CONSEIL FRANÇAIS DE L'ÉNERGIE
WORLD ENERGY COUNCIL

La R&D énergie et ses externalités de connaissance, pour une amélioration de la modélisation économique

SEURECO-ERASME

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Téléphone : +33 1 40 37 69 01 12 rue de Saint-Quentin – F-75010 Paris cfe@wec-france.org
Télécopie : +33 1 40 38 17 38 Twitter : @CFE_WEC_France www.wec-france.org

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Téléphone : +33 1 40 37 69 01
Télécopie : +33 1 40 38 17 38

12 rue de Saint-Quentin – F-75010 Paris
Twitter : @CFE_WEC_France

cfe@wec-france.org
www.wec-france.org

Innovation in Energy Technologies and Knowledge Externalities: How to Improve Economic Modelling?

Boris LE HIR
with the participation of Baptiste BOITIER, Pierre LE MOUËL and Paul ZAGAMÉ

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Synthèse

Les enjeux énergétiques liés à la fois au problème du réchauffement climatique, à la croissance de la consommation mondiale d'énergie et à la nécessité d'indépendance appèlent des réponses technologiques spécifiques à la fois du côté de la production d'énergie et du côté de l'efficience energétique. En outre, ces enjeux font intervenir de nombreuses externalités négatives, liées notamment aux dommages environnementaux, et positives, liées aux activités d'innovation. Ces externalités, qui induisent une divergence entre les bénéfices privés et sociaux, motivent l'intervention publique afin d'atteindre un optimum social prenant en compte l'impact global des stratégies énergétiques adoptées. L'évaluation ex-ante par des modèles économiques détaillés de ces politiques tournées vers le développement de technologies particulières liées à l'énergie, telles que le SET plan en Europe ou la transition énergétique en Allemagne, implique de déterminer les caractéristiques de l'innovation dans ces technologies. Jusqu'à présent, la majorité des études a porté sur l'identification des déterminants de l'innovation dans les technologies de l'énergie, tels que le prix du pétrole, les politiques environnementales, l'état des connaissances et les courbes d'apprentissage, mais peu d'entre elles analysent les interactions entre les efforts de développement de ces technologies et l'innovation au sein des activités économiques. En particulier, peu d'études traitent des intéractions entre les industries impliquées dans la production des technologies liées à l'énergie. Les principales raisons tiennent, d'une part, au manque de données sur la R&D affectée à ces technologies et, d'autre part, à la difficulté de faire des liens précis entre les technologies et les secteurs économiques. En effet, les données de R&D sont majoritairement définies par secteur économique sans aucune précision sur les technologies vers lesquelles la R&D est dirigée. Par ailleurs, leur part affectée aux technologies relatives à l'énergie est d'autant plus difficile à reconstruire que ces recherches sont mises en œuvre dans de multiples entreprises appartenant à des secteurs variés et dont l'activité principale n'est pas toujours liée à l'énergie. Les données de brevets permettent, quant à elles, d'étudier l'innovation concernant ces technologies de façon quantitative et aussi certains flux de connaissances entre inventeurs mais leur classification purement technologique ne permet pas directement de faire de liens avec les secteurs économiques. En somme, nous ne savons, à priori, ni dans quel(s) secteur(s) sont produites les innovations sur une technologie donnée, ni quelles interactions sectorielles et géographiques elles impliquent.

L'objet principal de cette étude est donc de pallier ce manque en applicant une table de concordance entre les classes technologiques et les secteurs économiques établie par Johnson (OCDE, 2002 [34]) sur les technologies relatives à l'énergie.

Cette concordance nous permet alors d'aborder deux questions principales :

1. La première concerne la quantification de l'innovation dans les technologies liées à l'énergie et la répartition de ces innovations entre les pays et les secteurs: Comment l'innovation relative à l'énergie se répartit entre les pays et les secteurs économiques?

2. La deuxième question est relative aux flux de connaissances internationaux et intersectoriels: Les flux de connaissances sont-ils un élément déterminant de l'innovation dans ces technologies et sont-ils dominées par des flux internationaux (si oui entre quels pays) ou par des flux intersecto-

riels (si oui entre quels secteurs)?

Les données de brevets ont un intérêt particulier car elles constituent une source très riche avec une étendue mondiale et permettent d'isoler les technologies étudiées. Pour l'évaluation des externalités de connaissance, nous nous concentrons sur les données de citations de brevets. En effet, chaque brevet fait référence à des brevets précédents constituant une base technologique sur laquelle ce nouveau brevet repose. Ces citations peuvent donc être vus comme des flux de connaissance: un brevet cité a généré de la connaissance qui a été utile pour créer l'innovation protégée par le brevet citant; ce qui peut être interpété comme une externalité de l'inventeur du brevet cité vers l'inventeur du brevet citant. Dans notre étude nous redistribuons ces données de citations de brevets, organisées en classes technologiques, par secteur à l'aide de la table de concordance de l'OCDE et par pays selon le pays de résidence des inventeurs. A partir de données de citations entre brevets et de traitement des biais intrinsèques, nous construisons alors des matrices de flux de connaissance entre pays et secteurs.

Afin d'illustrer la nature de ces flux considérons un brevet sur un rotor d'éolienne dont la classe technologique IPC (International Patent Classification) est F03D 1/06 (rotors) et qui est créé par un inventeur résident en allemagne citant un autre brevet portant sur la structure d'un rotor propre aux giravions de classe B64C 27/473 créé par un inventeur résident aux Etats-Unis. Selon la table de concordance de l'OCDE, une technologie protégée par un brevet de classe F03D 1/06 est produit dans le secteur "machines industrielles et agricoles" et une technologie protégée par un brevet de classe B64C 27/473 est produit dans le secteur "Equipement de transport". Par conséquent, dans notre matrice, cette citation sera représentée comme une unité de flux de connaissance du secteur "Equipement de transport" américain vers le secteur "machines industrielles et agricoles" allemand. Dans un souci de simplification, nous avons pris dans cet exemple un cas où le brevet cité et le brevet citant sont associés chacun à un unique pays et un unique secteur. Toutefois, une classe IPC pouvant être associée à plusieurs secteurs dans la table de concordance et chaque brevet pouvant être référencé dans plusieurs classes IPC et pouvant aussi avoir plusieurs inventeurs résidants dans des pays différents, une unique citation peut résulter dans nos matrices en plusieurs fractions d'unité de flux de connaissance entre plusieurs pays et secteurs.

En outre, les citations doivent être considérées dans les deux sens: (i) les citations émises par les brevets protégeant des technologies de l'énergie et reçues par des brevets antérieurs couvrant tout type de technologies (ii) les citations reçues par les brevets relatifs aux technologies liées à l'énergie et émises par des brevets ultérieurs couvrant tout type de technologies. (iii) les citations entre brevets couvrant un même groupe de technologie de l'énergie pouvant aussi être considérées afin d'isoler les flux internes à une technologie.

Nous avons construit ces matrices sur la période 1985-2007 en isolant douze groupes de technologies liées à l'énergie dont huit sont liés à la production d'énergie – production d'énergie d'origine pétrolière; nucléaire; éolien; solaire; geothermique; hydrolique; ou encore provenant de biofuels ou de piles à combustible – un groupe technologique est associé au stockage de l'énergie et un autre à la capture et au stockage du carbone et, enfin, les deux derniers sont liés à l'efficacité énergétique dans le bâtiment et les transports. Les classes IPC relatives à ces groupes sont définies en grande partie grâce au "IPC green inventory" établi par un commité d'expert à l'Organisation Mondiale de Propriété Intellectuelle mais aussi grâce à d'autres références comme l'OCDE.

Pour chacun de ces groupes technologiques, nous nous intéressons donc à déterminer quels secteurs et quels pays sont directement impliqués dans leur développement et quels autres secteurs ou pays génèrent des connaissances utiles pour développer ces technologies ou, à l'inverse, bénéficient des connaissances développées par ces technologies relatives à l'énergie.

Par ailleurs nous utilisons deux indicateurs de mesure de l'innovation dans ces technologies. Le premier indicateur est basé sur le nombre de citations reçues par les brevets couvrant les technologies liées à l'énergie. En effet, la mesure de l'innovation par le simple dénombrement des brevets ou des familles de brevets peut être biaisée par la forte hétérogénéité de la valeur de ces brevets or le nombre de citations reçues par chaque brevet peut être considéré comme un indicateur de qualité des brevets. Toutefois, si les résultats obtenus semblent cohérents avec d'autres études, cette mesure n'est pas non plus dénuée de biais. La seconde mesure alternative utilisée consiste à recenser le nombre de familles de brevets cités au moins une fois au cours d'une période fixe de 5 ans. Cette seconde mesure permet de pallier en partie les défauts de la première.

L'observation des indicateurs d'innovation dans les technologies liées à l'énergie dans le monde sur la période 1985-2007 révèle des tendances différentes selon les groupes technologiques. Pour les technologies relatives au pétrole, au solaire, aux piles à combustibles et au bâtiment, l'innovation semble croître jusqu'en 2003-2004 et se contracter ensuite, tandis que l'innovation relative au nucléaire montre une légère décroissance jusqu'en 2000 et une légère reprise ensuite jusqu'en 2005. Pour la plupart des énergies renouvelables, l'innovation semble augmenter sur la période et même s'accélerer après 2000. Les innovations concernant l'efficacité énergétique dans les transports et le stockage de l'énergie montrent une croissance constante sur la période 1985-2007 et relativement faible dans le domaine des agrocarburants et de la capture et du stockage du CO_2.

La comparaison géographique, elle aussi soumise à des biais importants, met néanmoins en évidence des caractéristiques similaires à celles décrites dans la littérature. En effet, nous observons que l'innovation relative à l'énergie aux Etats-Unis et au Japon semble être supérieure à celle de l'Europe en général et que l'Allemagne est le leader européen dans la quasi totalité des technologies considérées suivie par la France et le Royaume-Uni.

Concernant les flux de connaissances, les données semblent indiquer sans grande surprise qu'ils ont principalement lieu entre pays leaders au niveau international. Au niveau sectoriel, nous observons de même une concentration des flux entre secteurs producteurs de ces technologies, et dans certains cas, comme le solaire, les agrocarburants ou le stockage, les flux semblent converger vers un unique secteur. En effet, si l'ensemble des douze groupes technologiques considérés semblent bénéficier de flux de connaissances internationaux relativement importants et homogènes, l'importance relative des flux intersectoriels est très hétérogène selon les groupes technologiques. Les technologies liées à l'énergie solaire ou aux agrocarburants bénéficient relativement peu de flux intersectoriels, tandis que celles liées à l'énergie nucléaire et à l'efficience énergétique dans les transports semblent au contraire en bénéficier largement. L'importance relative des flux de connaissance provenant d'autres secteurs semble en particulier indiquer la transversalité des connaissances de ces groupes technologiques. Les autres technologies se trouvent dans une situation plus ou moins proche de celle que l'on obtient sur l'ensemble de nos données de brevets (incluant à la fois les technologies liées et non liées à l'énergie). Il est par ailleurs remarqué que les technologies liées à l'énergie citent davantage des brevets d'inventeurs étrangers que les autres technologies.

Les estimations réalisées dans la dernière section sont une première tentative d'évaluation des interactions interindustrielles et internationales dans le cadre du dévelopment de ces technologies. Elles mettent en évidence en particulier un impact positif du stock de connaissance national dans la technolgie considérée mais aussi des externalités provenant d'innovations sur cette technologie dans les mêmes secteurs d'autres pays. Ces premiers résultats empiriques semblent apporter une première validation de la méthodologie adoptée afin de représenter les interactions induites par l'innovation dans les technologies liées à l'énergie. Toutefois, des investigations plus poussées doivent encore être réalisées afin d'approfondir le rôle des externalités de connaissances entre secteurs et pays, dans le cadre des technologies de l'énergie.

Nous mentionnons par ailleurs que les données construites, notamment les matrices de citations de brevets ainsi que les allocations des innovations par secteurs et par pays, sont disponibles sur demande.

Contents

1 Introduction

The energy stakes linked in the same time to the climate change, the growth of the global demand, and the independence require technological solution both on the side of energy production and on the side of energy efficiency. Moreover, these stakes involve many externalities either negative, linked to environmental damages, or positive, linked to innovative activities. These externalities induce a divergence between the private and social returns and justify the intervention of a regulator in order to reach the social optimum. The assessment of policies targeted on specific technological development implies to define the features of the innovative activities directed to these technologies. In particular, it is necessary to identify the industries that are concerned and the interactions between them and the other sectors.

Consequently, for accurate policy assessments, it is necessary to grasp the links between technological field and industrial sectors to be able to assess the economic impact of the development of particular technologies. What sectors will be involved in the development of energy-related technologies and at which level? Which sectors will benefit from the knowledge created by the development of energy-related technologies? These are crucial questions that request to establish the connection between economic sectors and technological fields.

However, economists are facing several difficulties. On the one hand, most indicators of economic performance, such as investments in tangible capital or in R&D, employment, value added and therefore productivity, are given at sectoral level (according to official industrial classification such as NACE or ISIC). Whereas, on the other hand, most technology indicators are based on patent data which are classified according to the International Patent Classification (IPC henceforth), that is to say according to technological fields without any links with industrial classifications.

While the JRC-IPTS (Wiesenthal et al., 2009 [70]) attempted to partially overcome this lack of data by redistributing R&D investments among priority energy technologies of the Strategic Energy Technologies plan for the year 2007[1], these data are subject to uncertainties and we do not have real temporal series.

One of the main difficulties is that there is neither surjection nor injection between technological and sectoral classifications in the sense that a given industrial sector may be associated to several technologies, and a given technology may also be associated with several industries. This difficulty is especially important in the case of energy technologies as energy related innovations are mostly made by non-energy sectors such as machinery equipment industries, which cover a large range of technologies.

Innovation in energy related technologies, as it actually includes many different types of technologies, involves knowledge that belongs to many different fields. These technologies also benefit from previous technologies of widely different nature. In particular, G. Nemet (2012, [47]) reminds us some concrete case of such knowledge transfer from non-energy technologies to energy-related technologies with the example of the commonly used General Electric LM6000 50MW gas turbine which directly descends from the TF39 High-Bypass turbo-fan engine developed for military aircraft. He also gives

[1] With an update for 2009 for wind, PV and CSV (Gnamus, 2011 [16])

other examples such as "the development of thin, long and strong steel wires for use in the lining of radial tires" inducing the "emergence of wire saws that could slice ingots of silicon crystals into increasingly thin wafers" which benefit to the production of photovotaic cells. Or even, we can refer to the more expected contribution of the knowledge from marine and aerospace to wind power technology. The development of computers and software also was and is still an important source of the potential development of energy technologies[2].

These anecdotes reveal the strong interconnexions between innovation in different technologies and industrial sectors. However among these relationships, we should distinguish at least two different kinds. The first is linked to knowledge tranfers, that is to say to the use of the knowledge created by the development of a given technology to develop another technology without necessary using the first technology. While the second kind is linked to the enabling feature of certain technologies in the sense that the use of these technologies allow for the development of other technologies.

In this study , we focus on the first kind of relationship and, in particular, we deal with the issue of knowledge spillovers specific to energy technologies that occur between countries and economic sectors. The aim of this work is then to assess the interactions between sectors and countries in R&D activities specific to energy technologies in order to integrate them in the sectoral economic model, such as NEMESIS, for future energy R&D policy assessments.

For that purpose, we build data representing innovation and spillovers regarding 12 energy-related technologies. These technologies are either related to energy production, pollution control or energy saving. More precisely they are those related to fossil fuel based energy, nuclear power, wind power, solar power, biofuels, geothermal power, ocean-hydro power, fuel cells, carbon capture and storage, energy storage, energy efficiency in transport and in building, appliance and equipment.

In particular, we link technological innovation to economic sectors and we build matrices describing knowledge flows between countries and sectors based on patent citations data regarding the 12 energy-related technologies. For each of these technologies, we investigate which countries and sectors are directly involved in there development and the interaction between them as well as with the other countries and sectors in term of knowledge flows.

The paper is organized as follows. In section 2 we proceed to a brief review of the economic literature on innovation in energy-related technologies in order to explain the motivation of our methodological approach. In section 3 we comment the nature of patent data, their limits and how they can be used. In the next section, we describe the intersectoral and international knowledge flows matrices and we explain how we isolate energy technologies inside these general knowledge flows matrices. Then, in section 5 we undertake a descriptive analysis of the data obtained for the twelve energy technologies. From this basis, we define the construction of variables usable for estimations and calibration of eco-

[2]In this regard, P.-E Mounier-Kuhn (2010, [45]) point out in his book "L'informatique en France de la seconde Guerre Mondiale au Plan Calcul" that France is the only industrialized country where public research has failed to build a computer in the pioneer period. The author partly explains this failure by the lack of the national research during the inter-war period, especially in the electricity industry. This low level of research leading to law demand for calculation and computing machines. The American refusal in 1963 to provide large computer systems to France was also mainly justify by the anti-proliferation policy, that is to say to avoid other countries to be able to develop nuclear energy.

nomic models. And, finally, we presents preliminary estimations based on our data providing a first attempt of identifying the most important sources of knowledge spillovers in the case of energy-related technologies. The last section sums up the study and brings concluding remarks.

We remind here also that every data built in the framework of these study are available on request.

2 A quick overview of the literature

2.1 Measuring innovation activity in energy-related technologies

Empirical literature on innovation generally uses two types of data as proxy for innovation activity. The first measures inputs used in innovation activities and it is mainly based on R&D investment or scientific staff data. The second type measures output of innovation activity and it is mostly based on patent data. The accuracy of these data to proxy the two sides of innovation activity is obviously limited as these data neither reflect all innovation factors (not all inventions are the result of R&D investments) nor innovation output (not all inventions are patentable). Despite theese defaults and the current attempts to overcome their limitations[3], these indicators are, in the state of the art, largely accepted as the most significant.

In the case of a technological approach, the former proxy has a crippling drawback as it is not available in a technological distribution. Regarding energy technologies only public R&D investments are split by technology in the International Energy Agency[4] (IEA thereafter) database.

This lack of data is a serious limitation for specific technologies policy assessment. Indeed, for instance, unknowing the current R&D by technology makes all the more difficult the assessment of the cost of the achievement of a given technological target. One of the particular features of R&D related to energy efficiency is that most of it is realized by several equipment suppliers and not by one well identified sectors. And, in addition, these sectors are not necessarilly specialized in supplying energy-related technologies. Moreover, energy-related innovations involve a large range of different technological fields (from energy production to construction or transport technologies).

The JRC-IPTS (Wiesenthal et al., 2009 [70] and the update Gnamus, 2011 [16]) attempted to partially overcome this lack of data by redistributing R&D investments among priority energy technologies of the SET plan[5], thus focusing only on several types of energy production, for the year 2007[6]. For each technology, they distinguish between public national investments, public investments financed by European funds and corporate R&D investments for every European countries. With regard to public national funding, they use data from the IEA statistics on Research, Development and Demonstration (RD&D)[7] and also from Eurostat database on Government Budget Appropriations or Outlays on R&D (GBAORD). The European R&D investments are annualized figures under FP6 (2002-2006) Research Framework Program and EURATOM Framework Program. Contrarily to the USA and Japan, where there are large energy technology policies coordinated by a unique agent (Department of Energy in US and Ministry for Economy in Japan), there is no unified and homogeneous strategy in Europe, despite few attempts such as ERA-NET and NETWATC and, in consequence, this also leads to data disaggregation. Although total EU budget (national + FP) on R&D energy is larger than in US or in

[3] See for instance Corrado, Hulten and Sichel (2005 [10]) who enlarge the scope of the innovation activities by defining intangible investments.

[4] http://www.iea.org/stats/rd.asp; IEA, 2011 [28]

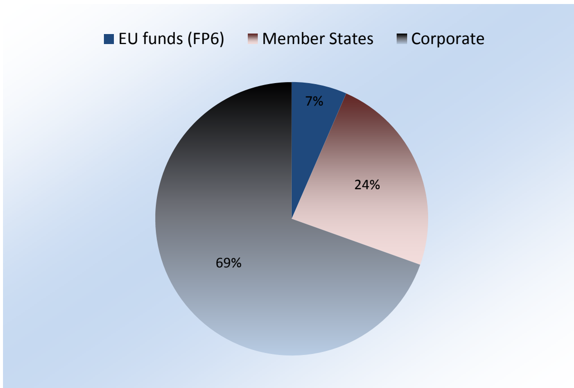
[5] The priority technologies of the SET plan are: wind energy; photovoltaics; concentrating solar power; biofuels; carbon dioxide capture and storage; hydrogen and fuel cells; smart grids; nuclear fission and nuclear fusion

[6] and also for the year 2009 for wind, PV and CSP

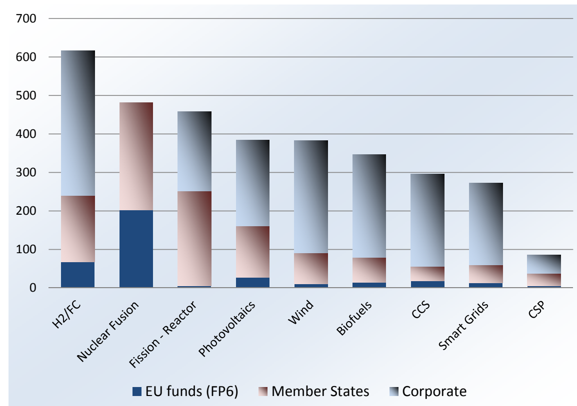
[7] Data from IEA include demonstration which is not the case for the other data, demonstration should overestimate R&D by 9%; Both GBAORD and IEA databases are incomplete at a certain technological detail.

Figure 1: Public and private R&D expenditures in energy technologies in 2007

(a) Shares in total R&D investments in non-nuclear priority technology of the SET plan in 2007



(b) R&D expenditures by technologies in Europe in 2007 (million €)



Source: JRC-IPTS; Wiesenthal et al., 2009 [70]

Japan, the innovative capacities are limited by the non-homogenization of the market, and the lack of coordination in research and policies.

Concerning the assessment of corporate R&D, for which data are very scarce, they applied a bottom-up approach using "basic data on individual companies taken from the EU industrial R&D investment Scoreboard and company's annual reports with other publicly available data as well as direct contacts with individual enterprises and stakeholder groups"[8]. Their methodology proceeds in four steps: (i) identification of major key firms for each technology, (ii) data gathering, (iii) allocation of firm's R&D by technology (according to firm's activities) and (iv) addition of the results for all firms by technology. This method is obviously subject to great uncertainties and the authors emphasise that the data quality depends on three factors: (i) the nature of the involved industries (multinational and diversified firms vs small specialized firms), (ii) the disaggregation level of data accounting of each member state and (iii) the nature of the EU funds (whether projects are specialized on one technology or not). However, this work consists in a first assessment and may initiates more systematic inventory.

In this context, they found that corporate R&D represents around 70% of the total R&D in non-nuclear priority technologies of the SET Plan (see figure 1 a). Nevertheless the distribution between corporate and public R&D depends on the technology (fig. 1 b). R&D for wind power generation, biofuel, smartgrid and carbon capture and storage (CCS) is largely financed by the private sector whereas for nuclear, photovoltaic, hydrogen and fuel cells (H2/FC), the public sector plays an important role. According to the authors, the specialization of countries depends on (i) its natural potential; (ii) the current energy mix, (iii) the historical developments and (iv) the industrial capacities.

Such estimate of R&D investment per technology is a tedious exercise, thus IPTS did such assess-

[8] The EU Scoreboard provides data for 1000 EU firms and 1000 Non-EU firms (the 1000 biggest R&D firms in Europe and outside, firms being allocated to a country according to his headquarter). In Europe the authors identify 136 firms as SET related, of which they obtain complete data for 115. In order to complete the EU-Scorboard, they use data available by Internet, direct contacts with firms or other databases (BERD, ERMINE, SRS NET. . .).

ment for few years which do not provide time series data. These difficulties explained why, instead of R&D expenditures, most studies explore patent data in order to proxy innovation activity.

In 2012, OECD (2012 [50]) has analysed the innovation activity in Climate Change Mitigation Technologies (CCMTs henceforth) using the number of "claimed priorities" (patent applications that have been claimed as priority elsewhere in the world). By taking only "claimed priorities" into account, they can overcome some difficulties linked to the use of patent data without too many restrictions. In particular, (i) it avoids double counting; (ii) it selects inventions through a quality threshold; (iii) and it keeps a truly world-wide coverage.

Their observation of the recent trendsFor in innovation in CCMTs reveals an increase of growth rate of CCMT claimed priorities relatively to the other energy technologies as well as other general technologies since the 90s. In particular CCMT with the most important increase are solar photovoltaic, wind power and CO_2 capture. Moreover, they identify as leader countries in these fields Japan, the United-States and Germany following by Korea (specialized in solar photovoltaic), France and the United-Kingdom. They indicate that 33% of the CCMT claimed priorities come from Japan and 80% come from the first five countries. Similarly, according to Dechezleprêtre et al. (2011 [11]) two-thirds of the inventions on CCMT patented worldwide between 2000 and 2005 have been developed in only three countries: Japan, the United-States and Germany. Moreover, Japan, the United-States and Germany are not only the three leaders regarding CCMT as a whole but they are also identified as leader for almost all technologies.

2.2 Determinants of innovation in energy-related technologies

Several studies also investigate the determinants of innovation in the domain of energy technologies. In particular they assess the relative efficiency of the different policies or the impact of exogenous factors, such as the price of fossil fuel and the knowledge available, on the level and the direction of innovation. The determinants of innovation in energy related-technologies may be divided into two channels: the determinants acting through demand mechanisms (or market pull determinants) and those acting through supply mechanisms (or technology push determinants).

Market pull innovation

The first channel results from the change in the demand composition consequently to an evolution of relative prices that will induce incentive to redirect innovation "for economizing the use of a factor which has become relatively expensive" (Hicks, 1932 [27]). For instance, following a relative increase of the energy prices, agents (households and firms) will reduce their energy consumption and firms will be encourage to supply lower energy consumming product.

Concerning the induced innovation, Atkinson et Halvorsen (1984 [4]) and Wilcox (1984 [71]) have shown strong evidences on the increase of the energetical performance of the automobile's engine and the evolution of the fuel price and Otha & Griliches (1986 [51]) have established that most of the technological improvement in the automobile industry over the period 1970-1981 can be attributed to fuel price increases. Newell et al. (1999 [48]) have also found such evidences for household appliances. More recently, the work of Popp (2002 [54]) has revealed the link between innovation for energy saving and increase of energy price, with a delay of four years. More specifically, on the direction of energy efficiency technologies, Lanzi and Wing (2011 [39]) has showed that an increase in fossil fuel price tends, until a threshold, to increase both innovation in fossil fuel efficiency and in renewable energy and, beyond this threshold, innovation in fossil fuel energy tend to decrease.

Technology push innovation

As remained Nordhaus (1973 [49]) and later Popp (2002 [54]), innovation is not only market pulled but it is also induced by the current available knowledge which enable technological opportunities. This supply of knowledge consitutes the second category of innovation determinants called “technology push”. If the first studies tended to underestimate its role (see Mowery and Rosenberg, 1979 [46]), latter studies revealed the real importance of such determinant (Rosenberg, 1982 [57]; Utterback 1996 [65]; Messner 1997 [44] or Rycroft and Kash 1999 [58]). Therefore this suggests that the public intervention to increase the stock of knowledge may have a positive impact on global innovation through a leverage effect.

For energy technologies, Braun et al. (2010 [7]) find that quotas or tradable certificates, that should play through a market pull effect, are non-significant, whereas public R&D have significant positive effect on patent. And this positive impact of public R&D should rather be justified by a leverage effect than by a better productivity of public research, as established by Jaffe et al. (2005 [31]). Pillu & Koléda (2011, [53]) and Verdolini & Galeotti (2011 [68]) show the double influence of the changes in prices and the state of the knowledge. Concerning the potential crowding out effect between public and private R&D, different studies showed a shift after the 70s. Before the 70s, public R&D on energy was a substitute to private R&D and became, thereafter,a complement(Popp, 2002 [54]; Jaffe and Lerner, 2001 [30]; Popp, 2006 [55]). Moreover, Popp and Newell (2009 [56]), find no evidence of crowding out effect across sector, despite evidences on the substitution between clean and dirty energies,.

Furthermore, the technology push innovation literature suggests that in addittion to the previous own knowledge, the knowledge from other sectors or countries also impact the innovative capacity. We will come back on this literature in the next sub-section.

Combination of demand pull and supply push leverage for energy policies

The theoretical work achieved by Acemoglu et al. (2012 [1]) emphasises the necessity to combine carbon tax and research supports for an optimal policy to develop clean technologies. This idea is thus in favour of intervention on both sides, demand pull and technology push. The complementarity between these two channels explains also the difficulties in the empirical literature to dissociate the contribution of market pull innovation and technology push innovation and it suggests that the accumulation of knowledge on specific technologies and its impact must be taken into account along with market mechanisms in economic models.

Even if there is still room for improvement, the demand pull side is now relatively well integrated in economic models through price elasticities and substitution elasticities and input-output tables. This is not as much the case for the technology push side. In particular, most raw data are too poor or do not suit to be able to make a complete assessment across sectors and countries and the assymetry of treatment may cause strong biases. Indeed, whereas prices related to each technologies may be easily identified, the knowledge as well as the spillovers (generated or used) are more diffcult to quantify. For instance, assuming only public R&D in energy technology, private R&D being not available, is obviously unsatisfactory. Moreover as explained above, main technological indicators are totaly dissociated from economic sectors and this strongly limits their ability to be exploited in macro-sectoral model. This limitation is especially important for modelling knowledge spillovers. Before trying to overcome these limitations, let us remind some key concepts on knowledge spillovers and present empirical works on energy technologies.

2.3 Technology transfers and knowledge spillovers

Generality on knowledge spillovers

As knowledge spillovers is one of the main reason why social return to R&D exceed the private one, its accounting is essential to analyse innovation in energy technologies and its economic impact. Several literature reviews have been established about knowledge spillovers in general, Griliches (1992 [20]); Keller (2004 [36]); Hall et al. (2010 [24] or Belderbos and Mohnen (2013 [5]) for instance, and we remind here some of the main concept and features of knowledge spillovers. Griliches identifies two types of knowledge spillovers. (i) The first category is due to the non-rival public good nature of knowledge and these spillovers arise if an agent (inventor) learn from ideas from other agents and uses it in its own research. This category may be considered as pure knowledge externalities as no monetary transaction is involved. (ii) A second category groups together spillovers that arise when firms purchase and use goods that embed a technology developped by others firms. Considering this type of spillovers as externality is controversial, however, as explained by Keller (2004 [36]), if the cost to purchase the intermediate is smaller than the firm's opportunity cost to create this knowledge by itself, the firm can be seen as benefiting from technology spillovers.

If these two spillovers may be theoretically well distinguished, they are however very difficult to disentangle empirically and are often very correlated. Knowledge spillovers may be captured through many different channels such as trade (Goto and Suzuki, 1989 [17]) or capital goods transactions (Sveikauskas, 1981 [63]), foreign direct investments (Globerman, 1978 [15], Van Pottelsberg and Lichtenberg, 2001 [66] or Javorcik, 2004 [33]), import share or exportation for international spillovers (Coe and Helpman, 1995 [9]), cross-hiring R&D personnel and labor mobility (Maliranta et al. 2009 [41]), R&D collaborations (Belderbos et al., 2004 [6]), licensing and technology acquisition, technological proximity (Verspagen 1997 [69]), countries where the innovation is protected (Dechezleprêtre et al, 2009 [12]), or patent citations (Maurseth and Verspagen, 2002 [42]). These indicators may also be used in two different ways: they can be used either to proxy directly for knowledge spillovers (such as in OECD, 2012 [50] or Dechezleprêtre et al. [12] in energy technology) or to weight the external R&D

from different origins (from different countries or sectors, such as in Peri (2005 [52]) or Verdolini and Galeotti (2011 [68]) for energy technology.

Technological transfers and knowledge spillovers in the case of energy technologies

The literature on energy technology innovation has naturally dealt with the issues of technological transfers and knowledge spillovers. We will not proceed to an extensive review of this literature here but we will focus on relevant recent articles for our study.

The OECD report, mentioned above, analyses technology transfers from the patent family size, measuring by the number of offices (which specifies countries) where the invention is protected. Overall, the authors find that the diffusion of CCMTs as a whole is similar to other inventions but differs depending on technology. They find also that most of transfers occur between OECD countries. More specifically they show that the sources of technology transfers depend on technology: the United-States seems to be the major source for photovoltaic whereas, for wind power and biofuel, transfers seems to come from Europe. On the recipient side, the main beneficiaries of CCMT technology transfers are China (by far), then Korea, Brasil, South-Africa. This study highlights also the peculiar paradox of Japan which is a dominant innovator without showing evidence of emitting technology transfers.

Dechezleprêtre et al (2009 [12]) characterize the factors that promote these technology transfers[9]. Their main conclusions are that lax intellectual protection regimes, restriction on international trade and foreign direct investments have negative effect on the diffusion of CCMT.

The authors of the OECD report have also been interested in co-operations in CCMT's innovation. They observe that Japan does not cooperate a lot and, on the contrary, the United-States often co-invent with foreign inventors. In particular they highlight a high degree of co-operation between European countries and the United States in solar PV and thermal, in wind and biofuels technologies.

Pillu & Koléda (2011, [53]) as well as Verdolini & Galeotti (2011 [68]), explore, in addition to demand determinants of innovation in energy-efficient technologies, how knowledge flows across geographical and technological space[10]. For that purpose they model the innovation activity as a function, on the one hand, of energy prices and environmental policy[11] as demand pull factors and, on the other hand, of an internal and an external stock of knowledge relative to the technology as technology push factors. Both studies show that national knowledge stocks and spillovers between countries have significant positive impact on innovation in energy-efficient technologies. Moreover, Verdolini & Galeotti (2011) also find evidence that both geographical and technological distance play a negative role in the diffusion of knowledge in a given technology.

Braun, Schmidt-Ehmcke and Zlocszysti (2010 [7]) adopt a sectoral approach "with a special emphasis on the role of knowledge spillover" in wind and solar photovoltaic technologies. They consider three distinct knowledge flows: (i) intra-technology and intra-national (knowledge flows in the

[9] They also measure technology transfers using patent data; they retain the country of residence of the inventors for the issuer countries and the offices where patents are filed for defining recipient countries.

[10] There are no real inter-sectoral externalities in both model but Verdolini & Galeotti (2011 [68]) test whether technological distance (according to a definition of Jaffe, 1986) has an impact on intra-sectoral knowledge flow between countries.

[11] Verdolini & Galeotti (2011) also add value added.

same technology inside the country); (ii) intranational knowledge from "related-technologies" and (iii) intra-technology and inter-national[12]. The sectoral approach is then used to define what they called related-technologies: they first extract patent applications relative to wind and solar PV using the corresponding IPC defined by Johnstone et al (2010 [35]); then, using the Schmoch et al (2003 [61]) concordance that links industrial sectors to IPC classes, they identify those sectors that encompass the IPC defining wind and solar PV. Knowledge flows coming from related technologies are thus defining as knowledge coming from technologies belonging to the same sectors. By this way it excludes externalities from and toward sectors non-related to the considered technology. For instance, externalities that may exist between aeronautics and industrial machinery are ignored. They also estimate a knowledge production function and also find that innovation is strongly driven by knowledge spillovers and especially by the intra-national one. However, contrarily to Verdolini & Galeotti (2011 [68]), they find no significant effect of extra-national knowledge stock on domestic innovation capacities. Concerning sectoral spillovers, they show different results for wind and solar PV. If both are positively stimulated by previous innovations in the same technology field, only wind seems benefit from innovation in related technologies.

While Braun et al. study real intersectoral externalities considering only energy-technology related sectors, Nemet (2012 [47]) studies inter-domain knowledge flows without restriction on the extent of domains. If the author stays on a technological approach, his classification of technological domain[13] may be roughly associated to economic activities. Moreover, he uses patent citations to proxy for knowledge flows between domains instead of number of patent application to construct knowledge stock. The author examine, among other issues, the breadth of knowledge fields on which each energy-related technology is based. That is to say the number of different technological domains cited by patent covering a given energy technology. He finds that photovoltaic is the energy technology that makes external citations to the broadest set of categories and, more generally, the study "supports the claim that knowledge spillovers across technological domains have been essential aspects of the most important energy inventions".

These two last papers are certainly the closest to our study which actually combines their approach and extends the analysis to a broader set of energy technologies and also to a braoder range of countries.

According to the literature on knowledge spillovers and the availability of data, we deduced that patent data are the most suitable to study innovation activities in the field of energy technologies as they allow us to make the link with economic sectors with the help of concordance tables and to keep a large scope of geographical and time coverage. However, the use of patent data needs several precautions. We describe in the next section the nature and the weaknesses of patent data as well as the way we can use these statistics.

[12]The authors omit knowledge flows from other technologies and other countries because of correlation problems with the other international knowledge stock.

[13]The technological domains match with the super classes: Computer and communications; Drugs and medical; Electrical and electronics; Chemical; Mechanical; Others

3 Indicators from patent data

In this study, we are using the PATSTAT database which is a worldwide patent statistical database developped by the European Patent Office (EPO). This database is available without confidentiality restrictions since 2008 and provides rich compurized information on patents such as: IPC codes; filing or granted dates; number of claims; families (group of patents covering the same invention); country of residence of the applicant and of the inventors[14]; references to previous related patents; etc.

So patent statistics provide very useful data on research output covering many geographical areas as well as many technological fields and many authors have used them on a large scale for economic research[15]. In particular, patent statistics are used to measure innovation output and knowledge spillovers mainly by counting patents and patent citations.

However, the use of patent data requires a lot of caution. Many articles deal with this issue, among them we can cite Schankerman and Pakes (1986 [59]); Grilliches (1990 [18]); Harhoff et al. (1999 [25]) or Jaffe et al. (2005 [29]). So we will not treat the issue again here but we shall mention the main biases that we must consider and the way we can use patent data. Especially, we will see that difficulties appear when we use patent data from different origins simultaneously. In particular, characteristics of patents, such as cost or procedures, differ between countries and patent offices.

There are two main consequences of these biases for our analysis:

1. All patents do not have the same coverage: the number of patents corresponding to the same invention differ between office;

2. The average number of citations per patent differs between offices.

3.1 Patent number and forward citations as a measure of innovation

As we have seen in section 2, R&D data or scientific personal engaged in R&D provide us with a relatively good information on the innovative activity by sectors and countries. However, such data does not consist in a measure of innovation but of the input for innovation. Moreover the data is not available at technological level[16]. For that purpose, patent statistics could give us more information as a patent could be considered as an output of innovation activity (Griliches, 1990 [18]). Nevertheless, raw data on the number of patents must be taken with cautiousness to measure innovation for two main reasons. Firstly, it does not cover all types of innovation. In particular, service innovations are often not patentable. Secondly, the real value of patents is very heterogenous (Trajtenberg, 1990 [64]; Harhoff et al., 2002 [26]; Gambardella et al. [14], 2008; OECD, 2009 [72]).

An important source of heterogeneity of patents' value arises from the differences in standards and procedures. The strict definition of the scope of an invention depends on the country, leading to different propensities to patent. In particular, in Japan, the unity of an invention covers a smaller area

[14] This information depends on the office where the patent is filed

[15] One of the first authors to highlight the potential of patent data for economic research was Schmookler (1966 [62]), later follwed by Scherer, 1982 [60]; Grilliches and Lichtenberg 1984, [19]

[16] Except few assessments such as those of Wiesenthal et al., 2009 [70] and the update of Gnamus, 2011 [16] for energy technologies of the European SET plan that we described above.

Table 1: Patent breadth coefficient

Country/Office	**Germany**	**Italy**	**EPO**	**France**	**USA**	**UK**	**Japan**
Breadth Coef.	1.15	1.08	1	0.99	0.97	0.94	0.72

Source: Dechezleprêtre et al., 2009 [12]

than in other countries so that an invention, which would be covered by a single patent in Europe, could result in five patents in Japan. Dechezleprêtre et al. (2009 [12]) made an assessment of the differences between patent offices in terms of the number of patents per invention, defining a patent breadth coefficient for the different geographic areas. Some of their results is presented in table 1. They find that on average "seven Japanese patents result in approximately five European patents when filed at the EPO" so that the Japanese patent breadth is egal to 0.72 if the breadth of EPO is normalized to one. Furthermore, procedural changes may take place in a patent office, such changes can lead to ruptures in data that must be taken into account. This is also likely to happen at the EPO with the European Agreement on a joint patent for all European countries[17].

Therefore, when making international comparisons, this bias should be taking into account. A method to limit it consists in using patent families, which group together patents that cover a single invention, instead of individual patents. Moreover, we only take patents filed at the USPTO and EPO into account, which have a similar patent breadth.

In addition to these "standard and procedure biaises" that influence the mean value of patents according to the office where they are filed, patenting strategies are different depending on the sector and, all innovation have not the same value. Therefore, the number of granted patents is not sufficient data for measuring innovation. In this matter, the economic literature on the measurement of the value of patents determines the value of patent using the following additional data (see Guellec and Van Pottelsberghe, 2000 [22]):

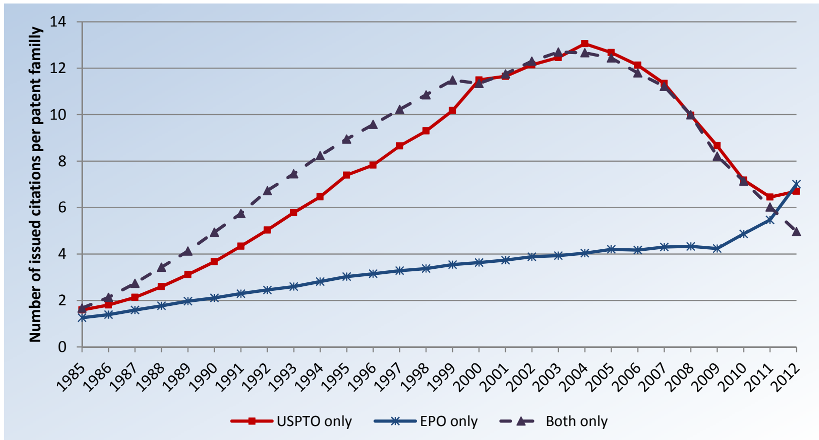
- the number of times the patent is cited (called forward citations);
- the length of its renewal;
- or the number of countries where it is taken out.

In our study, we consider forward citations for controlling the quality of the innovations covered by patents. As Nemet (2012 [47]) reminds, the positive relationship between forward citations and the value of patent has been founding using different indicators of value: sales-based estimates of social value (Trajtenberg, 1990 [64]); stock market value of the assignee firm (Hall et al., 2005 [23]); payment of patent renewal fees (Griliches et al., 1986 [21]; Harhoff et al, 2002 [26]), wether a law suit was filed (Allison et al., 2004 [2]), filing patents for the same invention in multiple countries (Lanjouw and Schankerman, 2004 [38]) or using multiple measures (Van Zeebroeck, 2011 [67]).

Therefore, the total number of citations received by all patents covering energy technologies may be

[17] Agreement reached on June 29, 2012

Figure 2: Backwards citations per patent familly



Sources: author's calculation from PATSTAT data.

taken as an indicator of innovation in these fields[18]. But again, the differences between patent offices' rules bias the propensity to cite per patent. Indeed, the average number of patents which each patent refers to (the number of backwards citations) varies both depending on the patent office and over time. The figure 2 shows the evolution of the average number of citations per patent family over the period 1985-2012 for patents family only filed at the EPO (not filed at the USPTO), only filed at the USPTO or filed in both offices. We can observe that, up to 2012, patent families filed at the USPTO cite more than those filed at the EPO. One of the main reasons for such differences in US compared to other regions is the "duty of candor" effect, that is to say that citations of previous related art is a legal duty in the application at the USPTO. Moreover, the time evolution of the propensity to cite also differs between offices. While at the EPO the average number of backwards citations increases at a constant rate until 2009 and with a slight acceleration in the latest years, at the USPTO we observe a strong increase over the first twenty years (this number has been multiplied by 6) following by a decrease after 2004. Therefore, we must take such biases into account and control them when using citation data. One way to limit this bias is to consider the number of patents that are cited at least ones instead of the total number of forward citations. This method has the drawback to assume that all patents that are cited have the same value but it allows to remove most of low quality patents and irrelevant patents representing rather protection strategies than real innovations. We present the two alternative measures, total forward citations and patents cited at least ones, for describing innovation in energy technologies in section 5.

[18]This indicator corresponds to the multiplication *Number of patent granted* × *Average number of citations per patent* that may reflect the *Number of innovations* × *Average quality level of innovation*, which may be taken as an indicator of the whole level of innovation in the sector.

3.2 Patent citations as a measure of knowledge flows

As we mentioned in section 2, there exists a wide range of channels to measure knowledge flows in economic literature[19]. Among this literature, patent citations have been extensively used during the previous two decades, thanks to the availability of databases in a computerized form, providing one of the richest and widest data sources on innovation. Among the information provided, patent documents contain a list of references to previous patents or other types of documents such as scientific articles indicating the knowledge upon which the patent is based and characterizing the legitimacy of the patent's claims. Therefore, these citations represent both the knowledge used by the inventor(s) of the new innovation and the legal limitation of the scope of the property rights associated to the patent.

Consequently, as long as these citations reflect the prior art used by an inventor, they can constitute a direct measure of pure knowledge spillovers and they are certainly more suitable than other indicators, that are more indirect, to assess these spillovers. These data have thus rejected the idea that "knowledge flows are invisible; they leave no paper trail by which they can be measured and tracked" (Krugman, 1991 [37]). However, the ability of these citations to represent knowledge spillovers from the inventor of the cited patents to the inventor of the citing patent is controversial. This controversy is mainly due to the fact that a large part of citations is added by the examiner, which is particularly important for patent filed at the EPO where only less than 4% is added by the inventors themselves. Moreover the differences in patent procedures induce differences in the weight of citations added by inventors. For instance, for an application at the USPTO, inventors (or applicant) must provide the references on the state of the art which the invention is based on, this is called the "duty of candor" rule, whereas this is optional for an application at the EPO.

A second reason of this controversy relies on the fact that inventors may conduct a review of the prior art after completing the invention (by the patent applicant's lawyer). Jaffe et al. (2000 [32]), who surveyed 166 US answers of inventors about citing USPTO patents, find that only 38% of the cited inventions were known before and during the development of their invention (30% after completing their invention and 32% never known before the application). Therefore, they conclude that "a large fraction of citations, perhaps something like half, does not correspond to any apparent spillovers" and that "citations are a noisy signal of the presence of spillovers".

Nevertheless Breschi and Lissoni (2004 [8]) put this into perspective and argue that "There is no reason to exclude that examiner's citation (i.e. "unaware citations") may indeed hide a knowledge flow" and argue that "some confusion exists between the two issues of awareness (whether citing inventors actually knew of the cited patents) and existence of a knowledge flow (whether some information on the contents of the cited patents has however reached the, possibly unaware, citing inventor)". Indeed, after building a measure of social proximity, they find that the probability to observe a citation between two inventors is positively influenced by the social proximity between the cited and the citing patents. In addition, Duguet and Mac Garvie (2005 [13]) and Mac Garvie (2006 [40]) also find evidence of the validity of EPO patent's citations to represent knowledge flows.

[19] Such as input-output matrices, international trade, foreign direct investments, labor mobility, office of patent granted, patent citations, etc..

4 Country-sector knowledge flows matrices through patent citations

In this section we describe the inter-industry and international knowledge flows matrices based on patent citations and a technology-sector concordance. At first, we describe the concordance tables that allows us to convert technological classification to industry classification. Second, we explain the general conception of these knowledge flows matrices, and then, how specific energy technologies may be isolated in this approach.

4.1 The concordance table

In order to convert citations between patents distributed accross patent classes into citations between sectors, we use the OECD technology concordance (OTC) established by Johnson (2002 [34]) which is an update of the so called Yale Technology Concordance (YTC). The OTC allows us "to transform IPC-based patent data into patent counts by sector of the economy", and therefore to transform the cited patents into the sector of origin of the knowledge and, respectively, the citing patent into the sector of destination of the knowledge[20].

This concordance is based on data of the Canadian Intellectual Patent Office, which, between 1972 and 1995, simultaneously assigned IPC codes along with the most likely sectors of origin of the invention, called industries of manufacturing (IOM thereafter), and with the most likely sectors of use of the invention, called sector of use (SOU thereafter). The statistical distribution of IPC accross sectors is obtained on the basis of more than 300 000 granted patents. This allocation is originally done in the Standard Industrial Classification (the 1980 SIC-E version)[21] which is thereafter converts into the NEMESIS model (the concordance between these two classification is given in appendix 9.2).

Then, from the information provided by this database, the Yale Technology Concordance (YTC) and later the OECD technology concordance (OTC) were developed to translate IPCs into industrial definitions based on Industry Of Manufacture (IOM) and Sector Of Use (SOU). The original YTC provided concordance between IPC codes and the Standard Industrial Classification (the 1980 SIC-E version) and OTC translated or concorded, so that the industries of manufacture and sectors of use are consistent with the international standard ISIC definitions.

Johnson provides a good example to illustrate this transformation: "In the IPC of B05 (sprayers and atomisers), a cosmetics atomiser might have an IOM in the glass container industry or metal valve industry, while a pesticide sprayer might have an IOM in the chemical fertiliser or agricultural machinery industry. Sectors of use (SOUs) would also differ, with the cosmetics atomiser used in the personal hygiene or cosmetics sector, and the pesticide sprayer used in field crop sectors."

In this study we only consider the industry of manufacture and, therefore, we only look at spillovers between industries of manufacture of the inventions. Indeed, IOM are the most likely sectors that un-

[20] Another commonly used concordance table is the one established by Schmoch et al. (2003 [61]). The authors adopt a different approach: taking patents of 3000 firms, patent being allocated to IPC and firms to industrial classification, they are able to determine a distribution of patents from each IPC through industries.

[21] http://www.statcan.gc.ca/subjects-sujets/standard-norme/sic-cti/sice-ctie80_menu-eng.htm

dertake the research corresponding to the considered product. Thus, the number of patent families and forward citations by sectors of manufacturing would be able to be confronted to the R&D investments efforts (according to a product field approach at least).

4.2 The general country-sector citations matrices

The general matrices have been first established by Meijers and Verspagen (2010 [43]) and consist in counting the number of citations representing knowledge flows between countries and sectors. The allocation of the origin and the destination of citations across countries and sectors is made as follows:

- The country of origin (resp. destination) of the knowledge spillover is defined by the country of residence of the inventor of the cited (resp. citing) patent family
- Each cited and citing IPC is distributed to its IOMs according to the OECD Concordance Table
- Each citation is spread according to the number of
  - Countries of inventors (for both cited and citing invention);
  - IOMs which IPC belongs to (for both cited and citing side).

In order to avoid the vintage effect of patents, we retain only the citations issued by patents within a fix 5 years window from the filing date of the cited patent, which approximately match with the peak of citations.

The resulting patent matrices have thus the following form, where Q_{qikj} is the number of citations of patents with IOM i in country q by a patent with IOM j in the country k, P is the number of countries and N the number of sectors (size of the matrix for each year = $(P * N)^2$):

Table 2: Final citation matrix

Year t			***Citing Country-Sector***												
	Countries		**C_1**			**...**	**C_k**					**...**	**C_P**		
		Sectors	**S_1**	**...**	**S_N**	**...**	**S_1**	**...**	**S_i**	**...**	**S_N**	**...**	**S_1**	**...**	**S_N**
Cited Country-Sector	**C_1**	**S_1**													
		...													
		S_N													
	...	**...**													
	C_q	**S_1**													
		...													
		S_i							Q_{qikj}						
		...													
		S_N													
	...	**...**													
	C_P	**S_1**													
		...													
		S_N													

These matrices are derived from the PATSTAT database by taking into account only patent families, in order to avoid double counting of patent covering the same invention, for which the authorities involved are the USPTO or the EPO. They represent the knowledge flows for each country of the EU27, Norway, Japan, United States and the rest of the world as a whole and for each of the 34 sectors for each years from 1985 to 2007 for forward citations (when citations are allocated to the filing year of the cited patents) and from 1990 to 2011 for backwards citations (when citations are allocated to the filing year of the citing patents).

4.3 The submatrices for energy technologies

The concordance table is very useful because it allows the translation of data from a technological approach to an economic approach. However, a drawback is that the technological sources of the knowledge is lost as, in our final matrices, we are not able to identify technologies anymore. Since in this study we would like to focus on inter-sectoral and inter-national interactions linked to specific technologies, these general matrices are not directly useful.

Adding the technological dimension to these matrices would be obviously too heavy. Nevertheless we can focus on few specific technologies, that is to say on few IPC classes and, then, build "partial matrices" taking into account only IPC classes related to these few technologies. This implies to distinguish technologies both on the citing side and on cited side. Moreover, as a patent of a given IPC could be cited by other IPC and reciprocally could cite patents of other IPC, we can establish at least three different matrices per technology. In the first matrix, we only keep, as cited patent, patents covering the considered technology, that is to say we retain only the forward citations by technology; in the second matrix we only keep, as citing patent, patents covering the considered technology, that is to say the backwards citations of the technology. Finally, in the third matrix, we keep only patents covering the considered technology on both the cited and the citing sides. The general terms of these three matrices are the following:

1. *Forward citations by technology* (Isolation of a technology in cited side): $X_{qikj}^{T_{Cited}}=$ Number of citations received by patents of IPC T with IOM "i" in country "q" issued from patents with IOM "j" in the country "k". Answering the question: "What intersectoral/international knowledge spillovers are created by inventions in technology T?"

2. *Backwards citations by technology* (Isolation of a technology in the citing side):$X_{qikj}^{T_{Citing}}=$ Number of citations received by patents with IOM "i" in country "q" issued from patents of IPC T with IOM "j" in the country "k". Answering the question: "From which sectors/countries comes the knowledge useful for inventing in technology T?"

3. *Intra-technology citations* (Isolation of a technology both in the citing and the cited side):$X_{qikj}^{T_{Citing-Cited}}=$ Number of citations received by patents of IPC T with IOM "i" in country "q" issued from patents of IPC T with IOM "j" in the country "k". This matrix allows to isolate the intra-technological dimension in the previous two questions.

Table 3: Energy-related technologies

ENERGY SOURCES	TRADITIONAL ENERGY	1 FOSSIL FUEL ENERGY
	RENEWABLE ENERGY	*2 WIND*
		3 SOLAR (PV & CSP)
		4 BIOFUELS
		5 GEOTHERMAL
		6 OCEAN & HYDRO
	OTHER ENERGY PRODUCTION FOR EMISSION MITIGATION	*7 HYDROGEN & FUEL CELLS*
		8 NUCLEAR
POLUTION CONTROL	CO_2 MITIGATION	*9 CARBON CAPTURE AND STORAGE*
ENERGY SAVING/EFFICIENCY	ENERGY MANAGEMENT	10 ENERGY STORAGE
	ENERGY DEMAND	11 TRANSPORTATION
		12 BUILDING

More concretely, if we focus, for instance, on wind power technology, these matrices may be interpreted as follows:

- By taking into account only wind-related patents at the cited side, we adress the question « which sectors/countries benefit from innovation in wind-energy technology? »;
- By taking into account only wind-related patents at the citing side, we adress the question « which sectors/countries create knowledge useful for wind-technology innovation? »
- By taking into account only wind-related patents both on the citing and the cited side, we adress the question « which sectors/countries are creating knowledge in wind-technology useful for other wind-technology innovations? »

We compute these matrices for 12 energy-related technological groups:

For each technological group, we establish the list of the corresponding IPC codes using the "IPC green inventory" of the WIPO[22] combined with Johnston et al. (2010 [35]) and Dechezletprêtre et al. (2012 [11]) and the list established in OECD (2012 [50]) for fuel based energy. The list of retained IPC is given in appendix 9.1. Then, we select patents according to these IPC in order to build the sub-matrices related to each group of technologies.

[22] http://www.wipo.int/classifications/ipc/en/est/

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WORLD ENERGY COUNCIL

5 Descriptive analysis

The table 4 sums up (i) the total number of patent families cited at least ones; (ii) the total number of citations received by patent families belonging to each technology group (forward citations) and (iii) the total number of citations issued by patent families belonging to each technology group (forward citations) over the studied period[23]. The differences in these numbers between technology may reflect both the differences in research efforts and differences in the propensity to patent.

The group that counts the highest numbers of both patent families and citations is “Building insulation and lighting” (often called building thereafter) with 26 717 patent families cited at least ones, 113 606 forward citations and 159 439 backward citations. This category groups together innovations directed towards thermal building insulation and low energy lighting. On the opposite, the technology that accounts for the lowest quantity of patents and citations is “Geothermal energy” with only 878 patent families cited at least ones, 2 264 forward citations and 3 544 backward citations.

Table 4: Number of patent families and citations per technology over the considered period*

Technology	**Fuel**	**Nuclear**	**Wind**	**Solar**	**Geothermal**	**Ocean-Hydro**
Patent families	11 983	10 448	4 969	20 667	878	2 270
Forward citations	38 717	26 016	18 544	97 963	2 264	6 085
Backward citations	46 272	33 747	31 357	157 243	3 544	9 719
Technology	**Biofuels**	**Fuel Cells**	**Energy Storage**	**CCS**	**Building**	**Transport**
Patent families	20 408	17 436	17 085	11 812	26 717	13 122
Forward citations	67 843	83 183	75 084	41 054	113 606	68 569
Backward citations	68 208	103 192	99 719	56 038	159 439	95 314

* (i) the Nb of patent families considered patent families that are first filed between 1985 and 2007 and that are cited at least ones; (ii) the Nb of forward citations represents the number of citations received by patents covering energy technologies filed between 1985 and 2007; and (iii) the Nb of backward citations done by patents families covering energy technologies and filed between 1990 and 2011.

We proceed here to a brief descriptive analysis of the raw data on patents and citations distributed across sectors and countries. In particular, we describe our indicators on innovation output on the one hand and, on the other hand, we depict our knowledge spillovers matrices between countries and sectors through patent citations.

5.1 Innovation activity through patents data

As we mentioned in section 3, citations received by patents may be taken as an indicator of the output of innovative activities quatifying both the number of innovation and their quality. Therefore, looking at the evolution of the global number of citations received by patents belonging to a specific technology may give us a first idea of the trend of innovation in this field. Notwithstanding, this indicator is also

[23] As mentioned above, citations taken into account are only citations coming from patent filed in a fix window of 5 years from the filing date of the cited patent.

subject to several biases and considering the number of patents cited at least ones can be taken as a compromise. Therefore we analyse these two indicators for the 12 studied energy technology groups, by describing the trends of innovation in these technologies and by trying to identfy the leading countries.

Trends in innovation in energy-related technologies using forward citations and patent cited at least ones

Figures 3 show the evolution of the total citations received by patents belonging to each technologies in the world. The general dynamics are the following:

- For four technologies, fuel based energy, solar, fuel cells and building, we observe that citations increase until 2003 or 2004 and decrease afterwards.
- For most renewable energies and technologies directed towards energy saving and conservation, citations increase all over the period and accelerate after 2000 for wind power, ocean-hydro and geothermal energy. Innovations directed towards energy saving in transport and energy storage increase relatively constantly between 1985 and 2007. Except a short lessening at the end fo the 80s for biofuels, biofuels and CCS show a relatively weak increase.
- On the contrary, citations towards patents in nuclear power seems to decrease slightly over the period despite a short recovery from 2000 to 2004.

As explained above, these evolution of forward citations should reflect the evolution of innovation in each field. Nevertheless we must consider it with a lot of caution since three main elements could bias the temporal evolution of forwards citations.

1. The first element is the evolution of the average number of citations done by patents. Indeed, we have seen in the section 3.1 that this average number is not constant in time, especially for patents filed at the USPTO. In particular, as this number strongly increases until 2004 and strongly decreases afterwards, we can observe an increase of citations received by patent filed between 1985 and 2000 and a decrease of forward citations after 2000 just because of this effect. In the same way, the constant growth in average (backwards) citations at the EPO, following by an acceleration from 2009, may artificially biased the trend by inducing a constant increase of forward citations until 2005 and an acceleration thereafter. Thus, we must control this average number of backwards citation per patents in forward citations.
2. The second bias relies on the variation of the citation lag. If the citation lag decreases over the studied period, that is to say if the percentage of total citations that a patent will received without time limit which is received during the five years window increases, the average forward citations by patent accounting in this fix window will increase over the period. This increase will not reflect the increase of the value of the patent but rather an increase in the rate of diffusion of the knowledge embedded in the patent. We could expect that it was the case over the studied period 1985-2007, especially with the globalization and the digitalization of patent data that occured over this period. Further investigation have to be done in that direction.

3. The third element that biases the trend in forward citations is the number of patents filed during the five years window of citing patents. Indeed the increase of forward citations between two adjacent years t and t+1 for instance may actually be due by an increase of patents filed 4 years after (between t+4 and t+5). Therefore, this increase of forward citations observed does not reflect an increase in innovation between t and t+1 but the increase in innovation between t+4 and t+5. A normalization of forward citations by the number of patent families filed during the five years window should be done to avoid this effect.

So, as a compromise in order to limit the previous biases, we also consider the number of patent families cited at least ones. The graphs 4 show the evolution of this indicator over the same period for all technologies. The trends of this indicator are similar in general, except for solar power technology for which no scaling back appears at the end of the period. Mainly, the most visible difference with respect to the forward citations based indicator is that variations are smoothed.

Leader countries per technology

Figure 5 represents the shares of the US, the EU27, Japan and the rest of the world in forward citations per technology. In the same way, the figure 6 gives the shares in Patent families cited at least ones.

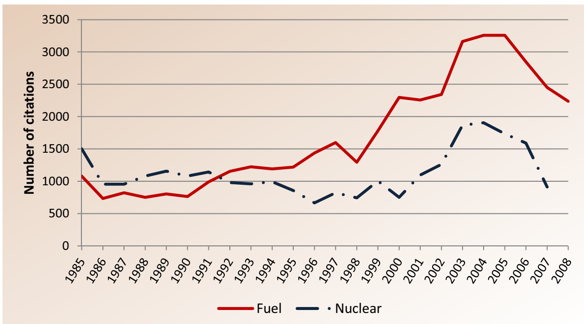
These two figures show that the US, EU27 and Japan represent more than 80% of forward citations and more than 70% of patents cited ones for all technologies. Moreover, according to our results, the three first countries always count for more than the majority. In complement, figures 10 in appendix 9.3 show the temporal evolution of the number of cited patent families in leader countries 10 the temporal evolution of forward citations. For each energy-related technology, we identfy the leader countries:

- In *Fuel based energy technologies*, the three leader countries are the United States, Japan and Germany which count for 75% of forward citations and 68% of cited patents.
- In *Nuclear power,* the US, Japan, Germany and France are the four most important countries and represent 78% of forward citations and 81% of the cited patents..
- *Wind power* is the only technology where the EU27 is the leader region, which is consistent with the IPTS report (IPTS 2011 [16]). Nevertheless this latest report warns us that is seems to changed since the crisis and the emergence of developing countries. The four first countries, the US, Germany, Denmark and Japan, represent 65% of citations received and 59% of the cited patents.
- Leaders in *Solar power technology* (including both Concentrated Solar Power and Photovoltaic) are the US, Japan and Germany[24] and count for 79% of forward citations and 75% of cited patents.

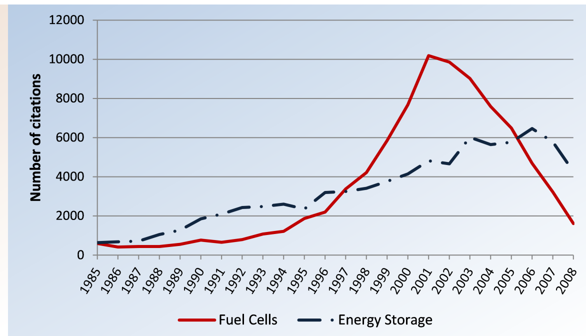
[24] The OECD 2012, identifies KR as the third country, in our case it is included in the rest of the world which represents 15% of forward citations during the period, whereas Germany represents only 9% and is thus far from Japan with his 32%.

Figure 3: Forward citations in energy technologies*

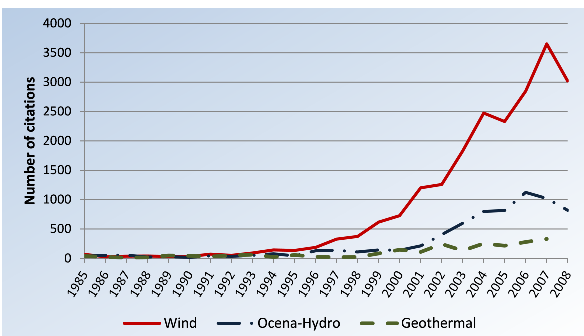
(a)



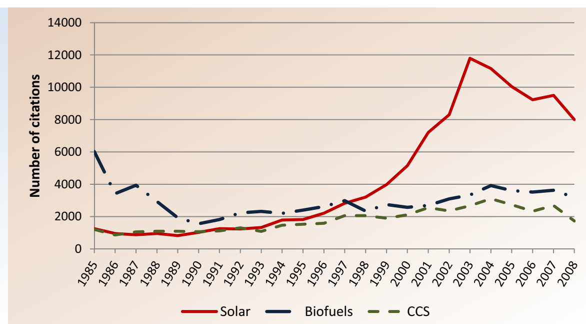
(b)



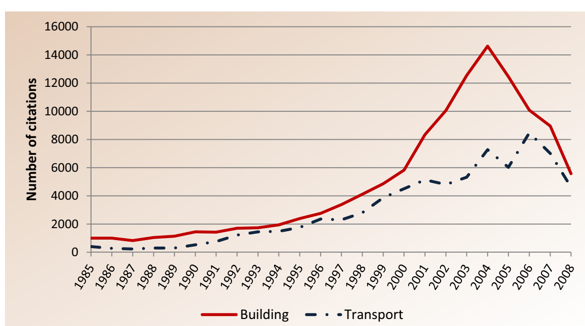
(c)



(d)



(e)

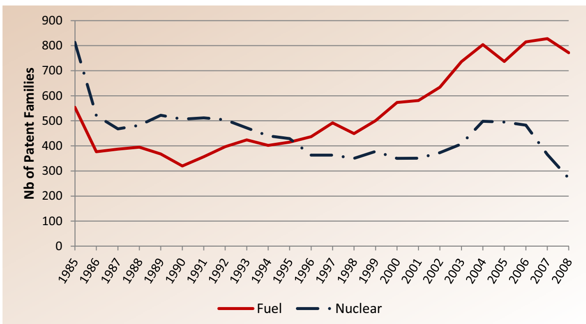


*Citations received by patents in a fixed window of 5 year from the filing date, and filed either at the USPTO or at the EPO.

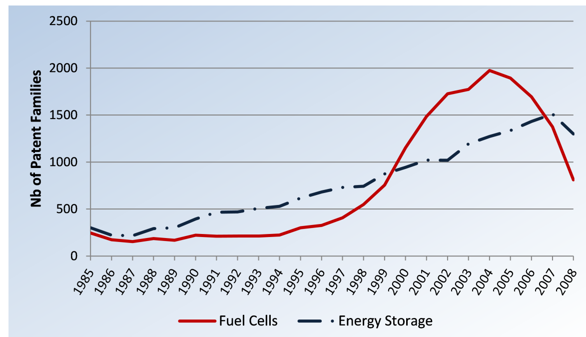
Remark: the year 2008 is included in graphs but it must be underestimated as all potential citing patent from the year 2012 are not available in the version of the database that we used.

Figure 4: Number of patent families cited at least ones in energy technologies*

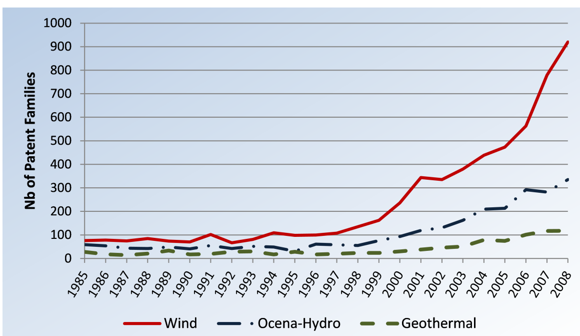
(a)



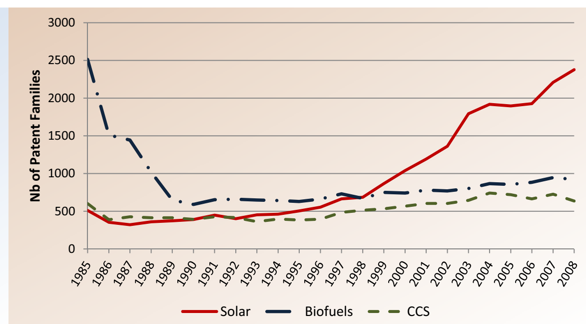
(b)



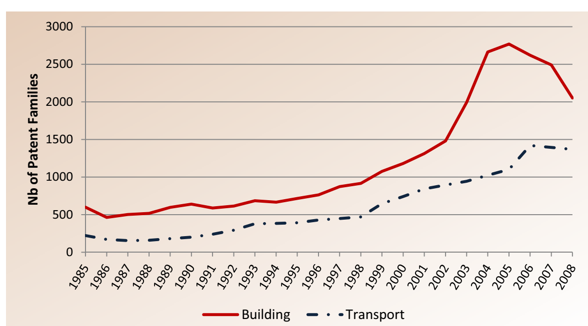
(c)



(d)



(e)



*Number of patents cited at least ones in a fixed window of 5 year from the filing date, and filed either at the USPTO or at the EPO.

Remark: the year 2008 is included in graphs but it must be underestimated as all potential citing patent from the year 2012 are not available in the version of the database that we used.

- For *Geothermal energy* which counts the lower number of citations, the leader countries are the US, Japan and Germany (62% of citations received by the three first countries and 58% of the cited patents).
- In *Ocean-Hydro*, the US, the UK and Germany dominate, followed by Japan and Norway (61% of citations received by the three first countries and 49% of patents).
- Finally the US, Japan and Germany are the three leaders for *biofuels*, *fuel cells*, *CCS*, *energy storage*, *building insulation and lighting* and *energy efficiency in transport* (accounting respectively for 72%, 83%, 79%, 81%, 71% and 90% in forward citations and 67%, 77%, 71%, 73%, 58% and 80% in cited patents). Among these technologies, Germany is at the second place in CCS.

As reminded above, the different biases that exist between offices make the comparative analysis between countries hard to undertake. Indeed, the home bias induces a greater wheight of the US inventors in patent filed at the UPSTO and these patents tend to cite more than patents filed in another office (see fig. 2). Therefore, the home bias combined with the office bias leads to overweight the US inventors in patent citations[25]. Nevertheless, the second measure, using the number of patent families cited at least ones, limits such bias and, in addition, our results are still consistent with previous studies such as OECD, 2012 ([50]) based on another patent data indicator. Moreover, if the comparison is especially biased when we compare US to another country, the comparison between European countries may be undertaken more accurately, since their respective situation is symetric with respect to the patent offices taken into account. The review of our results show three main points: (i) despite the biases, the US and Japan seems to dominate Europe for most energy-related technologies; (ii) Germany is the European leader in almost all technologies; (iii) France and the United-Kingdom are also often in the top five after the US, Japan and Germany.

[25]European countries may also be overweighted in patent filed at EPO but this bias should have a lower impact on our results as the number of citations per patent is not so high at the EPO as at the USPTO.

Figure 5: Shares in forward citations

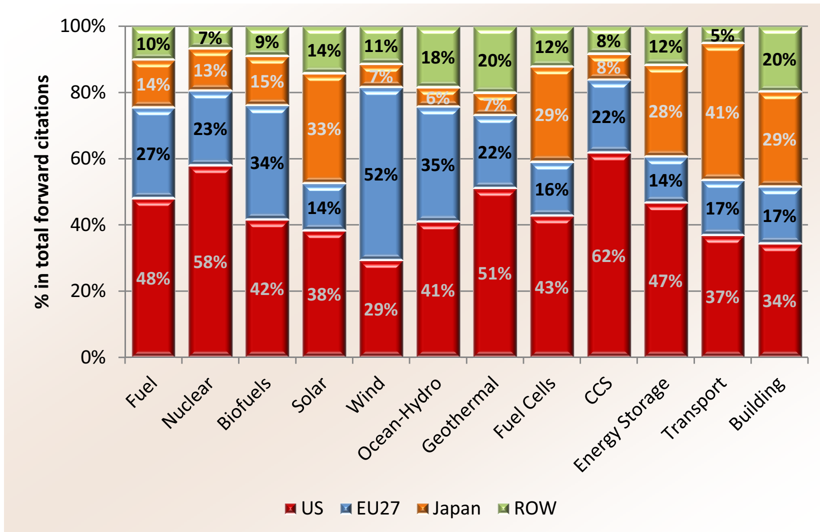
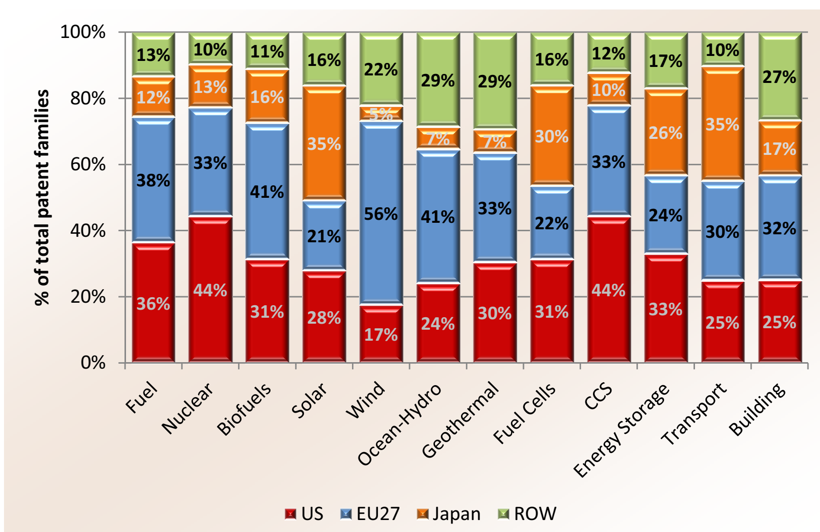


Figure 6: Shares in Patent Families cited at least ones



5.2 Knowledge flows through patent citations

In this section we present the description of raw data on citations between patent families that are allocated through countries and sectors according to the methodology described in section 4. As explained above three categories of spillovers matrices have been computed: (i) one isolating energy technologies on the cited side, (ii) one isolating energy technologies on the citing side and (iii) one isolating energy technologies on both sides. We make here a descriptive analysis of these matrices.

In the first sub-section, we describe the allocation of citations across countries as an indicator of international knowledge spillovers. In the second sub-section, we describe the allocation across sectors as an indicator of intersectoral knowledge spillovers. Obviously, the data is not directly usable to describe knowledge spillovers but they can provide us with some first information.

International knowledge spillovers

The figures 12 (a) to (l) in appendix 9.4 show the total citations, allocated through countries, received by patents belonging to energy-related technologies filed during the period 1985-2007 for the most important countries. The main observations we can do are the following:

Leader countries cite each other (in fuel based energy technology most citations occur between US, Japan and Germany, as well as in fuel cells, energy storage, building or in transport) and citations are relatively symetric but there are also particularities depending on technologies:

- In *nuclear power*, the symetry is rather limited between the US and European countries as French and German inventors cite more US inventors than US inventors cite French or German inventors. In addition, there are only few citations between French or German inventors and Japanese inventors.

- In *wind power* technology German inventors are as many cited by US inventors as by Danish inventors but Danish inventors are mostly cited by German inventors.

- In *geothermal* technology, Japanese inventors cite almost only US inventors while Germany seems to be another important source of knowledge in that field.

- In *CCS* as well as in ocean-hydro, US seems to be the main source and destination of knowledge transfers. Especially, in these technologies, US is more cited by other countries than it cites the other countries.

Regarding the citations issued by patents belonging to energy-related technologies, the figures 13 (a) to (l) highlight in the same way that inventors of energy related innovations based their inventions on knowledge created in countries that are leaders of the considered technology. The relationships between countries are rather similar than those observed with forward citations of innovation in energy technologies.

Contrarily to the authors of the OECD report (2012 [50]) who find that Japan do not show evidence of emitting technology transfers[26], we find that Japan is both an issuer and a receiver of knowledge.

Intersectoral knowledge spillovers

In appendix 9.5, figures 14 to 25 show the sectors involved in each technology. Every figures (a) represent the total number of cited patent families covering energy technologies and allocated through industries of manufacturing (IOM) according to the Johnson methodology.

[26] The authors used co-invention as indicator technology transfers

In our methodology, the selected cited patents belonging to an energy technology may also refer to IPC not related to the considered energy technology. Therefore the cited sectors are not necessarily restricted to the IOM of the IPC corresponding to the energy technology. While we select only cited patents that include energy-related IPC, we keep all references to other IPC of these patents. So, as these other IPC can have other IOM than those of the energy-related IPC, we can obtain more IOM than only those that are strictly related to energy IPC. Taking wind power as an example, the IOM corresponding to the IPC F03D are given in table 5. In addition to these sectors, we can see on fig 16 that the sector "Transport equipment" is also considered as a cited IOM. On the contrary, in the case of nuclear power, the figure 15 does not reveal further sectors than the initial IOMs given in table 6.

Table 5: Industries of manufacturing of patents related to wind power (from IPC F03D) according to the OTC

IOM in SIC-E classification		**IOM in our classification**	
3111	Agricultural Implement (only 2% of the class F03D003)	12	Agr & Indus Machines
3190	Other Machinery and Equipment Industries		
3191	Compressor, Pump and Industrial Fan		
3194	Turbine and Mechanical Power Transmission Equipment		
3199	Other Machinery and Equipment Industries n.e.c.		
3379	Other Electrical Industrial Equipment Industries	14	Non ICT Electrical Goods
3911	Indicating, Record. and Control. Instrument	15	ICT Electrical Goods

Table 6: Industries of manufacturing of patents from IPC related to nuclear power technology according to the OTC

Johnson's IOM in SIC-E classification	Our classification
3611 Refined Petroleum Products Industry (except Lubricating Oil and Grease) 3699 Other Petroleum and Coal Products Industries	5 Refined Oil
4911 Electric Power Systems Industry 4999 Other Utility Industries n.e.c.	6 Electricity
2919 Other Primary Steel Industries	8 Ferrous and non Fer. Metal
3542 Structural Concrete Products Industry	9 Non Metallic Mineral Products
3731 Plastic and Synthetic Resin Industry 3799 Other Chemical Products Industries n.e.c.	10 Chemicals
3011 Power Boiler and Heat Exchanger Industry 3061 Basic Hardware Industry	11 Metal Products
3092 Metal Valve Industry 3190 Other Machinery and Equipment Industries 3192 Construction and Mining Machinery and Materials Handling Equipment Industry 3194 Turbine and Mechanical Power Transmission Equipment Industry 3199 Other Machinery and Equipment Industries n.e.c.	12 Agr. & Ind. Machinery
3370 Electrical Industrial Equipment Industries 3372 Electrical Switchgear and Protective Equipment Industry 3379 Other Electrical Industrial Equipment Industries 3912 Other Instruments and Related Products Industry	14 Non-ICT Elec. Goods
3350 Communication and Other Electronic Equipment Industries 3359 Other Communication and Electronic Equipment Industries 3911 Indicating, Recording and Controlling Instruments Industry	15 ICT Elect. Goods
1620 Plastic Pipe and Pipe Fittings Industry	20 Rubber & Plastic
3999 Other Manufactured Products Industries n.e.c.	21 Other Manufactures
4111 Power Plants Construction (except Hydroelectric)	22 Construction

In the same manner as for countries, figures (b) (c) and (d) show the distribution of patent citations between industries of manufacturing. The figures (a) show intersectoral spillovers inside the considered technology by selecting the related IPC on both cited and citing sides. Thus one can logically observe a strong symetry between citing and cited sectors. Figures (c) represent the citations issued by patents covering energy technologies towards patents covering other technologies and, reciprocally, figures (d) represent the citations received by patents covering energy technologies from patents covering other technologies.

In regard to the breadth of sectors that produce and receive knowledge, we find that for some technologies, such as solar, geothermal, ocean-hydro, biofuels, CCS, one sector is dominating and this sector diffuses and captures knowledge to/from other sectors. Technologies directed to energy efficiency in building and in transport are those that involve the greater number of IOM. The other energy-related technologies involving a large number of sectors are nuclear power, energy storage and fuel cells. Finally we observe that in the three cases, most citations occurs between the main industries of manufacturing of these technologies.

A synthetic approach

In order to have a synthetic view of the citations between countries and sectors one can summarizing their distributions by distinguishing intra/extrasectoral and intra/extranational. By this way we define four categories of spillovers. The table 7 shows these distributions for each energy technology group with respect to forward citations, while the table 8 does the same with respect to backward citations. We can read the first table as follows in the case of biofuels: 36.34% of citations received by patents concerning biofuels are done by patents allocated to the same sector and the same country than the cited patent; 18.69% by patents allocated to the same country but to another sector; 29.16% by patents allocated to the same sector but to another country and 15.81% by patents allocated to another country and another sector. It also means that 36.34%+18.69%= 55.03% are done by inventors from the same country as the inventors of the cited patents and 44.97% are done by foreign inventors. As well as we can say that 36.34%+29.16%=65.5% of citations received by "biofuel patents" are intrasectoral.

Taking all technologies (including non energy related technologies) into account, we observe that the forward citations are more intranational than extranational. This seems to be also the case for most of energy related technologies, except for ocean-hydro and wind, but the wheight of extranational citations are more important for these technologies than for other technologies (for which only 17.84%+17.69%=35.53% of forward citations are extranational).

When taking backward citations, these features are also observed and the classification of the energy related technologies according to the distribution of their spillovers is similar between forward and backward approach. This would suggest that, on the one hand, energy technologies are more suject to international spillovers than other technologies in average. Wind and ocean-hydro seem to be particularly influenced by foreign innovations. On the other hand, innovation in energy technologies seem to generate more international externalities than other technologies in average, which would mean that innovation incentives for developing energy technologies require more international regulation than for other technologies. National strategies will be even less optimal than international ones in the case of promoting innovation in energy technologies compared to other technologies.

Looking at the sectoral distribution of the spillovers, energy technologies are more heteregenous. While some of them, such as innovation in biofuels or solar power, exchange more with other innovation in the same sector, innovation in other technologies such as in energy efficiency in transport, exchange rather with innovations belonging to other sectors. So the classification shows that innovation in biofuels, solar and ocean-hydro are more influenced by intrasectoral innovations than in average for all technologies; on the contrary, innovation in fuel cells, geothermal energy, energy storage, CCS, nuclear and transport are more influenced by extrasectoral innovations than other technologies. One can also observe that these latest energy technologies are also those that involved the most important number of sectors.

Table 7: Distribution of forward citations in energy technologies compared to all technologies

	Intra National		Extra National	
	Intra Sectoral	Extra Sectoral	Intra Sectoral	Extra Sectoral
Biofuels	36.34%	18.69%	29.16%	15.81%
Solar	35.37%	19.38%	28.45%	16.80%
Ocean-Hydro	23.06%	20.76%	31.50%	24.68%
Fuel	26.36%	25.13%	24.07%	24.43%
Wind	19.22%	18.10%	31.46%	31.23%
All Technologies	*31.61%*	*32.87%*	*17.84%*	*17.69%*
Building	26.14%	27.75%	21.48%	24.62%
Fuel Cells	24.11%	28.28%	21.65%	25.96%
Geothermal	27.44%	33.50%	16.36%	22.70%
Energy Storage	22.96%	29.22%	21.61%	26.21%
CCS	25.57%	32.18%	18.87%	23.37%
Nuclear	20.52%	37.77%	14.53%	27.19%
Transport	17.95%	39.77%	13.76%	28.52%

*cited patents filed over the period 1990-2003

Table 8: Distribution of backward citations in energy technologies compared to all technologies

	Intra National		Extra National	
	Intra Sectoral	Extra Sectoral	Intra Sectoral	Extra Sectoral
Biofuels	34.02%	19.44%	29.02%	17.52%
Solar	31.40%	21.92%	26.79%	19.89%
Ocean-Hydro	22.96%	21.25%	32.06%	23.74%
Fuel	26.47%	25.48%	23.86%	24.19%
Wind	18.47%	18.71%	30.61%	32.21%
All Technologies	*31.24%*	*32.39%*	*18.28%*	*18.09%*
Building	25.41%	27.09%	22.76%	24.74%
Fuel Cells	23.48%	27.90%	21.98%	26.64%
Energy Storage	23.03%	28.65%	21.88%	26.44%
CCS	24.83%	32.19%	19.13%	23.85%
Geothermal	25.88%	34.36%	15.78%	23.98%
Nuclear	20.00%	37.54%	14.84%	27.62%
Transport	18.03%	39.89%	13.83%	28.25%

*citing patents filed over the period 1990-2011

Notwithstanding, these observation are only based on raw data on patent citations and must be interpreted with a lot of cautions. Econometric tests should be realized in order to validate the interpretations. In particular these data can help to highlight at which level innovations in energy technologies relies on the own previous knowledge of the industry and weither the ability of a country to innovate in these technologies is strongly related to its own industrial structure and its own past innovations. In the following part, we describe the construction of variables for such assessments.

6 Construction of variables for estimation and calibration in economic modelling

In the endogenization of innovation in economic modelling, one of the objectives is to link the innovation outputs to innovation inputs. In other words, the technical progress must be represented as a resultant of innovative efforts, especially R&D investments. However, as reminded above, the lack of compatibility between indicators in innovation outputs, available according to technological classification, and innovation inputs, given according to economic activities classification, makes the implementation of such mechanisms very difficult in the case of energy related technologies. For that purpose, the aim of this work is to propose a methodology to join both data on innovation output in energy technologies based on patent statistics and data on R&D investments given by economic sectors. The previous parts described the method in order to bring technological information closer to economic classications. This part deals with the building of innovation inputs variables from these data and data on R&D investments at sectoral level.

The first section focus on R&D investments. It first describes the data on public investment in R&D per energy related technologies that provided by the International Energy Agency and it presents the method to assess private R&D investments per technology. Finally it deals with the construction of the knowledge stocks proper to each sector in each technology. The second section deals with knowledge externalty variables by defining the external knowledge stocks related to each energy technology.

The geographical coverage of this part is more restricted than for patent based statistics as R&D at sectoral level is not available for all countries. We consider here 17 countries of which 14 are European. These countries are: Austria, Belgium, Germany, Denmark, Spain, Finland, France, Greece, Ireland, Italy, the Netherlands, Portugal, Sweden, the United-Kingdom, Norway, the United-States and Japan. The period covered is 1990 to 2007.

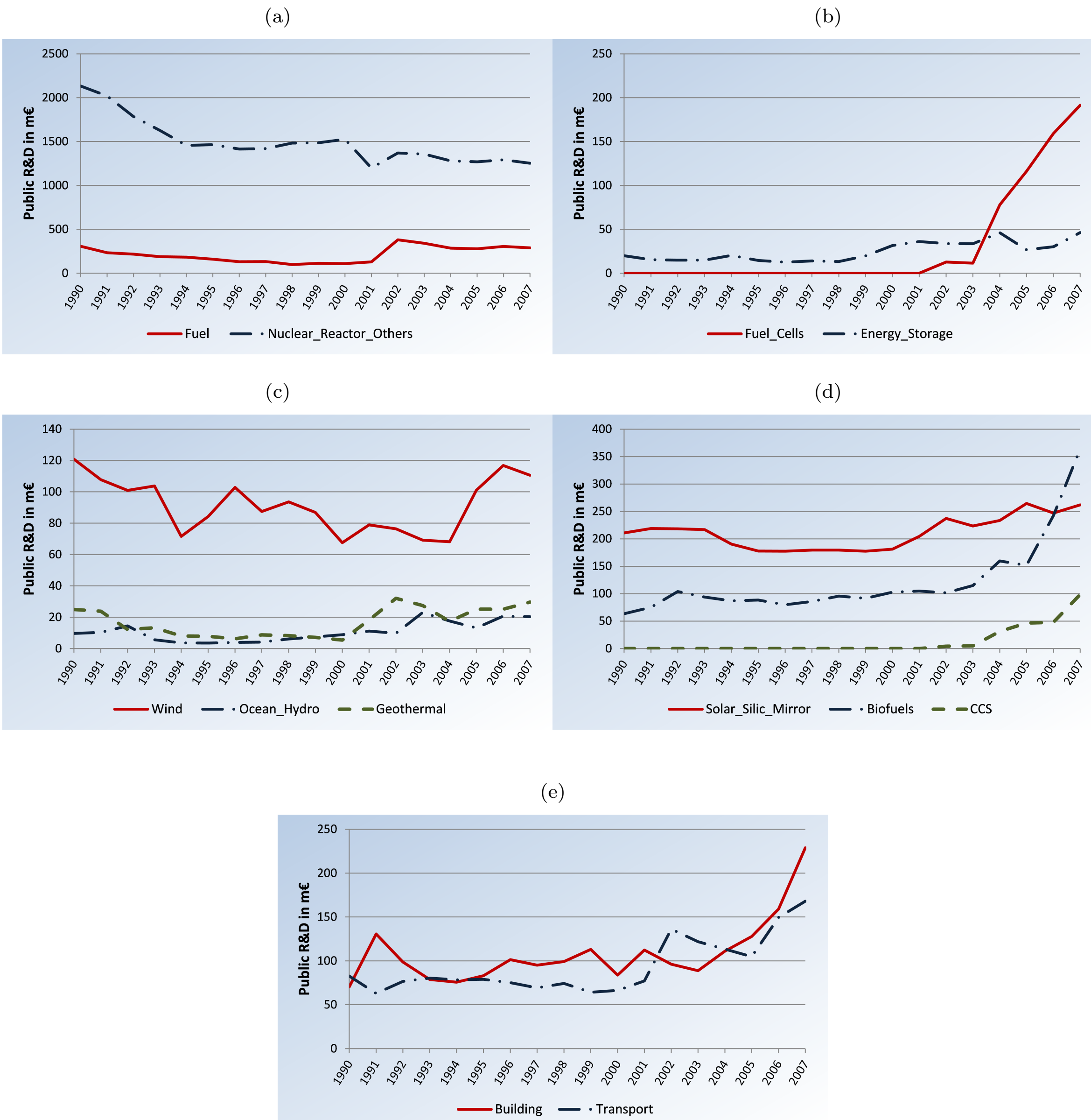
6.1 R&D investments in energy technologies and related knowledge stocks

Public investments in R&D per energy related technology

The public investments per energy related technology is given by the International Energy Agency at national level. The figures 7 show the evolution of these investments in the 14 European countries for each considered energy technology. The graph show that the technology that benefited the most of public R&D investments is the nuclear power energy. But public R&D in htat field is decreasing over the period. Other energy production technologies that are benefiting important public support for innovation are fuel based energy, solar and wind power and, more recently biofuels. In addition, governements invest also in research in technologies aiming at improving energy efficiency in building, appliance and equipment as well as in transport. These efforts are accelerating from 2000. The fuel cells technology has the particular feature to start being developped during the period and public investments in research in that field start after 2002 and show an explosive profile until 2007 up to almost 200 m€, becoming higher than investments in wind and reaching almost the level of public in solar power.

This data is given at national level and is not allocated through sectors. It will therefore not be affected to the direct knowledge of each sector in each technology.

Figure 7: Public investments in R&D per energy technology in the studied 14 European countries (source: IEA)



Assessment of private investments in R&D per energy related technology

As explain before, data on R&D investments per technology does not exist. We only have at our disposal data at sectoral level whithout any distinction of technology. We therefore establish a method to proxy these invesments by a variable homogenous to R&D expenditures in constant currency. For the sake of clarity, we call this proxy “private R&D investments in technology T” but this variable must obviously be taken with as much caution as possible since no real verification of the robustness of such assessment of R&D investment per technology is possible. Indeed, at our knowledge, only Wiesenthal et al. (2009 [70]) provide an estimation of R&D investments for several energy technologies at national level for the year 2007 and neither time series nor sectoral data is available .

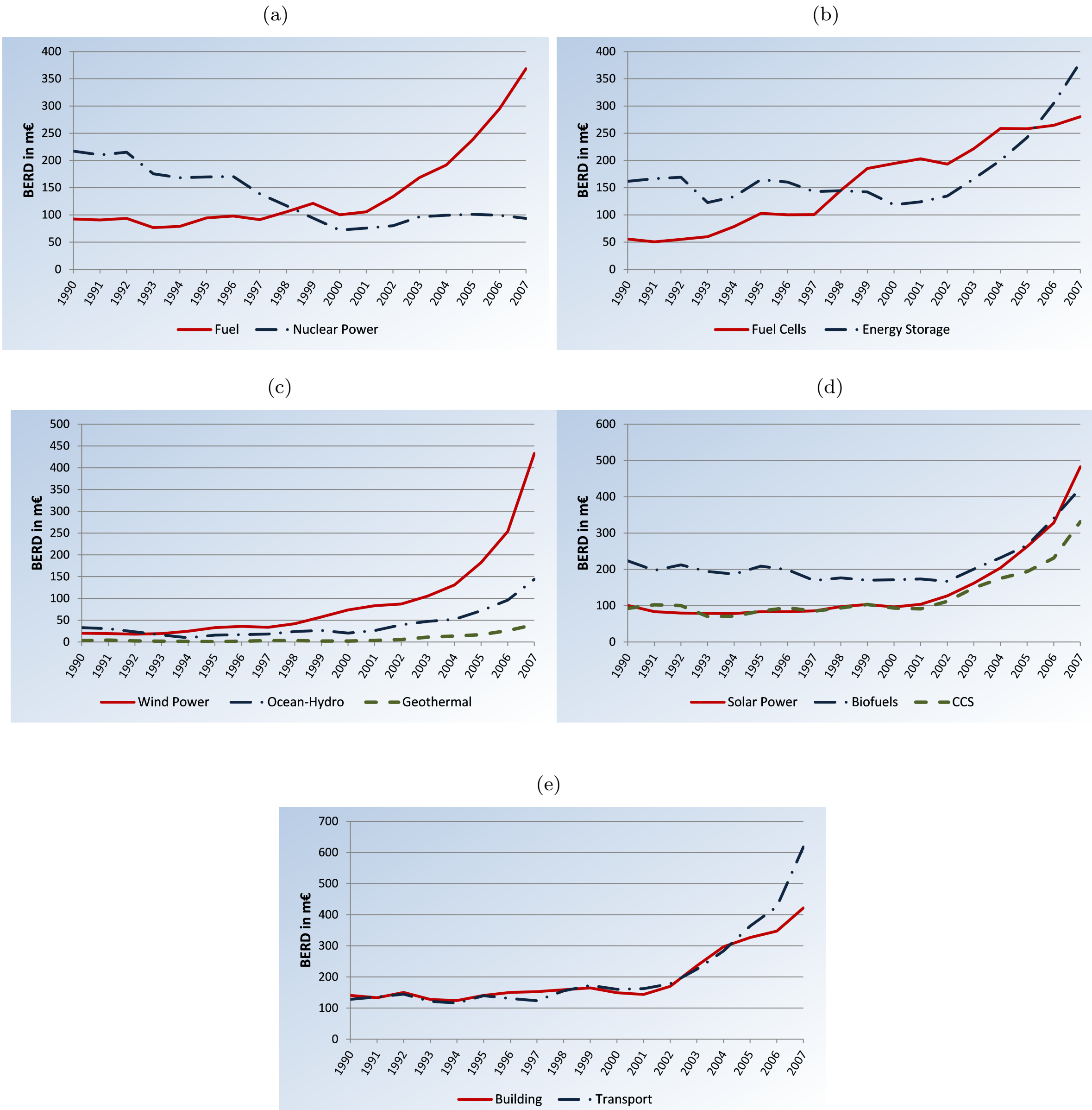
We assess these investments as following:

$$IRD^T_{i,c,t} = IRD_{i,c,t} \times \frac{NP^T_{i,c,t}}{NP_{i,c,t}} \times \Theta_i \tag{1}$$

Where $IRD_{i,c,t}$ is the R&D investment in sector i and country c at time t; $NP_{i,c,t}$ is the total number of patents filed during the 3 following years and cited at least once allocated to the sector i according to the OECD concordance table (2002 [34]) (i defined as Industry Of Manufacturing); $NP^T_{i,c,t}$ is, among these patents those concerning the considered technology T and Θ_i is the share of patentable inventions of the sector i estimated by Arundel and Kabla (1998 [3]). By multiplying by this latest coefficient, we assume that inventions relative to the energy technologies that we consider are patentable and, therefore, that research effort targetting these technologies can be proxied by the share of the patented inventions of each sectors related to these technologies. This is a strong hypothesis Nevertheless it leads to more realistics level of R&D expenditures and as the sectors involved in innovation in energy related technology have relatively close coefficient, this should not greatly affect estimations based on this proxy.

By this way we established variables representing R&D investments per energy technology for 17 countries, 20 sectors, from 1990 to 2007. The figure 8 show the evolution of these calculated private R&D investments per technology for the aggregated 14 European countries from 1990 to 2007. These results can be confronted with the assessment realized by Wiesenthal et al. (2009 [70]) and we find comparable results for the common technologies.

Figure 8: Assessment of private business R&D investments per energy technology



The own knowledge stocks

As R&D expenditure may be considered as investment, we built from these variables a proxy of the R&D capital at the sectoral level. This proxy can be considered as a proxy of a knowledge stock proper to each sector and each country related to the given technology.

The own knowledge stock related to the technology T of the country c and the sector i at time t, $SRD^{T}_{i,c,t}$, is calculated following the perpertual inventory method:

$$SRD^{T}_{i,c,t} = SRD^{T}_{i,c,t-1}\,(1-\delta) + IRD^{T}_{i,c,t} \tag{2}$$

where the knowledge obsolescence rate $\delta = 0.15$;

The initial value of the direct knowledge stock is calculated as follows:

$$SRD^{T}_{i,c,Y_0} = \left[IRD^{T}_{i,c,Y_0} + \frac{IRD^{T}_{i,c,Y_{0+1}}}{1+r} + \frac{IRD^{T}_{i,c,Y_{0+2}}}{(1+r)^2} \right] \times \frac{1}{3} \times \frac{1+r}{r+\delta} \tag{3}$$

With

$$r = \left(\frac{IRD_{c,i,Y_{0+8}} + IRD_{c,i,Y_{0+9}} + IRD_{c,i,Y_{0+10}}}{IRD_{c,i,Y_0} + IRD_{c,i,Y_{0+1}} + IRD_{c,i,Y_{0+2}}} \right)^{1/8} - 1 \tag{4}$$

6.2 Knowledge flows coefficients and external knowledge stocks

One of the main characteristics of innovation relies on the fact that its fruits cannot be fully appropriate by its inventors as it creates non-excludable knowledge potentially useful for other inventors. This feature makes social returns of innovation higher than private ones. This property can be represented at sectoral and country level using patent citations as explained in section 3.2 and section 4.

The degree to which the knowledge produced in sector s in country p is potentially useful for the sector i in the country c is evaluated according to the number of citations between patents belonging to these sectors. The underlying idea is that the more patents belonging to (c,i) have a propensity to cite patents belonging to (p,s) the more an innovation in (p,s) is potentialy useful for (c,i) and, therefore, the more R&D engaged in (p,s) may generate knowledge spillovers to (c,i). Nevertheless, the raw number of citations between (c,i) and (p,s) must be controlled by the size in terms of patents of these two sectors. Indeed the more patents are filed by (p,s), the more patents from (p,s) will be cited by patents from (c,i) and, conversely, the more patents are filed in (c,i), the more patents from (c,i) will cite patents from (p,s) for a given propensity to cite. That means that raw citations does not only reflect the propensity of an innovation in (p,s) to affect the innovation capacity of (c,i) but also integrate the innovation activity of these two sectors which will already be taken into account by R&D investment. Thus, in order to avoid double counting, we control this raw number of citations by the number of patents belonging to these two sectors. The spread[27] parameter from (p,s) to (c,i) is then defined as:

$$\Phi_{(p,s)\to(c,i)} = \frac{C_{c,i\to p,s}}{N_{p,s} \times N_{c,i}} \tag{5}$$

In our model, we normalize this coefficient by the total flows received by (c,i) :

$$\Phi_{(c,i)} = \sum_{q=1}^{P}\sum_{k=1}^{S} {C_{c,i\to q,k}}\big/{N_{q,k}\times N_{c,i}}$$

and we obtain:

[27] I call it "spread parameter" instead of "diffusion parameter" as it reflects the diffusion of the knowledge through space and not through time.

$$\Phi_{(p,s)\to(c,i)} = \frac{C_{c,i\to p,s}/N_{p,s}}{\sum\limits_{q=1}^{P}\sum\limits_{k=1}^{S} C_{c,i\to q,k}/N_{q,k}} \tag{6}$$

This final coefficient represents the propensity of an innovation from (p,s) to be used to invent in sector (c,i) compared to all innovation that are used by (c,i). By this way knowledge is supposed to be non exclusive and non-rival[28].

In addition to the sector of origin, we can distinguish whether the knowledge spillovers concern the technology T or not.

$$\Phi_{\mathrm{T},p,s,c,i} = \phi^{\bar{T}T}_{(p,s)\to(c,i)} = \frac{C^{T\bar{T}}_{c,i\to p,s}/N^{\bar{T}}_{p,s}}{\sum\limits_{q=1}^{P}\sum\limits_{k=1}^{S}\left(\frac{C^{T\bar{T}}_{c,i\to q,k}}{N^{\bar{T}}_{q,k}} + \frac{C^{TT}_{c,i\to q,k}}{N^{T}_{q,k}}\right)} \tag{7}$$

$$\Phi_{\bar{T},p,s,c,i} = \phi^{TT}_{(p,s)\to(c,i)} = \frac{C^{TT}_{c,i\to p,s}/N^{T}_{p,s}}{\sum\limits_{q=1}^{P}\sum\limits_{k=1}^{S}\left(\frac{C^{T\bar{T}}_{c,i\to q,k}}{N^{\bar{T}}_{q,k}} + \frac{C^{TT}_{c,i\to q,k}}{N^{T}_{q,k}}\right)} \tag{8}$$

where $C^{T\bar{T}}_{c,i\to p,s}$is the number of citation issued by patents related to the technology T in sector i in country c received by patents not related to the technology T in sector s in country p; $N^{T}_{c,i}$ is the number of patents in the country c and sector i that cover the technology T and $N^{\bar{T}}_{p,s}$ is the number of patent in the country p and sector s covering other technologies than T.

We assume a constant spread parameter and we take the value of citations and number of patents during the whole period covered by the study. This coefficient is therefore an average over this period.

The external knowledge stocks is finally defined as

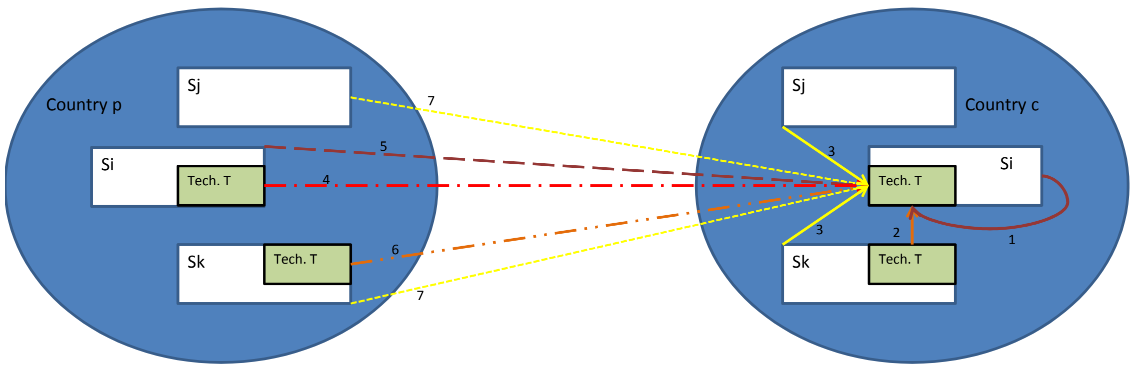
$$KNOWEXT_{\Gamma,p,s,c,i,t} = \Phi_{\Gamma,p,s,c,i} \times SRD_{\Gamma,p,s,t-\Delta} \tag{9}$$

where $\Delta$is the diffusion lag that we take equal to 2 years.

Thus, according to our methodology we can therefore distinguish seven different categories of external knowledge stocks depending of their origins that are illustrated on fig. 9

[28]This is not the case if we use a measure, sometimes used in the litterature, $C_{c,i\to p,s}/C_{p,s}$where $C_{p,s}$is the total number of citations received by (p,s)

Figure 9: Graph on knowledge spillovers



The arrows on the diagram represents the spillovers that come from:

1. the same sector in the same country and concerning other technologies;
2. other sectors in the same country and concerning the same technology;
3. other sectors in the same country and concerning other technologies;
4. the same sector in other countries and concerning the same technology;
5. the same sector in other countries and concerning other technologies;
6. other sectors in other countries and concerning the same technologies;
7. other sectors in other countries and concerning other technologies.

However, this detailed level of external knowledge stock disagregation lead to several collinearities and, therefore, can not really be used for estimation but only for detailling spillovers in economic modelling.

7 Estimations

In order to test the impact of the knowledge stocks related to the considered technology as well as the impact of the knowledge externalities at stake in the innovation process in energy related technologies, we estimate an innovation production function relative to the 12 studied energy technology groups: fossil fuel; wind; solar; biofuels; geothermal; ocean-hydro; fuel cells; nuclear; carbon capture and storage; energy storage; energy efficiency in transport; and building insulation and lighting. These estimations are based on the data described above consist in a first attempt. Results should therefore be considered as preliminary results and may be subject to modifications in the future. We will first describe the model and, then, we will comment the first estimation results.

7.1 Estimated model

We estimate the following fonction:

$$Innov_{c,t}^{T} = \alpha \times srd_{c,t}^{T} + \beta \times prd_{c,t}^{T} + \sum_{q} \gamma_q \times sek_{c,q,t}^{T} + \Psi_c + \Psi_t \tag{10}$$

Where $Innov_{c,t}^{T}$ is the number of innovations in technology T realized in country c at time t measured by the log number of patents related to the technology T filed at time t whose inventors reside in country c.

$SRD_{c,t}^{T}$ represent, as described above, the sum of the direct knowledge stock accumulated in each sector of invention of the technology T in country c at time t which is captured by the accumulation of the private R&D investments of allocated to this technology in each sector. The small letters stand for the log of the variable.

In addition to this direct private knowledge stock, we take into account the current public R&D investments specific to these technologies $PRD_{c,t}^{T}$. These data are extracted from the IEA database.

$SEK_{c,q,t}^{T}$ stands for the external knowledge stock potentially useful at time t for the country c for inventions related to the technology T. External knowledge stocks may have several origins q.

Finally, Ψ_T, $\Psi_c$and Ψ_t stand for the technology, country and time fixed effect. regarding the time dimension, we also estimate the equation with a time trend instead of time dummies.

As we estimate at the macro level the innovation production function, we add these categories over all sectors. That means that, refering to the previous diagram 9, we add the flows 1 of all sectors in country 2 to built the national intrasectoral spillovers from other technologies; all flows 2 of all sectors to obtain the national intersectoral spillovers from inventions in the same technology; etc.

However, as already mentioned, this detailed level of external knowledge stock disagregation lead to several collinearities (see tables 9 and 10 in appendix) and, therefore, can not really be estimated. We keep only the following externalities into consideration (the numbers refers to the diagram):

$$3:\ KNEOT_c = \sum_i \sum_{\substack{p=c \\ s\neq i \\ \Gamma=\bar{\tau}}} \Phi_{\Gamma,p,s,c,i} \times SRD_{\Gamma,p,s,t}$$

$$4:\ KIIT_c = \sum_i \sum_{\substack{p\neq c \\ s=i \\ \Gamma=\tau}} \Phi_{\Gamma,p,s,c,i} \times SRD_{\Gamma,p,s,t}$$

$$5:\ KIIOT_c = \sum_i \sum_{\substack{p\neq c \\ s=i \\ \Gamma=\bar{\tau}}} \Phi_{\Gamma,p,s,c,i} \times SRD_{\Gamma,p,s,t}$$

7.2 First empirical findings

We estimate the equation 10 both in log level and in log variations with the OLS method. The results of the estimations are given in tables 11 and 12 in appendix. In the innovation production function we retain as determinant of the innovation the knowledge stock in the considered energy technology, the public investment in R&D in this technology, three sources of externalities: the knowledge spillovers coming from other sectors in the same country and concerning other technologies, *kneot*; knowledge spillovers coming from the same sector in other countries and concerning the same technology *kiit*; and knowledge spillovers coming from the same sector in other countries and concerning other technologies *kiiot*.

In this first estimation attempt, we estimate the function of innovation at the national level in pooled panel data pooling both countries and technologies.

We start with a specification including only national knowedge stock related to the technology, *srd*, and public R&D investments, *prd*, as determinant of innovation (models 1 with full fixed effect and 2 with country and technological dummies). Both models in log level and in log variations show high significancy of the national knowedge stock related to the technology. The model 2 shows also in both cases significant positive impact of public R&D on innovation.

The models 3 and 4 include the two first knwoledge spillovers, *kneot* and *kiit*, in addition to the national knowledge stock related to the technology but exculde *prd*. While the national knowledge in other technologies seems to have a negative impact on innovation in the considered technologies, the current capital of knowledge existing in the same sectors in foreign countries and related to the technology have a significant highly positive impact in all cases. Taking the model 3 in log level, an increase of the national knowledge stock in the technology of 1% would increase national innovation of 0.43% and an increase of foreign knowledge stock in this same technology would induce an increase of national innovation in this technology of 0.23%. The models 5 and 6 add the knowledge spillovers coming from the same sector in other countries and concerning other technologies *kiiot* with respect to the two previous models. these knowledge spillovers seems to have in all cases significant positive impact on innovation in energy related technologies but lower than *kiit*.

The models 7 and 8 put all the considered determinants of innovation together, taking national knowledge stocks on the technologies, public R&D and the three knowledge spillovers. The results are consistent with the previous one, providing evidence of significant positive effect of the national knowledge stocks, public R&D and international spillovers and, on the contrary, of the negative impact of national knowledge stocks on non related technologies.

In order to test the robustness of the estimations, in addition to the implementation of different dummies and fixed effects, as well as considering both level and variations, we implement the estimation using different sub-samples. In the model 9 we only take into account technologies that can be considered as multisectorial technologies, that is to say that involve several sectors in their development. these technologies are those related to: CCS, energy storage, fuel based energy, nuclear power, ocean-hydro, wind power, energy efficiency in transport and building. The results are similar with the previous one for *srd*, *kneot* and *kiit* but neither *prd* nor *kiiot* has significant effect on innovation in these technologies. On the contrary, the model 10 take into account technologies that mostly involve one sector in their development, including technologies related to biofuels, fuel cells, geothermal power and solar power. In this case, all parameters are significant and have the same sign as well as the same magnitude than in previous estimations.

Finally the model 11 consider the most mature technologies: biofuels, fuel based, nuclear power, ocena-hydro power, solar power, and wind power as well as energy efficiency in transport and building. The findings are consistent with the findings of the other models.

As mentioned above, these estimations consist in a first attempt of identifying the most important sources of knowledge spillovers in the case of energy-related technologies. We must going deeper in the analysis of the spillovers at industrial and international level by improving the econometric model. In particular, estimations per technology could provide differentiated evidences among energy-related technologies. Considering innovation output at the sectoral level and estimating the innovation function in a pooled panel pooling industries and countries may also allow considering more knowledge spillovers sources by diminishing the correlation between spillovers. These developments will be the subject of future works.

8 Summary and concluding remarks

The rate of the global economic growth, the climate change and the fossil fuels that are increasingly scarce are creating great challenges related to the production or the use of energy in the world. These challenges will find answers in a shift in energy mix as well as in a change in the energy consumption behavior but also in strong innovation activities directed to particular technologies. Because of all the different externalities involved, positive or negative, and the global nature of the problems, the optimal strategies will not be adopted spontaneously by households and firms and a global concerted public intervention is, without doubts, necessary. Many countries and supranational organizations are already involved in considering these challenges. At the same time there is consequently an increase in the need for ex-ante assessment of policies that are targeting on particular energy-related technologies development. One of the major difficulties inherent in such exercises is to make the links between technologies and economic sectors. The aim of this study is to improve the ability to make such link in the framework of economic modelling. Innovation in general is driven by two main mechanisms. The first is related to market incentives, whereas the second relies on the technological opportunities enabled by the the current available knowledge. We focus here on a part of the second mechanism and the way to model the knowledge spillovers specific to energy-related technologies. For that purpose, we use a patent database which provides us with very rich information combined with the OECD concordance table that allows us to convert information at technological level to information at economic sector level.

In this paper, we deal with two main issues:

1. The first is about the quantification of innovation directed to energy-related technologies and the distribution of the corresponding innovative activity between countries and sectors. This issue is subject to strong uncertainties but may consist in a valuable approach to calibrate the research effort directed to these technologies in each country and sector in an economic model

2. The second issue is about international and intersectoral knowledge flows linked to energy-related technologies. The aim is to determine the relative importance of these flows depending on their origin and the technology.

More specifically, regarding the second, we built knowledge flows matrices between sectors and countries based on patent citations for twelve energy-related technologies described in table 3. For the assessment of the knowledge flows, we use the patent citations data from patents filed at the EPO and the USPTO. This measurement of knowledge flows relies on the fact that each patent refers to previous patents which consist in a technological basis upon which the new patent rests. These citations can be considered as an indicator of the knowledge flows since a cited patent is supposed to have created knowledge used by the inventor(s) of the citing patent. In our study we distribute these citations data, organized according to a technological classication (IPC), through sectors by using the OECD concordance table and through country according to the country of residence of the inventors. We obtain by this way the knowledge flows matrices between countries and sectors.

As an example, we can consider a patent that protects an invention about a rotor for a wind turbine, whose the IPC is F03D 1/06 and which is created by a German resident inventor. This patent cites another patent protecting an invention about a rotor for helicopter, whose the IPC is B64C 27/473 created by an American resident inventor. According to the OECD concordance table, a technology protected by a patent classified in the IPC F03D 1/06 is produced in the sector “Agricultural and industrial machinery”; and a technology protected by a patent classified in the IPC B64C 27/473 is produced in the sector “Transport equipment”. Consequently, in our matrices, this citation will lead to a unit flow of knowledge from the sector “Transport equipment” of the United States to the German “Agricutural and industrial machinery” sector. For the sake of clarity, we provide here an example with a unique sector of production and a unique country of residence of inventors for each patent. Nevertheless, as an IPC may have several industries of manufacturing (called IOM in the paper) and as a patent may belong to several IPC as well as it can be invented by inventors from different countries, one citation may be split into several fractions of knowledge flows between several countries and several sectors.

In addition, the citations must be considered in both directions: (i) the “backward citations”: the citations issued by patents covering energy-related technologies and received by previous patents covering all kind of technologies; (ii) the “forward citation”: the citations received by patents covering energy-related technologies and issued by later patents covering all kind of technologies. (iii) in addition, we can isolate the case in which patents covering an energy-related technology cite other patents covering the same energy-related technology

We built these matrices over the period 1985-2007 for cited patents and 1990-2011 for cinting patents for each of the twelve technological groups mentioned above by isolating patent belonging to the corresponding IPC mainly defined by the IPC Committee of Experts and other studies such as Johnstone et al (2010 [35]).

For each of these groups we tried to determine which countries and sectors are involved in their development and which countries and sectors generate knowledge useful to develop these technologies or, conversely, benefit from the knowledge created by the development of these technologies.

At the same time, we use the relative number of citations received by patent covering energy-related technologies to assess the relative importance of the innovative activities in that field. While several studies use the number of patent families which may be biaised by the strong heterogeneity of the value of each patent, we use an indicator based on citations as the citations received by a patent family may reflect its quality. Nevertheless, as raw number of citation is also subject to strong bias uncertainties we also use an alternative indicator of innovation accounting the number of patents cited at least ones in fixed duration window from the filing date.

The innovation indicators over the period 1985-2007 reveal different trends depending on the technology group. For technologies related to fuel-based energy, innovation seems to grow untill 2004 and to decrease afterwards, while innovation about technologies related to nuclear-based energy shows a slow decrease until 2000 following by a short recovery and decrease again after 2003. Concerning the renewable energies, most of them show an increase over the period and an acceleration after 2000; in solar-based energy, innovation to decrease after 2003. Innovation in fuel cells show similar features with an acceleration until 2001 and a decrease afterwards as well as innovation in building insulation and lighting whose point break occurs in 2004. Innovation concerning energy efficiency in transport and energy storage show a constant increase over the period and innovation in biofuels and CCS seems to be almost constant.

The geographic comparison, despite important bias, is consistent with the existing literature. We oberve that the innovation on energy-related technologies is relatively higher in the United States and in Japan than in Europe and that Germany is the European leader country for most of the twelve technological group taken into account following by France and the United-Kingdom.

Regarding knowledge externalities, from our citation matrices and patent data, we establish spillovers coefficients between 34 sectors and 32 countries plus the rest of the world as a whole. These coefficients represent the propensity of an innovation to be useful for other innovation in other sectors/countries and they isolate the cases of energy-related technologies. Then, we built knowledge stocks per sector and country corresponding to different origins. Our citation matrices suggest that if all technologies benefit from international knowledge flows, that mainly occur between leader countries, the relative importance of the intersectoral knowledge flows is highly heterogenous between the considered technologies. In particular, technologies related to solar-based energy and to biofuels highlight relatively few intersectoral citations whereas technologies related to nuclear-based energy or to efficiency in transport seems to benefit strongly from intersectoral knowledge flows. The relative importance of the intersectoral flows may reveal the transversality of the knowledge related to these technologies. The other technologies are distributed around a mean result obtain by taking into account all technologies (including both energy-related and non energy-related technologies). This is also noticeable that energy-related technologies seem to cite more patents from other countries than other technologies in average.

The estimations, realized in the last section, consist in a first attempt of assessment of the relative importance of innovation determinants. It shows in particular highly significant positive impact of national knowledge stocks and spillovers coming from the same sectors in other countries and related to the same technologies. The empirical findings bring a first validation of our methodology to represent interactions induced by innovation in energy technologies but further investigations have to be done to deepen the analysis of intersectoral and international knowledge spillovers concerning energy-related technologies.

References

[1] Daron Acemoglu, Philippe Aghion, Leonardo Bursztyn, and David Hemous. The Environment and Directed Technical Change. *The American Economic Review*, 102(1):131–166, 2012.

[2] John R Allison, Mark A Lemley, Kimberly A Moore, and R Derek Trunkey. Valuable patents. *Geo. LJ*, 92:435–1309, 2004.

[3] Anthony Arundel and Isabelle Kabla. What Percentage of Innovations Are Patented? Empirical Estimates for European Firms. *Research policy*, 27(2):127–141, 1998.

[4] Scott E Atkinson and Robert Halvorsen. A new hedonic technique for estimating attribute demand: an application to the demand for automobile fuel efficiency. *The Review of Economics and Statistics*, pages 417–426, 1984.

[5] R. Belderbos and P. Mohnen. SIMPATIC Project, Deliverable D7: Intersectoral and international R&D spillovers. Technical report, MERIT, 2013.

[6] René Belderbos, Martin Carree, and Boris Lokshin. Cooperative R&D and Firm Performance. *Research policy*, 33(10):1477–1492, 2004.

[7] Frauke Braun, Jens Schmidt-Ehmcke, and Petra Zloczysti. Innovative activity in wind and solar technology: Empirical evidence on knowledge spillovers using patent data. 2010.

[8] Stefano Breschi and Francesco Lissoni. Knowledge Networks From Patent Data. *Handbook of quantitative science and technology research*, pages 613–643, 2004.

[9] David T Coe and Elhanan Helpman. International R&D Spillovers. *European Economic Review*, 39(5):859–887, 1995.

[10] C. Corrado, C. Hulten, and D. Sichel. Measuring capital and technology: an expanded framework, 2005.

[11] Antoine Dechezleprêtre, Matthieu Glachant, Ivan Haščič, Nick Johnstone, and Yann Ménière. Invention and Transfer of Climate Change Mitigation Technologies: A Global Analysis. *Review of Environmental Economics and Policy*, 5(1):109–130, 2011.

[12] Antoine Dechezleprêtre, Matthieu Glachant, and Yann Ménière. What Drives the International Transfer of Climate Change Mitigation Technologies? Empirical Evidence From Patent Data. *Environmental and resource economics*, pages 1–18, 2009.

[13] Emmanuel Duguet and Megan MacGarvie. How Well Do Patent Citations Measure Flows of Technology? Evidence From French Innovation Surveys. *Economics of Innovation and New Technology*, 14(5):375–393, 2005.

[14] Alfonso Gambardella, Dietmar Harhoff, and Bart Verspagen. The value of European patents. *European Management Review*, 5(2):69–84, 2008.

[15] Steven Globerman. Foreign Direct Investment and 'Spillover' Efficiency Benefits in Canadian Manufacturing Industries. *Canadian journal of economics*, pages 42–56, 1979.

[16] Ales Gnamus. Capacities Map 2011; Update on the R&D Investment in Three Selected Priority Technologies within the European Strategic Energy Technology Plan: Wind, PV and CSP. Technical report, JRC IPTS European Commission, 2011.

[17] Akira Goto and Kazuyuki Suzuki. R & D Capital, Rate of Return on R & D Investment and Spillover of R & D in Japanese Manufacturing Industries. *The Review of Economics and Statistics*, pages 555–564, 1989.

[18] Z. Griliches. Patent statistics as economic indicators: a survey. *Journal of Economic Literature*, pages 1661–1707, 1990.

[19] Z. Griliches and F. Lichtenberg. Interindustry technology flows and productivity growth: A reexamination. *The Review of Economics and Statistics*, 66(2):324–329, 1984.

[20] Zvi Griliches. The Search for R&D Spillovers. *The Scandinavian Journal of Economics*, pages S29–S47, 1992.

[21] Zvi Griliches, Ariel Pakes, and Bronwyn H Hall. The value of patents as indicators of inventive activity. Technical report, National Bureau of Economic Research Cambridge, Mass., USA, 1986.

[22] D. Guellec and B. van Pottelsberghe de la Potterie. Applications, grants and the value of patent. *Economics Letters*, 69(1):109–114, 2000.

[23] Bronwyn H Hall, Adam Jaffe, and Manuel Trajtenberg. Market value and patent citations. *RAND Journal of economics*, pages 16–38, 2005.

[24] Bronwyn H Hall, Jacques Mairesse, and Pierre Mohnen. Measuring the Returns to R&D. Technical report, National Bureau of Economic Research, 2009.

[25] D. Harhoff, F. Narin, F.M. Scherer, and K. Vopel. Citation frequency and the value of patented inventions. *Review of Economics and statistics*, 81(3):511–515, 1999.

[26] D. Harhoff, F.M. Scherer, and K. Vopel. Citations, family size, opposition and the value of patent rights. *Research Policy*, 1596:1–21, 2002.

[27] John Richard Hicks. *The theory of wages*, volume 2. Macmillan London, 1963.

[28] International Energy Agency. *IEA Guide to Reporting Energy RD&D Budget/ Expenditure Statistics*, June 2011.

[29] A.B. Jaffe, M. Trajtenberg, and P.M. Romer. *Patents, Citations, and Innovations: A Window on the Knowledge Economy.* The MIT Press, 2005.

[30] Adam B Jaffe and Josh Lerner. Reinventing public R&D: Patent Policy and the Commercialization of National Laboratory Technologies. *Rand Journal of Economics*, pages 167–198, 2001.

[31] Adam B Jaffe, Richard G Newell, and Robert N Stavins. A Tale of Two Market Failures: Technology and Environmental Policy. *Ecological Economics*, 54(2):164–174, 2005.

[32] Adam B Jaffe, Manuel Trajtenberg, and Michael S Fogarty. Knowledge Spillovers and Patent Citations: Evidence from a Survey of Inventors. *The American Economic Review*, 90(2):215–218, 2000.

[33] Beata Smarzynska Javorcik. Does Foreign Direct Investment Increase the Productivity of Domestic Firms? In Search of Spillovers Through Backward Linkages. *The American Economic Review*, 94(3):605–627, 2004.

[34] D.K.N. Johnson. The OECD Technology Concordance (OTC): Patents by Industry of Manufacture and Sector of Use. *OECD Science, Technology and Industry Working Papers*, 2002.

[35] Nick Johnstone, Ivan Haščič, and David Popp. Renewable Energy Policies and Technological Innovation: Evidence Based on Patent Counts. *Environmental and Resource Economics*, 45(1):133–155, 2010.

[36] Wolfgang Keller. International Technology Diffusion. *Journal of Economic Literature*, 42(3):752–782, 2004.

[37] Paul R Krugman. *Geography and Trade*. MIT press, 1991.

[38] Jean O Lanjouw and Mark Schankerman. Patent quality and research productivity: Measuring innovation with multiple indicators. *The Economic Journal*, 114(495):441–465, 2004.

[39] Elisa Lanzi and Ian Sue Wing. Directed Technical Change in the Energy Sector: an Empirical Test of Induced Directed Innovation.

[40] Megan MacGarvie. The Determinants of International Knowledge Diffusion as Measured by Patent Citations. *Economics Letters*, 87(1):121–126, 2005.

[41] Mika Maliranta, Pierre Mohnen, and Petri Rouvinen. Is Inter-Firm Labor Mobility a Channel of Knowledge Spillovers? Evidence from a Linked Employer–Employee Panel. *Industrial and Corporate Change*, 18(6):1161–1191, 2009.

[42] Per Botolf Maurseth and Bart Verspagen. Knowledge Spillovers in Europe: a Patent Citations Analysis. *The Scandinavian journal of economics*, 104(4):531–545, 2002.

[43] H. Meijers and B. Verspagen. Construction of Technology Flow Matrices. Technical report, European Commission; Demeter Project, 2010.

[44] Sabine Messner. Endogenized Technological Learning in an Energy Systems Model. *Journal of Evolutionary Economics*, 7(3):291–313, 1997.

[45] P.E. Mounier-Kuhn. *L'informatique en France de la seconde guerre mondiale au Plan Calcul*. L'émergence d'une science, Presses de l'Université Paris-Sorbonne, 2010.

[46] David Mowery and Nathan Rosenberg. The influence of market demand upon innovation: a critical review of some recent empirical studies. *Research Policy*, 8(2):102–153, 1979.

[47] Gregory F Nemet. Inter-Technology Knowledge Spillovers for Energy Technologies. *Energy Economics*, 2012.

[48] Richard G Newell, Adam B Jaffe, and Robert N Stavins. The Induced Innovation Hypothesis and Energy-Saving Technological Change. *The Quarterly Journal of Economics*, 114(3):941–975, 1999.

[49] William D Nordhaus. Some Skeptical Thoughts on the Theory of Induced Innovation. *The Quarterly Journal of Economics*, pages 208–219, 1973.

[50] OECD. Energy and Climate Policy, Bending the Technological Trajectory. Technical report, OECD, 2012.

[51] Makoto Ohta and Zvi Griliches. Automobile prices and quality: Did the gasoline price increases change consumer tastes in the US? *Journal of Business & Economic Statistics*, 4(2):187–198, 1986.

[52] Giovanni Peri. Determinants of Knowledge Flows and Their Effect on Innovation. *Review of Economics and Statistics*, 87(2):308–322, 2005.

[53] H. Pillu and G. Koléda. Déterminants de l'innovation dans les technologies énergétiques efficientes et renouvelables. *Economie & Prévision*, 2011/1-2, 197-198:105–128, 2011.

[54] David Popp. Induced Innovation and Energy Prices. *American Economic Review*, 92(1):160–180, 2002.

[55] David Popp. International Innovation and Diffusion of Air Pollution Control Technologies: the Effects of NO_iX_i and SO_2 Regulation in the US, Japan, and Germany. *Journal of Environmental Economics and Management*, 51(1):46–71, 2006.

[56] David Popp and Richard G Newell. Where Does Energy R&D Come From? Examining Crowding Out From Environmentally-Friendly R&D. Technical report, National Bureau of Economic Research, 2009.

[57] N. Rosenberg. *Inside the black box: technology and economics*. Cambridge University Press, 1982.

[58] Robert W Rycroft and Don E Kash. *The Complexity Challenge: Technological Innovation for the 21st Century*. Burns & Oates, 1999.

[59] M. Schankerman and A. Pakes. Estimates of the value of patent rights in European countries during the post-1950 period. *The economic journal*, 96(384):1052–1076, 1986.

[60] F.M. Scherer. Inter-industry technology flows and productivity growth. *The Review of Economics and Statistics*, 64(4):627–634, 1982.

[61] Ulrich Schmoch, Francoise Laville, Pari Patel, and Rainer Frietsch. Linking technology areas to industrial sectors. *Final Report to the European Commission, DG Research*, 2003.

[62] J. Schmookler. *Invention and economic growth*. Harvard University Press Cambridge, MA, 1966.

[63] Leo Sveikauskas. Technological Inputs and Multifactor Productivity Growth. *The Review of Economics and Statistics*, 63(2):275–282, 1981.

[64] Manuel Trajtenberg. A penny for your quotes: patent citations and the value of innovations. *The Rand Journal of Economics*, pages 172–187, 1990.

[65] James M Utterback. *Mastering the Dynamics of Innovation*. Harvard Business Press, 1996.

[66] Bruno van Pottelsberghe and Frank Lichtenberg. Does Foreign Direct Investment Transfer Technology Across Borders? *Review of Economics and Statistics*, 83(3):490–497, 2001.

[67] Nicolas van Zeebroeck. The puzzle of patent value indicators. *Economics of Innovation and New Technology*, 20(1):33–62, 2011.

[68] Elena Verdolini and Marzio Galeotti. At Home and Abroad: An Empirical Analysis of Innovation and Diffusion in Energy Technologies. *Journal of Environmental Economics and Management*, 61(2):119–134, 2011.

[69] Bart Verspagen. Estimating International Technology Spillovers Using Technology Flow Matrices. *Review of World Economics*, 133(2):226–248, 1997.

[70] Tobias Wiesenthal, Guillaume Leduc, Hans-Günther Schwarz, and Karel Haegeman. *R&D investment in the priority technologies of the European strategic energy technology plan*. Office for Official Publications of the European Communities, 2009.

[71] James A Wilcox. Automobile Fuel Efficiency: Measurement and Explanation. *Economic Inquiry*, 22(3):375–385, 1984.

[72] P. Zuniga, D. Guellec, H. Dernis, M. Khan, T. Okazaki, and C. Webb. OECD patent statistics manual, 2009.

9 Appendices

9.1 IPC for energy-related technologies

Technology	IPC codes
Fuel-Based Energy	
Coal gasification	
Production of combustible gases containing carbon monoxide from solid carbonaceous fuels	C10J 3
Burners	
Combustion apparatus specially adapted for combustion of two or more kinds of fuel simultaneously or alternately, at least one kind of fuel being fluent	F23C 1
Combustion apparatus characterized by the arrangement or mounting of burners; Disposition of burners to obtain a loop flame.	F23C 5/24
Combustion apparatus characterized by the combination of two or more combustion chambers (using fluent fuel)	F23C 6
Combustion apparatus characterized by the combination of two or more combustion chambers (using only solid fuel)	F23B 10
Combustion apparatus with driven means for agitating and for advancing the burning fuel	F23B 30
Combustion apparatus characterized by means for returning solid combustion residues to the combustion chamber	F23B 70
Combustion apparatus characterized by means creating a distinct flow path for flue gases or for non-combusted gases given off by the fuel	F23B 80
Burners for combustion of pulverulent fuel	F23D 1
Burners in which drops of liquid fuel impinge on a surface	F23D 7
Burners for combustion simultaneously or alternatively of gaseous or liquid or pulverulent fuel	F23D 17
Fluidized bed combustion	
Chemical or physical processes (and apparatus therefore) conducted in the presence of fluidised particles, with liquid as a fluidising medium	B01J 8/20-22
Chemical or physical processes (and apparatus therefore) conducted in the presence of fluidised particles, according to “fluidised-bed” technique	B01J 8/24-30
Fluidised-bed furnaces; Other furnaces using or treating finely-divided materials in dispersion	F27B 15
Apparatus in which combustion takes place in a fluidised bed of fuel or other particles	F23C 10

Boilers for steam generation	
Modifications of boiler construction, or of tube systems, dependent on installation of combustion apparatus; Arrangements or dispositions of combustion apparatus	F22B 31
Steam generation plants, e.g. comprising steam boilers of different types in mutual association; Combinations of low- and high-pressure boilers	F22B 33/14-16
Steam engines	
Plants characterised by the use of steam or heat accumulators, or intermediate steam heaters, therein	F01K 3
Plants characterised by use of means for storing steam in an alkali to increase steam pressure, e.g. of Honigmann or Koenemann type	F01K 5
Plants characterised by more than one engine delivering power external to the plant, the engines being driven by different fluids	F01K 23
Superheater	
Superheating of steam	F22G
Gas turbines	
Gas turbine plants – Heating air supply before combustion, e.g. by exhaust gases	F02C 7/08-105
Cooling of gas turbine plants	F02C 7/12-143
Gas turbine plants – Preventing corrosion in gas-swept spaces	F02C 7/30
Combined cycles	
Plants characterised by more than one engine delivering power external to the plant, the engines being driven by different fluids; the engine cycles being thermally coupled	F01K 23/02-10
Gas turbine plants characterised by the use of combustion products as the working fuel	F02C 3/20-36
Combinations of gas-turbine plants with other apparatus; Supplying working fluid to a user, e.g. a chemical process, which returns working fluid to a turbine of the plant	F02C 6/10-12
Compressed-ignition engines	
Engines characterised by fuel-air mixture compression ignition	F02B 1/12-14
Engines characterised by air compression and subsequent fuel addition; with compression ignition	F02B 3/06-10
Engines characterised by the fuel-air charge being ignited by compression ignition of an additional fuel	F02B 7
Engines characterised by both fuel-air mixture compression and air compression, or characterised by both positive ignition and compression ignition, e.g. in different cylinders	F02B 11
Engines characterised by the introduction of liquid fuel into cylinders by use of auxiliary fluid; Compression ignition engines using air or gas for blowing fuel into compressed air in	F02B 13/02-04
Methods of operating air-compressing compression-ignition engines involving introduction of small quantities of fuel in the form of a fine mist into the air in the	F02B 49
Cogeneration	
Use of steam or condensate extracted or exhausted from steam engine plant; Returning energy of steam, in exchanged form, to process, e.g. use of exhaust steam for drying solid	F01K 17/06
Plants for converting heat or fluid energy into mechanical energy	F01K 27
Using the waste heat of gas-turbine plants outside the plants themselves, e.g. gas-turbine power heat plants	F02C 6/18
Profiting from waste heat of combustion engines	F02G 5
Machines, plant, or systems using waste heat, e.g. from internal-combustion engines	F25B 27/02

Technology	IPC codes
Wind Energy	
	F03D
Solar Energy	
Photovoltaics (PV)	
Devices adapted for the conversion of radiation energy into electrical energy	H01L 27/142 H01L 31/00-31/07 H01G 9/20 H02N 6/00
Electric lighting devices with, or rechargeable with, solar cells	F21S 9/03
Charging batteries	H02J 7/35
Thermal (Th)	
	F24J 2/00
Solar updraft towers	F03G 6/00
For treatment of water, waste water or sludge	C02F 1/14
Others	
Roof covering aspects of energy collecting devices	E04D 13/18
Geothermal Energy	
Production of mechanical power from geothermal energy	F03G 4/00
Mechanical-power-producing mechanisms using pressure differences or thermal differences occurring in nature	F03G 7/04
Use of geothermal heat	F24J 3/08
Heat pumps characterised by the source of low potential heat	F25B 30/06
Electric motors using thermal effects	H02N 10/00
Ocean-Hydro Energy	
Water-power plants	E02B 9/00
Machines or engines for liquids	F03B3 F03B7 F03B 13/06-26
Regulating, controlling or safety means of machines or engines	F03B 15/00
Ocean thermal energy conversion (OTEC)	F03G 7/05
Biofuels	
Solid fuels	C10L 5/42-5/44
Liquid fuels	
Biodiesel	C07C 67/00 C07C 69/00 C10L 1/02 C10L 1/19 C11C 3/10 C12P 7/64
Bioethanol	C12P 7/06-7/14
Biogas	C02F 3/28 C02F 11/04 C12M 1/107
Engines or plants operating on gaseous fuels from solid fuel e.g. wood	F02B 43/08
Fuel Cells	
Inert electrodes with catalytic activity	H01M 4/86-4/98
Non-active parts	H01M 8/00
Within hybrid cells	H01M 12/00
Nuclear Energy	
Fusion reactors	G21B
Fission reactors	G21C
Nuclear power plant	G21D
Protection against X-radiation, gamma radiation, corpuscular radiation or particle bombardment; treating radiactively contaminated material	G21F
Converseion of chemical elements; radioactive sources	G21G
Obtaining energy from radioactive sources; applicaiton of radiation from radioactive sources; utilising cosmic radiation	G21H

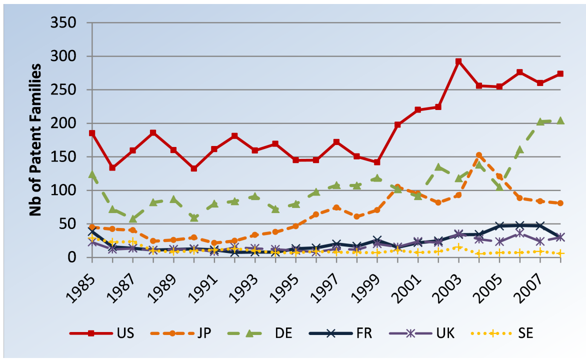
Technology	IPC codes
Energy Storage	
Storage of electrical energy	
Methods for charging or discharging; Accumulators structurally combined with charging apparatus	H01M 10/44-10/46
Hybrid capacitors, i.e. capacitors having different positive and negative electrodes; Electric double-layer [EDL] capacitors; Processes for the manufacture thereof or of parts thereof	H01G 11/00
Arrangements for balancing the load in a network by storage of energy	H02J 3/28
Circuit arrangements for charging or depolarising batteries or for supplying loads from batteries	H02J 7/00
Systems for storing electric energy	H02J 15/00
Storage of thermal energy	
Heat-transfer, heat-exchange or heat-storage materials, e.g. refrigerants; Materials for the production of heat or cold by chemical reactions other than by combustion	C09K 5/00
Storage heaters, i.e. heaters in which the energy is stored as heat in masses for subsequent release	F24H 7/00
Heat storage plants or apparatus in general; Regenerative heat-exchange apparatus	F28D 20/00
Transport	
Vehicles in general	
Hybrid vehicles, e.g. Hybrid Electric Vehicles (HEVs)	B60K 6/00
Control systems	B60W 20/00
Regenerative braking systems	B60L 7/10-7/22
Electric propulsion with power supply from force of nature, e.g. sun, wind	B60L 8/00
Electric propulsion with power supply external to vehicle	B60L 9/00
Electric propulsion with power supply whithin the vehicle	B60L 11/00
Electric devices on electrically-propelled vehicles for safety purposes;	B60L 3/00 B60L 15 B60K 1
Power supply from force of nature, e.g. sun, wind	B60K 16/00
Vehicles other than rail vehicles	
Drag reduction	B62D 35/00 B63B 1/34-1/40
Rail vehicles	
Drag reduction	B61D 17/02
Marine vessel propulsion	
Propulsive devices directly acted on by wind	B63H 9/00
Propulsion by wind-powered motors	B63H 13/00
Propulsion using energy derived from water movement	B63H 19/00
Building Appliance and Equipment	
Low energy lighting	
Electroluminescent light sources (e.g. LEDs, OLEDs, PLEDs)	H01L 33/00 H01J 61 H05B 33/00
Thermal building insulation	
In general	E04B 1/62 E04B 1/74-1/80 E04B 1/88-1/90
Insulating building elements	E04C 1/40-41
For door or window openings	E06B 3/263 E06B 3/24
For walls	E04B 2/00
For floors	E04B 5/00 E04F 15/18
For roofs	E04B 7/00 E04D 1/28 E04D 3/35 E04D 13/16
For ceilings	E04B 9/00

9.2 List of economic sectors

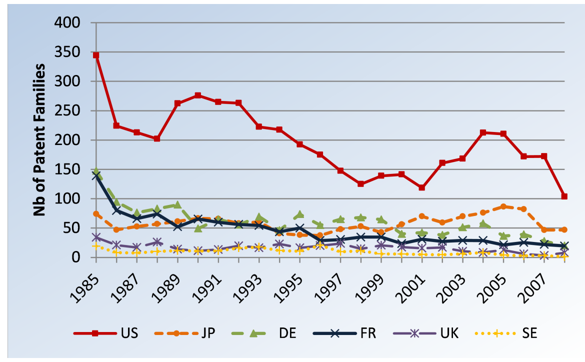
N°	Sector's Name	SIC-E (1980) classification
1	Agriculture	0-599
2	Coal and Coke	600-699, 800-899, 920-929
3	Oil & Gas Extraction	700-799, 910-919
4	Gas Distribution	4920, 4921
5	Refined Oil	3600-3699
6	Electricity	4910-4919, 4990-4999
7	Water Supply	4930-4939
8	Ferrous & non Ferrous Metals	2910-2999, 3922
9	Non Metallic Min Products	2720-2729, 3500-3599
10	Chemicals	3700-3799, 1810, 1811
11	Metal Products	3000-3069
12	Agr & Indus Machines	3070-3199
13	Office Machines	3360-3369
14	Non-ICT Electrical Goods	3300-3340, 3370-3379, 3390-3399, 3910, 3912-3919
15	ICT Electrical Goods	3341, 3350-3359, 3380, 3381, 3911
16	Transport Equipment	3210-3299
17	Food, Drink & Tobacco	1000-1199, 1200-1299
18	Textile, Cloth & Footwear	1700-1799, 1820-2499
19	Paper & Printing Products	2700-2719, 2730-2799, 2800-2899, 3970-3979
20	Rubber & Plastic	1500-1699
21	Other Manufactures	2500-2699, 3920, 3921, 3930-3939, 3990-3999, 5900-5919
22	Construction	4010-4499
23	Distribution	5000-5599, 5600-5899, 5920-6999, 9941
24	Lodging & Catering	9100-9299
25	Inland Transports	4530-4539, 4560-4591, 4600-4699
26	Sea & Air Transport	4500-4529, 4540-4559
27	Other Transports	4592-4599, 4700-4799, 9960-9991
28	Postal services	4840-4899
29	Telecommunications	4800-4839
30	Bank, Finance & Insurance	7000-7499
31	Other Non ICT Market Services	7500-7719, 7730-7799, 9600-9799, 9900-9939, 9940, 9942-9959, 9999
32	Computer Services	7720-7729
33	Non Market Services	8100-8499, 8500-8599, 9800-9899
34	Non market health services	8600-8699

9.3 Trends of innovation in energy technologies in leader countries

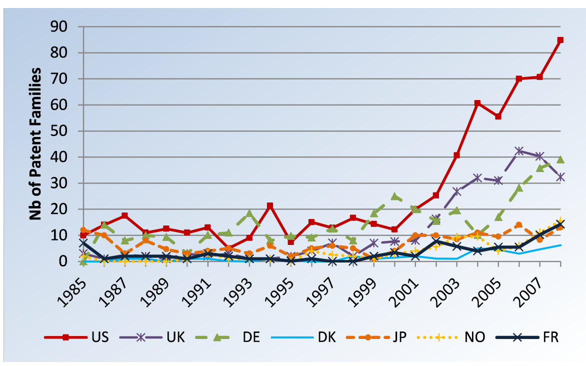
Figure 10: Patent families cited at least ones per technology in leader countries



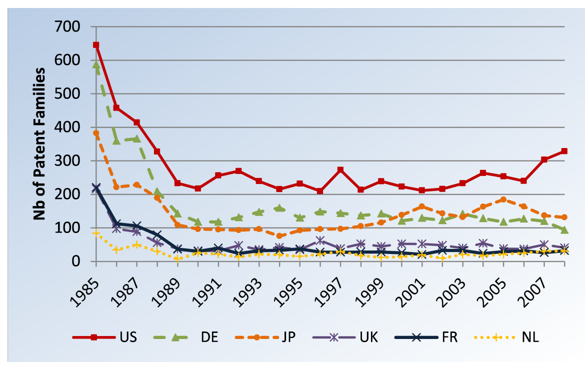
(a) Fuel



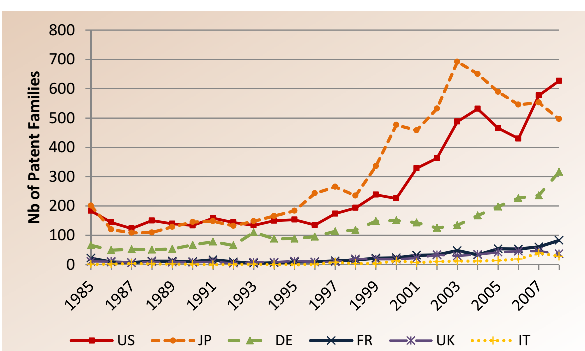
(b) Nuclear



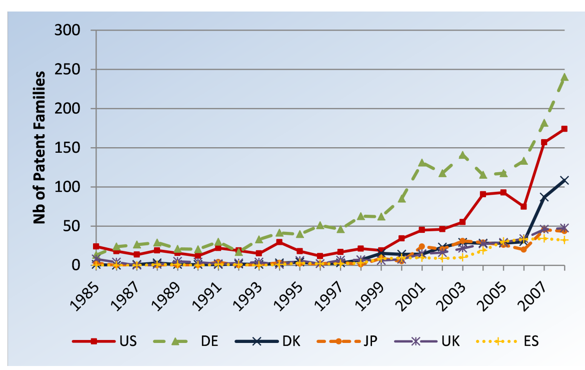
(c) Ocean-Hydro



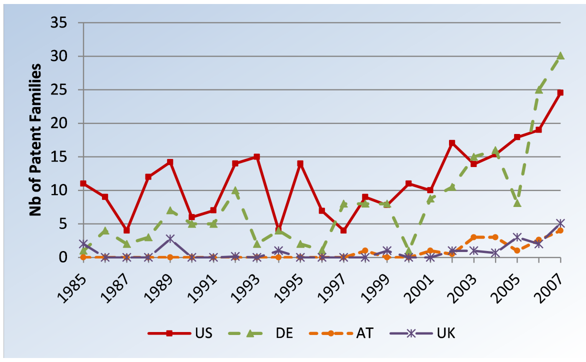
(d) Biofuels



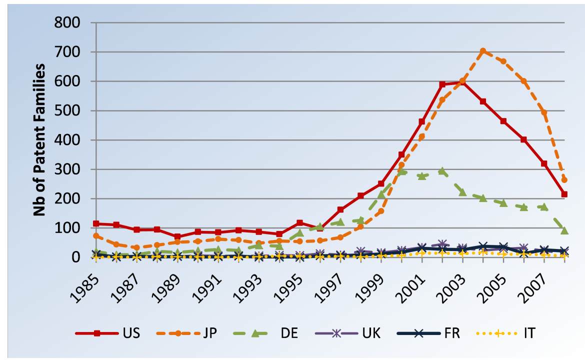
(e) solar



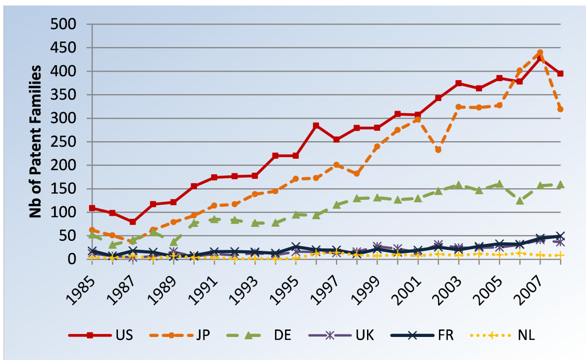
(f) Wind



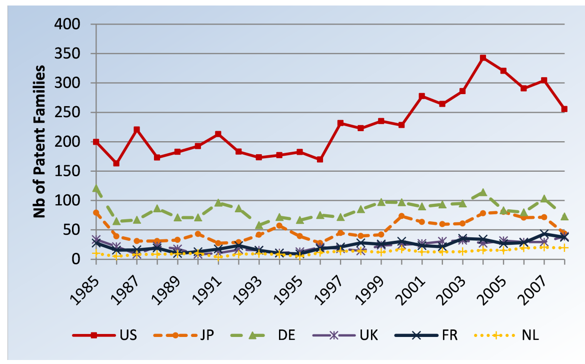
(g) Geothermal



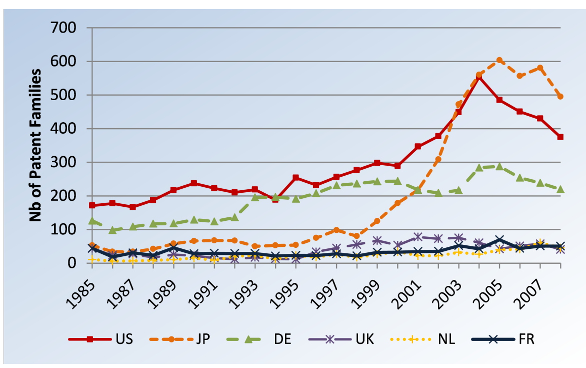
(h) Fuel Cells



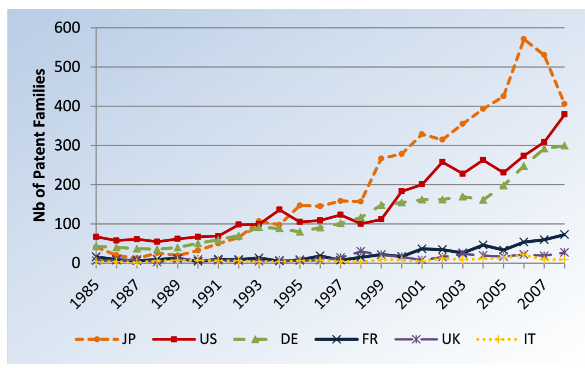
(i) Energy Storage



(j) Carbon Capture and Storage

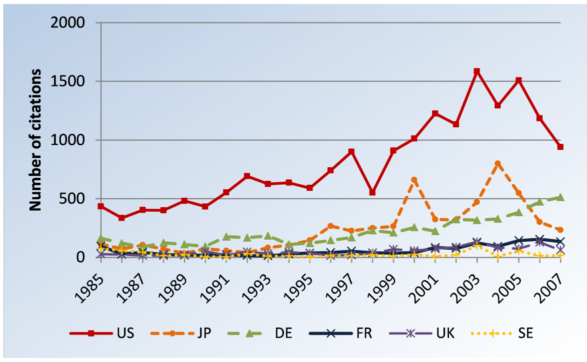


(k) Energy Efficiency in Building

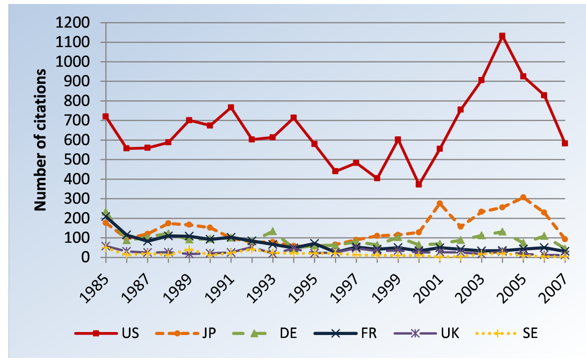


(l) Energy Efficiency in Transport

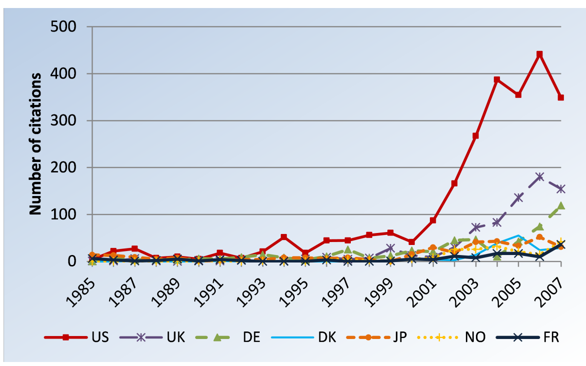
Figure 11: Forward citations per technology in leader countries



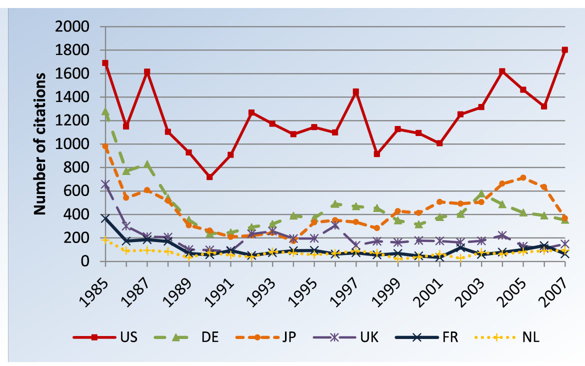
(a) Fuel



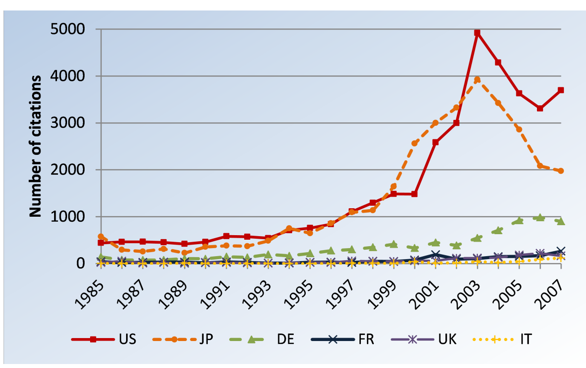
(b) Nuclear



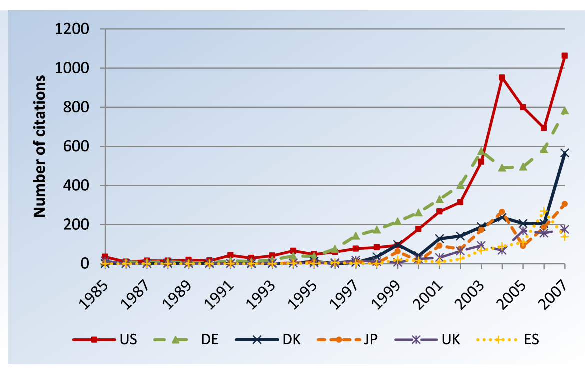
(c) Ocean-Hydro



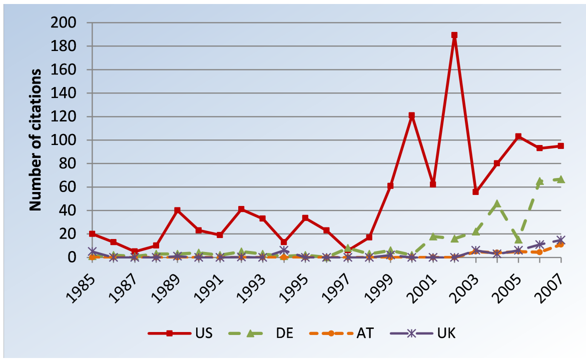
(d) Biofuels



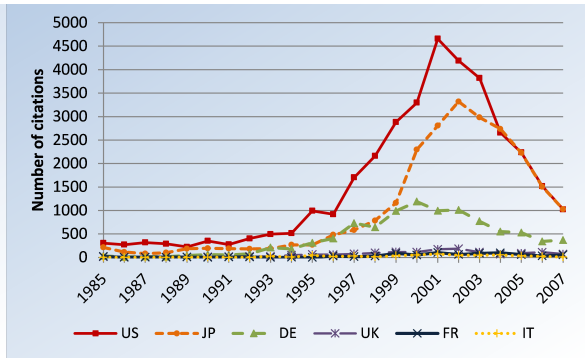
(e) solar



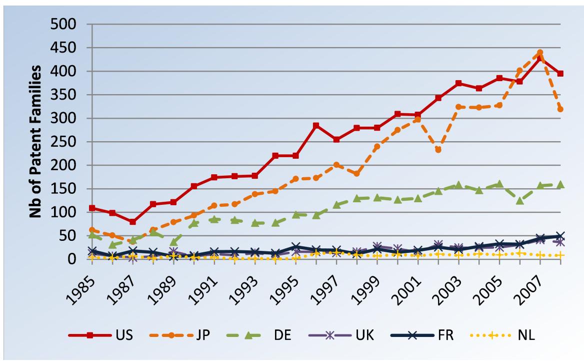
(f) Wind



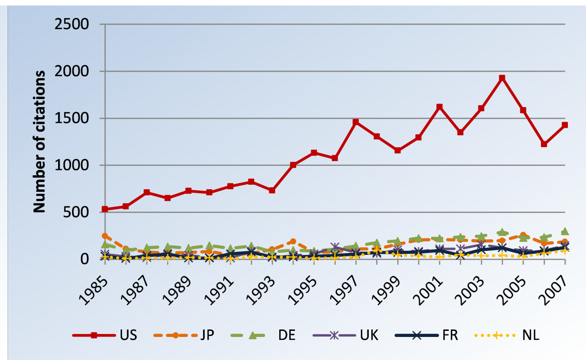
(g) Geothermal



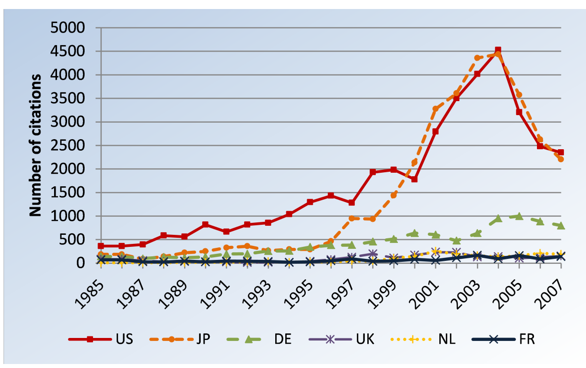
(h) Fuel Cells



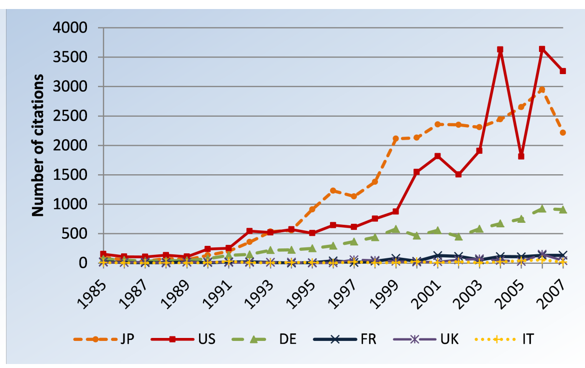
(i) Energy Storage



(j) Carbon Capture and Storage



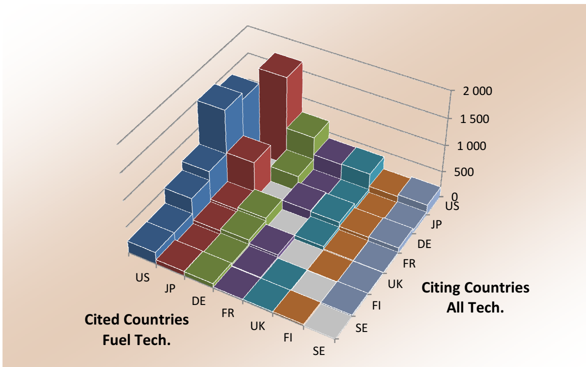
(k) Energy Efficiency in Building



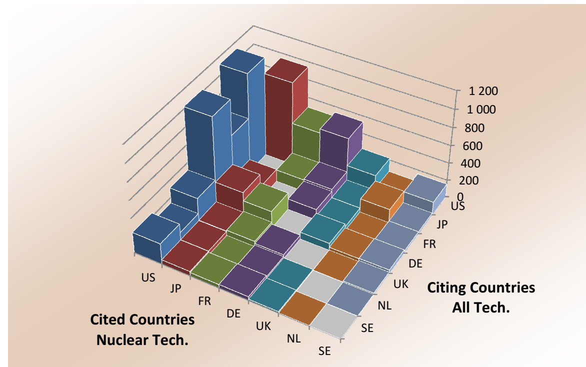
(l) Energy Efficiency in Transport

9.4 Spillovers between countries

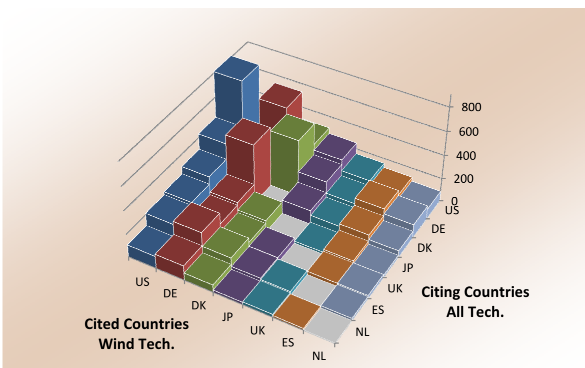
Figure 12: Distribution of forward citations between leader countries



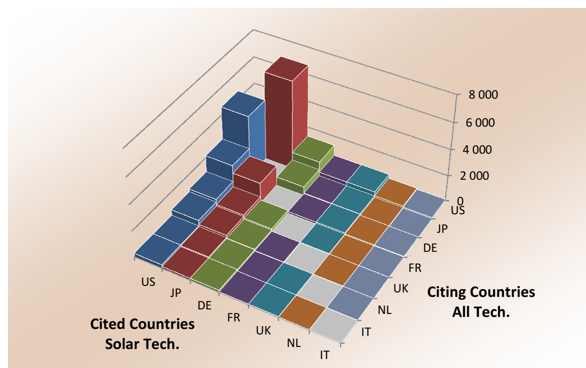
(a) Fuel based



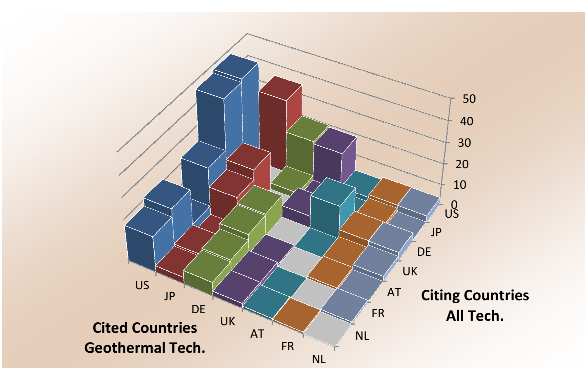
(b) Nuclear



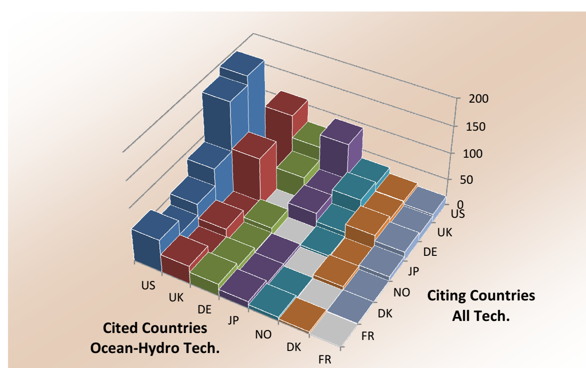
(c) Wind power energy



(d) Solar energy



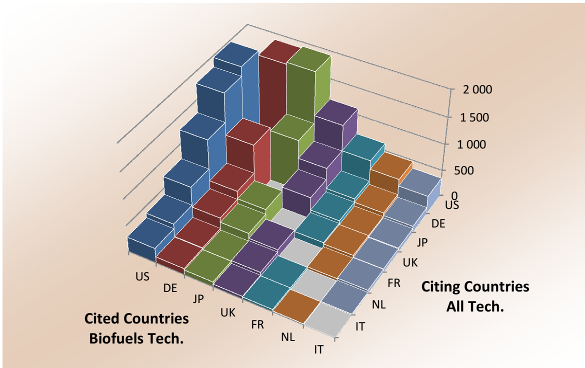
(e) Geothermal energy



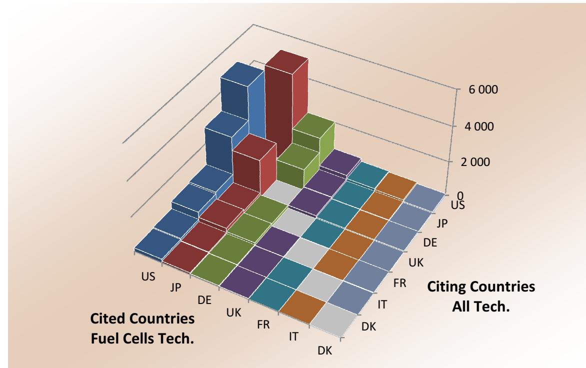
(f) Ocean - Hydrolic energy

SEURECO ERAΣME

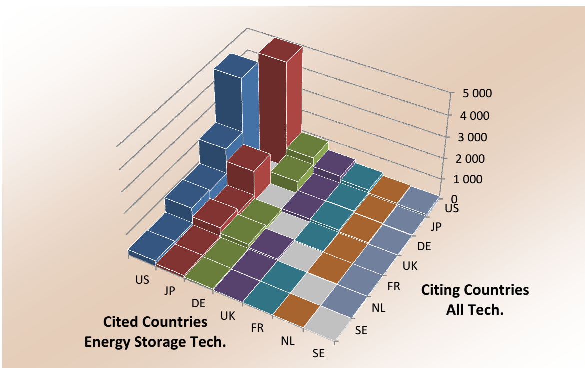
Conseil Français de l'Energie
WORLD ENERGY COUNCIL



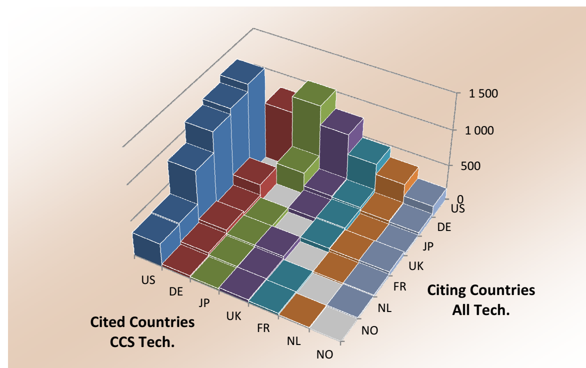
(g) Biofuels



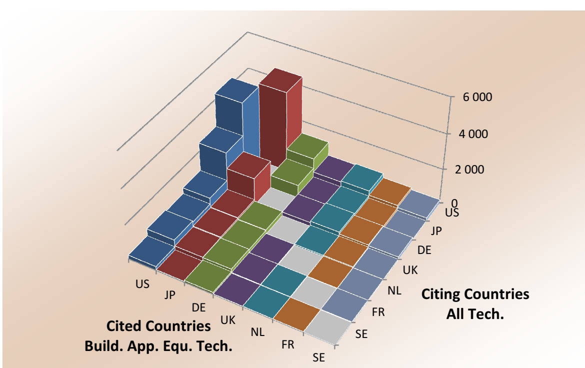
(h) Fuel Cells



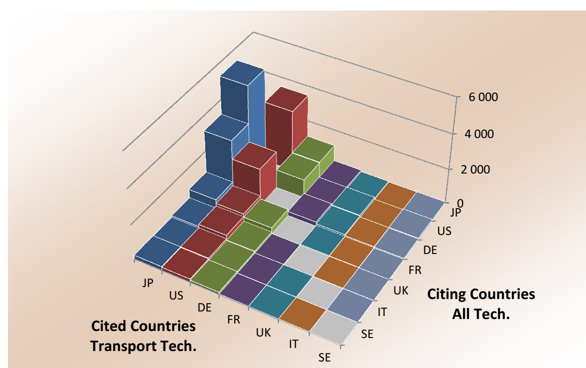
(i) Energy Storage



(j) Carbon Capture and Storage

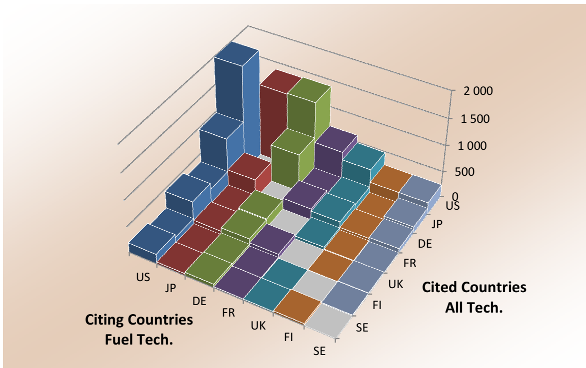


(k) Building appliances and equipments

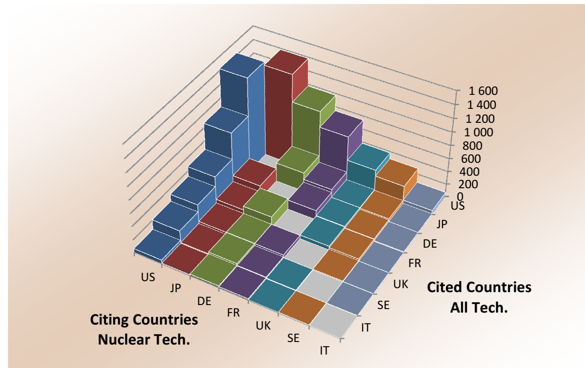


(l) Transport

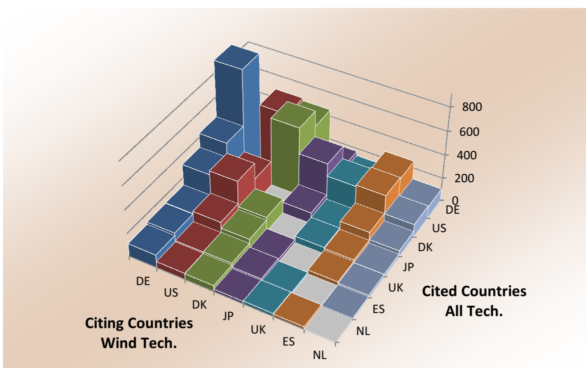
Figure 13: Distribution of backward citations between leader countries



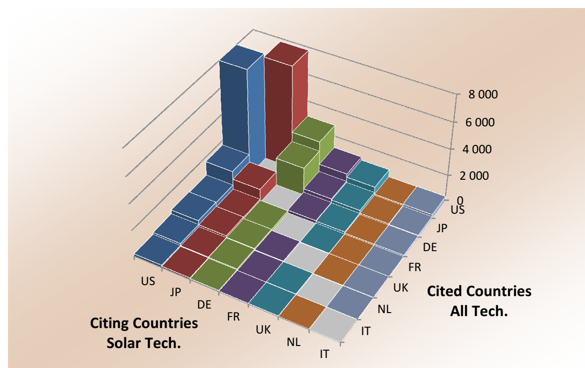
(a) Fuel based



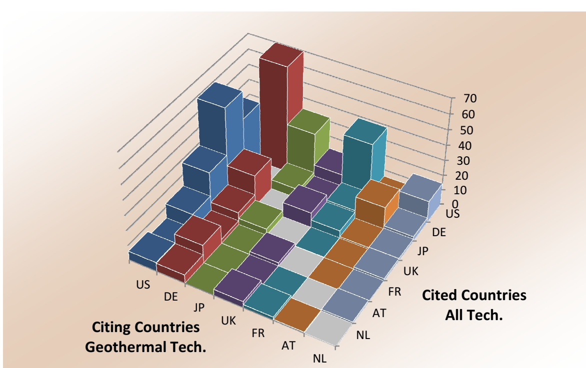
(b) Nuclear



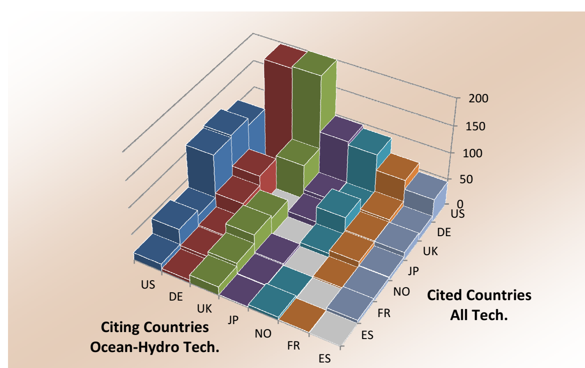
(c) Wind power energy



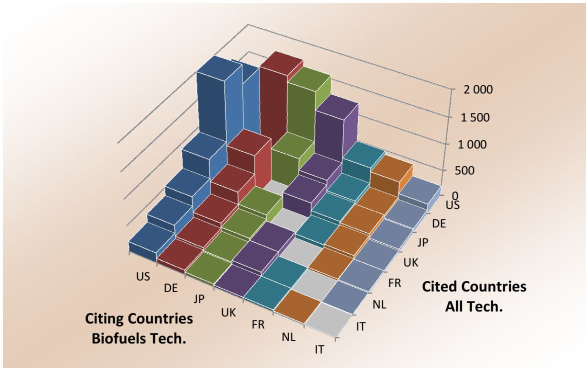
(d) Solar energy



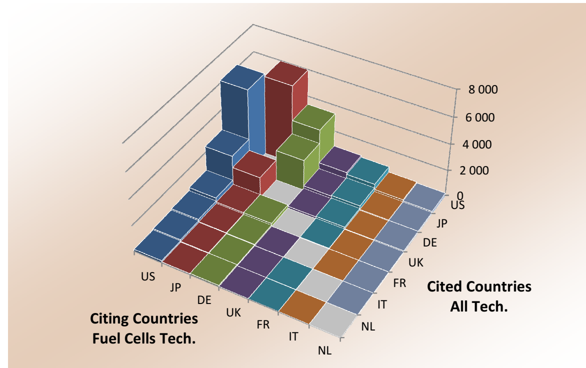
(e) Geothermal energy



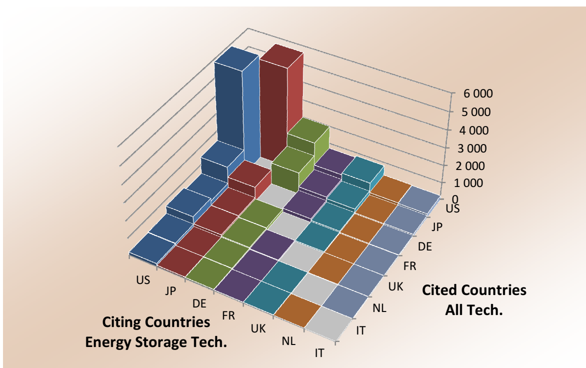
(f) Ocean - Hydrolic energy



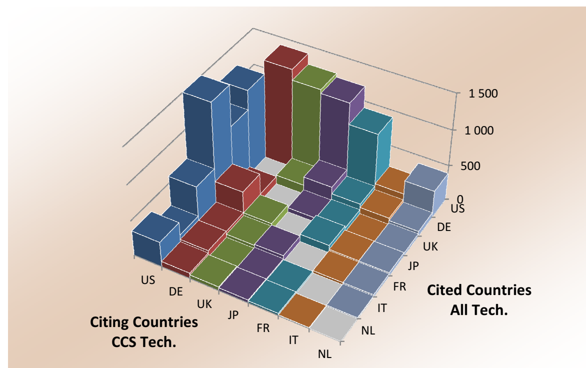
(g) Biofuels



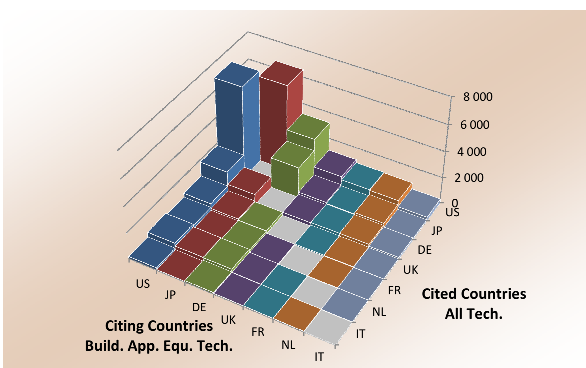
(h) Fuel Cells



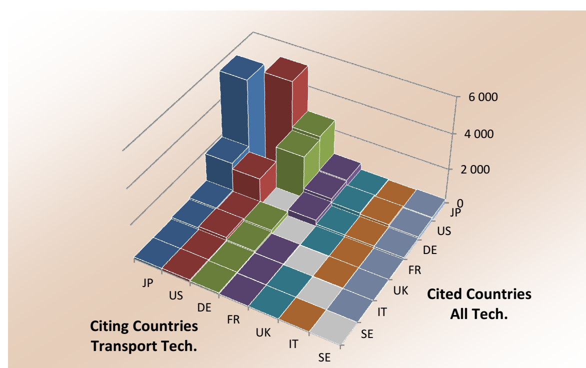
(i) Energy Storage



(j) Carbon Capture and Storage



(k) Building appliances and equipments

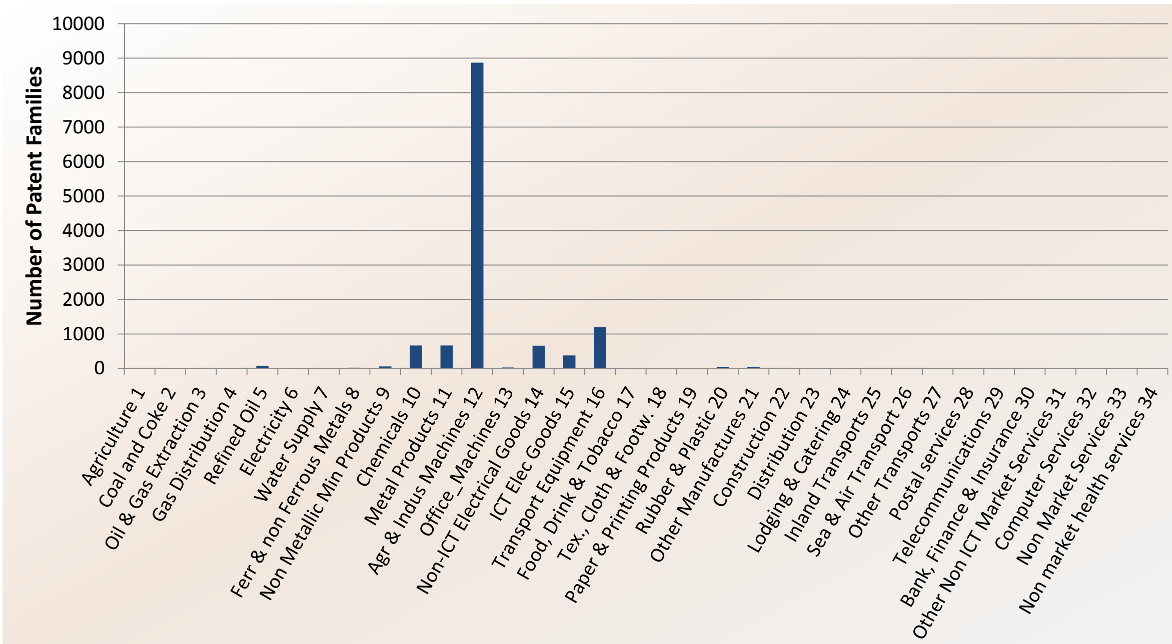


(l) Transport

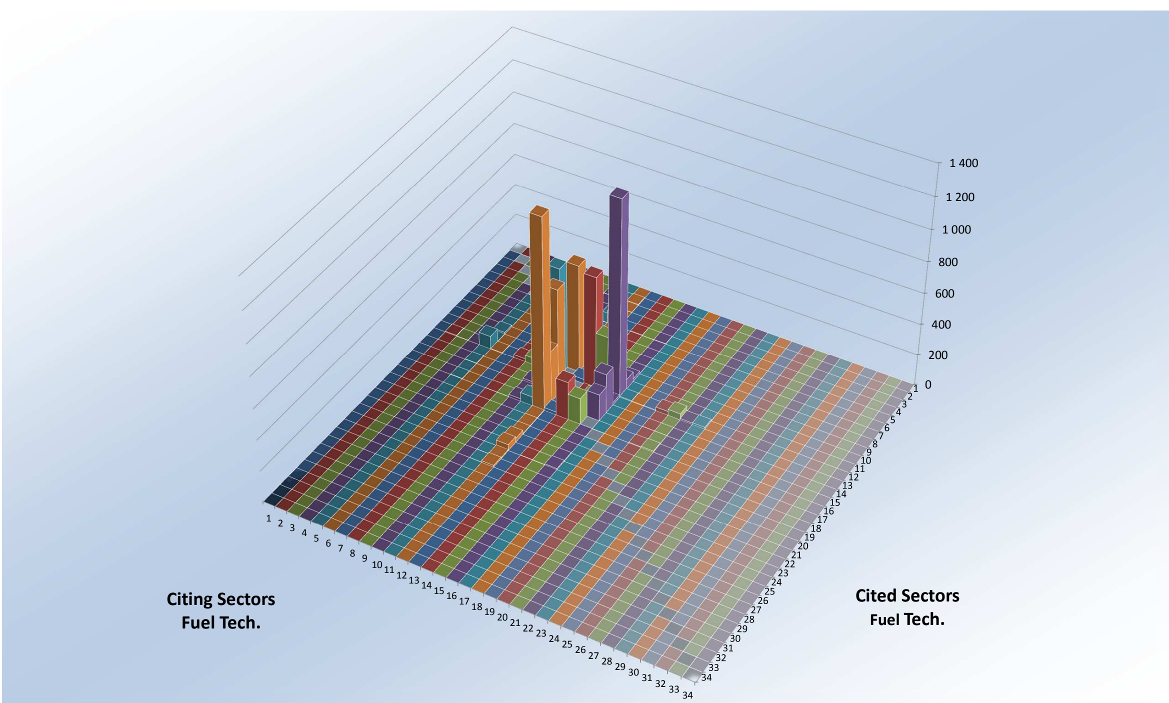
9.5 Sectoral distribution of innovation and spillovers

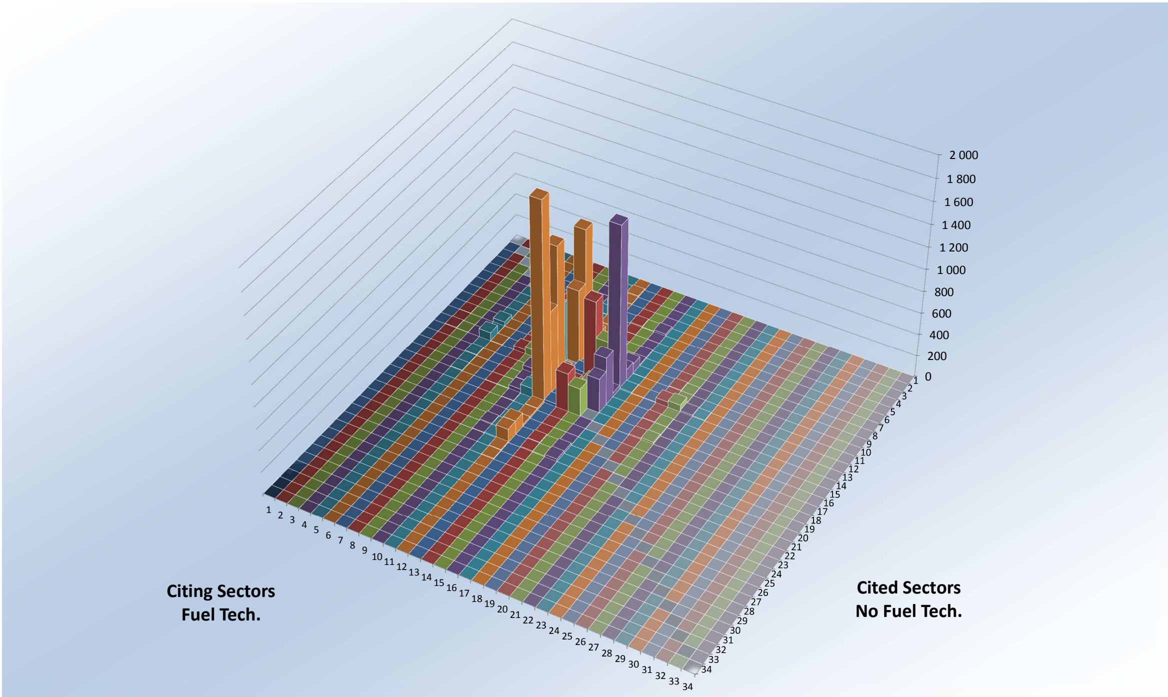
Figure 14: Sectoral distribution of innovations in Fuel based energy technologies

(a) Sectoral distribution of patents

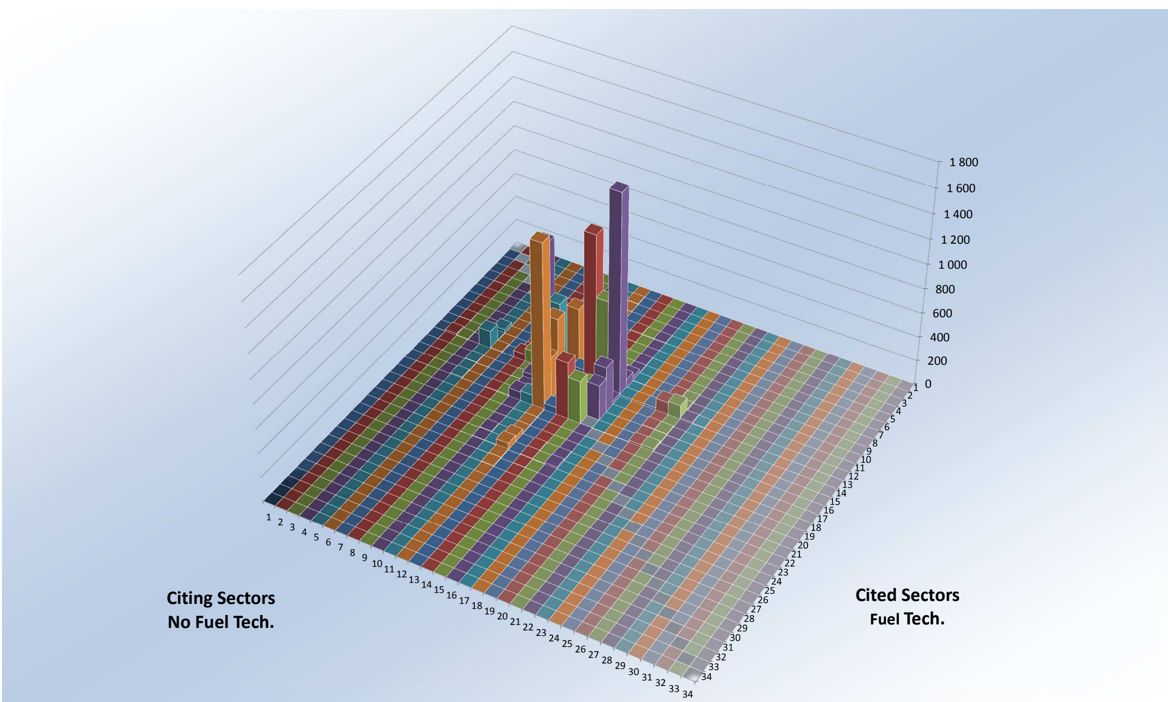


(b) Intersectoral citations between Fuel related technologies





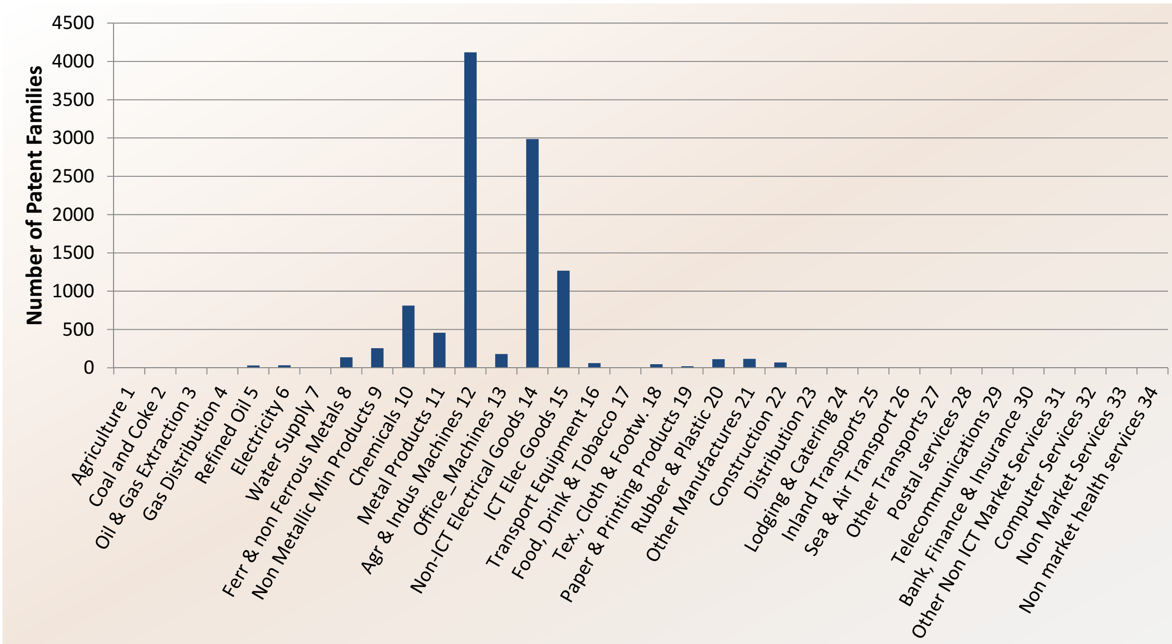
(c) Intersectoral citations by Fuel related technologies toward other technologies



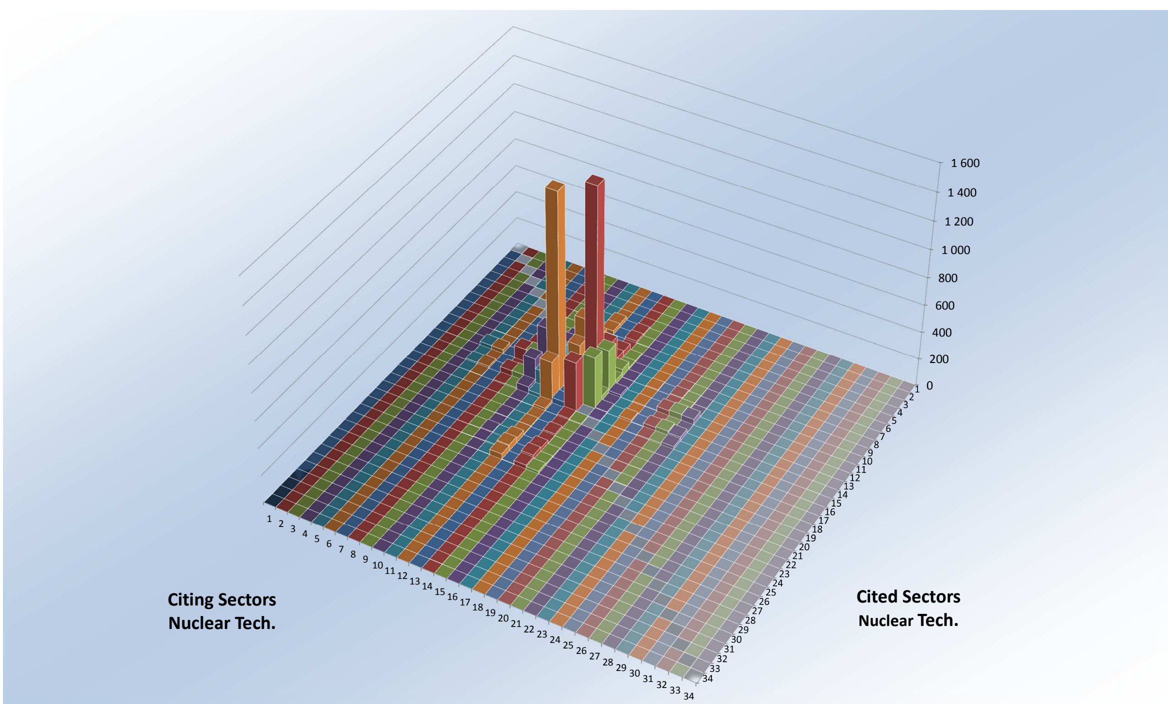
(d) Intersectoral citations toward Fuel related technologies by other technologies

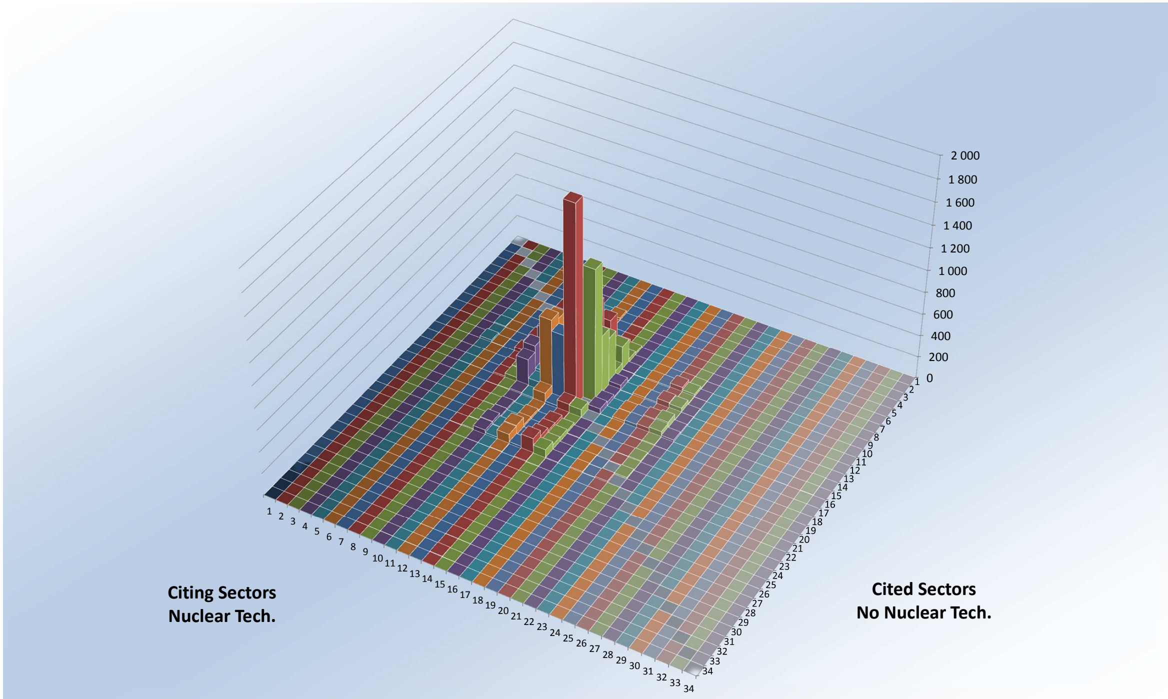
Figure 15: Sectoral distribution of innovations in Nuclear power technologies

(a) Sectoral distribution of patents

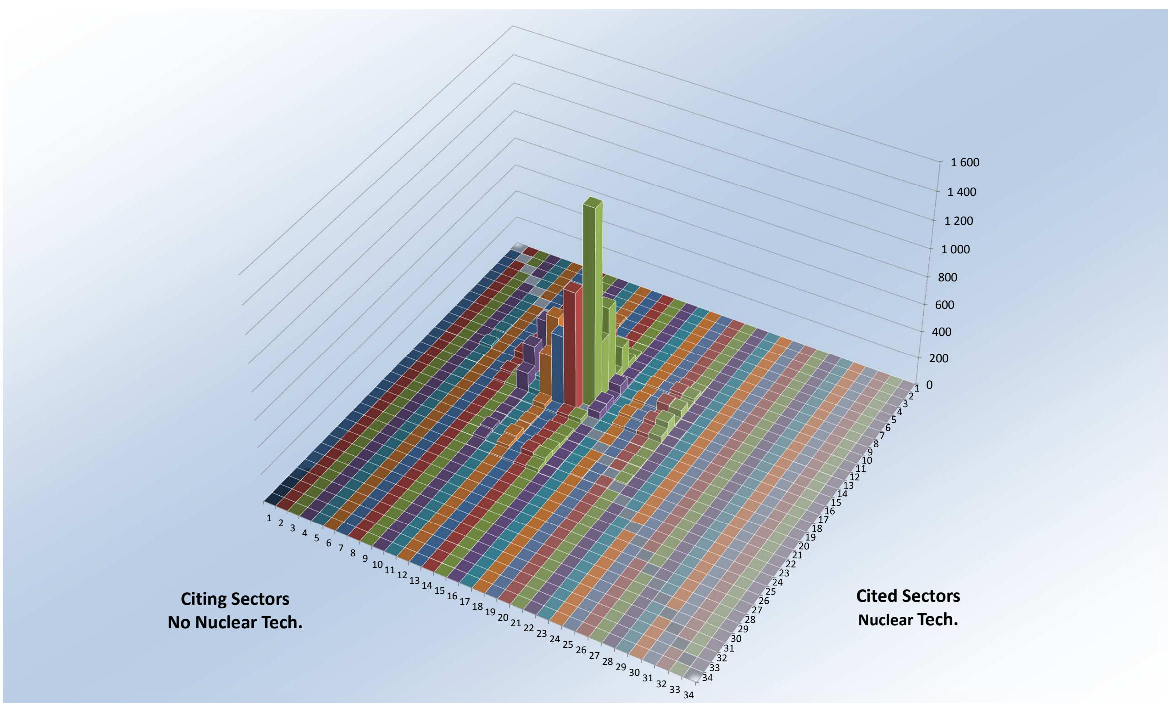


(b) Intersectoral citations between Nuclear related technologies





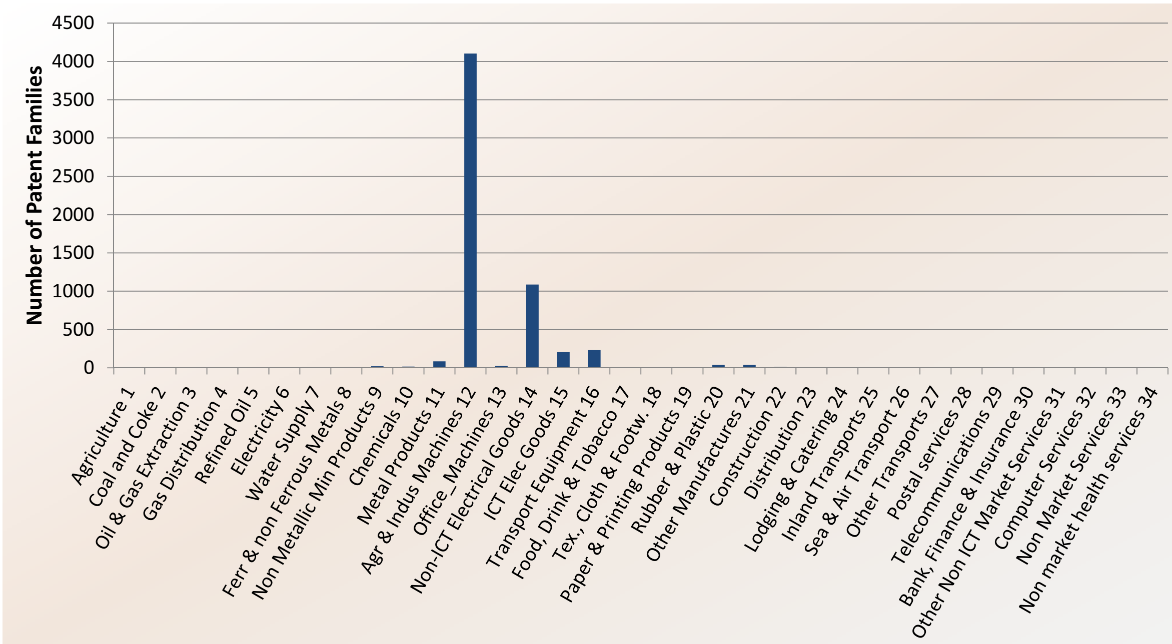
(c) Intersectoral citations by Nuclear related technologies toward other technologies



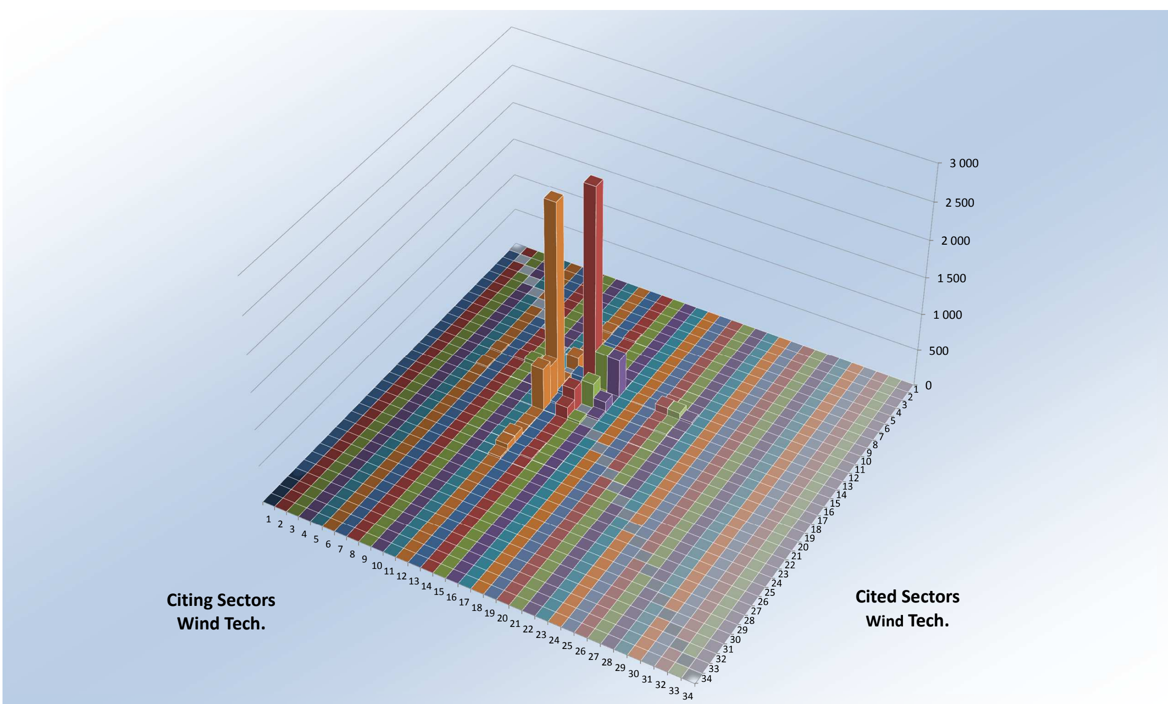
(d) Intersectoral citations toward Nuclear related technologies by other technologies

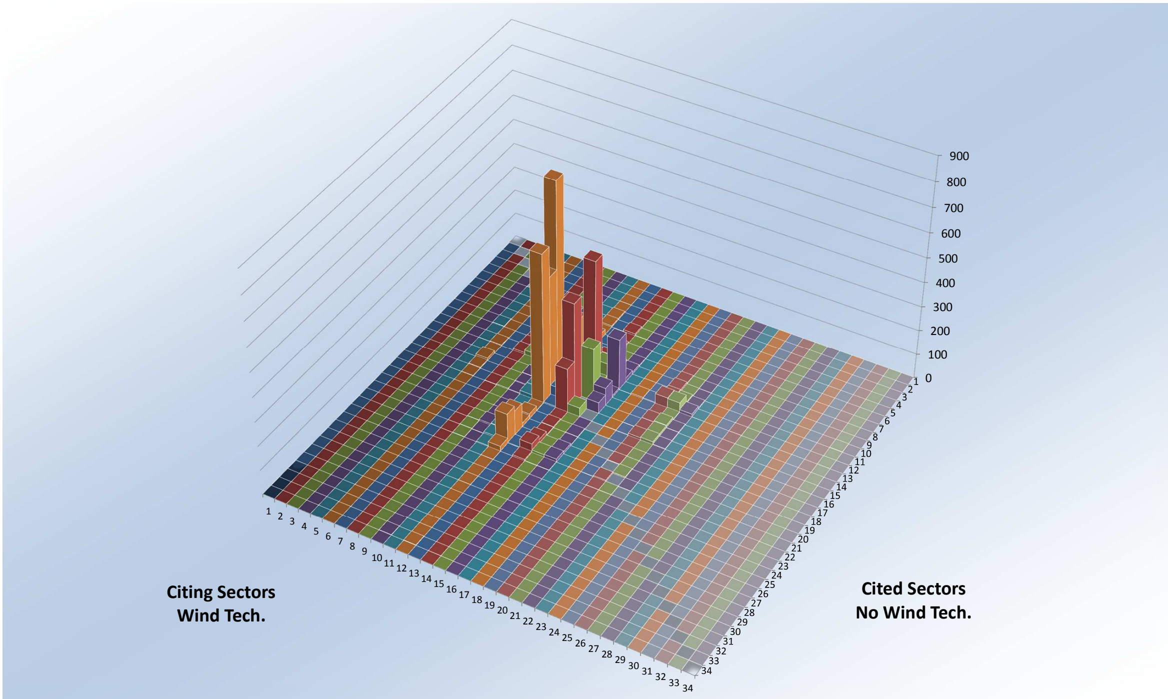
Figure 16: Sectoral distribution of innovations in Wind power technologies

(a) Sectoral distribution of patents

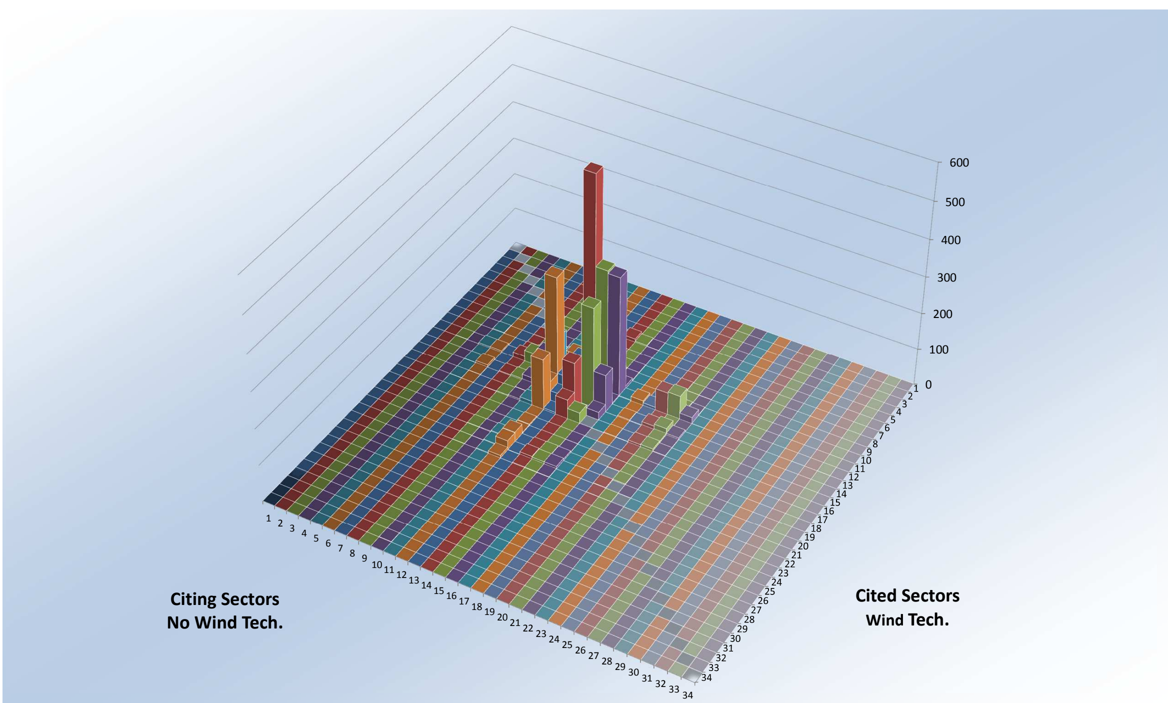


(b) Intersectoral citations between Wind power related technologies





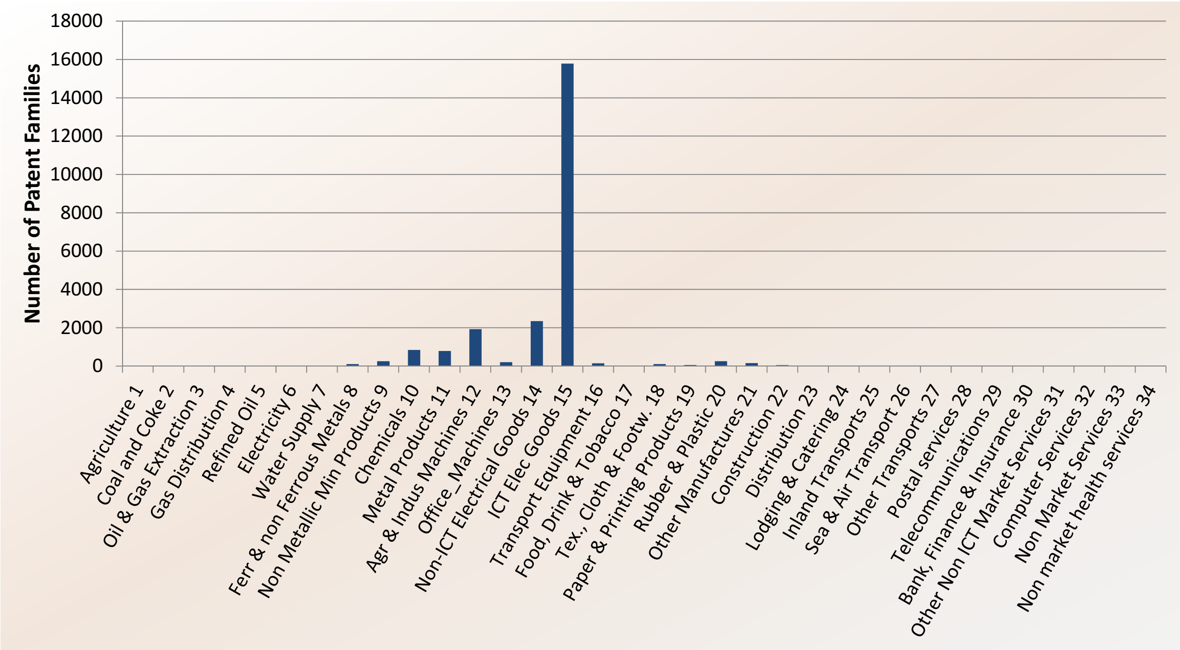
(c) Intersectoral citations by Wind power related technologies toward other technologies



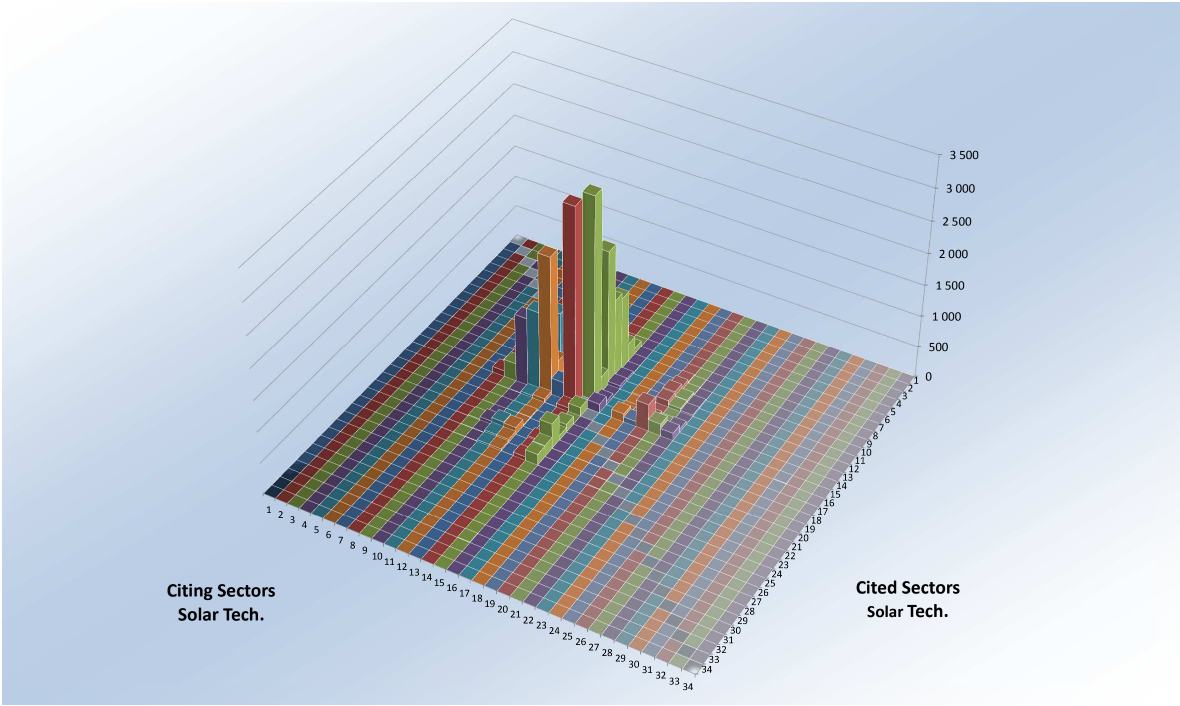
(d) Intersectoral citations toward Wind power related technologies by other technologies

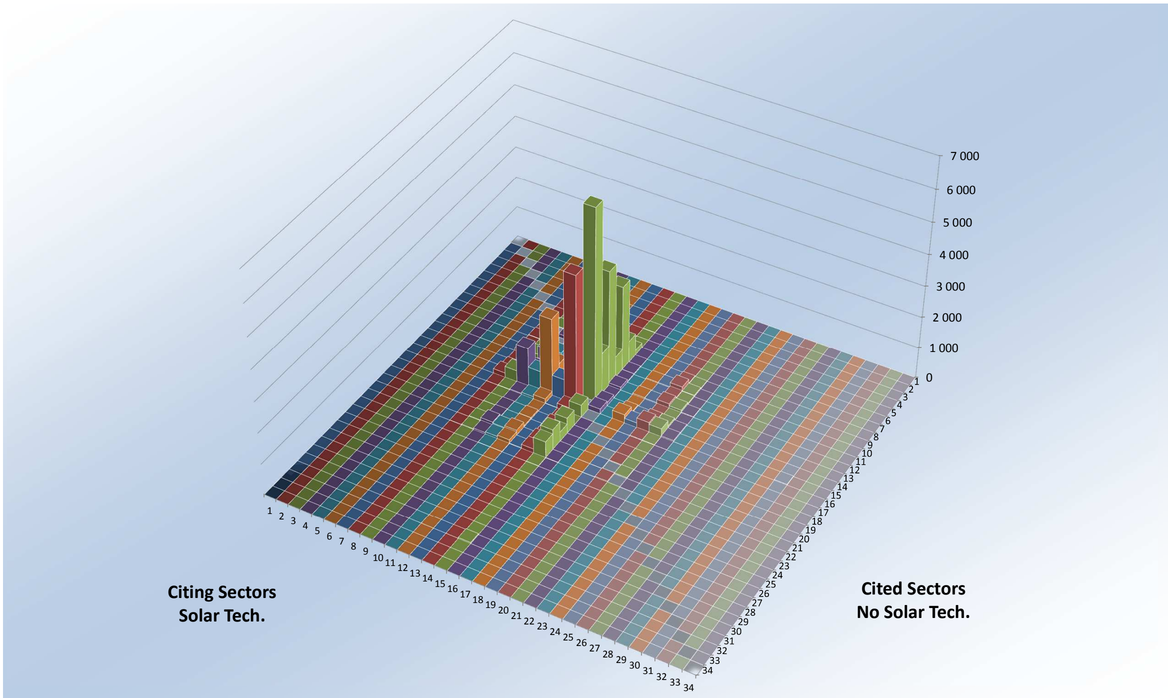
Figure 17: Sectoral distribution of innovations in Solar power technologies

(a) Sectoral distribution of patents

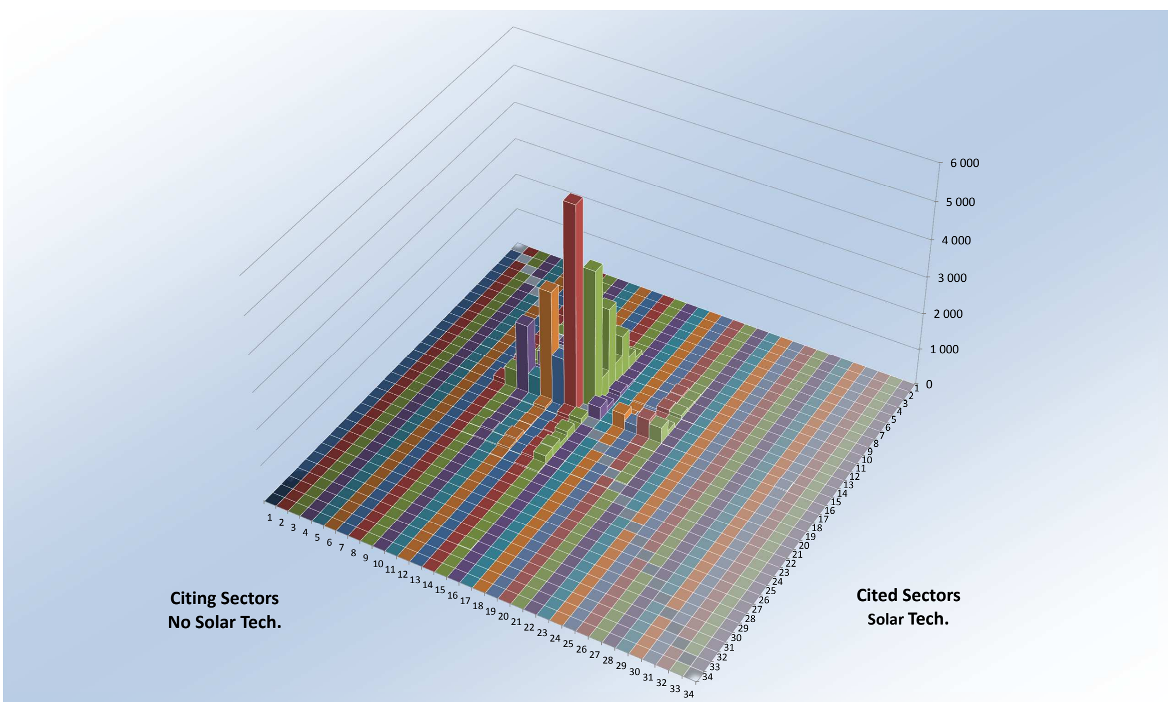


(b) Intersectoral citations between Solar power related technologies





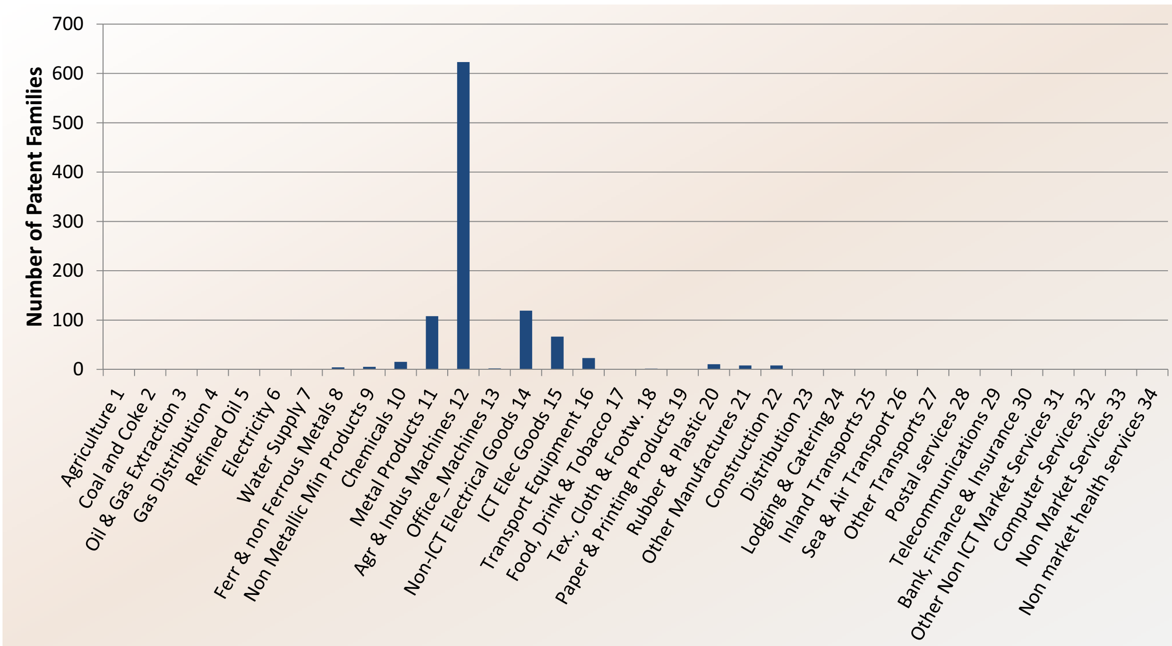
(c) Intersectoral citations by Solar power related technologies toward other technologies



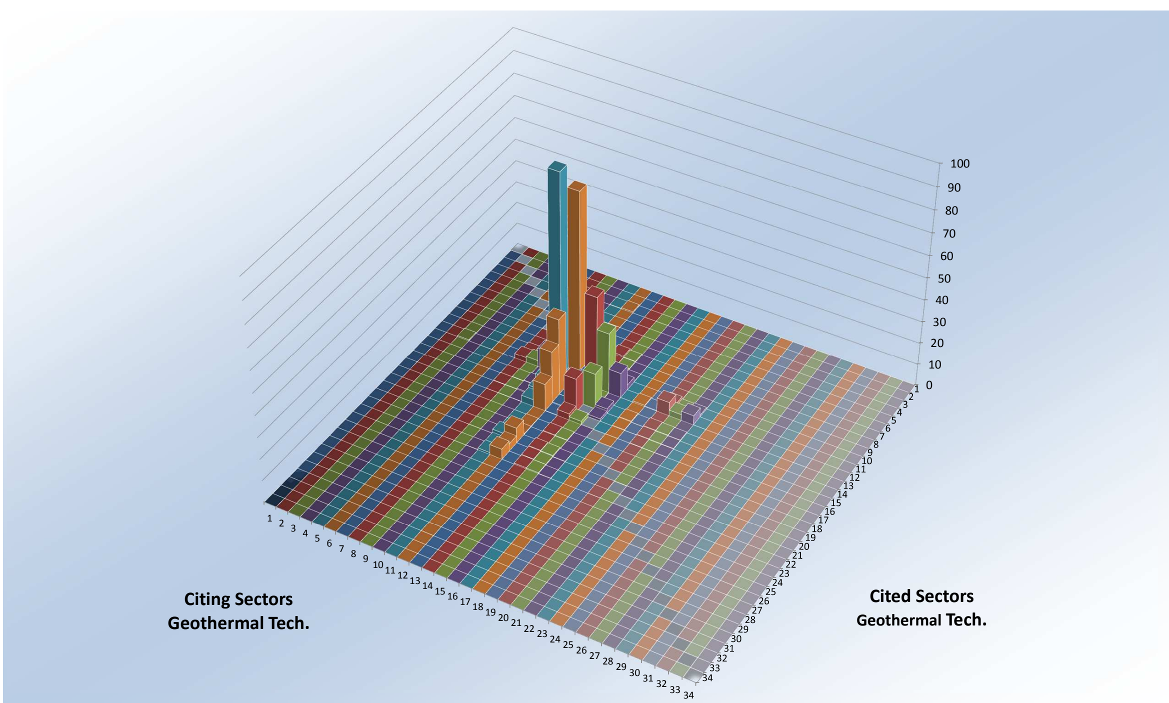
(d) Intersectoral citations toward Solar power related technologies by other technologies

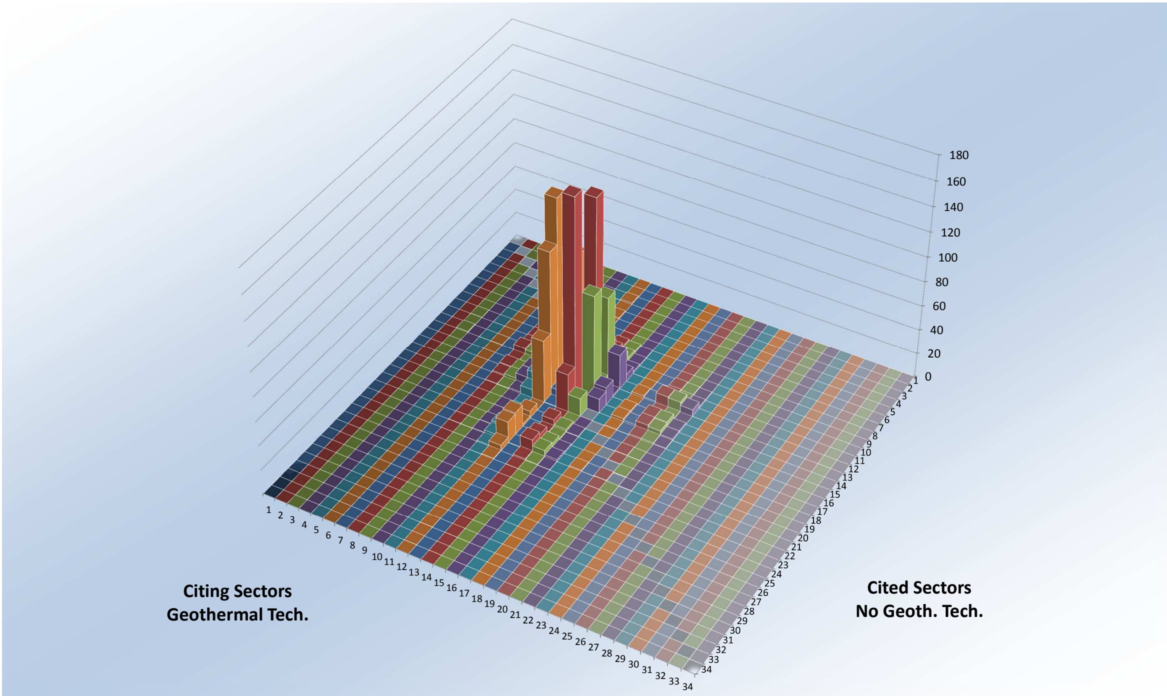
Figure 18: Sectoral distribution of innovations in Geothermal power technologies

(a) Sectoral distribution of patents

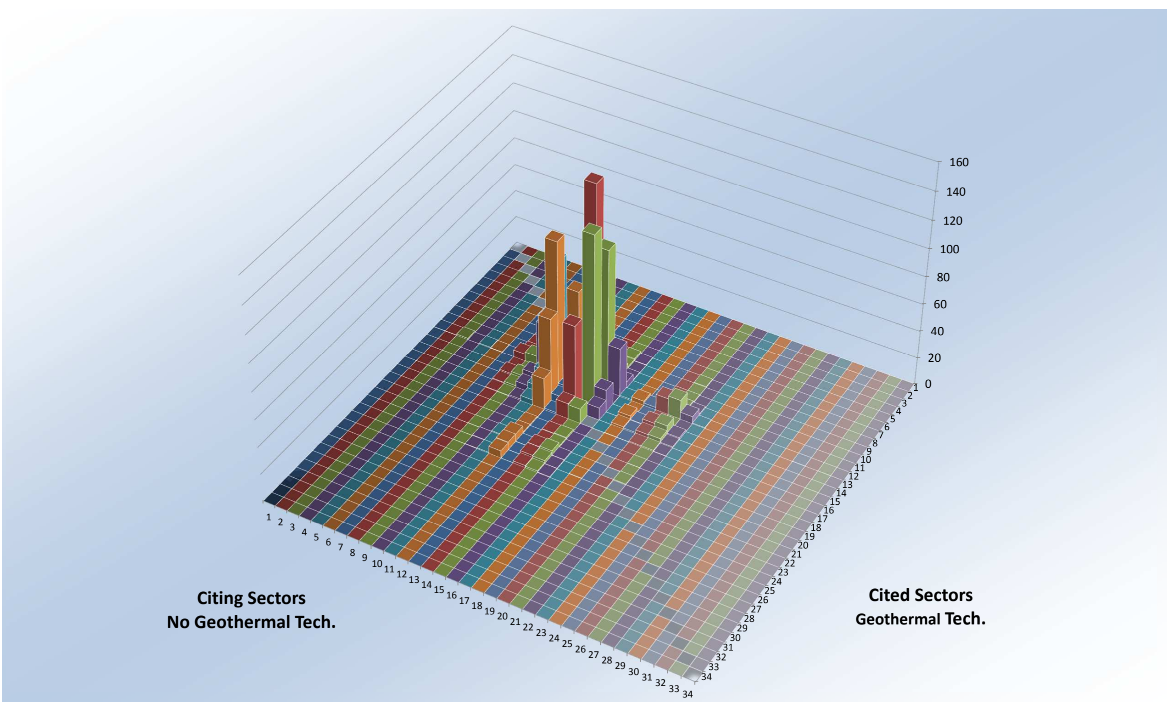


(b) Intersectoral citations between Geothermal power related technologies





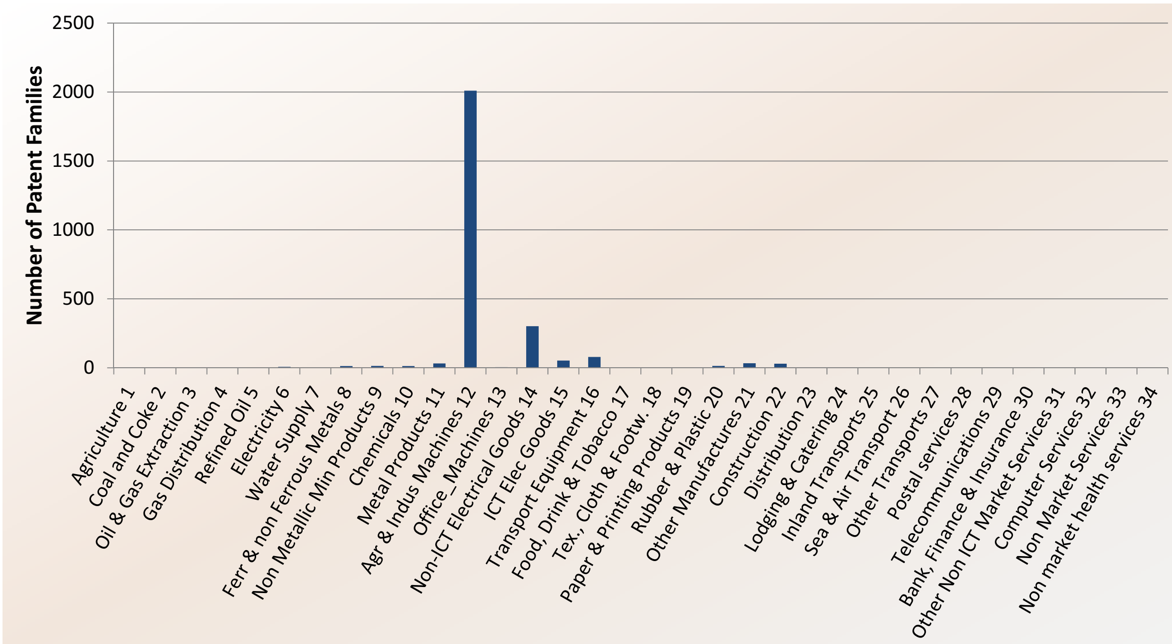
(c) Intersectoral citations by Geothermal power related technologies toward other technologies



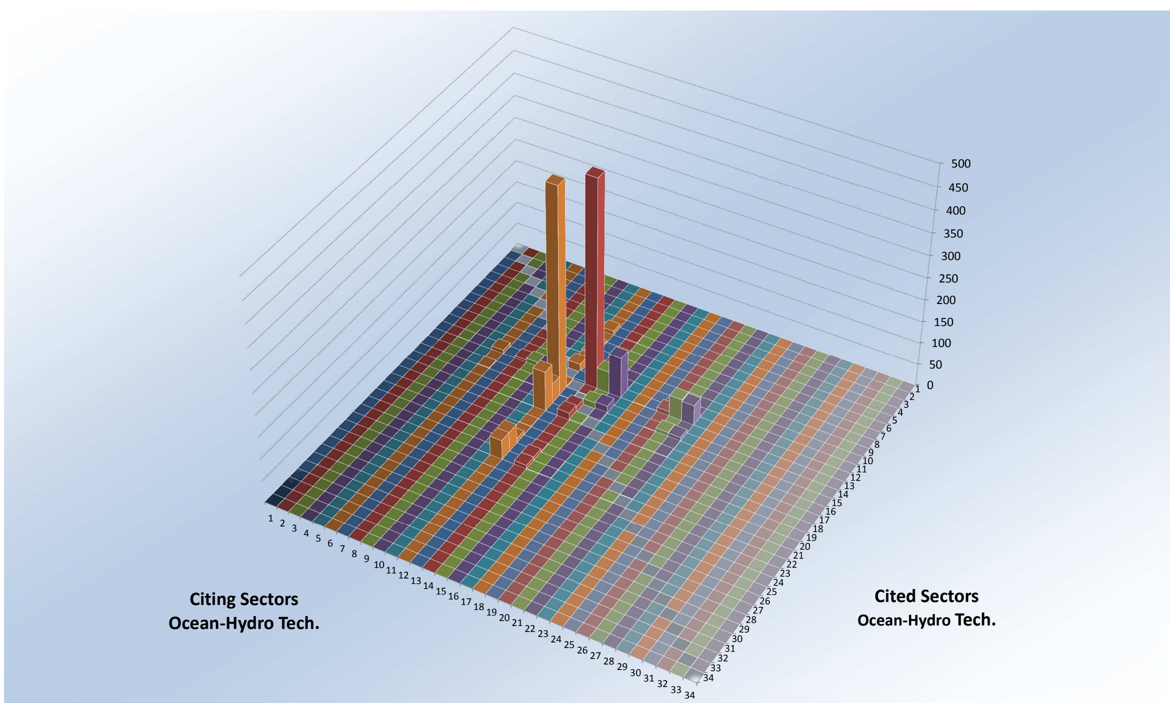
(d) Intersectoral citations toward Geothermal power related technologies by other technologies

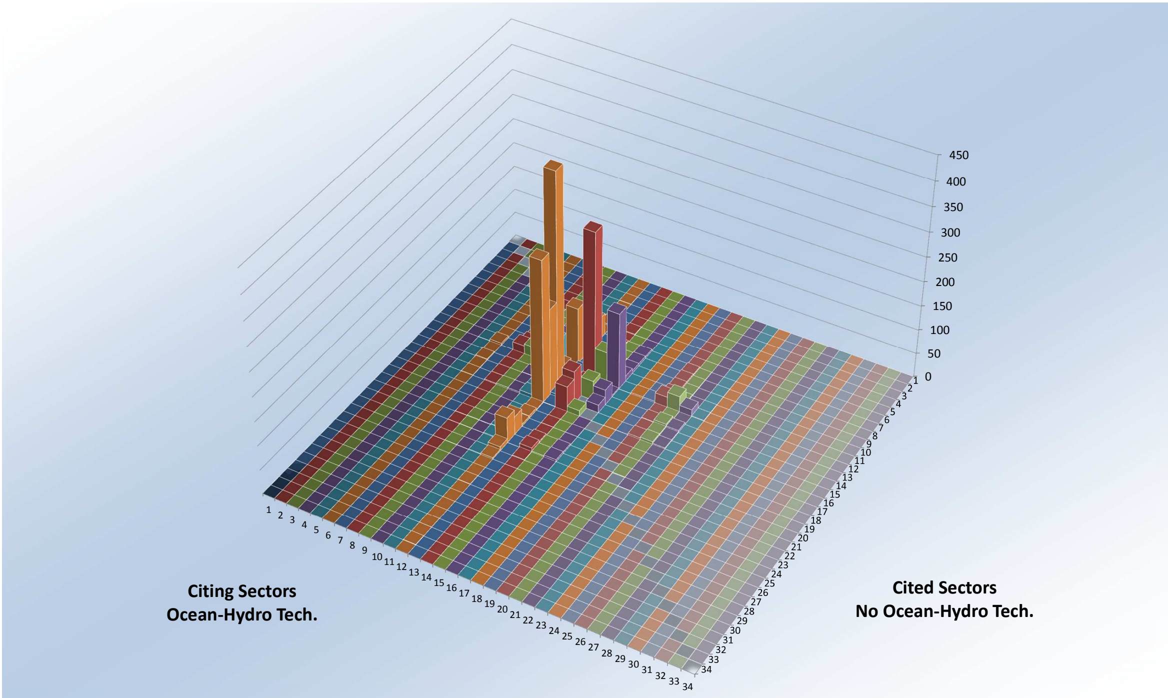
Figure 19: Sectoral distribution of innovations in Ocean-Hydro power technologies

(a) Sectoral distribution of patents

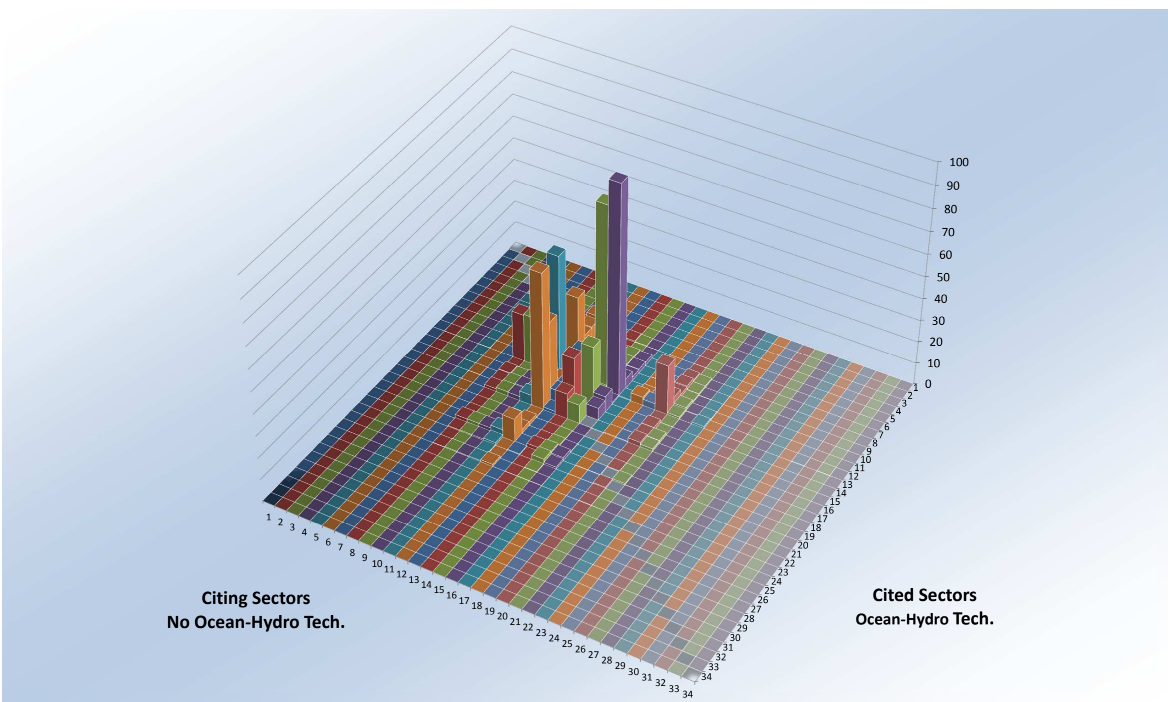


(b) Intersectoral citations between Ocean-Hydro power related technologies





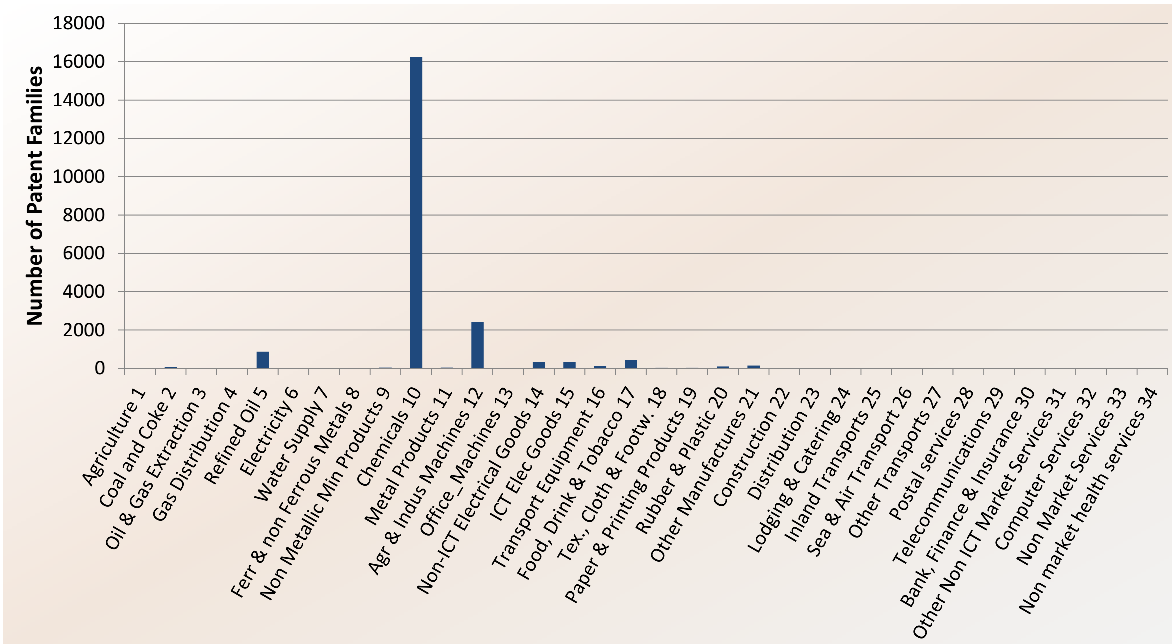
(c) Intersectoral citations by Ocean-Hydro power related technologies toward other technologies



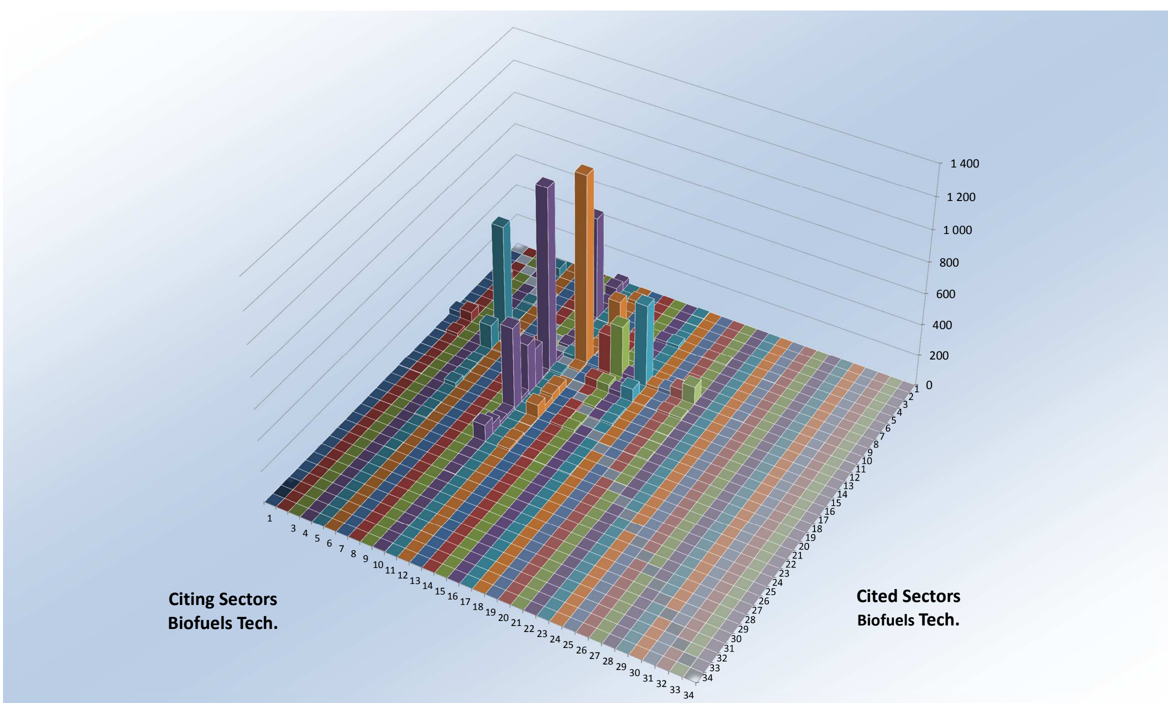
(d) Intersectoral citations toward Ocean-Hydro power related technologies by other technologies

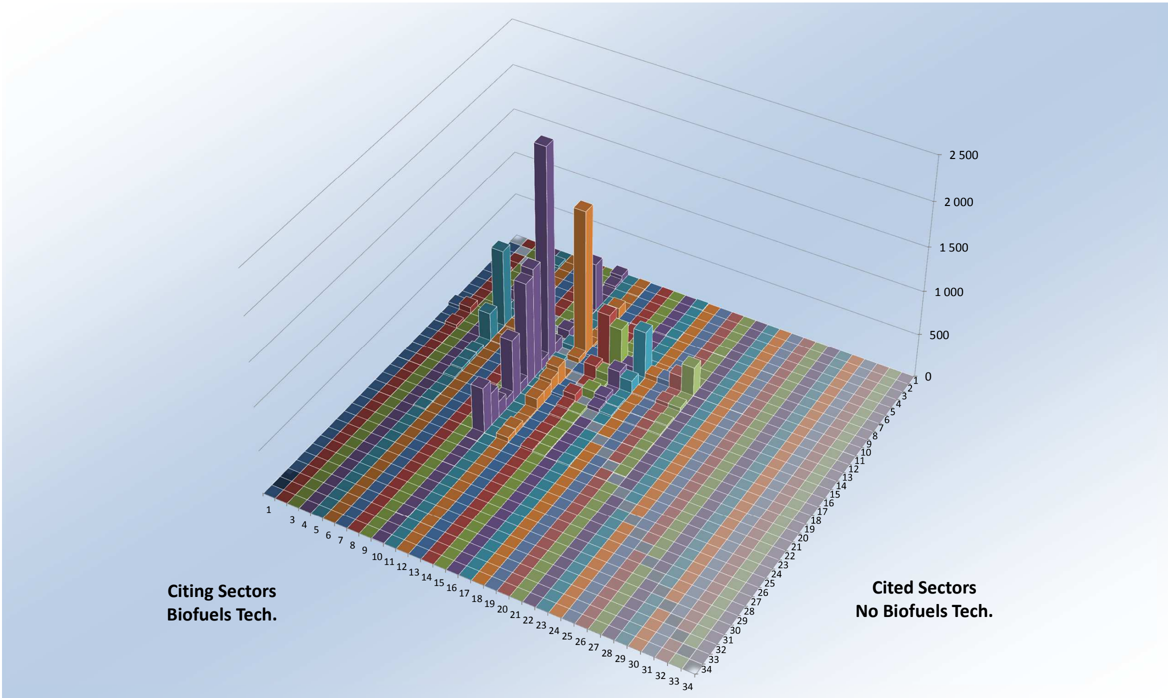
Figure 20: Sectoral distribution of innovations in Biofuels based energy technologies

(a) Sectoral distribution of patents

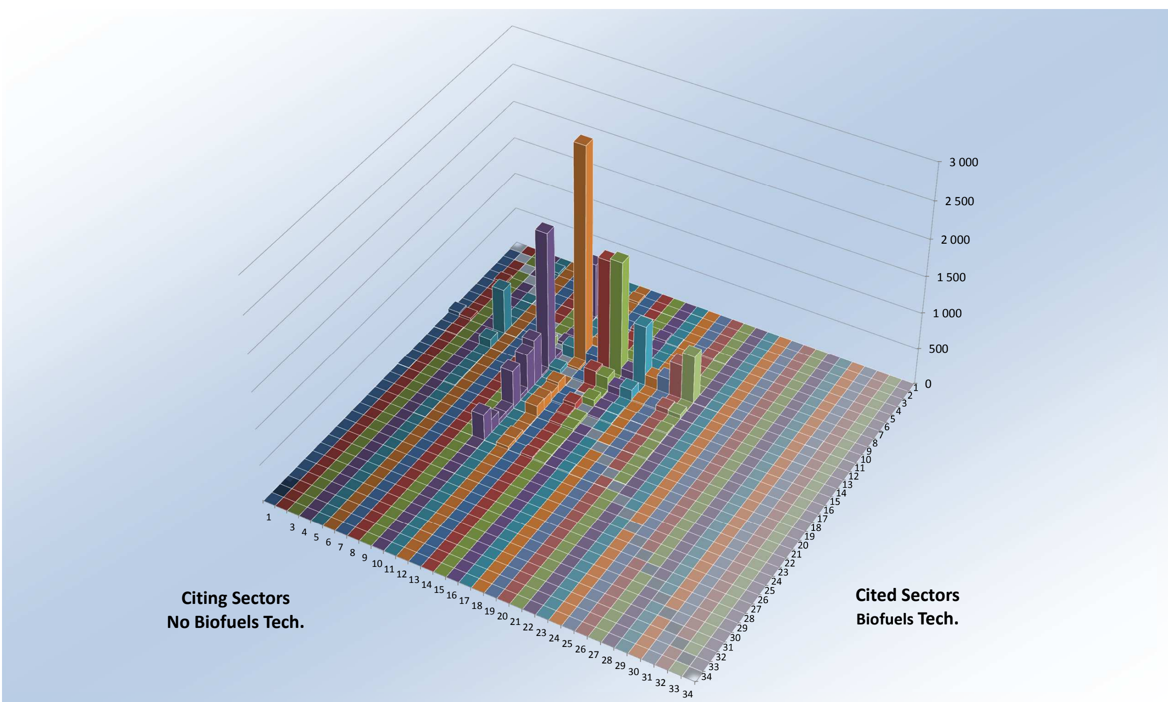


(b) Intersectoral citations between Biofuels related technologies





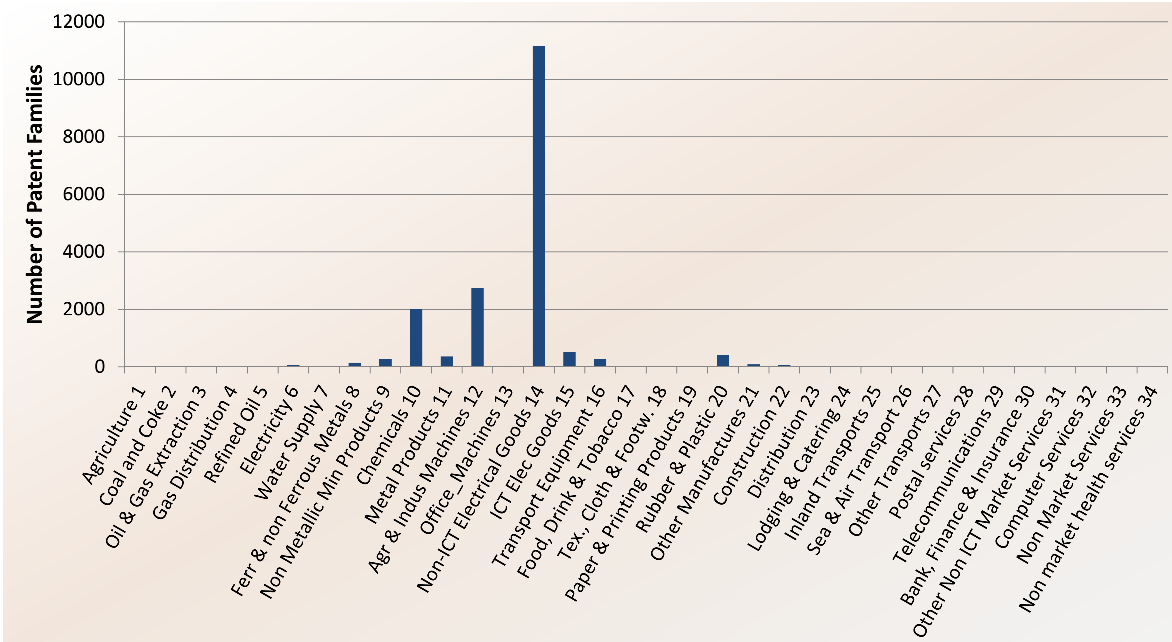
(c) Intersectoral citations by Biofuels related technologies toward other technologies



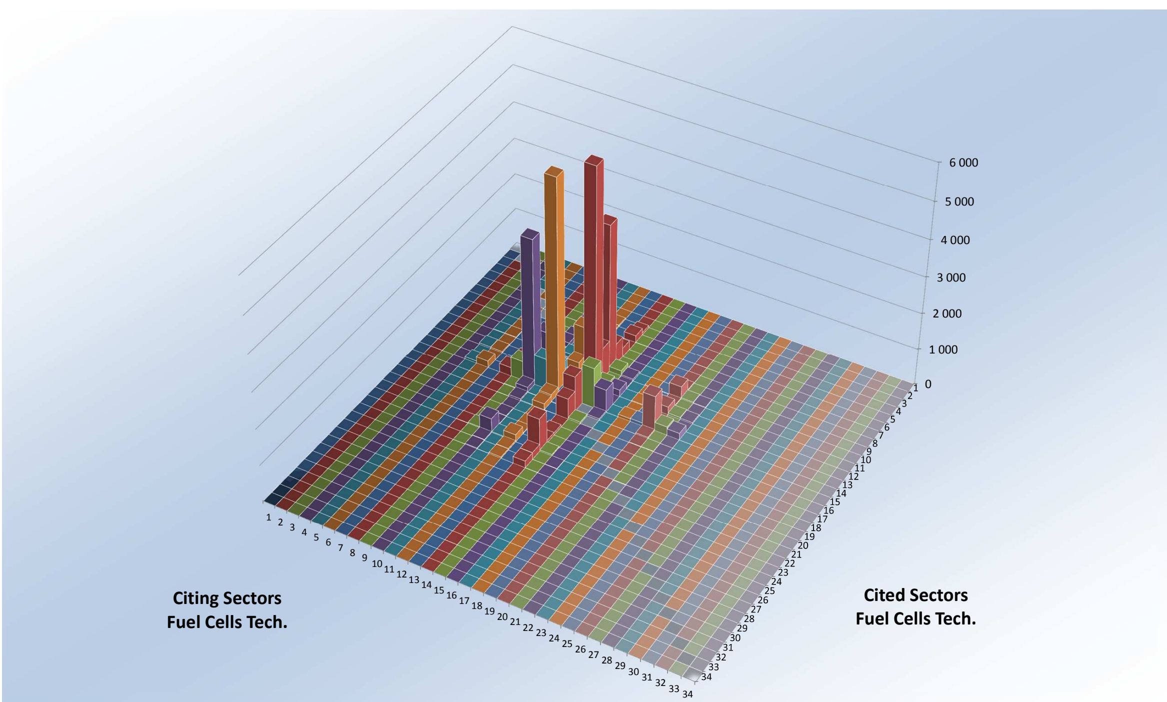
(d) Intersectoral citations toward Biofuels power related technologies by other technologies

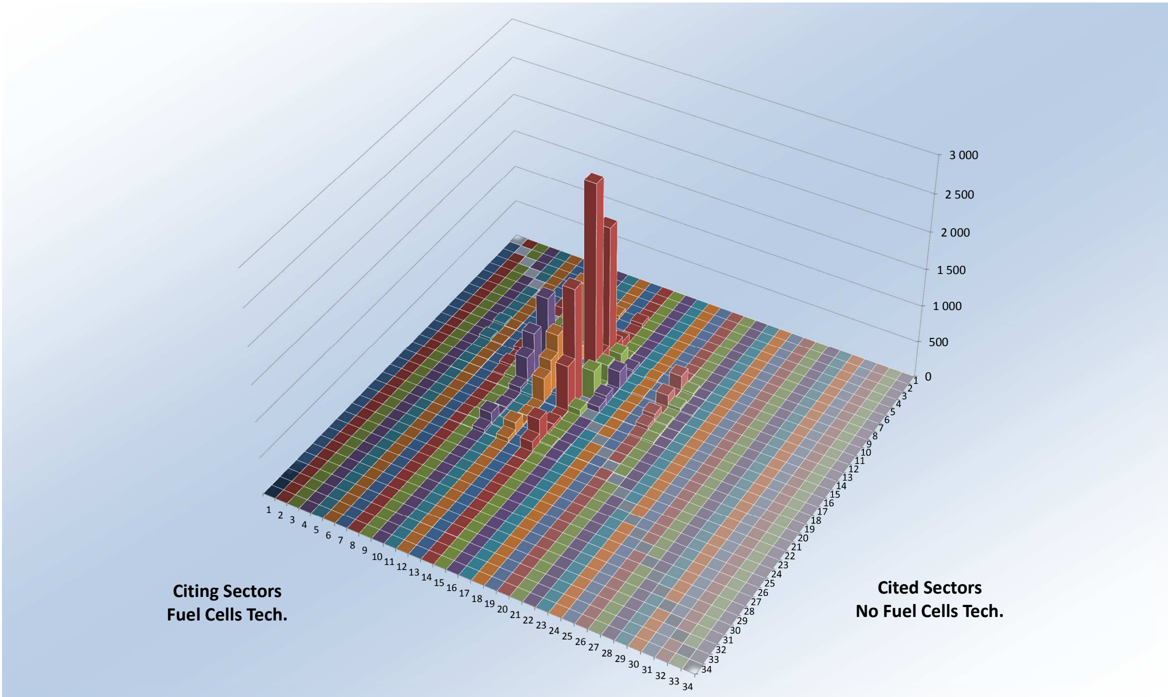
Figure 21: Sectoral distribution of innovations in Fuel Cells technologies

(a) Sectoral distribution of patents

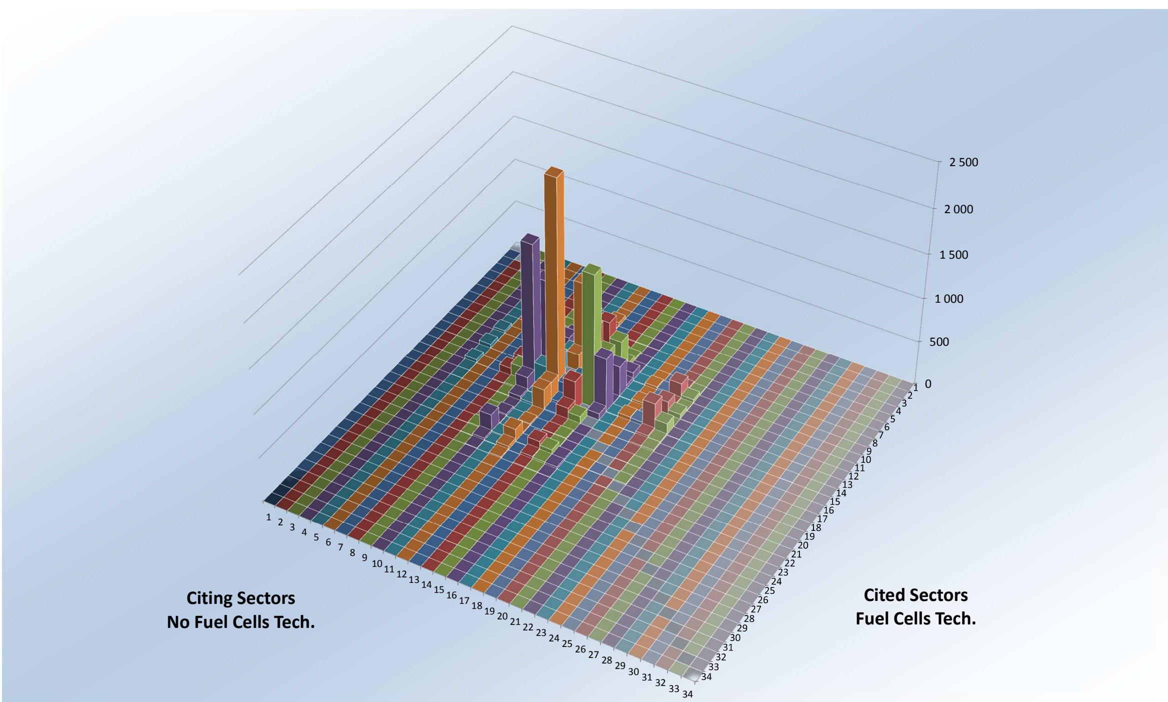


(b) Intersectoral citations between Fuel Cells related technologies





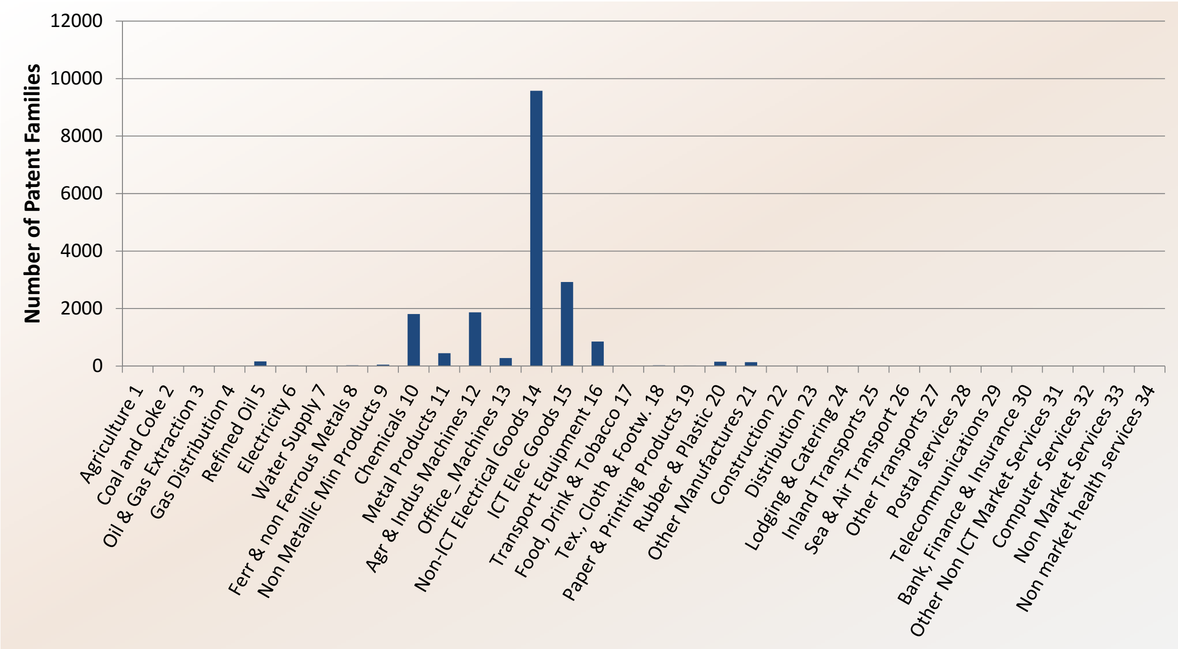
(c) Intersectoral citations by Fuel Cells related technologies toward other technologies



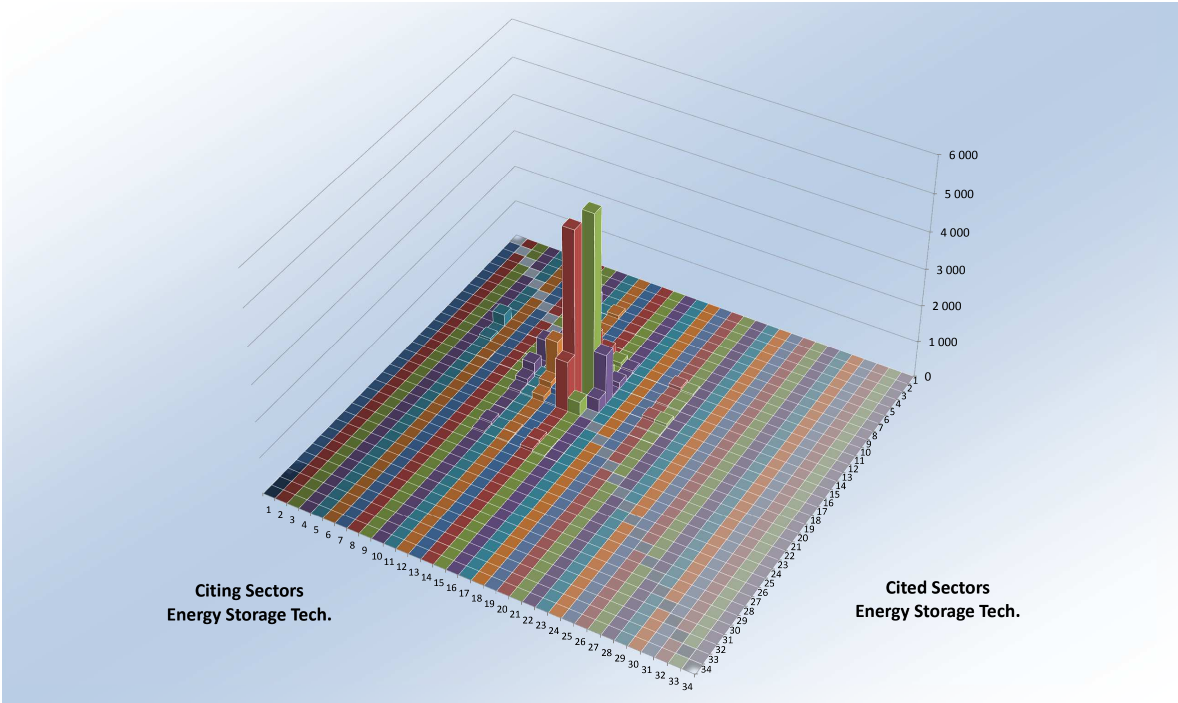
(d) Intersectoral citations toward Fuel Cells related technologies by other technologies

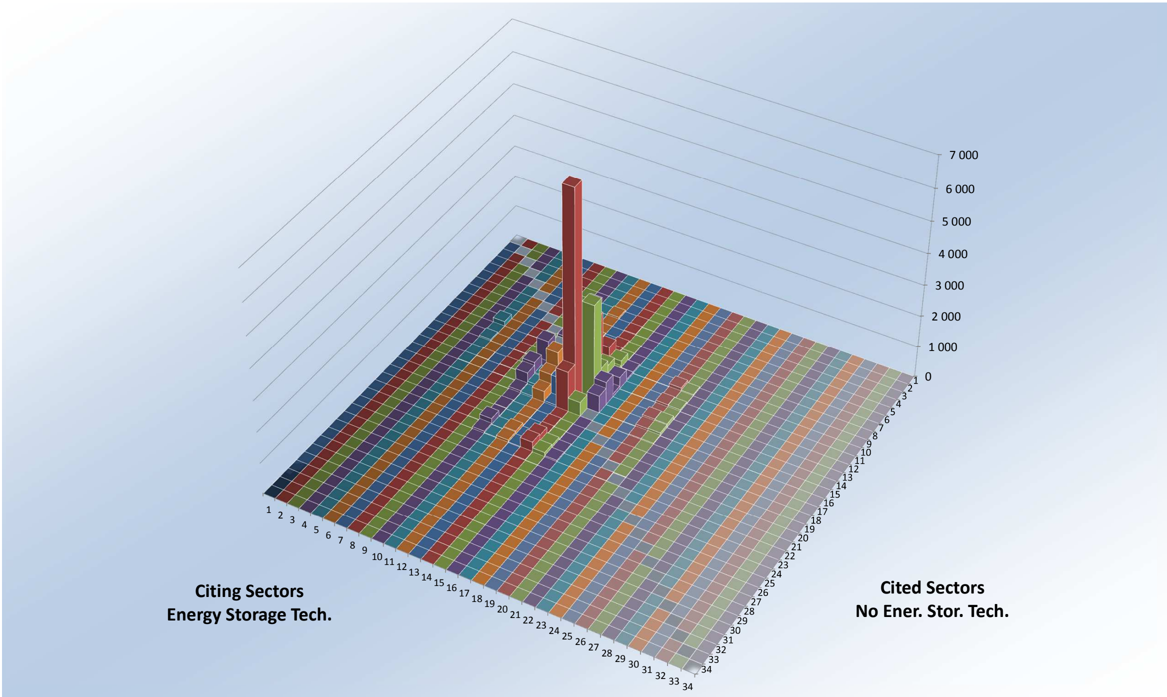
Figure 22: Sectoral distribution of innovations in Energy Storage technologies

(a) Sectoral distribution of patents

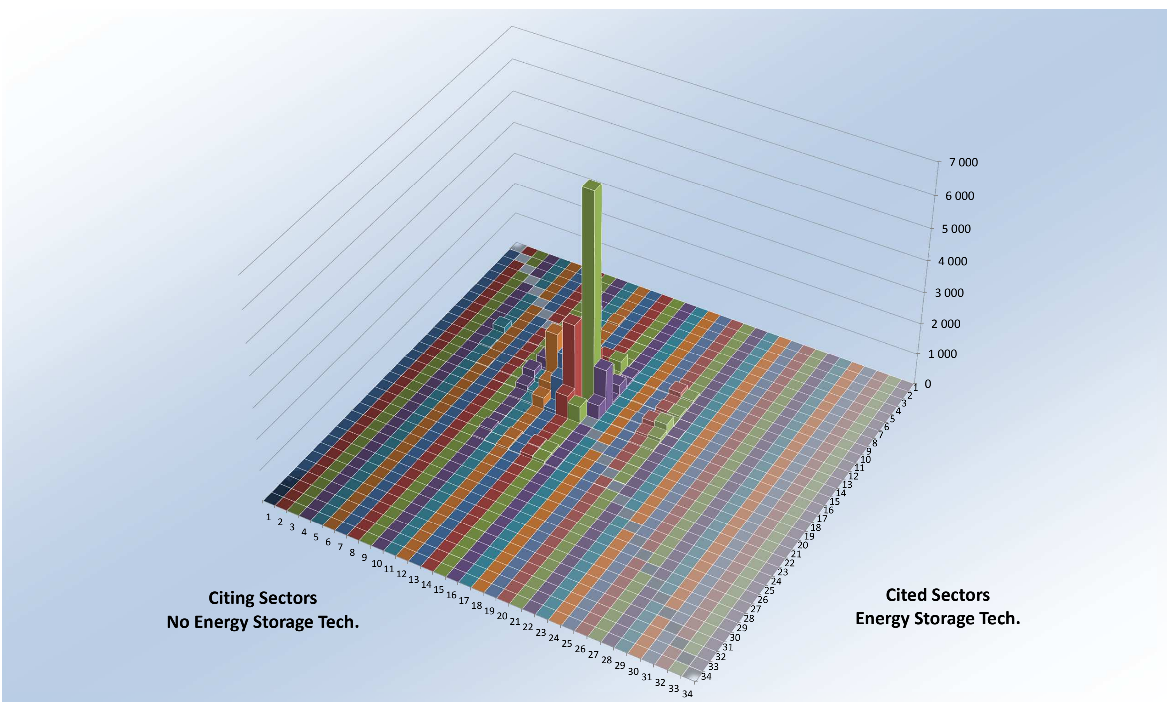


(b) Intersectoral citations between Energy Storage related technologies





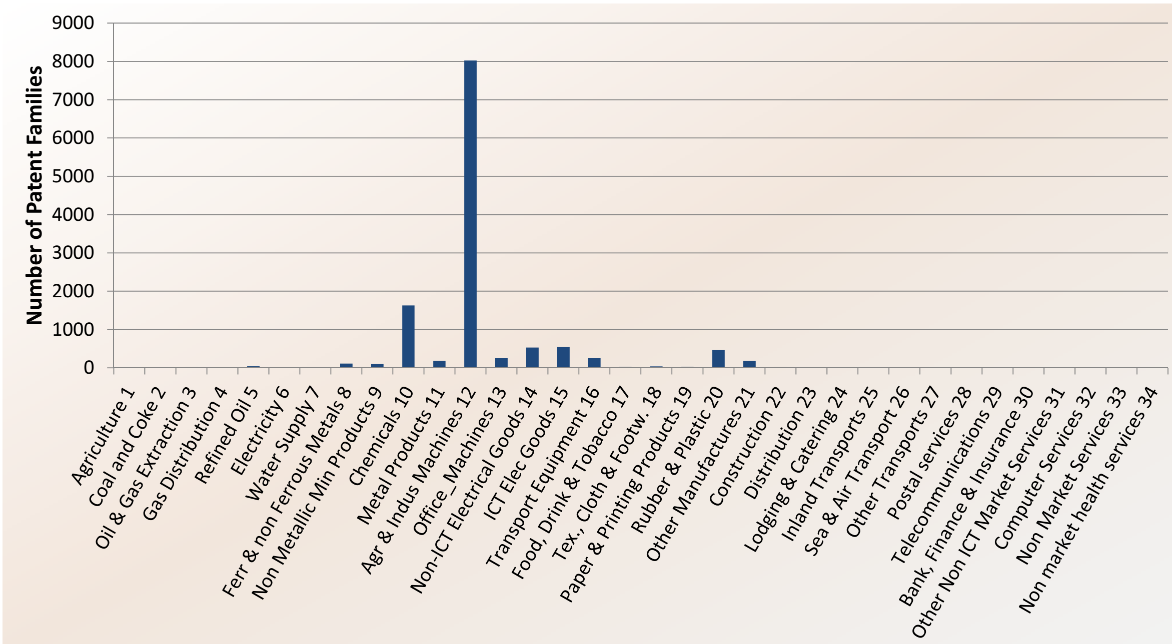
(c) Intersectoral citations by Energy Storage related technologies toward other technologies



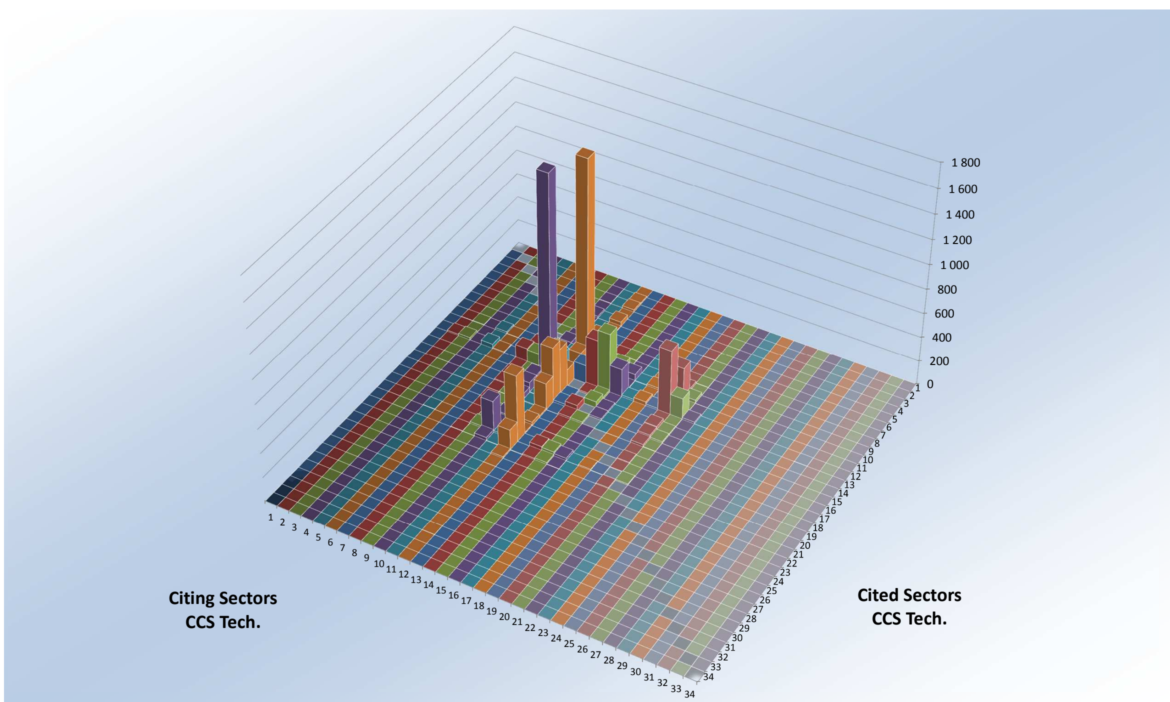
(d) Intersectoral citations toward Energy Storage power related technologies by other technologies

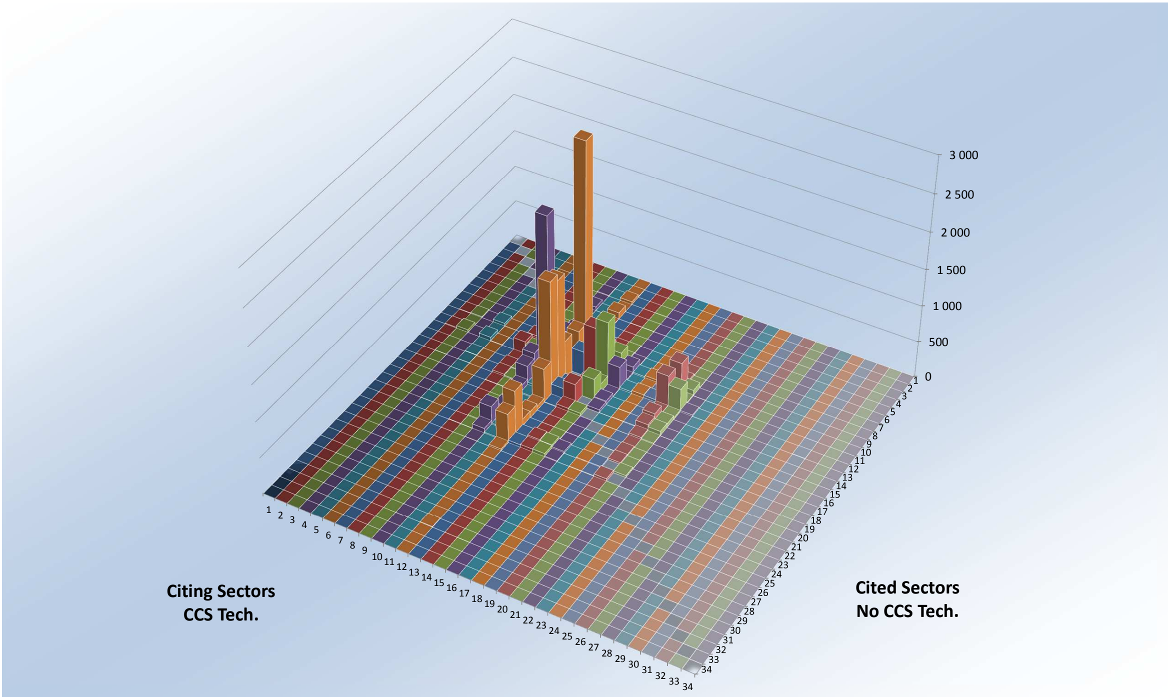
Figure 23: Sectoral distribution of innovations in Carbon Capture and Storage

(a) Sectoral distribution of patents

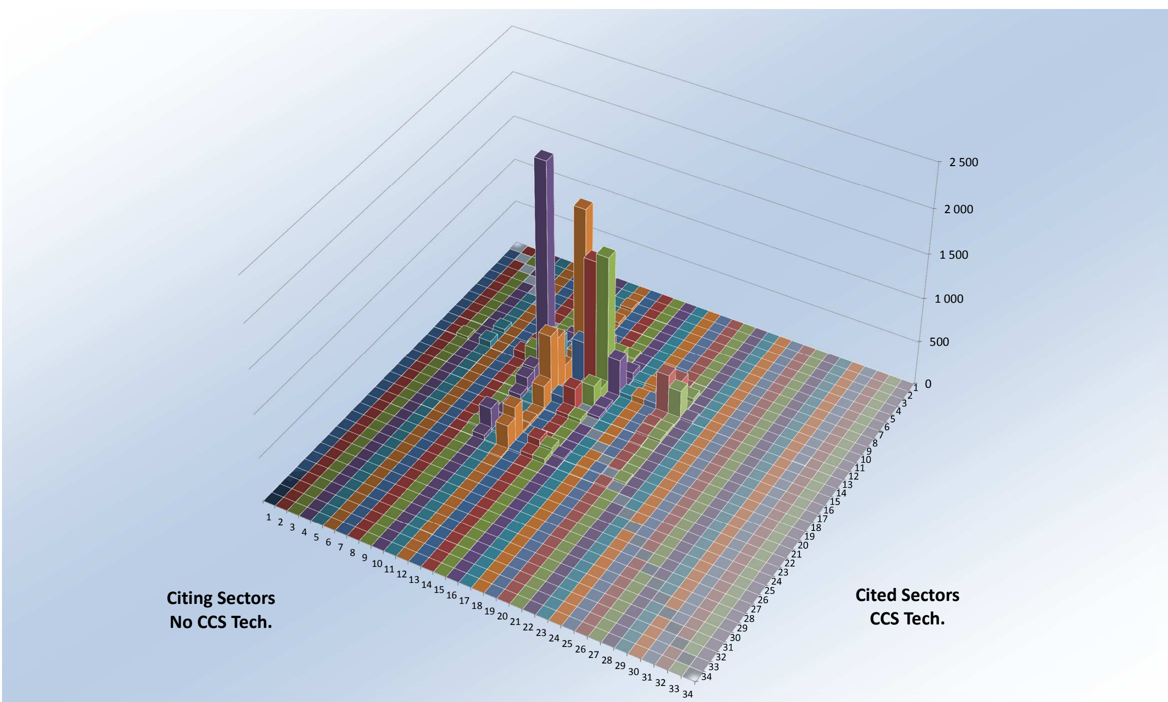


(b) Intersectoral citations between Carbon Capture and Storage related technologies





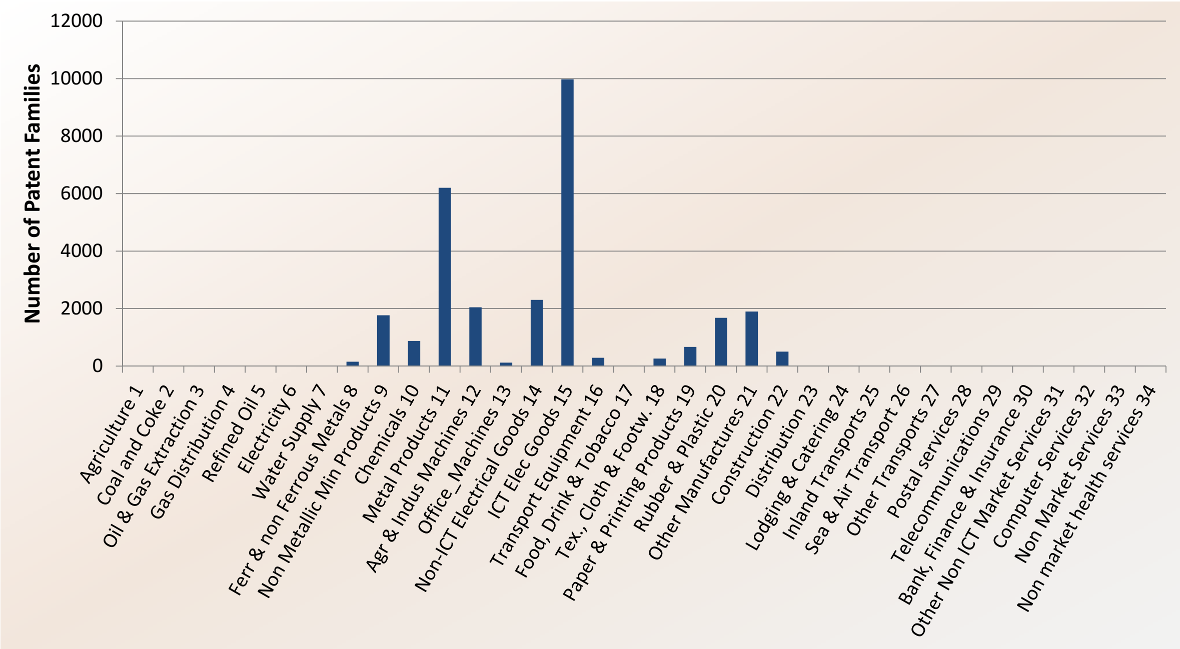
(c) Intersectoral citations by Carbon Capture and Storage related technologies toward other technologies



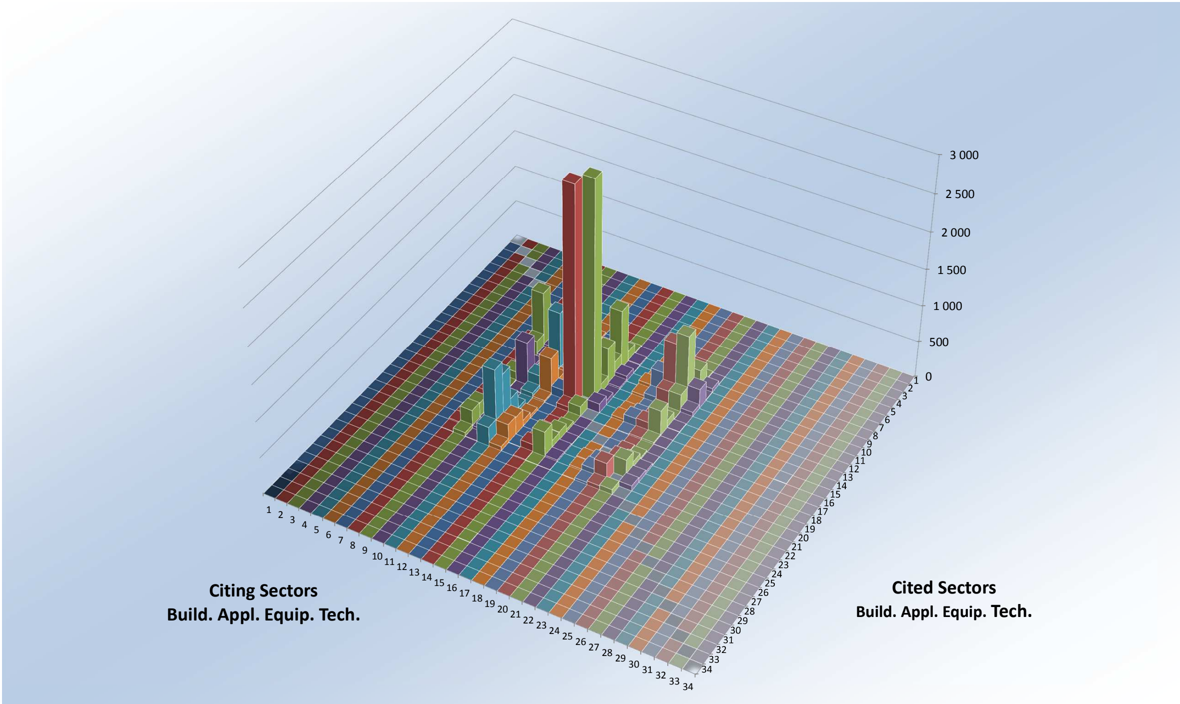
(d) Intersectoral citations toward Carbon Capture and Storage related technologies by other technologies

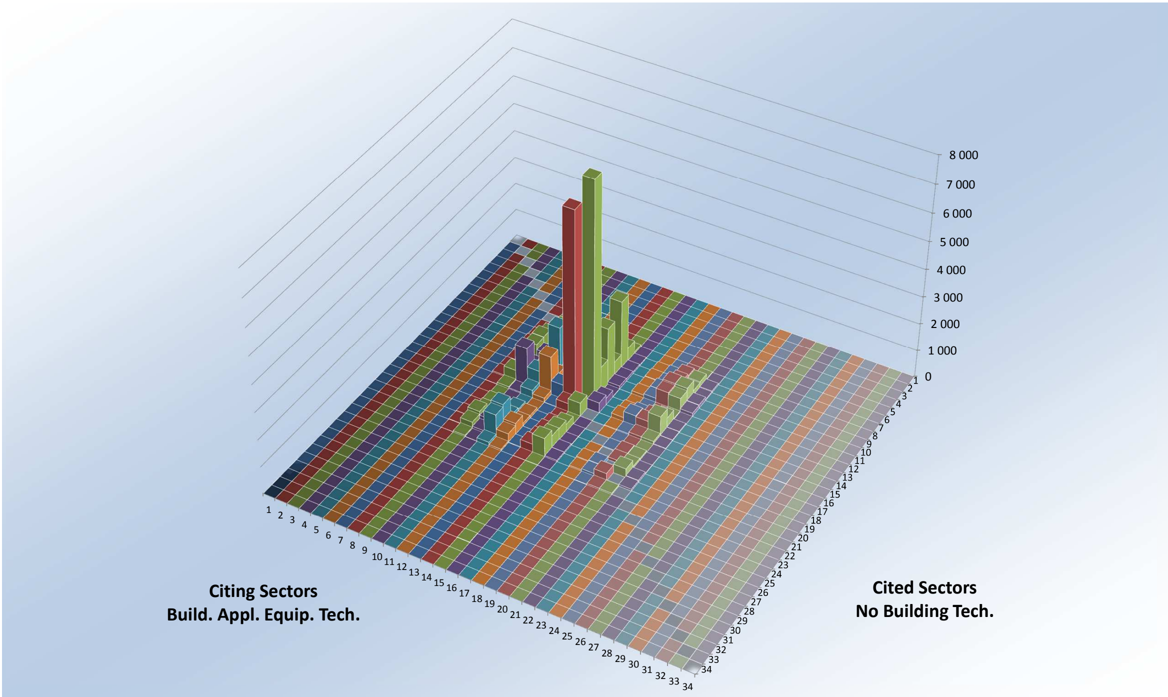
Figure 24: Sectoral distribution of innovations in Energy Efficiency in Building Appliances and Equip.

(a) Sectoral distribution of patents

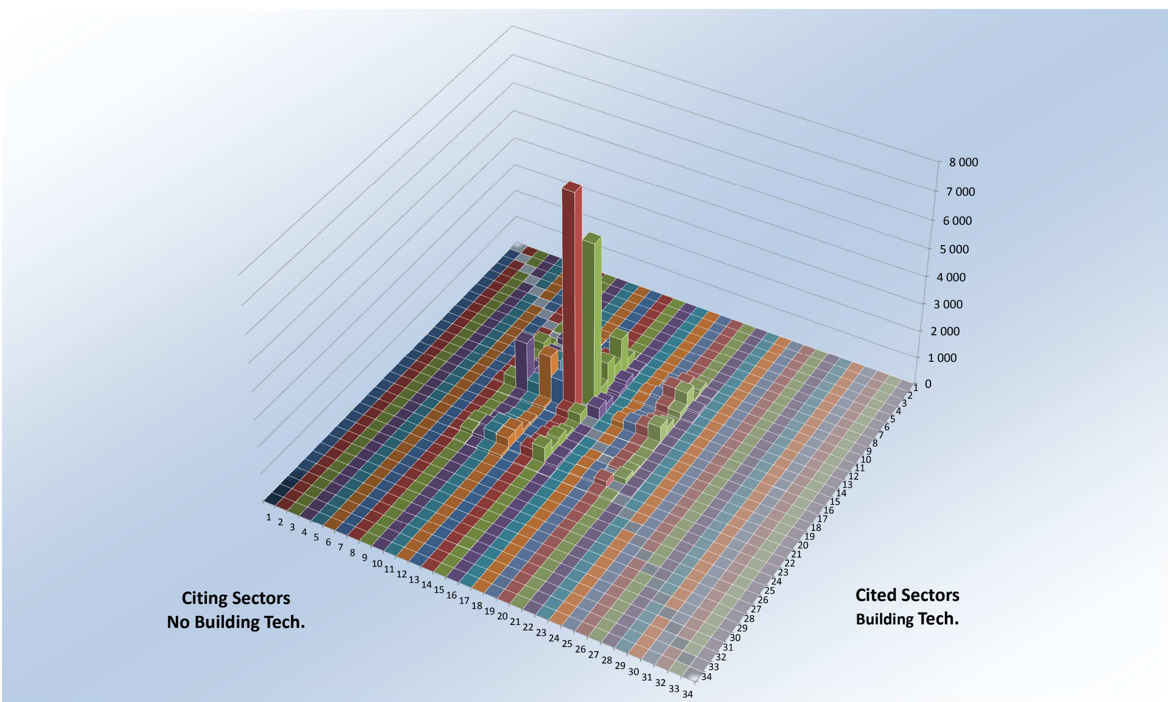


(b) Intersectoral citations between Building Appliances and Equip. related technologies





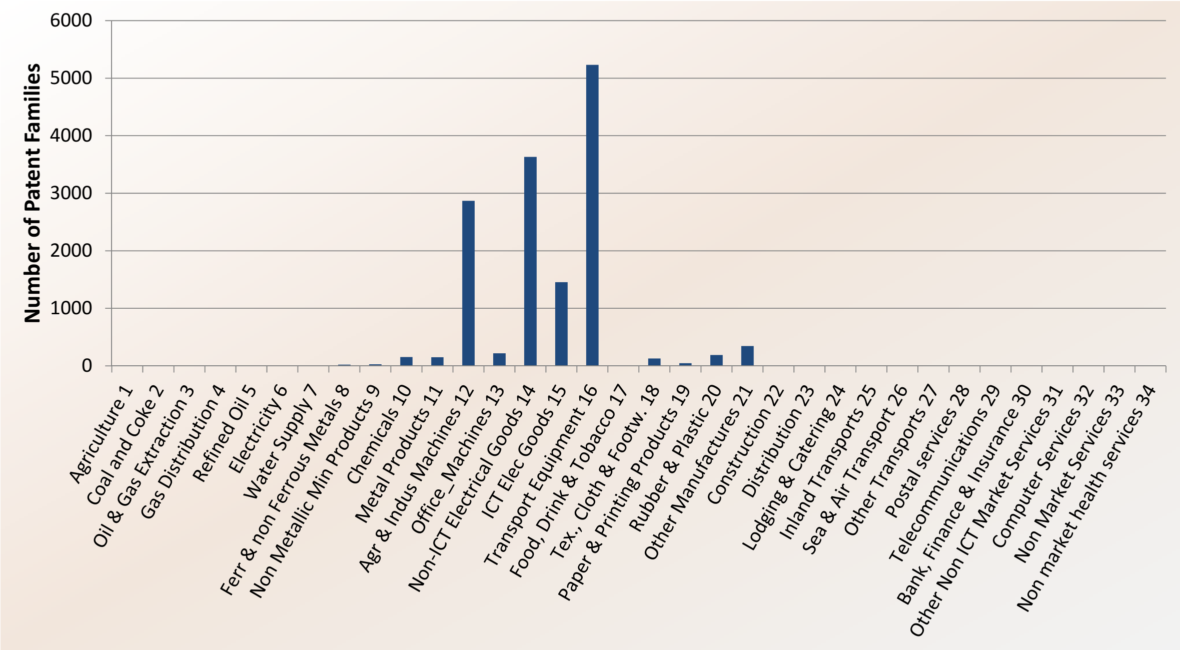
(c) Intersectoral citations by Building Appliances and Equip. related technologies toward other technologies



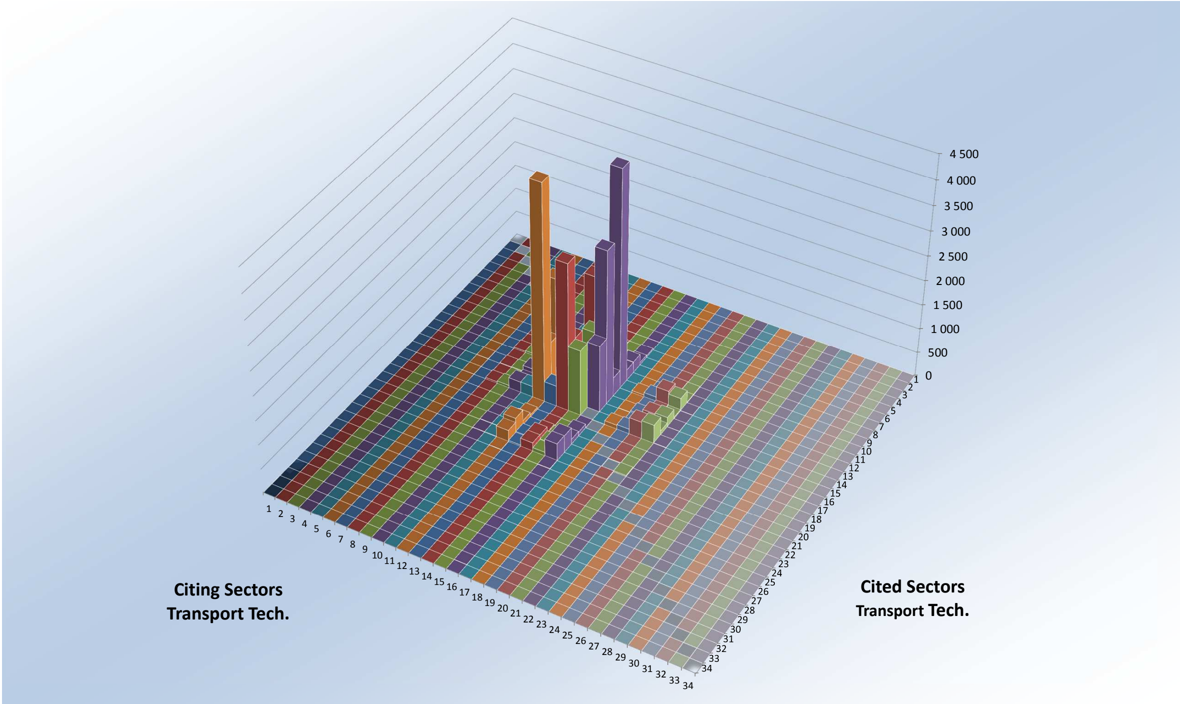
(d) Intersectoral citations toward Building Appliances and Equip. related technologies by other technologies

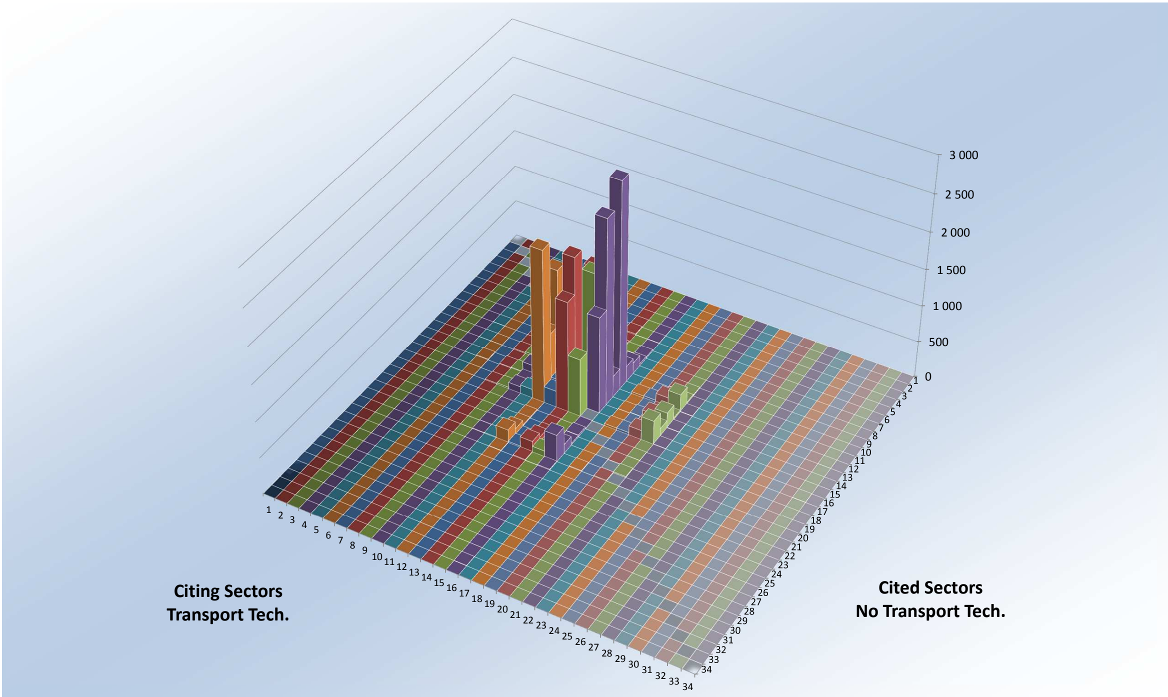
Figure 25: Sectoral distribution of innovations in Energy Efficiency in Transport

(a) Sectoral distribution of patents

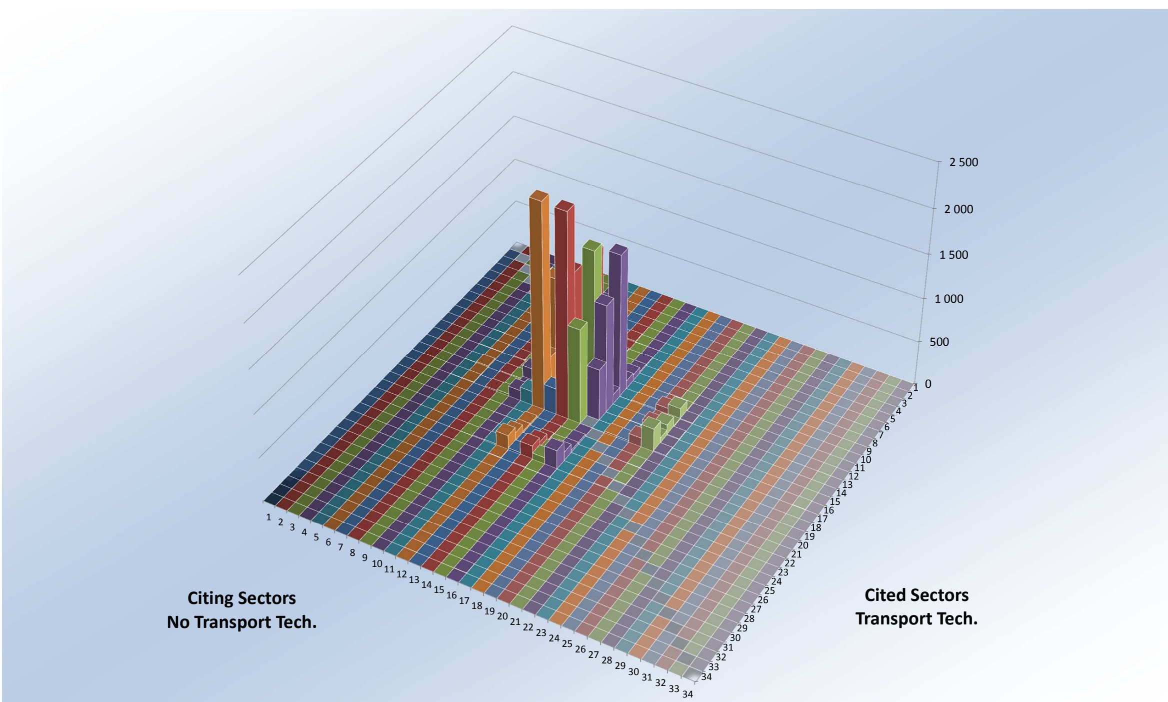


(b) Intersectoral citations between Transport related technologies





(c) Intersectoral citations by technologies related to Energy Efficiency in Transport toward other technologies



(d) Intersectoral citations toward technologies related to Energy Efficiency in Transport by other technologies

9.6 Estimation results

Correlations

Table 9: Correlations between knowledge stocks in log level

	srd	kieot	kiet	kiiot	kiit	kneot	knet
srd	1.00						
kieot	0.05	1.00					
kiet	0.36	0.08	1.00				
kiiot	0.01	0.56	0.09	1.00			
kiit	0.38	0.05	0.80	0.16	1.00		
kneot	0.54	0.16	0.22	0.19	0.12	1.00	
knet	0.96	-0.01	0.30	-0.02	0.32	0.57	1.00
kniot	0.66	0.02	0.19	0.11	0.20	0.82	0.66

Table 10: Correlations between knowledge stocks in log differences

	Δsrd	Δkieot	Δkiet	Δkiiot	Δkiit	Δkneot	Δknet
Δsrd	1.00						
Δkieot	0.05	1.00					
Δkiet	0.29	0.00	1.00				
Δkiiot	-0.09	0.52	0.02	1.00			
Δkiit	0.50	0.03	0.57	-0.03	1.00		
Δkneot	0.39	0.11	0.18	0.18	-0.07	1.00	
Δknet	0.96	-0.03	0.23	-0.11	0.43	0.43	1.00
Δkniot	0.70	0.01	0.14	0.02	0.35	0.68	0.70

Estimations

Table 11: Estimation results in log level

	1	2	3	4	5	6	7	8	9 Multisect. Tech.	10 Monosect. Tech.	11 Mature Tech.
srd	0.609 ***	0.461 ***	0.315 ***	0.428 ***	0.319 ***	0.430 ***	0.430 ***	0.392 ***	0.453 ***	0.394 ***	0.405 ***
prd	0.011	0.083 ***					0.069 ***	0.072 ***	0.032	0.087 ***	0.093 ***
kneot			0.048	-0.039 ***	-0.095	-0.045 ***	-0.064 ***	-0.075 ***	-0.080 ***	-0.052 **	-0.057 ***
kiit			0.462 ***	0.226 ***	0.447 ***	0.214 ***	0.256 ***	0.191 ***	0.382 ***	0.222 ***	0.295 ***
kiiot					0.179 *	0.032 **	0.049 ***	0.030 *	0.001	0.064 ***	0.038 **
Full fixed effect	X		X		X						
Count. dummies		X		X		X	X	X	X	X	X
Tech. dummies		X		X		X	X	X	X	X	X
Time fixed eff.								X			
Nb. Of Obs.	1996	1996	2555	2555	2555	2555	1940	1940	1095	845	1621
Adj. R2	0.413	0.795	0.358	0.807	0.306	0.808	0.813	0.791	0.788	0.866	0.818

Table 12: Estimation results in log variations

	1	2	3	4	5	6	7	8	9 Multisect. Tech.	10 Monosect. Tech.	11 Mature Tech.
Δsrd	0.267 ***	0.361 ***	0.088 **	0.344 ***	0.109 ***	0.345 ***	0.350 ***	0.385 ***	0.447 ***		0.368 ***
Δprd	-0.060 **	0.033 **					0.023	0.063 ***	0.010		0.077 ***
Δkneot			0.151	-0.052 ***	0.197 *	-0.054 ***	-0.073 ***	-0.075 ***	-0.102 ***		-0.069 ***
Δkiit			0.522 ***	0.164 ***	0.536 ***	0.161 ***	0.196 ***	0.180 ***	0.470 ***		0.215 ***
Δkiiot					-0.243 *	0.008	0.022	0.029 *	-0.023		0.021
Full fixed effect	X		X		X						
Count. dummies		X		X		X	X	X	X	X	X
Tech. dummies		X		X		X	X	X	X	X	X
Time fixed eff.								X			
Nb. Of Obs.	1848	1848	2395	2395	2395	2395	1797	1797	954	not enough	1621
Adj. R2	0.296	0.774	0.244	0.778	0.208	0.778	0.777	0.790	0.788		0.820

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