 3 years (Germany), to a 5 year perspective (Belgium), to scenarios with a time frame of up to 15 years (ENTSO-E, France and the Netherlands).
- In addition, the results of the generation adequacy assessment have different relevance in the process of ensuring adequacy, as previously shown in the comparison of the German and ENTSO-E methodologies.

It can thus be stated that there are differing country-specific approaches with respect to adequacy assessment, and these differences result primarily from the national responsibility for ensuring generation adequacy.

[8] In Switzerland, there are many analyses of the state of the power system in addition to the security of supply report produced by the Swiss Federal Electricity Commission (ElCom 2014). For example, the annual electricity statistics (BFE 2014) and the Energieperspektiven (Prognos 2012). These studies do not however examine security of supply in the strict sense, they rather only illustrate particular supply situations.

2.3 Demand for power plant capacity and grid expansion

The final step in ensuring generation adequacy is to cover the previously identified **requirements for reliable available capacity**. In addition to this, a corresponding **grid infrastructure** needs to be provided. This will ideally allow the required level of security of supply to be achieved. In particular, if the adequacy assessment determines that the current reliable available capacity is not sufficient to cover load, the question arises of what mechanisms can guarantee incentives for power plant capacity and the flexibilisation of demand for electricity.

In principle, **balancing markets** provide a mechanism for the **short-term cover of demand for electricity**. However, the need for balancing capacity is not determined by generation adequacy assessments, rather results from (stochastic) deviations and electricity supply forecast errors.

The determination of reliable available capacity requirements from a **medium and long-term perspective** results from analysis of the generation adequacy assessment. Incentive mechanisms for the demand for power plant capacity can serve to secure existing power plants, encourage the construction of new power plants and flexibilise demand. Potential options range from supplementing the existing market with targeted instruments (e.g. strategic and network reserves), to mechanisms based on a further developed electricity market (e.g. EOM 2.0), to capacity markets (of various designs). Investments in new power plant capacities usually require a long lead time in comparison to securing existing power plants, while the time frame of the impact of incentives can be from less than a year, to over many years..

There are different national approaches to incentive mechanisms and these mechanisms are now being redeveloped and revised in many countries. An intense discussion is currently taking place in Germany and Europe with respect to the various advantages and disadvantages of the various options within the framework of the future design of the electricity market. In addition to savings with respect to reliable available capacity, there is another possible potential efficiency to be achieved by harmonising incentive mechanisms: if international harmonisation were to occur, the capacity and flexibility options with the lowest costs could be applied internationally. The present study does not address this factor. However, looking at current developments in Europe leads to the conclusion that the heterogeneity of approaches in this field will not decrease in future.

2.4 Interim summary of the status quo

A comparison of the processes for ensuring generation adequacy at a national and international level reveals an extremely **heterogeneous picture**:

- There are **differing national definitions** of the **level of security of supply**. Some countries refer to explicit quantitative targets, while others provide only vague qualitative formulations. In addition, approaches to generation adequacy assessment consider the criteria for security of supply in different manners.
- **Approaches to generation adequacy assessment** in individual countries apply **different methodologies,** and their relevance in the process of ensuring generation adequacy features significant differences. In addition, some countries do not currently apply a methodology of generation adequacy assessment.
- **Incentives for power plant capacities and flexibility options** are also **nationally defined**, differently designed and are currently undergoing development with no signs of consolidation.

The **process of ensuring generation adequacy** is, in total, quite different across countries with respect to the responsible parties, the time frame and the depth of design.

3 Methodology and data set

As part of the second work package, an ex-post analysis was conducted on the hourly **residual load** for the European countries in the study. Following this, the future development of the residual load was determined, based on scenarios and sensitivities. The residual load denotes the demanded electric capacity less intermittent feed-in from non-controllable power plants, such as those powered by wind power, PV and run-of-the-river (ROR) hydropower. It thus represents the residual demand which needs to be met by controllable power plants, such as those powered by nuclear power, coal and natural gas. If less residual load needs to be covered, less reliable available capacity needs to be reserved with respect to ensuring generation adequacy.

The ex-post analysis of the residual load requires load analysis and analysis of the feed-in from renewable energies. The ex-post analysis shows how pronounced the **concurrence of the load** is in the countries studied. The lower the concurrence, the higher the savings potential with respect to ensuring generation adequacy across countries.

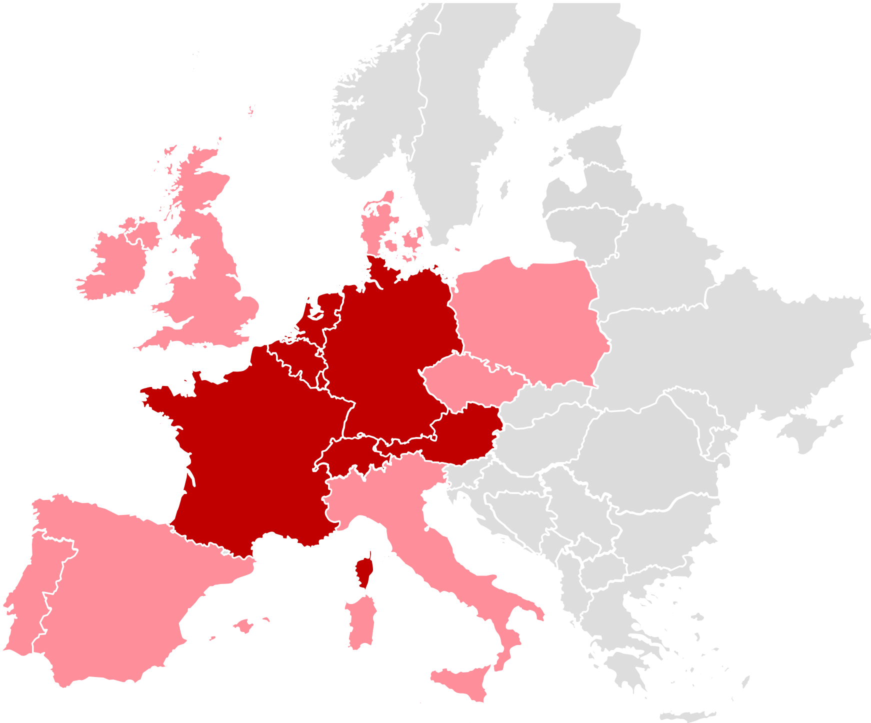
The subsequent **scenarios** reveal the possible development of residual load up to 2030. This allows a quantitative estimate of the potential of collectively ensuring generation adequacy.

3.1 Ex-post analysis methodology

The ex-post analysis of the load, the feed-in from renewables, and the residual load was conducted for 15 European countries, as illustrated in Figure 5. The harmonisation potential presented by a collective assessment scheme was determined for two groups of countries – the PLEF[9] (DE, BE, NL, LU, FR, AT, CH) and the (entire) study domain (PLEF + PL, IT, UK, ES, DK, CZ, PT, IE).

[9] Founded in 2005, the Pentalateral Energy Forum is led by the responsible ministries, regulatory authorities, network operators, electricity exchanges and other market participants from the Benelux countries, Germany, France, Austria and Switzerland. Its objective is to further develop electricity market integration.

Figure 5: Boundary of the study domain



Note: Two groups of countries are defined: the PLEF (red; DE, BE, NL, LU, FR, AT, CH) and the study domain (SD; pink; PLEF + PL, IT, UK, ES, DK, CZ, PT, IE)

As a first step, the **vertical network load** between 2009 and 2014[10] for the countries in the study was analysed. The ENTSO-E statistical database[11] served as the data basis. The vertical network load refers to the capacity delivered from the transmission system operators to the distribution system operators. This does not however include the loads for local grid supply and on-site consumption, as these do not flow through the transmission systems of the TSO. The vertical load was then scaled on a monthly basis to the monthly net power consumption (detailed monthly production; ENTSO-E) in order to produce a plausible estimation for the respective total capacity for the countries[12].

[10] The data analysis is restricted to 2010-2014 for the UK, DK and IE.

[11] Gaps in the data (UK: January 2010, AT: December 2014, LU: October-December 2014) were bridged using statistical methods (regression analysis with neighbouring countries).

[12] This approach is pragmatic and has the advantage of leaving the vertical load structure unchanged. It may nonetheless tend to mildly overestimate peak loads. However, in the entire context of the study, any uncertainty arising from this should be regarded as low, especially in the given the specification of ranges in the scenarios.

To take advantage of the possible savings arising from collective usage of synergy potentials with respect to ensuring generation adequacy, **two concepts** were compared, each depicting a different scale of European integration.

Concept I: **National assessment scheme**. This concept assumes that ensuring generation adequacy in the considered countries takes place at a largely national level. This corresponds more or less to the status quo.

Concept II: **Collective assessment scheme**. This concept assumes that the prerequisites described in Chapter 5 are fulfilled, and the synergy effects of European integration with respect to ensuring generation adequacy can be completely achieved. This assumes electricity transmission without bottlenecks (the "copper plate" concept).

Potential savings with respect to load were analysed by comparing these concepts. It is important to note:

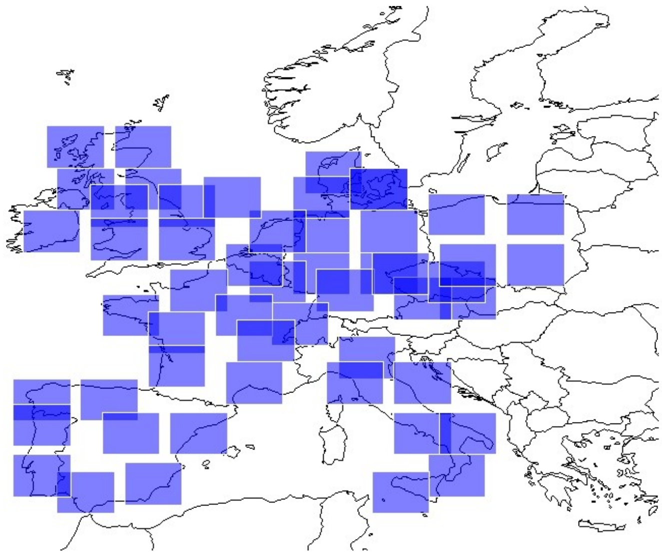
The sum of the individual load duration curves for all countries in a group of countries is not equal to the (concurrent) load duration curve of the group as a whole.

The potential of integrating the electricity and capacity markets at a European level is reflected not only in a smoothing out of the load curve, but also in the feed-in from weather-dependent renewables. The high variability of wind, PV and ROR can be stabilised by a collective assessment scheme, so that renewables can make a greater contribution to security of supply.

Therefore, the second step was to analyse the **feed-in from intermittent renewables**, such as wind power, PV and ROR for the countries in the study. The availability of data is significantly limited in comparison to load, as few countries have systematically collected data over many years for the feed-in from all renewables. Table 2 illustrates which countries, and for which years, the hourly feed-in for wind power and PV were published by TSOs and were used in this study.

In order to conduct a meaningful ex-post analysis of the residual load, **gaps in the data** were synthetically modelled on an hourly basis using installed capacity and meteorological data. For this purpose, the study used reanalysis meteorological data from NASA GES DISC, which is obtainable on an hourly basis. The wind speed parameter (considered at 50 meters above ground) and global radiation are obtainable for all of Europe in a grid with a spatial resolution of 0.67° x 0.5° (around 50 x 50 km in central Europe) – see Figure 27 in the Appendix. To fill gaps in the data with historical feed-in time series, country-specific wind power curves were estimated so that the correlation between wind speed and electricity generation from renewable energy could be determined. The power curves could be approximated with a polynomial, based on the year for the meteorological data and load factors. The modelling took place using a top-down approach for the 53 regions, with a spatial resolution of around 280 x 280 km, as depicted in Figure 6.

Figure 6: Modelling of the hourly wind and PV feed-in by region



For countries **without historical feed-in time series**, the entire ex-post periods had to be synthetically modelled. As, in this case, no country-specific power curves could be estimated, an average power curve of all available feed-in series was approximated for the remaining countries and their respective meteorological data. The meteorological data and data on the installed capacity for renewables were however available, so with the help of the average power curve, synthetic feed-in time series could also be modelled for countries without historical data.

Historical feed-in time series for **wind power** were more available than those for **PV feed-in time series**. As a result, significantly more PV feed-in time series had to be synthetically modelled in total.

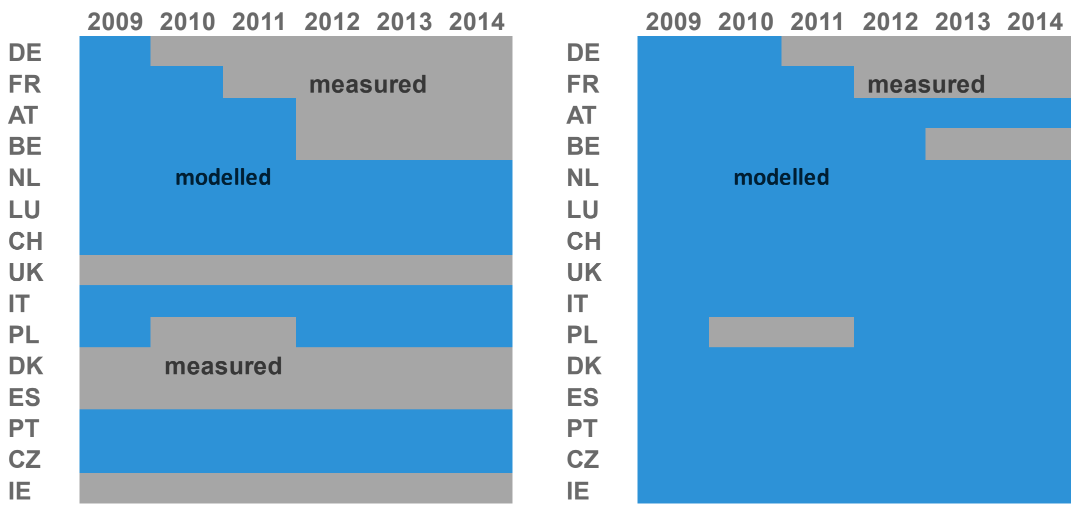
ROR hydropower should also be considered in the category of intermittent generation from renewables. In contrast to wind and PV, variability at the country level doesn't occur on an hourly or daily basis, but rather mainly on a monthly or seasonal basis. For 2010-2013, ENTSO-E reported ROR power plant generation under the category "detailed monthly production". This was interpolated on an hourly basis for all countries. For 2009 and 2014, statistical correlations between total hydropower generation and ROR hydropower generation had to be used from 2010-2013 in order to synthetically generate hourly profiles. Monthly ROR hydropower statistics were used for Austria and Switzerland (AT, E-Control: Electricity Statistics; CH, BfE: Electricity statistics).

The **hourly feed-in time series** for wind power, PV and ROR hydropower for 2009-2014 consist, where possible, of **observed** “measured” data. Missing data for years or countries were synthetically generated using the described methodology and the historical, hourly gridded meteorological data. This synthetically generated data complements the “measured” data. The so generated hourly “hybrid feed-in time series” allows a meaningful ex-post analysis to be conducted.

For the third step, the hourly residual load was determined by subtracting the renewable generation from the load for all 15 countries in the study. Environment-dependent power generation by intermittent renewables can be stabilised by a collective assessment scheme, so that renewables can make a greater contribution to security of supply. The savings potentials were also quantified here with the above-mentioned comparison between a “national assessment scheme” and a “collective assessment scheme”. In both concepts the residual load shows how much conventional power plant capacity has to be reserved. It is important to note:

The sum of the individual residual load duration curves for all countries in a group of countries is not equal to the (concurrent) residual load duration curve of the group as a whole.

Table 2: Availability of hourly feed-in time series for wind (left) and PV (right) by country, 2009-2014



3.2 Scenario simulation methodology

In addition to the ex-post analysis for 2009-2014, **scenarios** ("sensitivities") were calculated for 2030. The first step in doing so was to determine the power demand and the development path for renewable energies for all countries in the study. The current European Union targets (EU 2014) have to be taken into account with respect to power demand and renewable energies. According to these, renewable energies should account for 27 % of energy consumption by 2030. This means a 2030 target of at least 40 % for electricity by 2030. For the purposes of this study, standard power demand and development paths for renewables were used that ensure that the targets are met at a European level. The scenarios of the European transmission system operators, as described in the ENTSO-E Scenario Outlook & Adequacy Forecast (SO&AF) served as a basis for this. The SO&AF distinguishes between four visions for 2030: Vision 1 "Slow Progress", Vision 2 "Money Rules", Vision 3 "Green Transition", and Vision 4 "Green Revolution". This study considers two of the four Visions for the 2030 scenario calculations:

- Vision 1 (V1): Slow Progress
- Vision 3 (V3): Green Transition

The installed capacity of wind turbines and PV installations is illustrated in Table 3 and Figure 7.

To illustrate 2030 on an hourly basis in the scenarios, **hourly load curves** and hourly feed-ins from renewables have to be estimated for the same period in time. The 2030 scenarios were therefore simulated based on the ex-post period of 2009-2014, where the load structure and hourly weather is known. 2030 was simulated in the further analysis with all ex-post meteorological years from 2009-2014.

Based on the peak loads in the ex-post period 2009-2015, the hourly load was scaled to the respective peak loads of V1 and V3. The values are summarised in Table 4 and Figure 8.

Table 3: Installed wind power and PV capacity in 2014 and according to scenarios V1 and V3 in 2030

Wind [GW]	2014	2030 V1	2030 V3
DE	40.5	59.3	85.0
FR	9.3	20.0	40.0
NL	3.1	6.0	12.0
BE	2.0	4.8	8.5
LU	0.1	0.1	0.1
AT	2.1	3.3	5.5
CH	0.1	0.5	0.9
PL	4.6	8.4	10.0
IT	8.6	15.2	15.7
UK	12.0	27.6	47.0
ES	23.0	35.2	48.0
DK	4.9	6.9	10.5
CZ	0.3	0.7	1.4
PT	5.2	5.3	6.3
IE	2.4	4.0	5.7

PV [GW]	2014	2030 V1	2030 V3
DE	38.9	55.1	68.8
FR	5.3	12.0	30.0
NL	1.0	4.0	8.0
BE	3.2	4.0	5.7
LU	0.1	0.2	0.3
AT	0.8	0.9	3.5
CH	1.1	1.1	3.0
PL	0.0	0.5	1.0
IT	18.5	30.0	42.0
UK	4.5	4.6	8.0
ES	7.2	16.4	24.3
DK	0.6	1.0	3.0
CZ	2.2	2.5	3.0
PT	0.3	0.6	0.7
IE	0.0	0.0	0.1

Figure 7: Installed wind power and PV capacity ex-post 2009-2014 and according to scenarios V1 and V3 in 2030 for the study domain

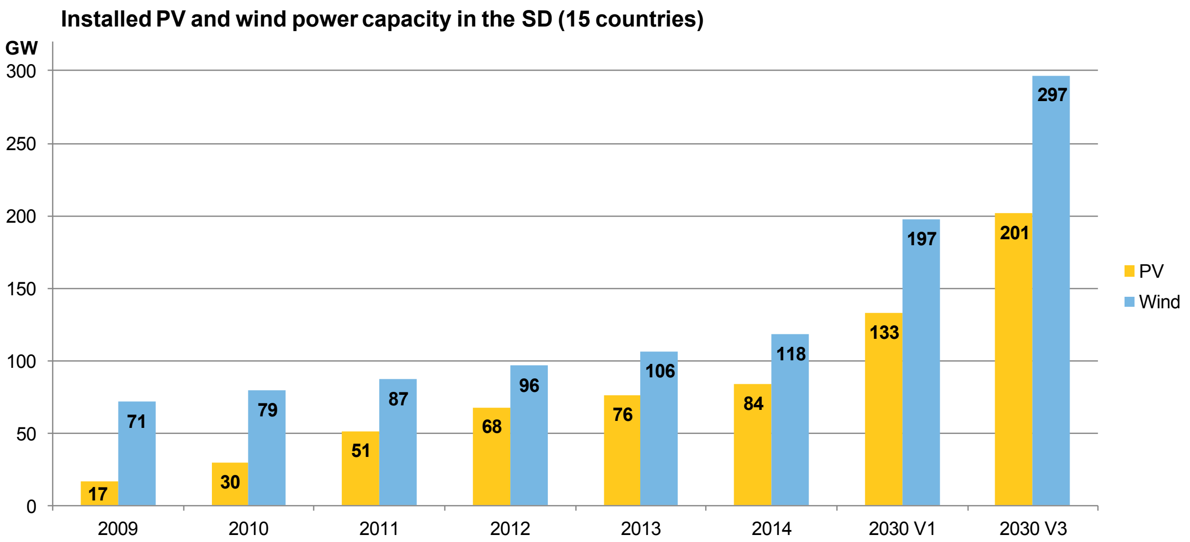


Table 4: *Development of national peak load in the PLEF and the study domain*

[GW]	Ex-post 2009-2014	2030 V1	2030 V3
DE	92.2	91.9	103.3
FR	102.2	81.0	87.8
NL	20.2	16.4	21.9
BE	14.3	14.2	15.6
LU	1.2	1.2	1.5
AT	12.0	10.9	13.4
CH	10.9	9.0	10.8
PL	23.5	26.7	32.0
IT	57.4	53.3	65.2
UK*	65.8	56.7	60.1
ES	45.6	51.1	59.9
DK*	6.4	6.2	7.6
CZ	10.8	11.6	13.2
PT	9.5	9.1	10.6
IE*	5.1	4.8	5.2

Note: Fields shaded green indicate a reduction in peak load as compared with the ex-post period, while red indicates an increase.

* Differing ex-post period of 2010-2014

The **modelling of the feed-in** from renewables in the 2030 scenarios was conducted according to the V1 and V3 Visions from the SO&AF, in 53 regions from 15 countries. In doing so, two different courses of development were simulated. In the first simulated course, development takes place in proportion to the current facilities, based on the assumption that the locations where there are many facilities today will also be where growth will occur in the future. In the second course, simulated solely for wind power, development takes place evenly across the regions of the individual countries. In order for technological advancement to be depicted, two different wind power curves were modelled for both courses of development in all 53 regions – a status quo wind power curve and a modern wind power curve. The modern wind power curve assumes that the nominal power is reached faster with increasing wind speed, producing greater wind output as a result. All eight combinations (two Visions, two courses of development, two power curves) were calculated for all six ex-post meteorological years from 2009-2014. As illustrated in Figure 9, 24 sensitivities were simulated for each SO&AF Vision, resulting in **a total of 48 sensitivities**. The results are reported in Chapter 4 for both the PLEF and the entire study domain (15 countries)[13].

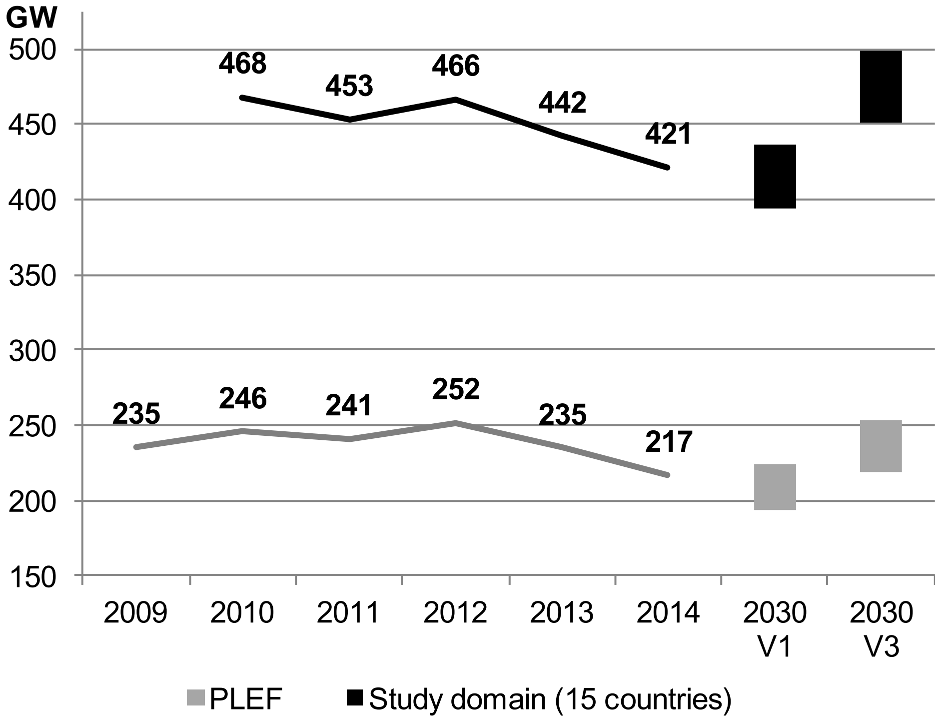
As no cohort model was used, the status quo and modern wind power curves relate to existing facilities and expected facility development respectively. It is thus possible, in individual cases, that the power curves for some countries in the 2030 scenario are slightly worse than in the ex-post period. As, in future, less suitable locations for new wind power facilities may have to be considered, this result doesn't seem unreasonable. The margin of safety in the selected wind power curves is thus, in any case, high.

The **hourly feed-in time series** could be modelled in the 48 sensitivities for 2030, based on the wind power curves, the meteorological data and the installed capacity. The PV feed-in time series for 2030 was generated for two scenarios, V1 and V3, in all regions. The difference between V1 and V3 was relatively small for ROR hydropower, so only scenario V3 was considered.

For each **meteorological year** (2009–2014) the hourly residual load could be calculated by deducting the hourly feed-in profile of renewables from the 2030 load. This produced the hourly residual load in 48 sensitivities (2 SO&AF Visions, 2 courses of development, 2 wind power curves and 6 weather years) and forms a meaningful basis for the present study.

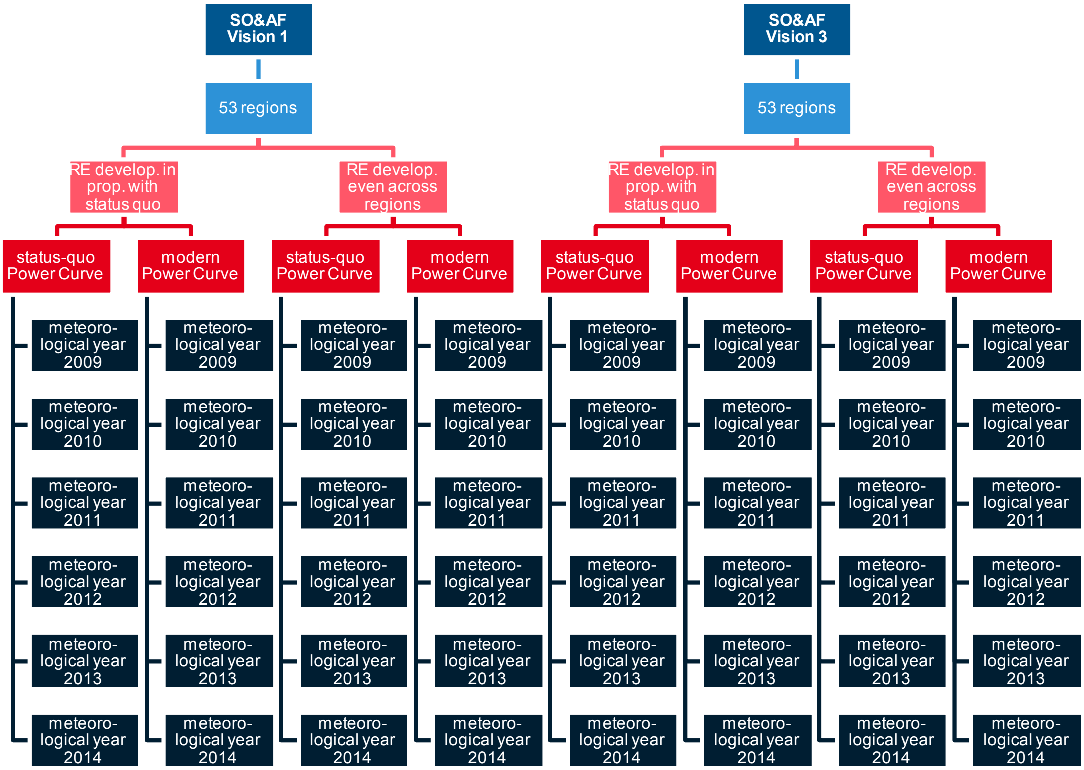
[13] Six ex-post years (2009-2014) were available for the PLEF region, while five were available (2010-2014) for the entire study domain. For the study domain, there are thus 20 scenarios per Vision, resulting in a total of 40 scenarios.

Figure 8: Development of the sum of national peak loads in the PLEF and study domain



Note: The development of the sum of national peak loads in the PLEF and SD for the ex-post period and 2030 V1 and V3 scenarios. The length of the columns for V1 and V3 indicate the minimum and maximum values, based on the meteorological years in the ex-post period.

Figure 9: Wind power scenario simulation (sensitivities)



Note: For both Visions (SO&AF V1 und V3) the wind power feed-in was modelled for 53 regions from 15 countries, using two different development courses, two different wind power curves, and for six different meteorological years.

4 Results of the ex-post analysis and scenario simulations

4.1 Analysis of the load

The load of a country exhibits a characteristic pattern during **days, weeks and years**. The daily course of load is characterised by lower values in the night and higher values in the day, and is very dependent on the length of the day. While a double-peak can be observed in the load curve for Central Europe in winter (with higher demand for power in the morning and evening, mainly from lighting), only one peak can generally be seen in summer (a midday peak). Load is higher during work days than at the weekend or on public holidays. Typical holiday weeks can also be clearly seen, such as the days around Ferragosto (August 15) in Italy. The temperature dependence of load can most clearly be seen over the course of the year but is not as strongly pronounced in all countries. Although the general level of load in **France** is around 40 % higher in winter than in summer, this difference is much less pronounced in **Germany** (although the highest load for the year still occurs on cold winter days). By contrast, the annual peak load in **Italy** regularly appears in summer before Ferragosto, when air conditioning systems are running at full power.

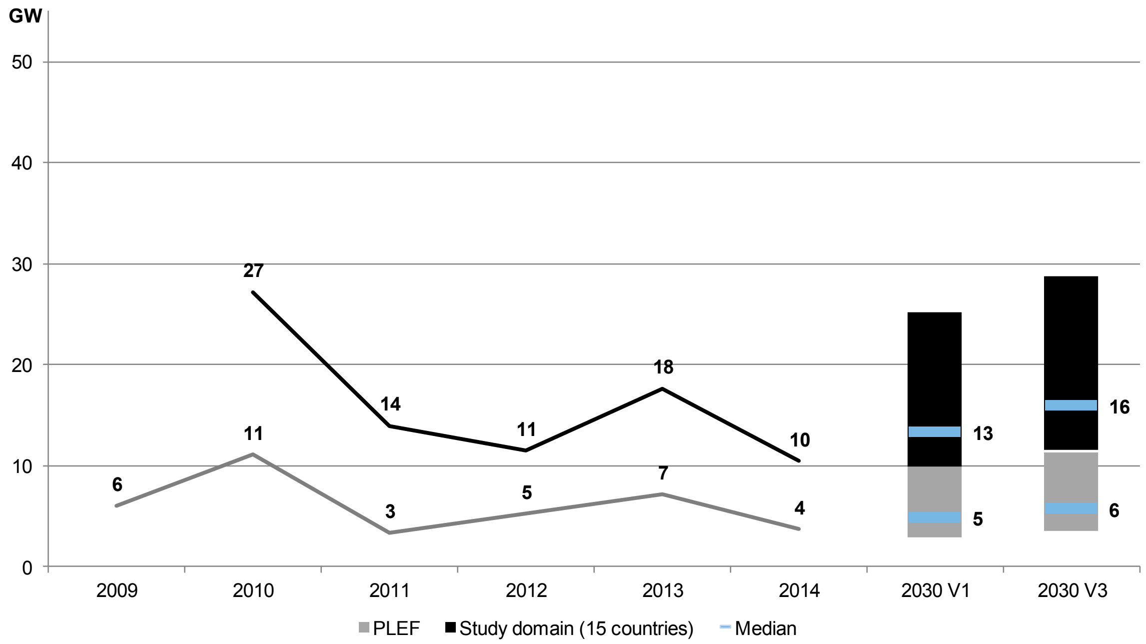
The most important load **influencing factors** occur in many European countries simultaneously, so the concurrency of load in the study domain is relatively high (see the red ellipses in Figure 11). Differences between countries with respect to economic structure, lifestyles, heating systems, weather conditions, time differences, etc. are apparent in asynchronicities (the blue ellipses in Figure 11). Figure 12 shows the load cross-correlation between Great Britain and France from 2011 to 2013. The strongest correlation occurs with a one hour time difference. The work day begins in both countries at the same local time, but there is a one hour time difference in real time. These asynchronicities already hold synergy potential to be realised through collective assessment.

The **peak loads** do not occur at the same time for the 15 European countries considered. Nevertheless, there is a close similarity in consumption patterns and thus a strong temporal correlation with respect to high capacity requirements. The sum of the national peak loads in the ex-post period of 2009 to 2014 and the scenarios are presented in Figure 8 in Chapter 3.2.

Figure 10 shows the **benefits of a collective assessment scheme** for peak load in the PLEF and the entire study domain (SD) of 15 countries. For the period from 2009 to 2014, the group load of the PLEF was between around 3 and 11 gigawatts (1.2 % to 4.5 %) below the sum of the peak loads under a national assessment scheme. For the entire study domain (including PL, IT, UK, ES, DK, CZ, PT, & IE), the group load was between 10 and 27 gigawatts (2.5 % to 5.8 %) lower than the sum of the peak loads under a national assessment scheme.

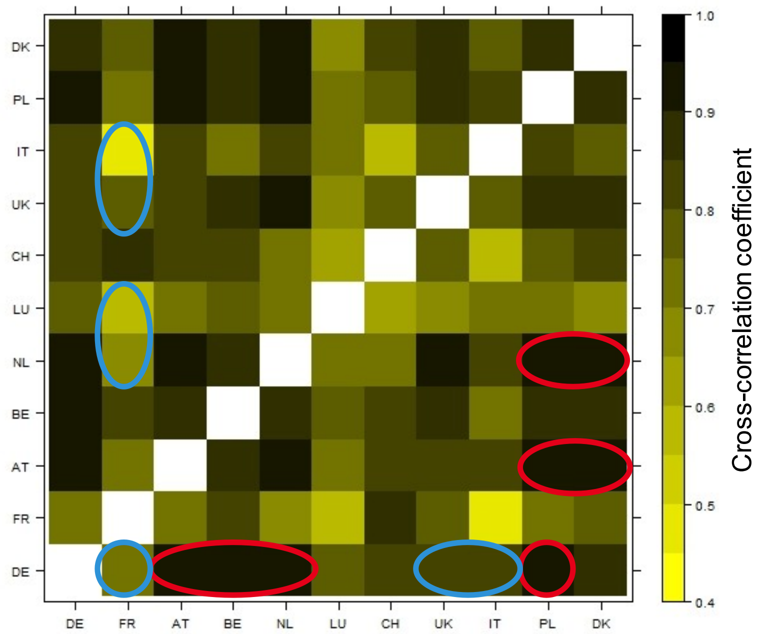
This **synergy potential** is still present in 2030 for scenarios V1 and V3, but barely increases. This is because the peak load in scenario V1 sinks for many countries, and, for V3, does not significantly increase. The structure of the hourly load also remains the same (see the Scenario simulation methodology in Chapter 3.2). For scenario V1 in 2030, depending on the underlying meteorological year (2009-2014), the group load of the PLEF was between 3 to 10 gigawatts (median: 4.8 gigawatts) below the sum of the peak loads under a national assessment scheme. For the entire study domain, this was between 10 to 25 gigawatts (median: 13.3 gigawatts). The figures are higher for scenario V3 in 2030, with between 4 to 11 gigawatts (median: 5.7 gigawatts) for the PLEF region and between 12 to 29 gigawatts (median: 15.9 gigawatts) for the entire study domain, as can be seen in Figure 10.

Figure 10: Reduction of the annual peak load achieved through collective assessment in the PLEF and study domain in comparison to national assessment, 2009(10)-2014 and 2030



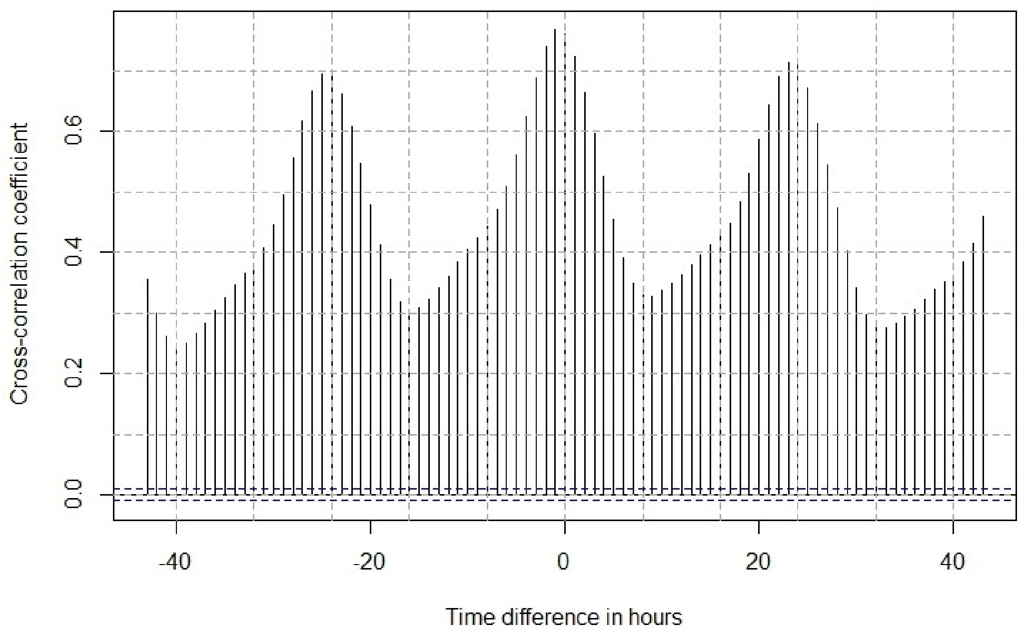
Note: The range of values presented in the scenarios arises from the different meteorological years

Figure 11: Load concurrency analysis, 2011-2013



Note: The colour legend (yellow to black) indicates the cross-correlation coefficient between two countries with no time difference. Darker fields indicate a high concurrency of load between two countries (the highest values have been highlighted with red ellipses). Lighter fields indicate a certain lack of concurrency between countries (and have been highlighted with blue ellipses). The figure is mirrored along the white diagonal

Figure 12: Load concurrency, 2011-2013. Cross-correlation between France and Great Britain



4.2 Analysis of renewables

The **feed-in from wind power, PV and ROR** is subject to high **fluctuation**. On a night with no wind, wind power and PV feed absolutely no electricity into the grid. Intermittent renewables thus cannot really provide reliable available capacity at a national level. When integrated with neighbouring countries, the availability of intermittent renewables rapidly increases by virtue of balancing effects. The larger the harmonised group of countries, the more reliable available capacity can be provided by renewables. Through collective assessment, poor local wind conditions can be compensated for and the length of the day can be effectively extended by taking advantage of the sunrise in Eastern Europe and sunset in Western Europe.

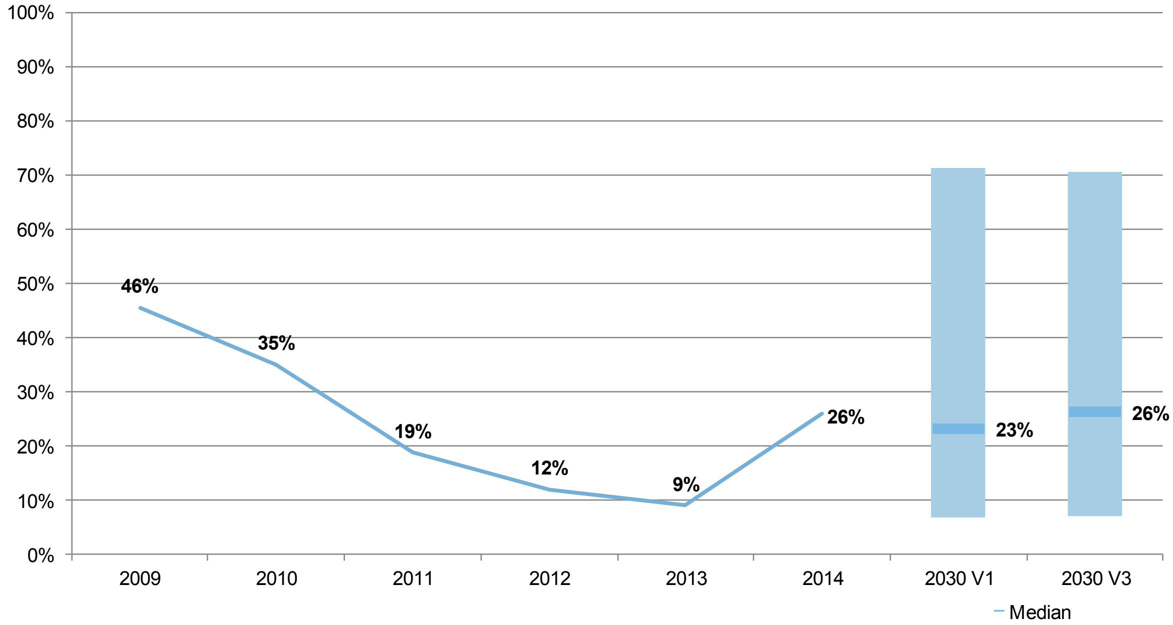
The **determination of the required scale of the power system** takes place at the time of peak load. It is therefore decisive how much reliable available capacity is provided by renewables during the peak load hour with a cross-border approach to assessment.

The analyses show that the **feed-in from wind power** during the group annual peak load hour for the PLEF region was never lower than 9 % of the installed capacity (2013), and in the best case even over 45 % (2009). In absolute figures, between 4 and 15 gigawatts of wind power was fed in for the PLEF region in the group annual peak load hour from 2009 to 2014, depending on the weather conditions. In scenarios V1 and V3 for 2030 the availability was between 7 % and 71 %, depending on meteorological year (2009-2014), course of development and technological advancement. This corresponds to a minimum feed-in of 6 gigawatts (V1) and 11 gigawatts (V3) in 2030, as depicted in Figure 13 and Figure 14.

For the entire study domain (15 countries), the availability of wind power rose up to between 24 % and 33 % (22 to 37 gigawatts) for the ex-post period 2010-2014 during the group peak load hour. In scenarios V1 and V3, the relative availability was in the range of 9 % to 54 %, depending on the meteorological year (2010-2014), course of development and technological advancement. Under a collective assessment scheme, in 2030, between 20 and 106 gigawatts of wind power were available during the group annual peak load hour according to scenario V1 for the entire study domain. For scenario V3, this was even as high as between 28 and 161 gigawatts. This is illustrated in Figure 28 and Figure 29 in the Appendix.

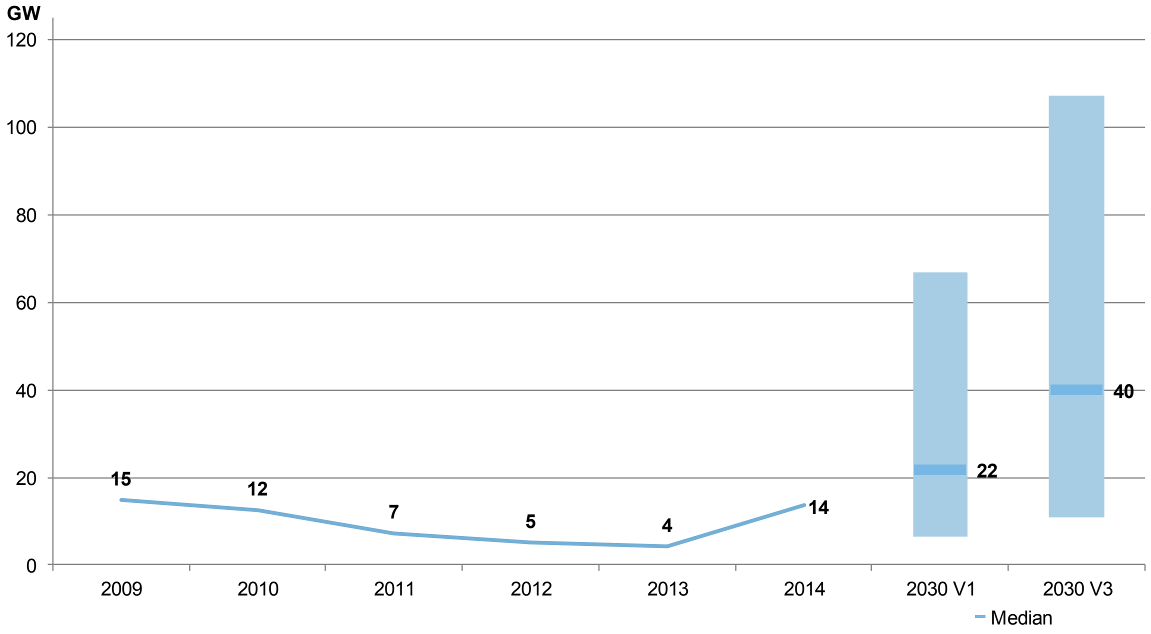
The large **range of values in the ex-post analysis** and the scenarios demonstrates that wind availability during the peak load hour is subject to major year-to-year variation, and, based on six meteorological years, it cannot be excluded that lower values could occur. However, the analysis also shows that the larger the group of countries is, the lower the variability of wind power (thus making it more predictable). While the spread of availability for the PLEF region was in the range of 7 % to 71 %, it was between 9 % and 51 % for the entire study domain. The probability that the lowest wind availability for a group of countries will occur at the same time as the peak load for these countries is likely to be low but is not examined in more detail within the scope of this project.

Figure 13: Wind energy availability (% of installed capacity) during the group peak load hour in the PLEF, 2009-2014 and 2030



Note: The range of values in the scenarios results from the different meteorological years, course of development and technological advancement

Figure 14: Wind energy availability during the group peak load hour in the PLEF, 2010-2014 and 2030



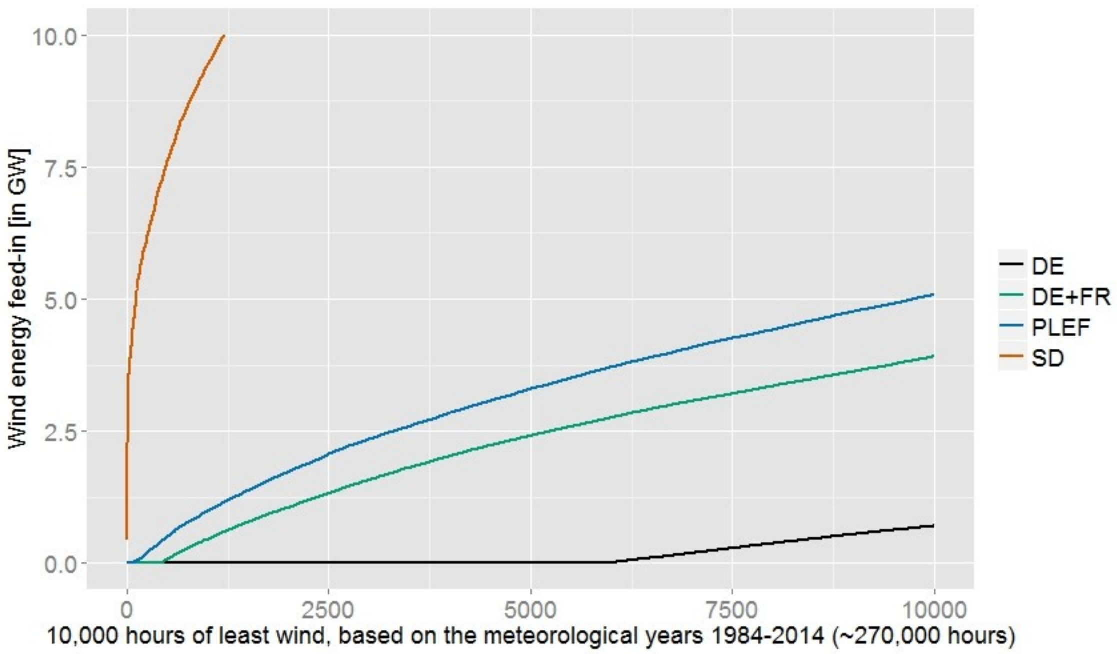
Note: The range of values in the scenarios results from the different meteorological years, course of development and technological advancement

The envisaged reliable available capacity from wind power in 2014 and 2030 was simulated based on the **historical meteorological data** from 1984-2014 (31 years) for all of Europe. The hourly feed-in from wind power for 53 European regions between 1984 and 2014 was modelled based on the installed capacity in 2014, as well as for the 2030 V1 and V3 scenarios with a modern wind power curve. The applied power curves presented proportionally low load factors with low wind speed in order to avoid an overestimation of wind availability (see Chapter 3.2; Scenario simulation methodology).

As can be seen in Figure 17, based on the hours between 1984 and 2014, a reliable (99 % availability) feed-in from wind power of 0.5 gigawatts is provided for the PLEF region, and 5.7 gigawatts for the entire study domain (15 countries) in 2014. Although the reliable available capacity from wind energy in the PLEF region is quite modest, it rapidly increases when the size of the group of countries expands, given the assumption of perfect transmission system development (copper plate). It should be noted that the geographical spread plays a greater role here than the additional installed capacity for the added countries. In scenario V1 for 2030, the reliable wind availability rises to 1.2 gigawatts, and to 9 gigawatts for the study domain. In the SO&AF development Vision V3, wind energy provides 2.2 gigawatts (1.4 % of installed capacity) for the PLEF in 2030 and 12.9 gigawatts for the entire study domain, corresponding to 4.4 % of installed capacity. As can be seen in Figure 19, the year-to-year variability is in the multiple percentage point range. With 99 % availability in every single year, the reliable available capacity was somewhat lower, as shown in Figure 19. The 99.9 % availability is depicted in Figure 18.

In contrast, the wind power availability is significantly limited under a national assessment scheme. In Germany, when the meteorological years from 1984-2014 (>270,000 hours) are considered, even with strong expansion of wind power (2030 V3), around 6,000 hours (~2 %) have no feed-in from wind power (see Figure 15). If the region considered is extended to France, the 2-country group would have only 400 hours (~0.1 %) without feed-in from wind power. For the PLEF region, there is even less than 100 hours (~0.04 %) without feed-in from wind power. For the entire study domain (15 countries) there are no hours in the meteorological years from 1984-2014 without feed-in from wind power (see Figure 16).

Figure 15: Wind energy availability in the 10,000 hours of least wind



Note: Wind energy availability in the 10,000 hours of least wind in 2030 (V3, even course of development) in Germany, in the Germany-France group, in the PLEF and in the entire study domain (15 countries), based on the meteorological years from 1984-2014 (~270,000 hours.

Figure 16: Wind energy availability in the 1,000 hours of least wind

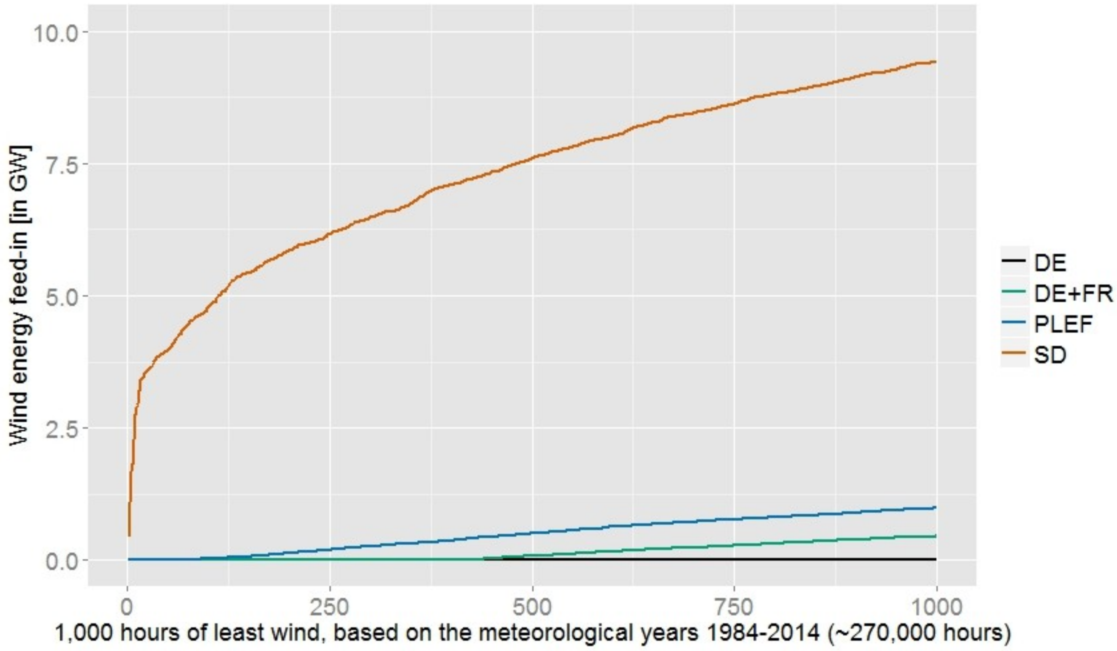


Figure 17: Reliable (99 %) wind energy availability in gigawatts of installed capacity, 2014 and 2030 V1 and V3, based on the meteorological years from 1984-2014

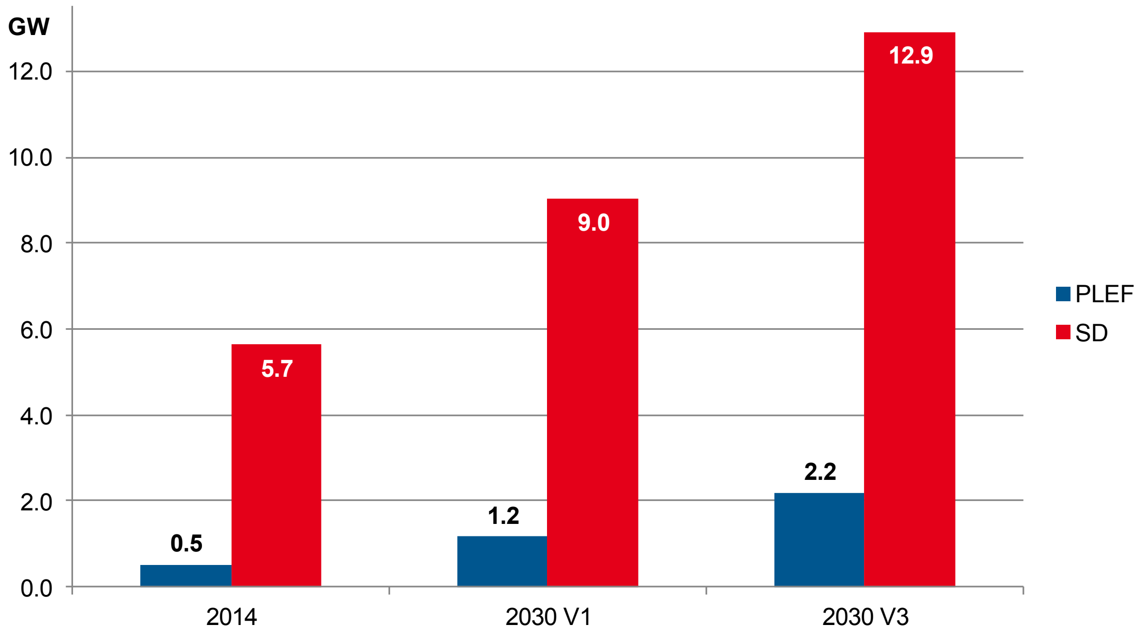


Figure 18: *Reliable (99.9 %) wind energy availability in gigawatts of installed capacity, 2014 and 2030 V1 and V3 scenarios, based on the meteorological years from 1984-2014*

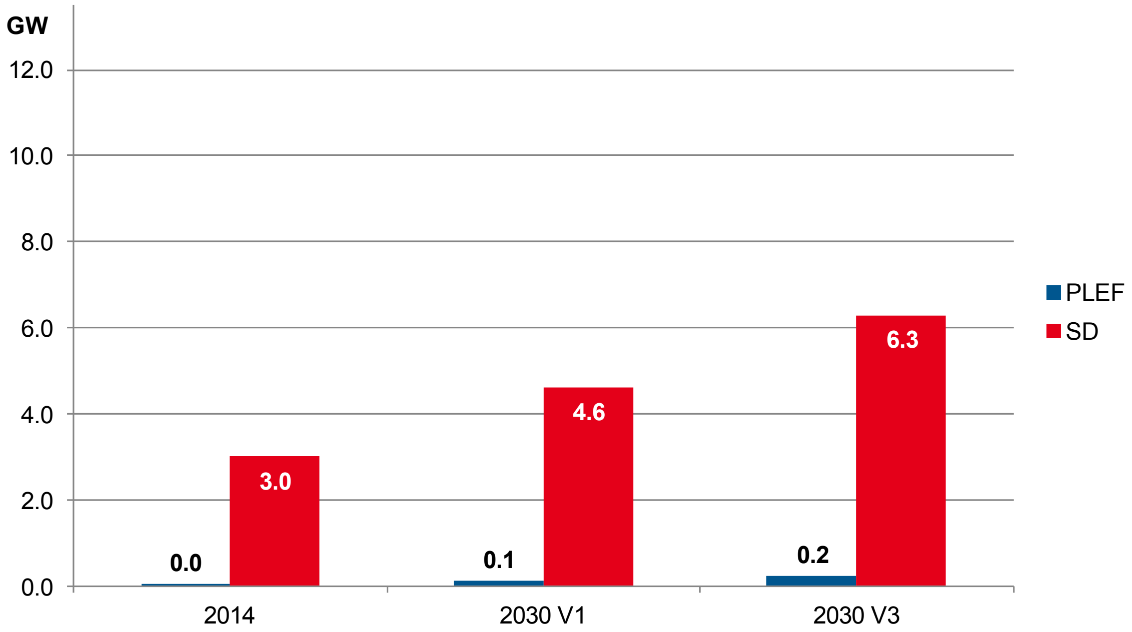
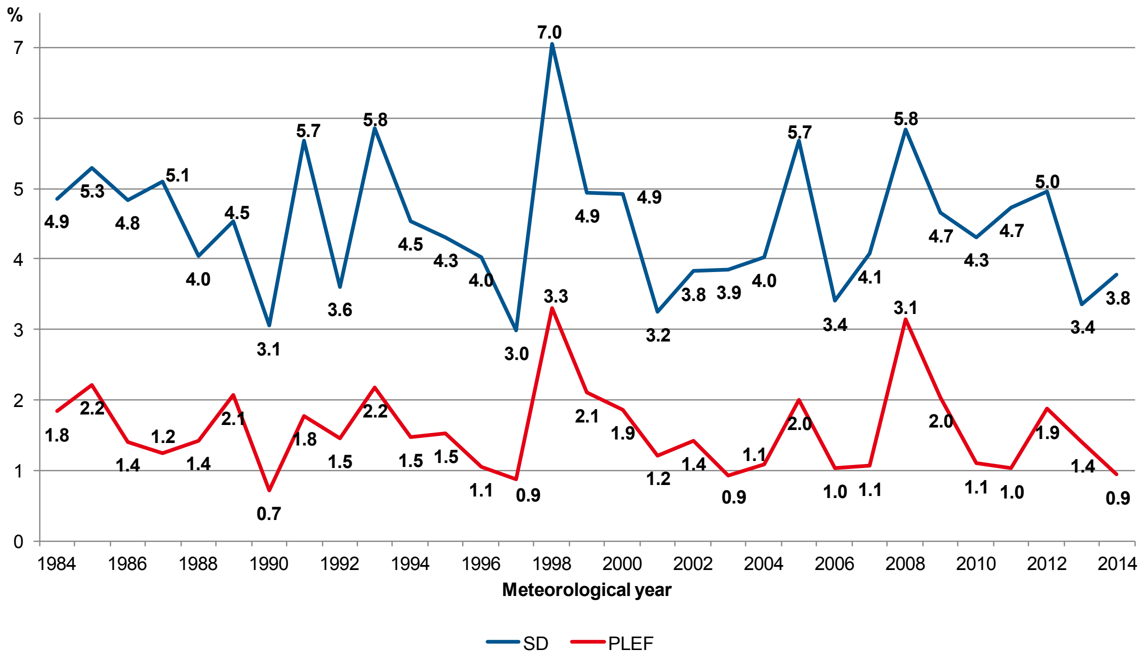


Figure 19: *Reliable (99.9 %) wind energy availability in % of installed capacity, 2030 V3, based on the meteorological years from 1984-2014*



4.3 Residual load

The required ensured generation adequacy is determined by the **residual load**[14]. The balancing effects on the load side and the stabilisation of the feed-in from renewable energy in the group of countries come to bear with the residual load determined for the countries in the study. The potential contribution of a cross-border assessment approach to reducing capacities held in reserve can consequently be seen in the analysis of residual load.

The **sum of the highest values of national residual load** in the PLEF region for the ex-post period of 2009-2014 was between 203 and 238 gigawatts, depending on the meteorological year. In scenarios V1 and V3 for 2030, the values ranged between 176 to 208 gigawatts (V1) and 199 to 233 gigawatts (V3). For the entire study domain, the sum of the highest values for national residual load in the ex-post period of 2010-2014 was between 393 and 441 gigawatts. In the 2030 simulations, depending on the sensitivity, the expected sum was between 359 and 406 gigawatts (V1) and 412 and 462 gigawatts (V3).

Under a collective assessment scheme for the study domain (in comparison to a national assessment scheme), the **highest values for residual load** fall in the ex-post period for the PLEF by 4 to 11 gigawatts, and by 17 to 30 gigawatts, as can be seen in Figure 20. As the residual load serves as a reference value for the capacity to be provided through controlled energy generation, this drop results in an economic benefit, as less capacity has to be reserved at a national level. The residual annual peak load balancing effects in the group will further increase in future, due to the expansion of wind power. While the lower range of the scenarios presents around the same values as in the ex-post period, the upper range represents a significant increase, especially for the entire study domain. The highest values for residual load are 40 gigawatts lower in scenario V1 under a collective assessment scheme for the study domain in comparison to a national assessment scheme, and up to 50 gigawatts lower for scenario V3. The most probable reduction for the entire study domain in 2030 is 27 gigawatts for scenario V1 and 34 gigawatts for scenario V3. This represents an increase of potential synergies of up to 50 % in comparison to the ex-post period. In the PLEF region, the highest values for residual load in 2030 were 8 gigawatts lower (V1) and 10 gigawatts lower (V3) than the national assessment scheme figures. Such values are already present in the ex-post period. On

[14] The residual load denotes the demanded electric capacity less intermittent feed-in from non-controllable power plants, such as those powered by wind power, PV and run-of-the-river (ROR) hydropower.

average however, the potential reductions for 2030 also increased for the PLEF region in comparison to the ex-post period by 14 % to 40 %.

The rapid expansion of renewables and the changed group load curve means that the **peak load time** in the ex-post period may not necessarily be the same as in the **scenarios**. The range of values in the scenarios results from the different meteorological years (2009-2014), the two different courses of development and the application of both wind power curves (status quo and modern). As a result, under certain circumstances, the potential reduction in the residual annual peak load under a collective assessment scheme in comparison to a national assessment scheme may also be lower than in the ex-post period. The lower end of the scenario columns represents the construction of wind farms in regions with low wind, and facilities that are barely more technologically advanced than today's (status quo wind power curve). The upper end of the scenario columns corresponds to development with advanced wind farm technology (modern power curve).

With the appropriate **flexibility mechanisms**, the hour with the highest residual load doesn't need to have the entire capacity provided by controllable energy generation, so that not only the hour of peak load is decisive for determining the scale of the required capacity, but also, for example, the 100 hours with the highest residual load.

Significant synergy potential for the group of countries in 2030 is apparent in the average of the **100 hours with the highest residual load** (see Figure 30 in the Appendix). The average of the 100 hours with the highest residual load is less strongly characterised by short-term weather influences and thus provides a more robust estimation of the savings potential. The average of the 100 hours with the highest residual load for the group of countries in the PLEF region in the ex-post period was 4 to 6 gigawatts lower than under a national assessment scheme. This reduction potential increases for the PLEF region in the 2030 scenarios to a reduction of 4 to 9 gigawatts (V1) and 5 to 11 gigawatts (V3). For the entire study domain of 15 European countries, the average of the 100 hours with the highest residual load in the ex-post period was 17 to 19 gigawatts lower than under a national assessment scheme. In 2030, the synergy potential in the study domain increases to a reduction of 35 gigawatts (V1) and 45 gigawatts (V3).

The **hour of lowest residual load** will also be strongly influenced by collective consideration, as shown in Figure 21. The values in the study domain for the ex-post period were 22 to 38 gigawatts higher under the collective assessment scheme as compared to the national assessment scheme. In 2030, the lowest residual load was between 46 and 106 gigawatts higher than with the national assessment scheme. For the PLEF region, the lowest residual load in the ex-post period was between 4 and 13 gigawatts higher than with the national assessment scheme. For 2030, this value rose to between 6 and 35 gigawatts.

This is important given the increasing proportion of renewable energies, as **national excess feed-in situations** (negative national residual load) can be avoided through the group of countries, and thus lead to better usage of renewable energies. The simulations show that, for scenario V1, there is no hour with negative residual load in 2030 under a collective assessment scheme. In contrast, a national assessment scheme can result in the occurrence of negative values up to -28 gigawatts. In the PLEF region, hours with negative residual load occur in only one year in scenario V1 2030, while these occur every year under a national assessment scheme. Even given strong growth in renewables (scenario V3 2030) there is almost no negative residual load[15] for the entire study domain (this is not the case for the PLEF region). In contrast, a national assessment scheme results in negative values up to -102 gigawatts. The reduction in negative residual load will also tend to reduce or delay the need for storage or other flexibility options in comparison to a situation with no European integration. Figure 22 depicts the residual load duration curves for a national assessment scheme and a collective assessment scheme for the study domain in 2030. The reduction in the highest levels of residual load and the increase in the lowest levels of residual load are clearly illustrated in Figure 23.

[15] In the simulations with a modern wind power curve, hours with negative residual load occur in two out of five meteorological years in the 2030 V3 scenario. The lowest residual load for these meteorological years is still 72 to 92 gigawatts higher than under a national assessment scheme.

Figure 20: Reduction of the residual annual peak load under a collective assessment scheme in the PLEF and study domain in comparison to a national assessment scheme, 2009(10)-2014 and 2030

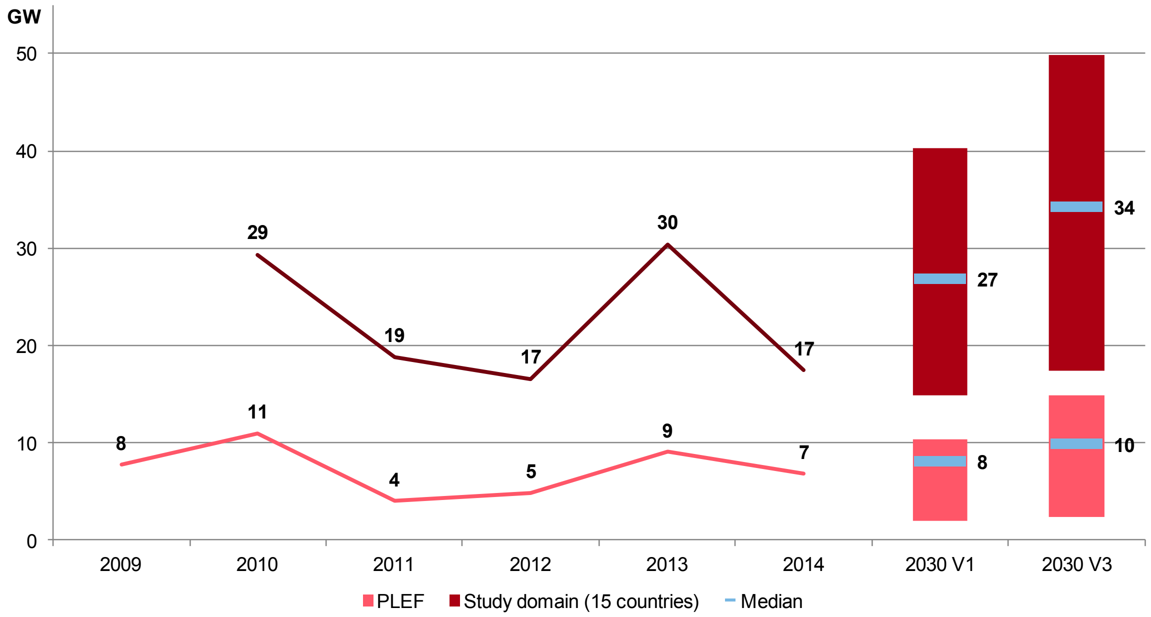


Figure 21: Increase in the lowest levels of annual residual load under a collective assessment scheme in the PLEF and study domain in comparison to a national assessment scheme, 2009(10)-2014 and 2030

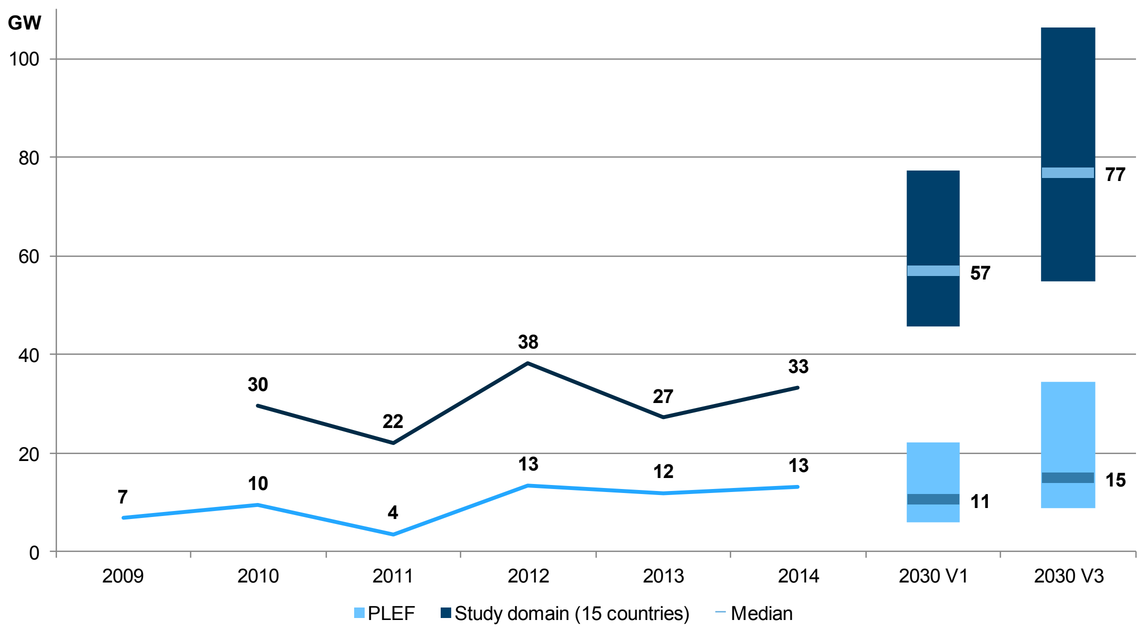
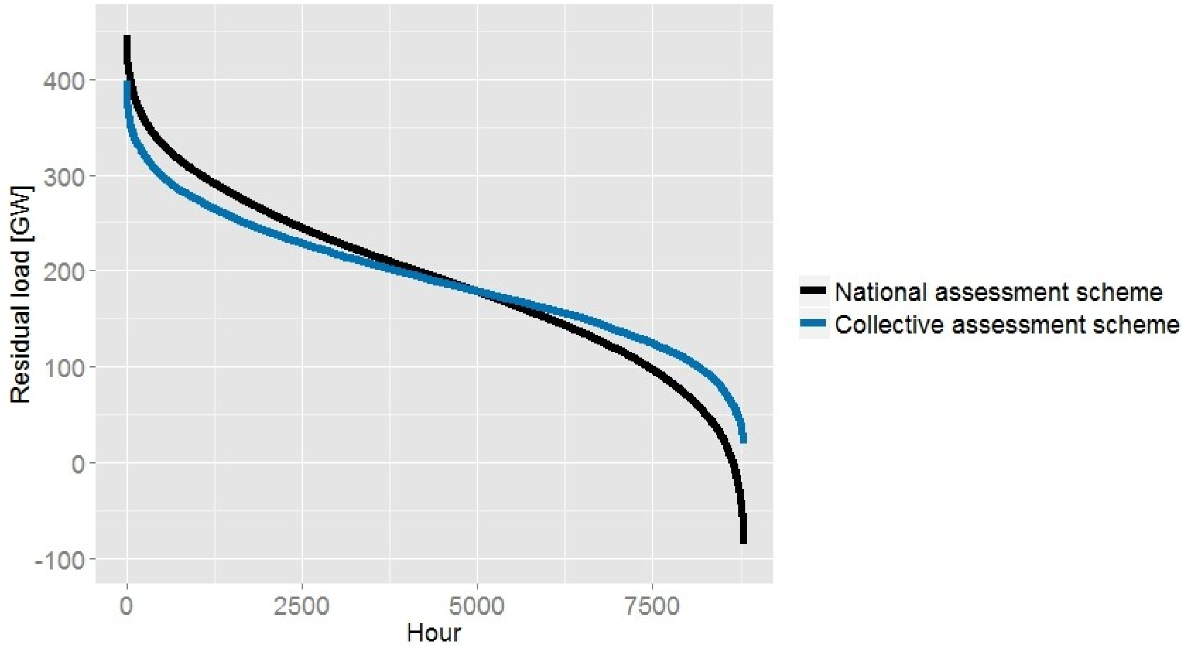
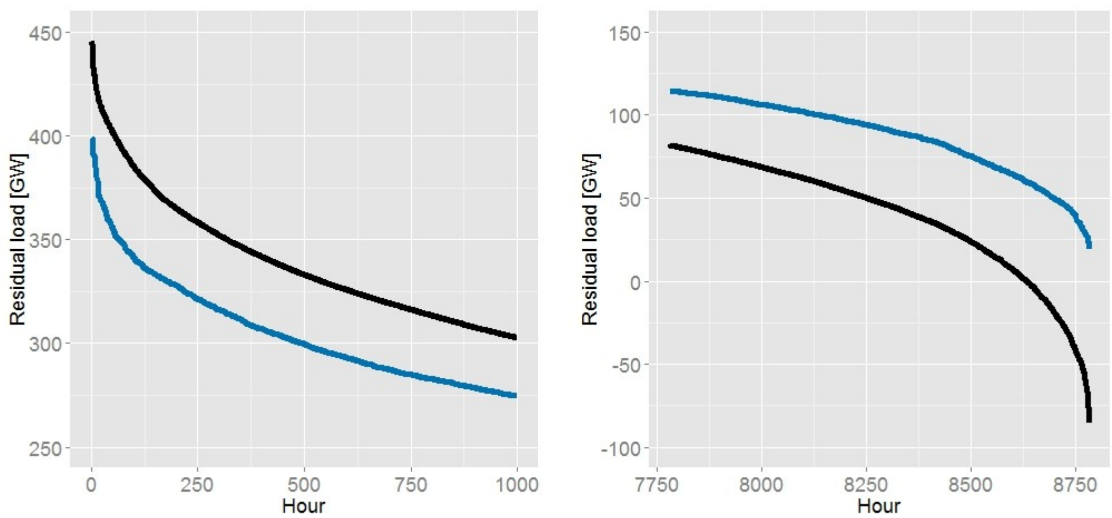


Figure 22: Residual load duration curves for a national assessment scheme and a collective assessment scheme in the study domain, 2030



Note: The sum of the residual load duration curves for all countries in the study domain (black: national assessment scheme) and the concurrent residual load duration curve for the study domain (blue: collective assessment scheme) in 2030 (development course V3, even development, based on the 2012 meteorological year

Figure 23: Analogous to Figure 22, but for the first (left) and last (right) 1,000 hours



4.4 Classification of the results based on current studies of generation adequacy assessment

This study has points of reference with **two current studies** which have a similar thematic background.

The **transmission system operators of the Pentalateral Energy Forum** (PLEF) developed a new international methodology of adequacy assessment in a study on cross-border generation adequacy (PLEF SG 2 2015). In this study, the adequacy assessment for various countries in the PLEF region was analysed for the period up to 2020/2021. As part of the analysis, the isolated consideration of individual countries was compared with cross-border networks of countries. The methodology developed for this used a probabilistic approach considering all relevant generation units (e.g. thermal power plants, renewables and conventional hydropower) and the load. In doing so, the transmission system operators orient themselves on the approaches currently implemented in France and Belgium, as well as the target methodology employed by ENTSO-E.

A comparison of the results for the isolated and the interconnected cases demonstrates that the regional integration of countries provides, in total, **substantial advantages with respect to security of supply**. This is especially true for countries with highly integrated international grids. Adequacy problems were identified for Belgium and France for the period considered and, due to the concurrency of various situations, not all critical situations could be resolved by means of regional integration. The results thus correspond to the conclusions of the national analyses. In a further step, a range of sensitivity analyses (including a model of the 2012 cold front) reviewed the robustness of the results.

In a study conducted by **Consentec/r2b** (2015), commissioned by the **German Federal Ministry for Economic Affairs and Energy**, regional balancing effects with respect to residual load and conventional power plant outages were examined. A method of monitoring the security of supply was developed with the aim of calculating the load balancing probability. The analysis is based on the scenarios from the ENTSO-E SO&AF (2014 to 2030), using the period up to 2025. The study domain overlaps largely with the present study, although omits the Iberian Peninsula and Great Britain and includes Norway and Sweden.

A **central result** of the study is that the concurrent residual peak load is between 10 gigawatts (in 2015) and 20 gigawatts (in 2025) less than the sum of the national peak loads and that balancing effects from conventional power plant outages are to be expected at the same time. The study comes to the conclusion that electricity exchange through portfolio and balancing effects can fulfil security of supply requirements at lower costs.

The results of the analyses conducted in the **PLEF** (PLEF SG 2 2015) and Consentec/r2b (2015) studies point in a similar direction to the present study. In both studies, a harmonised consideration of generation adequacy assessment leads to cost reductions with respect to the necessary reliable available capacity.

Due to differences in the applied methodologies, the quantitative results of the PLEF study cannot be directly **compared** with the present study. The methodology of the PLEF study applies a comprehensive generation adequacy assessment approach, also considering conventional power plants and using specific security of supply criteria. In contrast, the present study focuses on efficiency effects in the residual load. However, the basic message of the PLEF study corresponds with the results of the present study. Regional integration with respect to ensuring generation adequacy provides advantages for security of supply and thus the provision of reliable available capacity.

The Consentec/r2b (2015) study applies a fundamentally similar approach to the present study. Differences arise from the differing period of time considered and the smaller study domain examined in the Consentec/r2b study. Taking these limitations into account, it can be stated that the quantitative results are of a similar magnitude to the present study: a reduction of the residual peak load by 20 gigawatts (Consentec/r2b) in comparison to a reduction of the residual peak load by 15 to 45 gigawatts in the present study. This, in principle, confirms the results of the present study.

5 Requirements for intensified integration with respect to ensuring generation adequacy

5.1 Process of ensuring generation adequacy

As the results of the quantitative analyses show, **international harmonisation** with respect to ensuring generation adequacy has, in principle, potential synergies and can thus lead to a reduction in the reliable available capacity that has to be maintained. This, in turn, leads to cost reductions due to the lower level power plant capacities required to be reserved. These cost reductions can however only be realised when there is strong international cooperation with respect to ensuring generation adequacy.

At the moment, countries have physically connected power grids and engage in electricity trading with each other. The **process of ensuring generation adequacy** is, as described in Chapter 2, organised at a national level (see Figure 24).

Figure 24: Schematic representation of the national process of ensuring generation adequacy

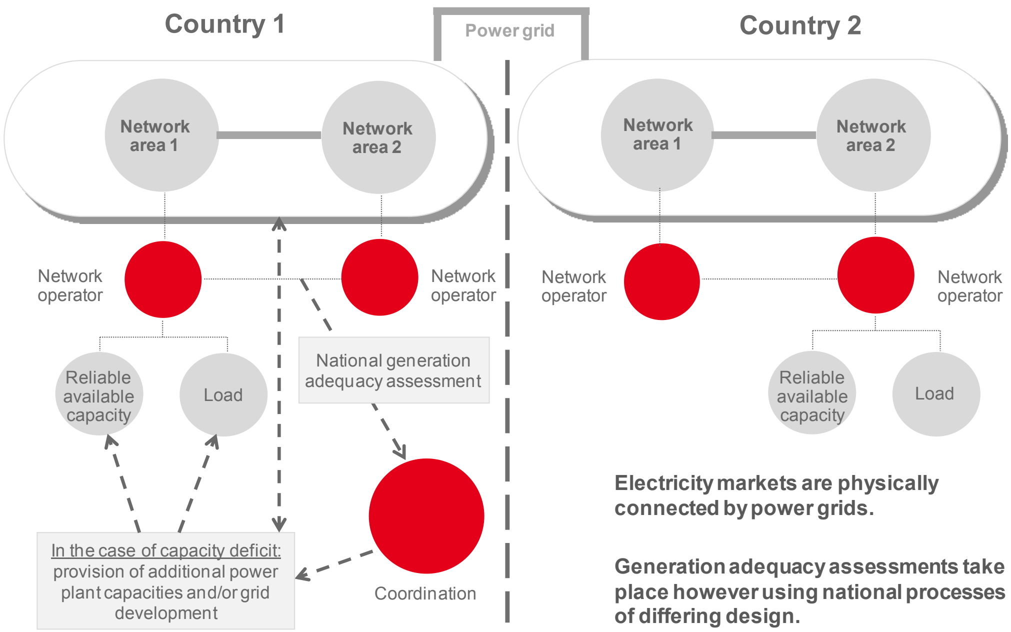
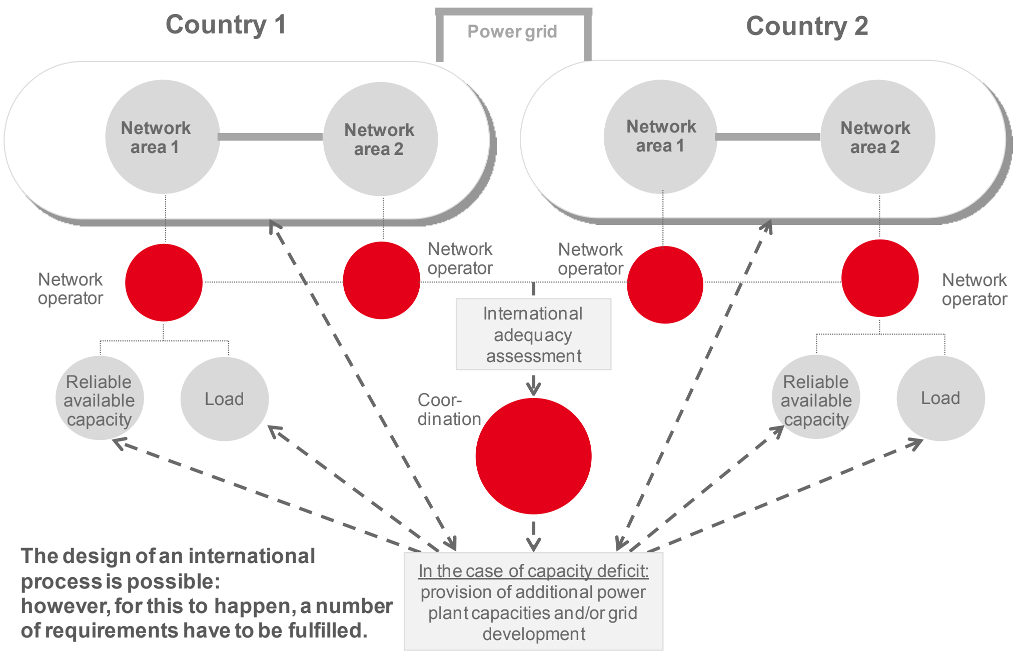


Figure 25: Schematic representation of the international process of ensuring generation adequacy



In order to achieve the potential benefits from synergies, the preconditions have to be established so that the (currently national) process of ensuring generation adequacy acquires an international dimension. This requires an international process of ensuring generation adequacy, depicted in Figure 25. The design of these international processes is open, and requires close coordination between countries and parties with cross-border operations.

In our opinion, to meet the requirements for international cooperation, targeted measures are of particular importance in the following **areas**:

- **Harmonisation of the methodology of generation adequacy assessment:**
  allows an internationally applicable and agreed upon calculation methodology with respect to generation adequacy so that an international dimension to ensuring generation adequacy can be established.
- **Harmonisation of the processes of ensuring generation adequacy:**
  through the development of additional cross-border processes establishes the relevant legal and organisational framework for harmonisation, so that the exiting potential for synergies can be realised.
- **Provision of grid infrastructure:**
  supplies the essential technical framework for harmonisation and finally determines the degree of potential synergies that can actually be achieved.

5.2 Harmonisation of the methodology of generation adequacy assessment

Establishing a harmonised methodology for generation adequacy assessment is fundamental to a coordinated process of ensuring generation adequacy. This creates a quantitative (instrumental) foundation for the calculation of the necessary reliable available capacity. This is the only way to ensure that the calculation of the capacity to be provided takes into account the electricity generation of all countries and the cross-border grid capacity of the selected geographical region. The selected methodology in the current study serves to demonstrate the synergy potential. However, an international approach to generation adequacy assessment also has to consider conventional electricity production (and its availability) in addition to the load-related aspects.

Current methods of generation adequacy assessment are nationally defined, follow disparate approaches, feature differing levels of detail and have different relevance with respect to the process of ensuring generation adequacy. National methods are also characterised by the challenges specific to their respective countries. For example, if there is an excess of power generation capacities over many decades, a detailed methodology of generation adequacy assessment is not urgently needed. On the other hand, the introduction of a comprehensive methodology of generation adequacy assessment is potentially more relevant for power systems that are characterised by centrality than for decentralised power systems. Other factors determining the approach to generation adequacy assessment include the cross-border integration of the system and the dominance of certain technologies (e.g. hydropower). An international approach requires that a cross-border methodology be established and implemented which satisfies all the necessary criteria.

This kind of approach to generation adequacy assessment requires that a meaningful **criterion for security of supply** is defined. This poses the question of which indicators for the level of security of supply (e.g. LOLE, coverage of a deficit in supply with a specific probability of occurrence) should be used.

In addition, a basic methodology has to be selected. **Deterministic approaches** are more suited to providing an overview of the supply situation. Integrated power systems with a high proportion of renewable energy generation may require further developed approaches. **Probabilistic approaches** appear better suited to these demands, as they can better illustrate the volatility of the system and uncertainties. However, the question arises if extreme results can be sufficiently catered for by probabilistic methods. In this context, it is relevant to ask to what extent extreme results should be modelled at all.

A current **example** of the application of an international approach to generation adequacy assessment is the approach taken by the transmission system operators within the framework of a study for the PLEF region (see Chapter 4.4). Approaches of this kind within a specific regional framework can represent a first step towards a harmonised cross-border methodology.

5.3 Harmonisation of the processes of ensuring generation adequacy

If an international approach is to have an institutional framework, new **cross-border processes** for ensuring generation adequacy need to be developed. These establish the required framework for harmonising the process of ensuring generation adequacy. In our opinion, the following **questions** need to be addressed with respect to this:

- What **legal framework** is necessary for this? Of particular relevance here is the question of whether the established regulatory framework can be developed or if a new legal basis needs to be established. In addition, it is questionable to what extent regulation with respect to electricity grids is impacted by attempts at harmonisation.
- How can **legal certainty** be established in an international process of ensuring generation adequacy? This impacts parties responsible for security of supply at a national level in particular. A suitable legal framework has to be developed for these parties that defines how cross-border load effects and feed-in from renewables should be taken into account and which regulations apply in cases of national supply deficits.
- Which **parties** are impacted and have a central position in the new process? If necessary, new parties and institutions may need to be established at an international level. The question then arises of which tasks will arise for the new and established parties, and how **international coordination** should take place in this context.
- What **level of security of supply** should be internationally defined? In this context there is a need to examine how national levels of security of supply can be reconciled with each other.
- Which **geographical boundaries** should define the region in which the harmonisation of the process of ensuring generation adequacy is introduced? To what extent should these bounda-

ries be open in future to new members, and what should the entry criteria be?

- What **time frame** should be applied when ensuring generation adequacy? That is, how much lead time does the process of generation adequacy assessment require to determine the need for reliable available capacity?

A number of potential obstacles need to be taken into account when **addressing these challenges**. The acceptance of adding an international dimension to security of supply is fundamental to the introduction of an international process of ensuring generation adequacy. This will involve nation states surrendering their sovereignty with respect to security of supply. This may be lead to certain problems with acceptance. In addition, certain parties operating at a national level will lose competencies and responsibility, which may not be accepted without question.

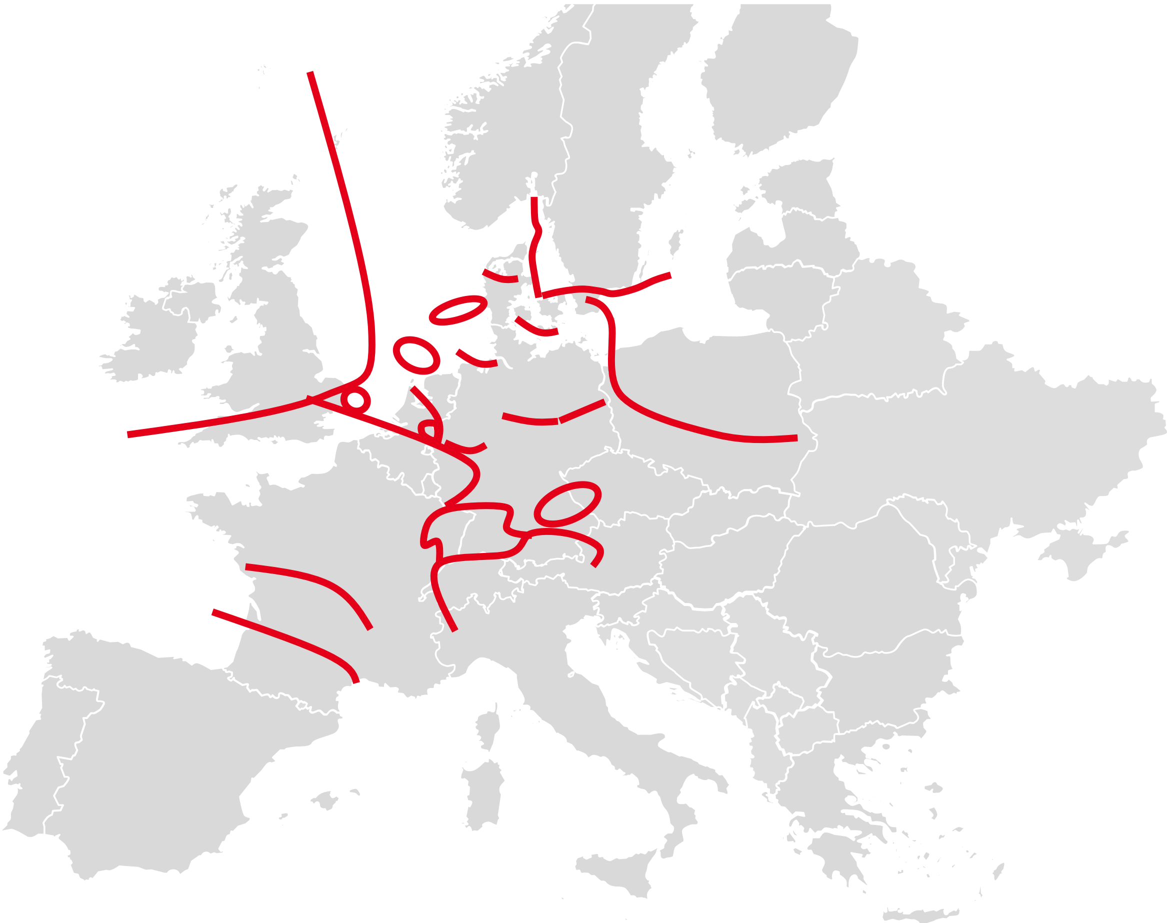
The entire process of adapting, establishing and further developing the framework, and the coordination of the various parties, will incur **transformation and transaction costs**. These should be compared with the achievable costs savings resulting from the reduced need for reliable available capacity. Due to uncertainty surrounding the depth of intervention necessary in the new framework and the general difficulty of quantifying these elements, the quantification of these cost components is possible only to a limited degree.

5.4 Grid infrastructure

The **available grid infrastructure** significantly determines the scale of the possible reliable available capacity savings. The potential to take advantage of balancing effects with respect to load and renewable generation depends on the extent of future grid expansion.

The **pan-European requirements** for developing transmission systems are forecast mainly in the TYNDP (Ten-Year Network Development Plan) conducted by ENTSO-E (2014b). The major challenge for grid development over the next 15 years is regarded as the connection of the “energy islands” of Spain/Portugal, Great Britain, Italy and the Baltic states to Central and Western Europe. A central driver for this is the development of renewable energy generation and the integration of these generation units. For this purpose, bottlenecks in the grid also have to be rectified within the existing internal markets and within the individual countries. Figure 26 provides an overview of the regions with the required development projects.

Figure 26: Potential bottlenecks in the CWE (Central Western Europe) region up to 2025



Note: the depicted bottlenecks result from Vision 4 of the SO&AF with major expansion of renewables, and should be regarded as an upper limit

Obstacles with respect to grids need to be considered which could delay the planned infrastructure development or even prevent it in extreme cases. Lack of public acceptance bears particular mention as it can present a significant role in delaying major grid development projects. The time needed to realise grid expansion is also difficult to estimate due to the complexity and scale of the projects and can lead to further delays.

The obstacles and costs involved in adjusting the framework for European harmonisation with respect to ensuring generation adequacy and the **grid expansion costs** should be compared with the cost reductions achieved by such a harmonisation. This also raises the question of how far should grid expansion proceed and what potential can be realised through specific grid expansion paths. This question is not addressed in the present study. Grid restrictions are not considered in the quantitative analysis and the potential reported is of a theoretical nature. The question of what proportion of the potential can be realised through various grid development paths presents another field for further analysis.

Furthermore, it should also be noted that ensuring generation adequacy also requires **other infrastructure**. For example, the provision of reliable available capacity by gas-fired power plants and the concurrence of peak load in the electricity and gas grids may lead to future bottlenecks. Access to gas infrastructure has to be possible if gas-fired power plants are to be regarded as available producers within the framework of ensuring generation adequacy. This requires an adjustment to the regulation and potentially a harmonisation of capacity products in the gas grid and in supply agreements at an international level.

Finally, it should be noted that all attempts at harmonisation with respect to international cooperation, grid expansion and a corresponding consideration of further infrastructure provide benefits not only in terms of ensuring generation adequacy. These attempts at harmonisation also provide **efficiency benefits** for **electricity trading** and the operational level of electricity supply. Accordingly, any cost benefit analysis should compare the costs not just with the benefits of a harmonised process of ensuring generation adequacy, but with the total benefit for the power system.

6 Conclusion and recommendations

An integrated assessment for ensuring generation adequacy in the countries studied holds potential for synergy even today, through the asynchronicity of load peaks and the feed-in from renewables (which varies regionally due to differences in the prevailing local weather conditions). By 2030, assuming there are no bottlenecks in the grid, a potential in the magnitude of **2 to 15 gigawatts** in the PLEF region could be reached (most likely between 6 and 10 gigawatts). For the entire study domain (15 countries) this potential increases to somewhere between 15 and 50 gigawatts (most likely between 27 and 34 gigawatts). 15 gigawatts is the equivalent of 42 power plant units with respective capacities of 350 megawatts each.[16] To achieve this potential, there needs to be greater **European coordination** complementing national approaches. Among other objectives, this coordination should serve to stipulate common targets for ensuring adequacy and establish reliability for all parties.

- The next steps listed in Chapter 7.3 of the Green Paper "Strengthening security of supply in the European context" are to be explicitly welcomed. There is particular need for a **common definition** and cross-border monitoring of **security of supply**. This also includes an agreement on clear rules for dealing with shortages.
- A first step has already been taken by the countries belonging to the **PLEF** through the submission of a joint report on security of supply in March 2015 (see Chapter 4.4). Cooperation with respect to ensuring generation adequacy can also be incrementally expanded to larger regions, as was done with market coupling.
- The larger the group of countries, the larger the **potential benefits from synergies** that can be achieved through cooperation. Obstacles and **transaction costs** can however be expected to increase with the size of the group. It is of particular importance that all involved countries share a common legal framework that defines how cross-border effects based on national responsibility for security of supply can be taken into account.
- We recommend a **review of the process of evaluating guaranteed wind power capacity** to better realise the potential of this rapidly expanding generation technology. The contribution of wind power to reliable available capacity is greater when

[16] In addition to power plants, further flexibility options will be applied.

cross-border regions are considered than at the national level. However, given the current level of development of wind power, the values quoted in the Green Paper for 2020 (7 % national, 14 % for the EU[17]) seem too high. We expect a reliable available capacity of at least 1.3 % of installed capacity for the PLEF region by 2030, and at least 4 % for the study domain. Probabilistic approaches with respect to generation adequacy are recommended for the volatile feed-in from renewables.

- In future, **group effects** with respect to ensuring generation adequacy need to be more tightly integrated in the planning of the necessary grid development. Political support for grid expansion needs to be sustainably ensured to cater for its long-term development. What also needs to be considered is that the expansion of wind power is progressing faster and more smoothly than the grid expansion needed to support it.
- At the same time, comprehensive **cost benefit analyses**, conducted on a rolling basis, are required to review if an economically viable level of integration has been achieved. In doing so, the transactions costs required to realise this level of integration need to be compared with the potential benefits from synergies.

17 The Green Paper “An Electricity Market for Germany’s Energy Transition” 2014, p. 33, quote from TradeWind (2009)

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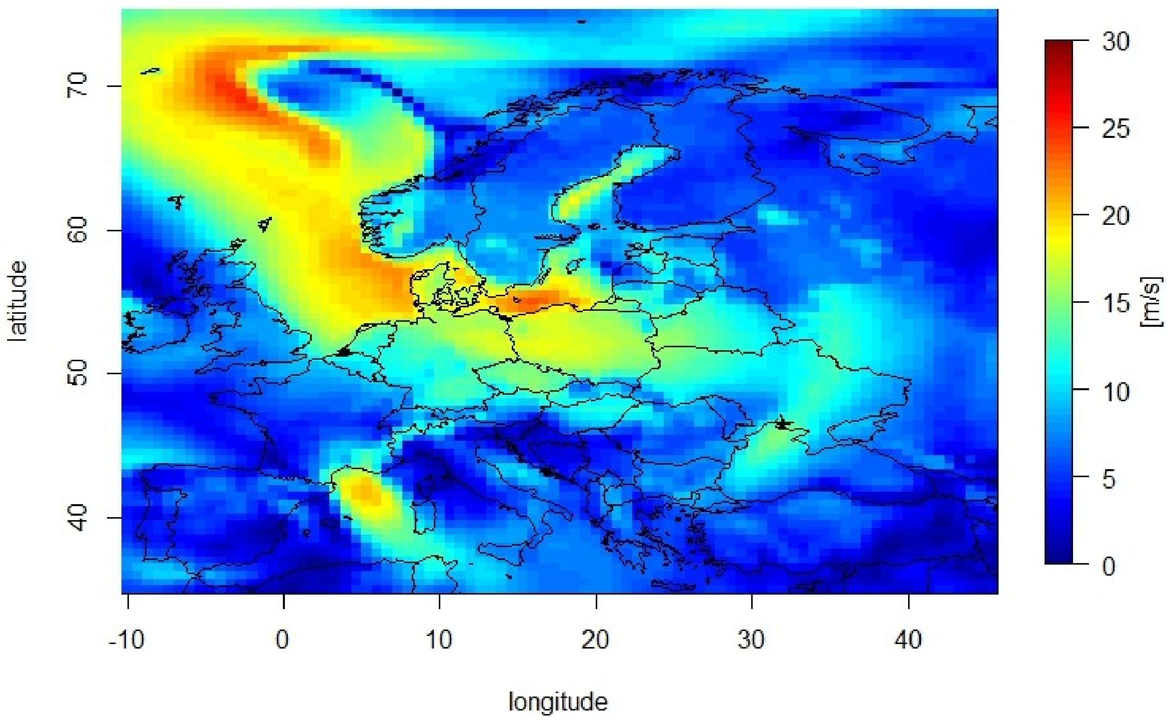
Appendix

Figure 27: NASA GES DISC reanalysis meteorological data used in the study.



Note: This study uses hourly grid-based meteorological data from NASA GES DISC: sample (6 December 2013, 12 UTC) average hourly wind speed [m/s] across Europe. The grid-like resolution of the meteorological data can be clearly recognised

Figure 28: Wind energy availability (in % of installed capacity) at the group peak load hour in the study domain, 2010-2014 and 2030

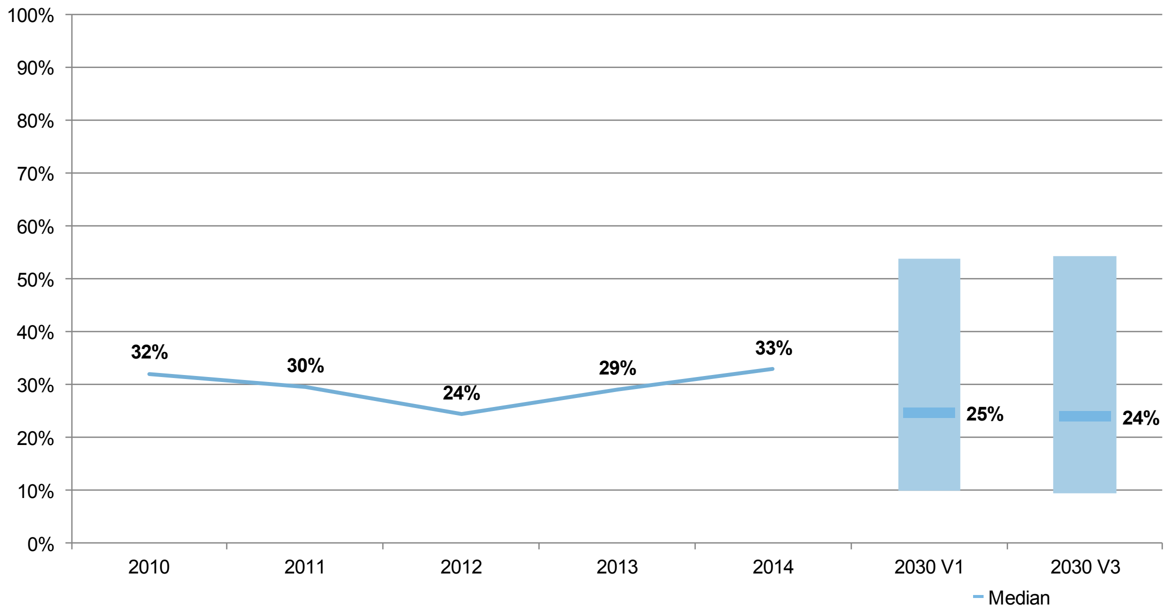


Figure 29: Wind energy availability at the group peak load hour in the study domain, 2010-2014 and 2030

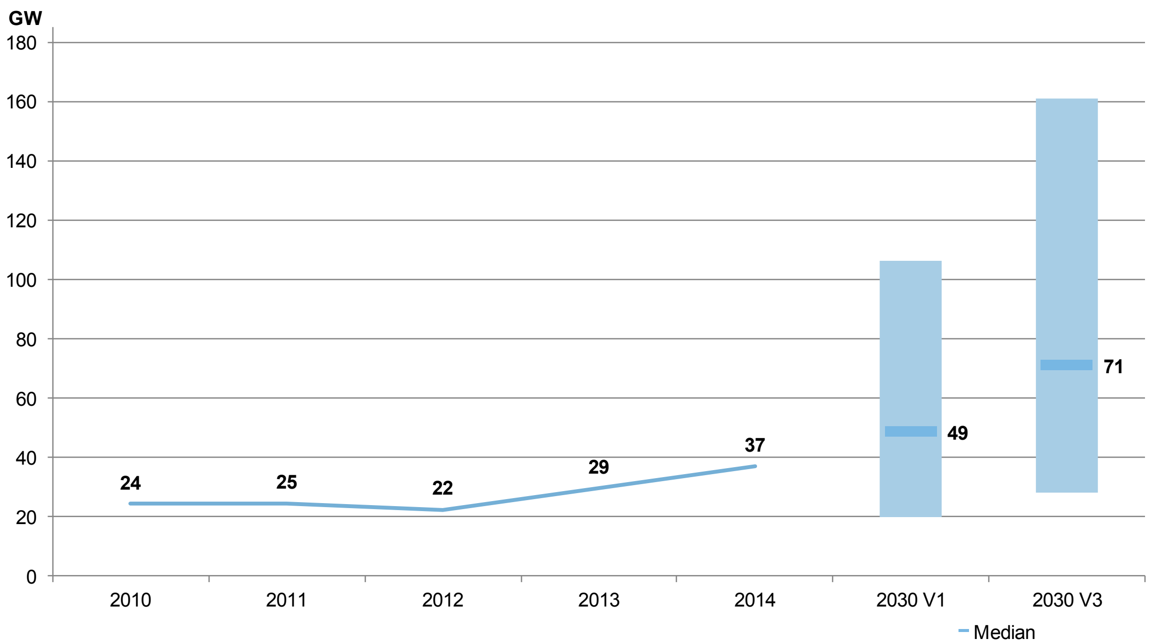
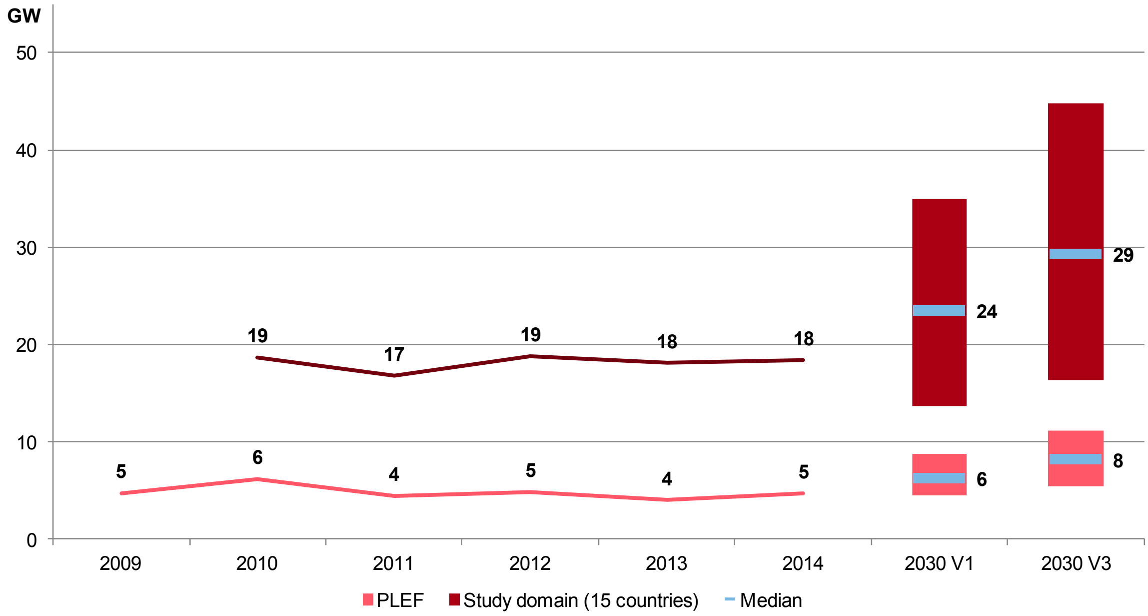


Figure 30: Reduction of the residual load in the highest 100 hours under a collective assessment scheme in the PLEF and SD, 2009(10)-2014 and 2030



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