Low-carbon innovation:
Renewable energy drivers and policies

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Doctoral Dissertation

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Wir träumen von Reisen durch das Weltall: ist den das Weltall nicht in uns? Die Tiefen unseren Geistens kennen wir nicht. Nach innen geht der geheinmisvolle Weg. In uns, oder nirgends ist die Ewigkeit mit ihren Welten, die Vergangenheit und Zukunft.

Novalis, "Blüthenstaub", 1798

This thesis is dedicated to all those who not knowing what a doctoral degree is, know much more about nature than anyone who will ever write one.

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Summary

Low-carbon innovation is required to match energy supply with GHG emissions reductions at a quick enough pace to avoid dangerous climate change. This calls for a deeper understanding of low-carbon innovation to explore factors capable of speeding up its development and diffusion. Low-carbon innovation in the energy sector involves a number of challenges due to its particular characteristics and dynamics which have renewed the interest in exploring its drivers. This doctoral dissertation combines a series of five research papers which address emerging issues regarding the particular dynamics of low-carbon innovation, namely: lead markets formation, technological diversity, technological trajectory, knowledge sourcing strategies and impact on GHG emissions reduction.

In the first research paper, an extension of the lead market framework is developed to include supply side factors and technology policy issues. By comparing the development of lead markets in the wind power industry in China, Germany and the USA, this study shows the role of countries' specific business contexts and policy responses on low-carbon innovation. The second study is dedicated to explore the role of diversity in low-carbon innovations. By looking at the solar photovoltaic (PV) industry, nine indicators of technological diversity are applied to map diversity trends in the industry and its impact on further innovation. Subsequently, the third research paper links scientific knowledge evolution and low-carbon innovation in wind turbines. Based on a novel approach to citation analysis, this study offers original evidence on this relationship. The fourth article is based on an original survey among research organisations to analyse the impact of distinct strategies of external knowledge sourcing on low-carbon innovation. By comparing research on solar and wind power, this study depicts the importance of technology-specific policies. The fifth and final study explores how fast deployment of low-carbon innovation can affect its potential of GHG emissions reduction. Considering the case of wind power, it addresses the mismatch between installed capacity and actual wind power output in four of the leading countries in terms of generation capacity, namely: China, the United States, Germany and Spain.

In summary, this dissertation combines different perspectives from evolutionary, environmental and ecological economics with innovation and climate studies to explore the particular dynamics of low-carbon innovation. By looking at the cases of solar and wind power, this dissertation builds up original evidence and sheds new light into the possibilities of fostering innovation in low-carbon technologies.

Resumen

El desarrollo de la innovación baja en carbono es necesario para generar energía suficiente y, al mismo tiempo, reducir las emisiones de gases de efecto invernadero de manera suficientemente rápida para evitar un cambio climático extremo. Esto hace con que sea fundamental el entendimiento de los factores capaces de acelerar el desarrollo y la difusión de la innovación baja en carbono. La innovación baja en carbono en el sector energético involucra diversos desafíos en función de la especificidad de sus características y dinámica, razón por la hay renovado interés en su investigación. Esta tesis doctoral reúne una serie de cinco artículos científicos que buscan explorar tópicos emergentes en torno a particular dinámica de la innovación baja en carbono, a saber: la formación de mercados líder, la diversidad tecnológica, la trayectoria tecnológica, estrategias de obtención de conocimiento, e impacto en la reducción de emisiones de gases de efecto invernadero.

El primer artículo presenta una extensión del marco de referencia para análisis de mercados líder donde son adicionalmente considerados los factores referentes a la cadena de suministro y a políticas tecnológicas. Con base en la comparación del desarrollo de mercados líder en la industria eólica de Alemania, China, y Estados Unidos, este estudio demuestra el papel de los contextos de negocios y de las políticas de suporte a la innovación baja en carbono específicos de cada país. El segundo artículo explora el papel de la diversidad en el desarrollo de la innovación baja en carbono. Con base en el caso de la industria de energía fotovoltaica, nueve indicadores de diversidad tecnológica son aplicados para mapear la tendencia en la industria y su impacto en el desarrollo de nuevas innovaciones. El tercero artículo investiga la relación entre la evolución del conocimiento científico y la innovación baja en carbono en turbinas eólicas. Basándose en una nueva modelo para el análisis de citaciones, este artículo presenta nueva evidencia empírica de la relación entre desarrollo de conocimiento científico y la innovación baja en carbono. El cuarto artículo discute los resultados de una encuesta original realizada con organizaciones de investigación para analizar el impacto de diferentes estrategias de obtención de conocimiento en la innovación baja en carbono. Con base en la comparación de la investigación en energía solar y eólica, este estudio demuestra la importancia de políticas direccionadas a tecnologías específicas. Finalmente, el quinto artículo explora de que forma la rápida difusión de innovaciones bajas en carbono puede afectar su efecto en términos de reducciones de emisiones de gases de efecto invernadero. Analizando el caso de la energía eólica, este estudio demuestra el desequilibrio entre

capacidad instalada y efectiva producción de energía eólica en cuatro países líderes en capacidad de generación eólica, a saber: Alemania, China, España y Estados Unidos.

En resumen, esta tesis combina diferentes perspectivas de economía evolucionaria, ambiental y ecológica con estudios de innovación y clima para investigar las particular dinámica de innovación baja en carbono. Al estudiar los casos de las energías solar y eólica, esta tesis ofrece datos empíricos originales e ilustra nuevas posibilidades de suporte a la innovación baja en carbono.

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Chapter 1

Introduction

1.1 Low-carbon innovation is key to climate change mitigation

The growing threat of dangerous climate change underpins the need for urgent low-carbon innovations. Such innovations include technologies that either exploit renewable resources or reduce the environmental impact of fossil-fuel using technologies, such as through energy-efficiency improvements. Underlying virtually all scenarios to keep climate change within 2°C limit is the expectation that innovation will deliver technologies capable of providing sufficient low-carbon energy to meet our future energy needs (Hallegatte et al., 2016; Hansen et al., 2013; IPCC, 2014a; Kennedy, 2015; Suranovic, 2013). Low-carbon innovations are crucial as only new technologies can respond to a global demand for primary energy that is likely to grow by 37% until 2040 under the condition of having to considerable reduce GHG emissions (IEA, 2015a; IPCC, 2014a). Even the most optimistic scenarios associated with the 2°C target indicate that GHG emissions need to be reduced by at least 40% by 2050 compared to 2010, and that emissions should approximate zero around 2100 (IPCC, 2014b). With roughly 75% of total GHG emissions coming from the energy sector (IEA, 2015a), efficiency improvements in fossil-fuel based energy/electricity generation and using technologies and shifts towards lower carbon fossil fuels (e.g. coal to gas) are incapable of achieving these emission reduction goals (Bistline and Blanford, 2016; Moriarty and Honnery, 2016; Schellnhuber et al., 2016). Hence the need for low-carbon innovation to align energy supply with GHG emissions targets, which motivates the studies reported in this thesis.

Most scenarios for lowering carbon intensity of energy supply point to decarbonisation of electricity generation as a key strategy, for several reasons (Hertwich et al., 2014; Kennedy, 2015; Sugiyama, 2012). First, electricity generation is the sector with by far the highest carbon emissions – representing 41% of worldwide carbon emissions, which is twice the share of the transport sector (IEA, 2015b). Second, several low-carbon electricity sources are already cost-competitive with fossil fuels. Next to the traditional hydro and nuclear power, solar and wind power have already achieved cost-parity with fossil fuel sources in various locations (Denholm et al., 2016; Hand, 2015; IEA, 2015a; IRENA, 2016). Third, due to its cost-efficiency and high deployment flexibility, electricity generation can be decarbonised more rapidly than any other sector, e.g. transport, buildings, industry (Capros et al., 2014; Mercure et al., 2014). Fourth, low-carbon electricity generation offers complementary advantages to GHG emissions reduction, known as co-benefits, such as less local atmospheric pollution and associated health effects (Buonocore et al., 2016; Novan, 2015), or increased energy security by reducing global interdependence of energy supply and market volatility (Edenhofer et al., 2013; Johansson, 2013). Fifth, low-carbon electrification of other sectors is required to achieve future GHG emissions reduction targets (IPCC, 2014a; Schellnhuber et al., 2016; Sugiyama, 2012).

Decarbonisation scenarios project an increase of low-carbon electricity supply from 30% in 2012 to more than 80% by 2050 (Drouet et al., 2015; Hansen et al., 2013; IEA, 2015a; IPCC, 2014a; Jacobson et al., 2015; Luderer et al., 2014). The International Energy Agency (2015) estimates that a global investment of at least US$ 19.7 trillion is necessary to decarbonise the power sector by 2040 (IEA, 2015a). Over 2004-2015, investment in non-hydro low-carbon energy has grown six-fold: from US$ 47 billion to US$ 286 billion (US$ 2.3 trillion in total) (BNEF, 2016). In 2015, low-carbon technologies accounted for most of the additional energy supply installations: 53.6% of the total capacity[1], of which solar and wind power received 94.5% of the total investment (BNEF, 2016). At the same time, low-carbon technologies have achieved significant cost reductions, with solar and wind power having shown the quickest cost decreases[2], namely, 65% and 30% between 2010 and 2015, respectively (IEA, 2016).

Despite these efforts, low-carbon technologies are not causing energy supply to reduce GHG emissions at the pace required to avoid dangerous climate change (Armstrong et al., 2016; Karlsson, 2016; Mowery et al., 2010). Considerable innovation is still needed in the

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[1] This excludes large hydro (>50MW).

[2] Refers to global average costs of generation for new utility-scale solar PV and onshore wind.

near future, ideally at a higher rate than over past decades. Recent studies indicate that urgent action is required as even under an optimistic scenario of 10 years delay of further energy supply decarbonisation the 2°C climate target becomes infeasible (Iyer et al., 2015; Jones and Warner, 2016; Moriarty and Honnery, 2016; Rogelj et al., 2015; Schellnhuber et al., 2016). This calls for a deeper understanding of low-carbon innovation to explore factors capable of speeding up its development and diffusion.

1.2 The dynamics of low-carbon innovation in the energy sector

Low-carbon innovation in the energy sector presents a number of distinctive characteristics and dynamics in comparison to other sectors which have renewed the interest in exploring its drivers. To begin with, low-carbon innovation suffers from a triple externality problem, since in addition to the common knowledge market failure, it faces drawbacks from environmental externality and even what might be called a "lock-in externality" (Acemoglu et al., 2012; Dangerman and Schellnhuber, 2013; van den Bergh, 2013). Low-carbon innovation involves large embodied capital and long turnover times, leading to a compounded effect of the typical market failure regarding knowledge appropriation. The large amount of investment increases the considerable losses in case of undesired knowledge spillovers, while the long turnover time raises the risk of benefits appropriation by third parties (Costa-Campi et al., 2015; Fischer, 2008). Next, the presence of an environmental externality, as is characteristic of environmental innovations, further discourages investment in low-carbon technologies because pollution and other environmental impacts are not internalized by the market (i.e. not adequately priced), preventing environmental investments to reap their full benefits (Popp et al., 2010; Weitzman, 2014). Finally, lock-in favours further development of incumbent, fossil fuel based technologies which benefit from increasing returns to scale and positive feedback cycles from a dominant technological infrastructure (Cecere et al., 2014; Dangerman and Schellnhuber, 2013).

Low-carbon technologies present a particularly slow pace of innovation and diffusion. A full transition towards a new technology requires a time span of several decades to possibly a century (Drouet, 2016; Negro et al., 2012; Wilson and Grubler, 2011). Several factors explain this slow pace of change, such as the high capital intensity of investment in the energy sector, with large scale projects, high upfront costs, long payback periods, high financial uncertainty, and highly specialised infrastructure (Kauffmann et al., 2012); the long lifetime of capital stock, e.g. electricity grids and power conversion facilities; and the long time required for market bridging of low-carbon technologies (Jewell et al., 2016; Kivimaa and Kern, 2016).

As a result, serious policy support is required to make low-carbon innovation happen at a pace, magnitude and direction relevant to current climate goals (GEA, 2012; IEA, 2015b; IPCC, 2014a). There is consensus that optimal policies to support low-carbon energy innovation should mix instruments from at least two realms: environmental regulation and technology policy (Acemoglu et al., 2012; Auld et al., 2014; Jaffe, 2012; Mowery et al., 2010). The implementation of a policy mix offers several advantages. Environmental regulation can address the environmental externality, whereas technology policy can address the knowledge and lock-in externalities. The combination of these policies enables the use of more precise, technology-specific instruments, lowering the cost of emissions reductions (Fischer and Newell, 2008). It also favours synergies between policy goals, since public research funding is more effective in foster low-carbon innovations when accompanied by emissions reduction policy, as the latter not only affect abatement with existing technologies but also adoption and innovation of new technologies (Popp and Newell, 2009). Additionally, a mix of policy instruments is key to avoiding the creation of rebound effects and escape routes. Indeed, technology support, such as through some form of renewables subsidies, will not contain rebound, whereas particularly carbon pricing will do so. (Font Vivanco et al., 2016; Grant et al., 2016; van den Bergh, 2015). Also, since emissions control policy commonly involves assuring future demand for low-carbon energy, it provides a positive investment stimulus on innovation in this field, reducing uncertainty (Peters et al., 2012) and lock-in to fossil fuels (Lehmann et al., 2012). So in many respects, environmental regulation and technology policies are complementary and mutually reinforcing effectiveness.

The impact of these specific characteristics on the dynamics of low-carbon innovation has received increasing attention in the last decade with a number of studies seeking to identify its drivers and possible speeding-up mechanisms (see Gallagher et al., 2012; Negro et al., 2012; Shi and Lai, 2013 for reviews). This doctoral dissertation aims to contribute to this literature by presenting studies that address a variety of emerging issues regarding the dynamics of low-carbon innovation, which are relevant for climate change mitigation. To this end, they draw on perspectives from environmental economics, ecological economics, innovation studies and climate studies. The specific research questions addressed and methods of analysis used are presented in the following section.

1.3 Scope and outline of the thesis

This doctoral dissertation includes five research papers which address emerging issues regarding the particular dynamics of low-carbon innovation, namely: lead markets formation, technological diversity, technological trajectory, knowledge sourcing strategies and impact on GHG emissions reduction. By looking at the cases of solar and wind power, this dissertation builds up original evidence and sheds new light on the possibilities of fostering innovation in low-carbon technologies. The central research questions addressed are:

- Do lead markets create competitive advantages for low-carbon innovations?
- What is the role of technological diversity in stimulating low-carbon innovations?
- How does the evolution of scientific knowledge relate to the technological trajectory of low-carbon innovations?
- What is the impact of knowledge sourcing strategies on low-carbon innovation?
- How does use of installed capacity of low carbon energy sources differ between countries and which factors can explain this?

The thesis is organized as follows. In Chapter 2, an extension of the lead market framework is developed to include supply side factors and technology policy issues, and then applied in a comparative analysis of the wind power industry in China, Germany and the USA. The analysis contributes to understand how countries' specific contexts and policy responses have affected the development of wind power industries, as well as how interactions among these three countries have affected the diffusion of wind power technologies. In Chapter 3, an empirical study of the solar photovoltaic (PV) industry is undertaken. This involves developing a theoretical framework, which leads to nine indicators of technological diversity. Subsequently, these are applied to relevant data to illustrate the impact of diversity on environmental innovation. Chapter 4 explores the link between scientific knowledge evolution and low-carbon innovation by considering the case of wind turbines. To this end, a novel approach based on citation analysis of scientific publications is developed. Chapter 5 investigates the effects of external knowledge sourcing on low-carbon innovation. Based on an original survey among relevant research organisations, the impact of distinct strategies of external knowledge sourcing is analysed. This includes a comparison of research on solar and wind power. Chapter 6 explores how fast deployment of low-carbon innovation can affect its potential of GHG emissions reduction by looking at the case of wind power. This addresses the mismatch between installed capacity and actual wind power output in four of the leading countries in terms of generation capacity, namely: China, the United States, Germany and Spain. The comparative analysis at the country level highlights the importance of electricity market characteristics to improve the low-carbon electricity output. Finally, Chapter 7 concludes and makes suggestions for further research.

Chapter 2

International Diffusion of Renewable Energy Innovations: Lessons from the Lead Markets for Wind Power in China, Germany and USA[*]

2.1 Introduction

Climate change is pushing a transition towards a new energetic system. Since energy use is responsible for about 83% of global anthropogenic greenhouse-gas emissions (IEA, 2015), current patterns of energy production and consumption have to be transformed to avoid dangerous climate change. Driven by technological change in energy sources and use, a transition to a new energetic system requires environmental innovations to take place in a particular pace and direction.

One issue that has not received very much attention is the potential interaction between international and national forces promoting renewable energy technologies. The strong international dynamics of energy markets, not limited by national boundaries, contrasts with policy support in the form of technology policies (e.g., subsidies) and environmental regulation coming mainly from domestic authorities. At the same time, policy to foster innovation in renewable energy technologies is increasingly being framed as serving multiple goals (Anadón, 2012; Fankhauser et al., 2013; Jaffe et al., 2005; Mowery et al., 2010). It is expected to not only spur innovation and increase national welfare (through contributing to

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[*] This chapter has also been published as: Lacerda, J.S., van den Bergh, J.C.J.M., 2014. International Diffusion of Renewable Energy Innovations: Lessons from the Lead Markets for Wind Power in China, Germany and USA. *Energies* 7, 8236–8263. doi:10.3390/en7128236.

energy security and affordability, and employment) but also to help conquer a leading position in the global market for renewable energy technologies.

In the last five years, China, the EU15, Japan and USA have all implemented policies aimed at achieving leadership in green technologies (European Comission, 2014; Lantz, 2014; UNEP, 2012). The idea is that through environmental and technology policy countries can gather first-mover advantages that will increase their competitiveness. In this case, a country takes the lead in the international diffusion of a particular innovation, benefiting from increasing returns of technological development, economies of scale and exports to expanding international markets. Yet, the factors that affect the potential of policy to improve competitiveness through renewable energy innovation are still poorly understood (Fankhauser et al., 2013).

Environmental innovation in the energy sector has been historically focused on large-scale supply-side technologies, such as hydro and nuclear power, which concentrate up to 80% of global annual investments in 2011 (GEA, 2012). Among all supply-side technologies, wind power stands out as one of the most promising by its low environmental impact, fast pace of growth and potential for cost reduction (GEA, 2012; IEA, 2013a; UNEP, 2014). Wind power technologies are already widely diffused and considered mature: they have become price-competitive with traditional fossil-fuel energy sources in specific settings; and subsidies for these technologies are already planned to be phased out in several countries (IEA, 2013b; IRENA, 2012a).

Wind power was responsible for 2.6% of global electricity generation in 2012, and saw its installed capacity grow at an average rate of 24% per year in this last decade (IEA, 2013a). But further growth is required since wind power is expected to provide 15% to 18% of the necessary CO_2 reductions in the electricity sector by 2050 (IEA, 2015). This explains the call for a rapid scaling up of annual installations and investment: from 45 GW in 2012 to 65 GW in 2020, 90 GW by 2030 and 104 GW in 2050, with annual investments going up to USD 170 billion (IEA, 2015).

This study contributes to the conceptual and empirical discussion on whether policy support to renewable energy innovation is capable of improving competitiveness. We examine the formation of lead markets regarding wind power technologies in China, Germany and USA, the three countries with larger installed capacity. For this purpose, we apply and extend the “lead market” approach from Beise and Rennings (2005). The extension aims at analysing supply side factors and policy instruments that address particular aspects of renewable energy innovations. Our analysis has two objectives: to understand how countries’ specific contexts and policy responses have affected the development of wind power industries; and to examine the impact of interactions among the three countries with respect to the diffusion of wind power technologies. Whether lead markets were actually formed and have created competitive advantages at the country level are the questions that guide our research. In this way, we intend to contribute to the literature on environmental innovation and sustainability transition studies, in line with the recent calls for addressing spatial factors (Binz et al., 2014; Coenen et al., 2012; Nill and Kemp, 2009).

The remainder of this paper is organized as follows: Section 2.2 presents the lead market approach, proposes extensions of this framework, and discusses its application to renewable energy innovation. Section 2.3 uses these indicators to analyse the development of lead markets in the wind power industry. Section 2.4 discusses the results and derives policy implications. Section 2.5 concludes the paper.

2.2 Lead Markets for Renewable Energy Innovations

The study of renewable energy has recently received much attention from a new angle in the emerging literature on environmental innovation and sustainability transitions. This approach aims to address social, institutional, political and economic considerations in an integrated manner (for different views, see Grubler, 2012; Pearson and Foxon, 2012; Verbong and Geels, 2010). Two dominant conceptual frameworks here are technological innovation systems (TIS) and the multi-level perspective (MLP). Both of these have, however, been criticized for neglecting, or giving little attention to, the geographical dimension of transition processes (Coenen et al., 2012; Markard et al., 2012; Smith et al., 2010).

Considering the global scale of the transition needed, it is relevant to understand the geographic unevenness of innovation processes so that privileged positions and their consequences are better explored. Whether countries or regions can achieve advantages of scale and scope and lead innovation through sheer size, localized concentrations of knowledge and capabilities or other intangible spillover effects is still unclear (Coenen et al., 2012). The recently developed lead market approach by Beise and Rennings (2005) offers an important entry-point for filling this gap since it pays explicit attention to the spatial dimension of technology diffusion. Moreover, it considers the implications of geographic aspects on environmental innovation in tandem with international competition (Quitzow, 2015).

Taking the concept of dominant design (Utterback, 1994) as its central theoretical underpinning, a lead market is defined as the market in which the diffusion of a dominant design first takes place. Following the tradition of innovation studies, dominant design here refers to the mechanism that, by creating standardization, leads competition to take place on the basis of cost, scale and product performance (Utterback, 1994). In the case of wind power technologies, this means that competition is based upon performances in terms of cost (such as costs of inputs and manufacturing process), scale (output increase along the supply chain) and power generation capacity (such as wind turbines, blades and tower sizes and power control mechanisms). The idea is that local preferences and environmental conditions in a specific geographic area favour the development of an innovation design that ultimately may become internationally dominant (Beise and Rennings, 2005). The lead market is identified by certain attributes of a geographic area where an innovation has been first broadly adopted, rather than where an innovation was first invented. It emphasizes that technological change is determined not only by sectoral dynamics but also by distribution of innovative activities in different geographic areas (Quitzow, 2015).

The introduction of a dominant design tends to shift the direction and rate of further technological change (Utterback and Suaréz, 1993). After the selection of a dominant design, the competitive emphasis begins to move towards cost, scale and product performance. The market reaches a point of stability in which products are standardized, or slightly differentiated, and radical innovations from within an industry are less likely to occur due to higher barriers to new entrants and decreasing competition (Fixson and Park, 2008). The early adoption of an innovation can generate learning benefits and economies of scale that are supplemented by a reduction of risk in the investment necessary to perform R&D for innovation. Thus the advantage of setting up a dominant design, as it can build up a competitive advantage to explore international markets and establish technological standards thereby creating a lead market position. As a result, a country would enjoy a first-mover advantage in terms of technology adoption. As such, it benefits from, for example, putting its firms in the forefront of learning curves and market development (Beise and Cleff, 2004).

In the case of renewable energy innovations, the formation of lead markets is intrinsically related to policy since such economically unlogical innovations critically depend on incentives provided by well-designed environmental and technology policies (Jaffe et al., 2005; Mowery et al., 2010; Popp et al., 2010). For the international diffusion of renewable energy in particular, the role of policy is even more critical. Because renewable energy sources offer no additional benefits in terms of cost, quality or functionality, their international diffusion has been typically preceded by the international diffusion of the regulation, which induced the original innovation underlying the lead market (Beise and

Rennings, 2005; Jänicke and Jacob, 2004). Lead markets are thus built upon a "regulatory advantage" [28], where the international adoption of a country's environmental regulation paves the way for the diffusion of an innovation. Hence, the interest from policy makers in establishing lead markets in sectors with a strong potential of becoming a technology supplier (Edler et al., 2012; European Comission, 2014). Within this perspective, the lead market concept is extended to embrace also lead supply (Quitzow, 2015; Walz and Köhler, 2014). The idea is that a lead market represents a competitive advantage built upon a dominant role in both innovation and international markets development (Köhler et al., 2013).

Lead markets can be identified by considering particular country-specific indicators that capture the likelihood that a design which first diffused domestically becomes globally adopted. According to the literature, these characteristics can be analysed through so-called lead market factors. Here, we extend the framework with lead market factors as developed in previous studies to address the idiosyncrasies and challenges specific to the international diffusion of low-carbon energy technologies. As discussed below, our framework is based on a set of five lead market factors: demand and supply side of domestic market, policy mix, technological capability and market structure (Beise, 2004; Beise and Cleff, 2004; Horbach et al., 2013; Quitzow, 2015).

2.2.1 Demand Side of Domestic Market

The demand side of a domestic market relates to price and demand advantages. Price advantages come from a relatively low price of one innovation design and are mostly based on economies of scale. These depend on market size and rate of market growth. Countries with rapid market growth can be earlier adopters because the cost of new technology is lower than that of late-comers when the production capacity is extended compared to production process of incumbent technologies. Moreover, faster growth lowers the risk of producers making full use of new investments (Beise, 2004). Additional sources of price advantage are lower costs of input factors and complementary goods. The price advantage can be considered one of the most significant lead market advantages since large reductions in input cost and prices have played a key role in the global diffusion of many innovations.

The demand advantage refers to a country's market characteristics that improve the demand for an innovation and can be reproduced by other countries later on. Market trends in technological, economic, social and environmental areas serve as an advantage whenever increasing the perceived benefit from an innovation (Beise and Cleff, 2004). Policy can affect the shaping of demand advantages in the case of renewable energy innovation. For example, previous research indicates acceleration on the rate of innovation diffusion in the countries that signed the Kyoto protocol (Popp et al., 2011).

2.2.2 Supply Side of Domestic Market

The supply side of the market covers demonstration and export advantages. Demonstration advantages are based on a trial effect which extends beyond national borders (Beise, 2004). Somewhat at odds with the concept of technological transfer traditionally present in innovation studies, demonstration advantages indicate the ability of a country to successfully deploy a new technology and share information about it, thus reducing uncertainty about its initial adoption by firms or consumers in other countries (Beise and Rennings, 2005). Sharing of information on the usability and reliability of the innovation design increases the perceived benefits from an innovation for later adopters, including those in other countries. For environmental innovations, for example, data about emissions reduction and implementation schemes are valuable inputs to build interest in foreign countries about the adoption of more restrictive environmental policies. The export advantage refers to a country's ability to respond to consumer needs in other countries (Beise and Rennings, 2005). Exports of environmental innovations are fostered, for example, by: similarity with foreign markets in terms of regulation (Costantini and Mazzanti, 2012), conditions of use (Beise, 2004), and degree of export orientation in a region or country (e.g., local incentives to develop exportable products, internationalization of domestic companies, foreign domestic investment).

2.2.3 Policy Mix

Here we extend the regulatory advantage as defined in previous studies (e.g., Beise, 2004; Beise and Rennings, 2005; Horbach et al., 2013; Köhler et al., 2013; Walz and Köhler, 2014), to consider the policy mix to support diffusion of renewable energy innovations. Since there is consensus that optimal policies to support environmental energy innovation should combine environmental regulation and technology policy (e.g., Jaffe et al., 2005; Mowery et al., 2010; Popp et al., 2010), the analysis here goes beyond the early focus of the lead market approach on environmental regulation to embrace elements of technology policy. Environmental regulation focuses on creating incentives to reduce potentially harmful consequences of economic activities (*i.e.*, environmental externalities), seeking to foster diffusion of environmental friendly technologies. Technology policy, on the other hand, focuses on keeping expensive but promising technological options open and stimulating their innovation through public support for knowledge creation, including public R&D, subsidizing private R&D and stimulating diffusion through market subsidies, technology transfer and capability building. Of course either policy affects the entire set of activities from invention through innovation to diffusion, but the emphases differ. The combined implementation of such policies increases the likelihood of arriving in the long term at a wide diffusion of the best technology while reducing the overall costs of the entire process (Chowdhury et al., 2014; Wilson, 2012).

A policy mix supporting environmental innovation is increasingly used as a strategic element of economic policy aiming at increasing competitiveness through stimulating first-mover advantages (Fankhauser et al., 2013; Jänicke and Lindemann, 2010). A policy mix to support environmental innovation works as a lead market advantage as it combines incentives for technological change with the setting of regulatory standards followed in other countries (Beise, 2004). Countries search for a “lead position” through policy support since early compliance by a domestic industry can be used as an advantage to export technology. In this case, the national industry benefits from economies of scale, learning effects and patent protection associated with early compliance, which facilitate the international expansion of the respective industry. As a regulatory advantage, the policy mix refers to the role of policy diffusion in the creation of lead markets for renewable energy innovations.

2.2.4 Technological Capability

It is widely agreed that technological capabilities influence trade performance at firm, sector and country levels (see Dosi et al., 1990 for a review). This suggests that the competence of a country to use a lead market for gathering higher competitiveness also depends on its comparative technological capability. On the competitive arena, technological capabilities can serve as barriers to imitation (Costantini and Mazzanti, 2012). In the domestic market, local knowledge flows and technology clusters can enhance knowledge spillovers, thus promoting further innovation (Autant-Bernard et al., 2013). Policies to support lead market formation are commonly influenced by the domestic industrial base and related technology capabilities, since the integration of supply-side aspects into the lead market development enhances competitiveness (Quitzow, 2015). Markets for renewable energy innovations are then shaped not only by market dynamics, but also by policy. Here, the role of policy in realizing a lead market position lies in the stimulation of innovation and diffusion through fostering continuous development of dynamic capabilities and keeping technological options open so that international competitiveness is maintained.

2.2.5 Market Structure

The structure and extent of competition in the domestic market can increase pressure to achieve more innovation and lower prices, in turn enhancing the chances of international diffusion. There are different definitions of market competition. A traditional indicator is the degree of market concentration, measured by the number of buyers and suppliers and the market share distribution among them. For example, a large number of suppliers tend to keep prices low and stimulate quality improvements and adoption of new products offering a better cost-benefit ratio. Increased competition at a sectoral level benefits innovation and international diffusion by inducing further market growth (Aghion et al., 2012). Hence, competition in the domestic market favours the development of lead markets by increasing the likelihood of innovation to appeal globally because of its lower price, superior quality or better cost-benefit relation.

The lead-market approach as developed and applied thus far involves the previous five factors, which are summarized in Table 2.1. They can be seen to jointly capture the possible advantages of a country in leading the international diffusion of an innovation. These factors are interrelated and can possibly be mutually reinforcing (Beise and Rennings, 2005). The precise lead market position not only depends on the presence of these factors but also on the way they interact. Within this lead market framework, we discuss in the next section the development of lead markets for wind power technologies in China, Germany and USA.

Table 2.1: Lead market factors

Factors	Definition
Demand side of domestic market	Ability of a country to develop a market earlier than others, creating the possibility to shape foreign markets and serve foreign demand.
Supply side of domestic market	Demonstration advantage: demonstration effect derived from the ability of a country to be the first to successfully diffuse a new technology. Export capacity: ability of a country's industry to respond to consumer needs in other countries.
Policy mix	Ability to define policy measures (in terms of environmental regulation and technology policy) that are followed in other countries.
Technological capability	Knowledge base and absorptive capability. Integration into knowledge networks (industrial clusters, research institutions and international partnerships).
Market Structure	High competition level in the domestic market enhances pressure to innovate and reduce prices.

Based on Beise, 2004; Beise and Rennings, 2005; Horbach et al., 2013; Köhler et al., 2013; Quitzow, 2015; Walz and Köhler, 2014.

2.3 Lead Markets in the Wind Power Industry

Following the lead market factors mentioned (Table 2.1), here we analyse wind power technologies in China, Germany and USA. Only onshore wind technologies of commercial scale are analysed since offshore and small scale ones are still in an early development stage and have not been widely diffused. The focus is on the distinctive elements among the countries in order to grasp a better view on possible competitive advantages and signals of lead markets formation. The aim of this comparative analysis is not to extract “best practices”, but rather to understand how variations in national contexts and policies have contributed to build wind power domestic industries, as well as to identify the contribution of interactions between countries.

2.3.1 Demand Side of Domestic Market

The domestic demand represents an advantage as it nurtures the development of a national renewable energy industry and enables competence building in terms of deployment of new technologies. Moreover, the ability of a country to develop a market earlier than others opens up the possibility of shaping foreign markets and benefiting from foreign demands (Walz and Köhler, 2014). Following previous studies (e.g., Blanco, 2009; Dechezleprêtre and Glachant, 2014; Gosens and Lu, 2013), we use installed capacity and installation costs as indicators of domestic market advantage. We employ costs instead of prices to enable the comparison among the three countries. International comparison of wind power prices provide little insight to understand innovation diffusion since it is predominantly driven by electricity market regulation.

The contribution of domestic demand for the wind power industry development has been acknowledged by different studies (e.g., Corsatea et al., 2014; Dalbem et al., 2013; Dechezleprêtre and Glachant, 2014; Gosens and Lu, 2013). Growing demand in protected domestic markets creates opportunities for experimentation and testing, as well as for cost reduction through learning-by-doing and economies of scale (Anadón, 2012; Gallagher et al., 2011).

From 2001 to 2012, China, Germany and USA have dominated the wind power market, accounting for an average of 53% of the global installed capacity. Leadership, in terms of installed capacity, initially belonged to Germany, which was taken over by USA in 2008 and by China in 2010 (Figure 2.1).

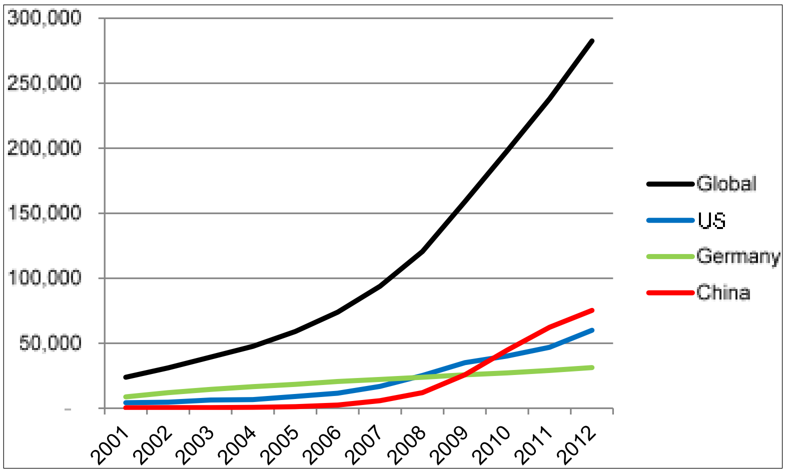

Figure 2.1. Total installed wind power capacity (MW); data from GWEC (2012).

In 2008, the leadership shift from Germany (only 7% additional installed capacity) to USA (50% additional installed capacity) came together with a decline of onshore turbine price estimated at 33% (IEA, 2013b). This price decline is attributed to the end of shortages of supply of turbines and components (e.g., gear boxes, blades and bearings), as well as declining prices of materials (especially steel and copper). China's leadership beginning in 2010 was based on a wider jump: 73.4% of installed capacity added, compared to 14.5% in USA and 5.6% in Germany (GWEC, 2012). Yet, cost can be seen as a main driver again. With yearly growth rates of added wind power capacity over a 100% between 2005 and 2009, the Chinese wind industry achieved strong cost reductions, and kilowatt electricity prices reached values between 35% and 55% below those in other countries (Lantz, 2014). In contrast, the expected advantage of scale has not always been realized in the wind industry. Between 2002 and 2008, global installed capacity doubled twice, while wind project costs in USA rose by more than 50% (Bolinger and Wiser, 2012). In this case, the 30% cost decline projected by the learning curve was neutralized by the increase in wind power capital cost due to supply side factors, such as rising commodity and raw materials prices, increased labour costs, improved manufacturer profitability, and turbine upscaling (Lantz, 2014).

Examining the evolution in terms of capital costs of wind power systems (composed by wind turbine, tower, foundations and grid connection components) enables further insights (Figure 2.2). Capital costs cover: wind turbine (production and transportation), grid connection (cabling, substations and buildings), construction (transportation and installation of wind turbine tower, construction of wind turbine foundation, and building roads and other related infrastructure required for installation of wind turbines) and other (development and engineering costs, licensing procedures, consultancy and permits, data management and monitoring systems). The capital costs for wind power systems vary significantly depending on the maturity of the technology and the local capital cost structure. The first, because internationally established, is considerably uniform; whereas the later provides a clear advantage for China and to a lesser extent for USA. Both these countries are expected to benefit from economies of scale due to the large number of new systems being installed in the coming years. Yet, China has an additional advantage in terms of lower labour costs and lower quality standards which reduce production costs and use of raw materials (Tan et al., 2013). An important reason for low prices of wind power systems in China until now has been low turbine efficiency. The Chinese market suffers from weak incentives to efficiency improvements due to the measurement of the renewable portfolio standard in kW of generation capacity, rather than realized production, and high levels of curtailment (Gosens and Lu, 2013).

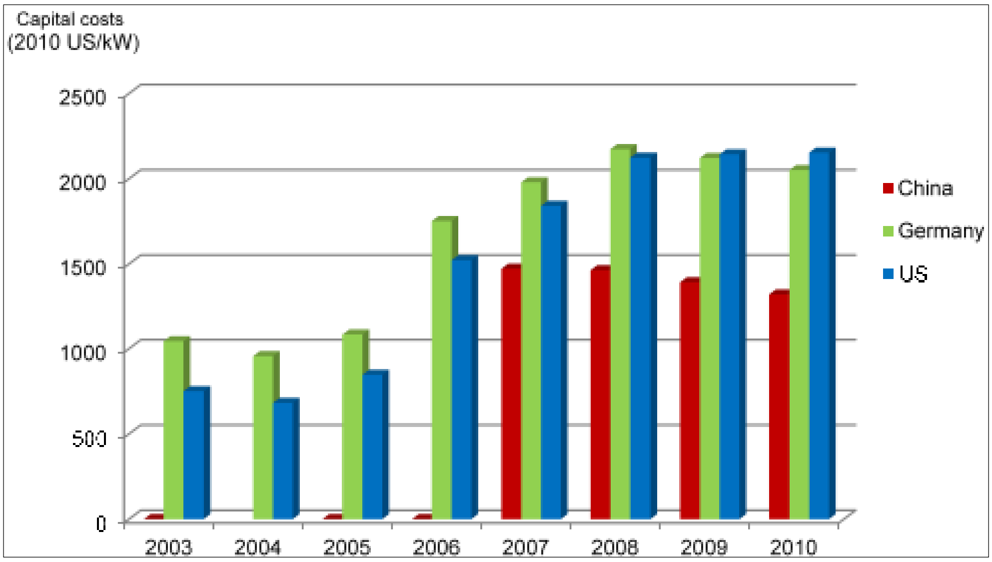

Figure 2.2: Capital cost of onshore wind power systems; data from IRENA (2012a).

A main factor driving the cost increase experienced by German installations between 2004 and 2008 (Figure 2) is the development of new turbine designs to improve adaptation to local wind conditions. German wind power system technology, compared to USA and Chinese ones, have higher power and larger hub heights. They are better suited to German wind conditions because they enable better wind capture and involve less land use, but they raise costs due to, among others, increased materials use and transport costs (Wiser and Bolinger, 2013). From 2009 onwards, Germany has benefited from subtle cost decreases explained mainly by economies of scale of production due to the diffusion of these larger power systems towards other countries, such as USA (Fraunhofer - IWES, 2014). Higher costs of installed capacity in the North-American market follow the same trend of an increase in turbine size as experienced in Germany in previous years. Still, by following the German innovation, USA wind power industry is benefiting from lower costs of larger turbines (compared to those of the initial development in Germany).

Considering the prospects for the near future, China is expected to maintain its advantage in terms of domestic market. According to the IEA (IEA, 2013b), by 2018, China will be the country with the largest cumulative capacity worldwide, with an estimated total of 185 GW wind power, followed by the United States (92 GW), Germany (44 GW) and India (34.4 GW). Chinese dominance is expected to be reinforced by the fact that the most significant factors associated with wind power price reduction in China are related to cumulative installed capacity: joint learning from technology adoption and learning-by-doing, and economies of scale (Qiu and Anadon, 2012). However, since it is based on low quality turbines, instead of investing in turbines development, the Chinese market seems to be driven by the benefits of imitation, simply reproducing turbines developed in foreign markets. These advantages of scale are also being pursued in USA. Recent reports point to turbine price reductions of as much as 33% for contracts signed by USA developers in 2011. This is considered to result partly from increases in manufacturing investment, production capacity, and industry growth in the national market, as well as a brief period of relative federal policy stability (Wiser and Bolinger, 2013). As well, both China and USA are expected to benefit from further reductions in operation and maintenance (O&M) costs, attributed to increasing turbine efficiency and additional economies of scale from very large wind farms.

2.3.2 Supply Side of Domestic Market

The supply side of the market takes into account the demonstration and export advantages. Demonstration advantages are based on a trial effect (Beise, 2004). It indicates the ability of a country to successfully establish a new technology and share information about it, reducing uncertainty about its initial adoption in other markets. The export advantage stays for the ability of a country to respond to consumer needs in other countries (Beise and Rennings, 2005). Here we seek to assess the export and demonstration advantages by comparing the performance on exports of wind power technologies by China, Germany and USA. We consider the demonstration and the export advantages together because, in the cases studied, countries started exporting wind technologies only after their initial deployment in domestic markets and mostly together with projects of technology transfer. Due to the high complexity characteristic of wind power technology, its deployment requires a minimum level of technological capabilities (Ru et al., 2012). Exports of wind power technologies have involved not only the parts and engines required to build a wind power systems, but also the information and knowledge needed to safely deploy them (BTM Navigant, 2014; Glachant et al., 2013).

Production of wind technologies in both China and USA has been directed mainly at the national market. Exports are a secondary goal, been strongly influenced by changes in their respective domestic markets. Factors that have commonly led to increases in exports are a production capacity surplus due to market entry of turbine and components manufacturers, a decrease in the annual rate of growth in the number of domestic installations, and higher turbine prices in the domestic market (Wiser and Bolinger, 2013). Germany’s production of wind technology, on the other hand, was traditionally focused on international markets, with export rates reaching up to 80% of production (Haščič, 2012).

Comparing the global share of exports and imports of wind technologies by China, Germany and USA (Figure 3.3) provides further insights. The higher shares of participation by USA and Germany, both in global exports and imports, indicates the effort of these countries to build a global position as a wind technology supplier as well as the benefits of building a local supply chain, in line with previous studies (e.g., David and Fravel, 2012; Neij and Andersen, 2012). China, on the contrary, appears to keep its wind technology industry prioritizing the national demand, which potentially explains its reduced involvement in foreign trade (Cao and Groba, 2013).

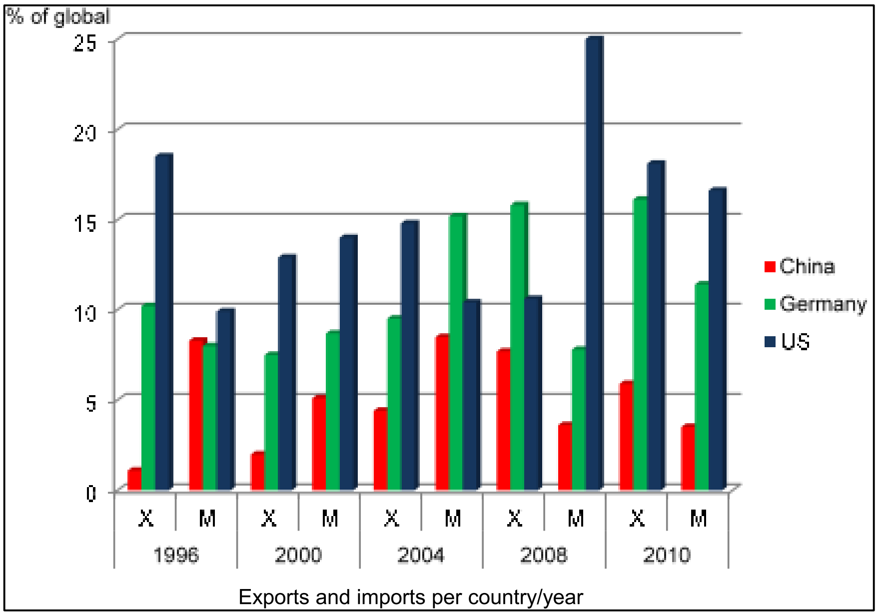

Figure 3.3: Percentage of global wind technology exports (X) and imports (M); data from UN Comtrade databasis (2014).

2.3.3 Policy Mix

Policy support works as a lead market factor by establishing domestic rules and market dynamics that later on influence international standards in policy design. Since policy typically paves the way for renewable energy diffusion, the first countries to adopt it tend to get a first mover advantage in terms of innovation and deployment (Beise and Rennings, 2005; Jänicke and Jacob, 2004). As is typically the case with environmental innovation, the regulation schemes to support renewable energy technologies evolved in tandem with the geographic diffusion path of wind power. The benefits from regulation towards the formation of lead markets in China, Germany and USA have developed differently depending, among others, on the timing and pace of diffusion in each country. Hence, the comparison of policy mixes takes these various features into account in determining their contribution for lead market formation. Building upon previous research, first date of implementation, uncertainty level, and scope are among the main criteria analysed (see Neij and Andersen, 2012; Wilson, 2012 for reviews).

Germany was a first mover, establishing a feed-in tariff (FIT) scheme to support wind power generation already in the early 1990s, and is perhaps the only country without any interruption in its feed-in tariff scheme since then (Haščič, 2012). Germany's FIT scheme is considered one of the most efficient in the world (Jenner et al., 2013). It is highly flexible due to a mechanism to adjust the FIT to the location, which increases the viability of projects in sub-optimal locations, promoting a more balanced geographical distribution of wind power generation. It also seeks to foster technological progress and cost reduction. Payment bonuses are offered as incentive to repowering and to increases in generation capacity, as well as adoption of the most efficient grid connection technologies (Ragwitz et al., 2012).

An additional advantage of policy support in Germany derives from its low uncertainty level. The stability and long term horizon of FIT together with priority dispatch and reimbursement for curtailment have reduced the risk of investment in wind power and kept costs of capital low. In addition, the national bank, KfW, has directly invested in projects and provided funds for commercial banks to finance wind power projects at low, fixed interest rates and with grace periods of up to 5 years (Fraunhofer - IWES, 2014). Altogether, this policy measures created a large renewables market in the country, fostered the development of domestic R&D capacities and consolidated the wind industry as a cluster. However, the creation of similar support schemes in USA and China in the last decade (Table 2.2) has shifted, at least partially, the initial advantages from Germany.

Table 2.2: Selected policy support instruments

Support Instrument Used by Country/Year of 1st Implementation	China	Germany	USA
Feed in Tariffs	2009	1991	
Premium or Adder System		2012	
Auction or tendering system	2002		
Tax based (electricity) production incentives			1992
Spot market trading		2008	
Investment subsidy or tax credit			1981
Tradable Green Certificate			1998 *
Concessionary finance through government supported agencies	2001	1989	1992
Concession on import duty	2003–2010		
Renewable energy Portfolio Standard or Purchase Obligation	2006		2002 *
Federal or state-level targets (binding or indicative) for electricity generation	2007	1991	2002 *
Project siting guidelines		1997	2002
Project permitting process	2001		2005
Priority access to the grid	2009	1991	
Grid code		2008	

Note*:* * At the State level, e.g., California. Data from: GWEC (2012); IRENA (2012b).

In China, regulation of wind played a key role promoting a transition from imitation and cooperation to indigenous innovation (Huang et al., 2012; Ru et al., 2012). While the Tenth and Eleventh Five-Year Plans (2001–2005; 2006–2010) put a strong focus on the R&D and innovation capabilities, the current Twelfth Five Year Plan (2011–2015) increased support to demonstration and diffusion activities to achieve the target of 11.4% of total energy use based on non-fossil sources (Lewis, 2011; Li and Wang, 2012). Moreover, in 2013, China’s public investment in renewable energy amounted to USD 56 billion, more than that in the whole EU (USD 48 billion) and USA (USD 36 billion) (UNEP, 2014). Challenges still to be addressed by policy support in China are the domestic supply of high-end components and grid connection technologies. In 2012, the Chinese market imported at least 50% of the high-added-value critical parts and components used, such as control and hydraulic systems (Li and Wang, 2012). Along the same line, further policy support is required to improve wind power connections to the grid and dispatch efficiency. In 2011, a third of wind capacity installed in China was not connected to the grid (GWEC, 2012). Up to now, there has been no incentive for a better distribution of wind farms within the country. For reasons of attractive land prices, the largest capacity has been installed at long distance from locations with the highest demand for electricity. Addressing these issues could create opportunities for China to further expand its wind power industry and, hence, to exploit additional advantages from public investment directed at wind power diffusion.

In USA, Renewable Portfolio Standards (RPS) targets, set at both state and federal levels, have been the main driver of diffusion of wind power. To meet the current RPS targets an average annual increase in renewable energy production of 3 to 5 GW between 2013 and 2020 is estimated to be necessary, well below the 16 GW of total renewable capacity added in 2012 (of which 13 GW were of wind power) (Wiser and Bolinger, 2013). This indicates important limitations of USA RPS programs to drive future wind power development. At the federal level, the past experience of stop-and-go wind energy support in the United States brings additional constrains to further increases in deployment. Since the early 1990s, federal support mechanisms (notably, the Investment Tax Credit, ITC, and the Production Tax Credit, PTC) have been erratic for political reasons. For example, between 1992 and 2010, USA Congress let the PTC for wind expire four times before eventually extending it again, contributing to wind deployment following cycles of boom-and-bust (IEA, 2013a). Even though this market uncertainty has not stopped local investments in wind manufacturing (possibly because of the large long-term market potential), it has affected the competitiveness of the local industries and prevented these from enjoying gains of scale and planning (Lewis and Wiser, 2007).

The comparison of selected policy instruments to support wind energy among the three countries illustrates the diversity of policy, in terms of instrumental design as well as timing. In Germany, policy support was initially developed in the 1990s, whereas the United States and China followed later, in the beginning and middle of 2000, respectively. From the 15 instruments analysed, only two are present in all three countries, namely concessionary financing through government supported agencies and targets for electricity generation. Concessionary financing is generally made through a loan provided at terms substantially more generous than those of market loans. The concession is achieved through interest rates below those available on the market, grace periods, or a combination of these (IMF, 2013). The adoption of priority access to the grid by China following the standards first established in Germany is the only clear example of a lead market advantage in wind power mainly built upon policy support. German companies have been the main suppliers of grid connection and management technologies for the Chinese market since the regulation of grid access was implemented (GWEC, 2012). However, no pattern of reproduction of instruments could be identified among the three countries, thereby no clear lead market advantage. This is in line with research showing that the design of policy support for renewable energy changes significantly to be adapted to local conditions, such as wind intensity, land availability, community acceptance.

2.3.4 Technological Capability

Technological capability refers to the ability to generate and manage change in technologies and is largely based on specialized resources (Bell and Pavitt, 1995). As a lead market factor, it represents an advantage in terms of dynamic efficiency that is difficult to imitate and requires deliberate investment and time to build since it does not follow automatically from the acquisition of foreign capital embodying new technology, nor from the accumulation of related operating know-how. Superior technological capabilities can form the basis of long-lasting first-mover advantages especially for technologies characterized as knowledge-intensive and highly dynamic, as is the case of wind power (Ek and Söderholm, 2010; Walz and Köhler, 2014). Thus, a country with a comparatively higher technological capability has an advantage in developing a lead market due to superior dynamic efficiency in technology management.

Here we use the share of domestic content of wind power facilities as an indicator of technological capabilities since the location of production involves availability of skilled technical personnel, information on available technologies and social institutions that reduce transactions costs. Previous studies have shown that countries with local supply networks have stronger technological capacities (Ernst and Kim, 2002). Moreover, technological capabilities facilitate local knowledge spillovers from international trade and foreign domestic investment, and thus contribute to knowledge diffusion within the domestic country (Glachant et al., 2013). Additionally, knowledge spillovers play a significant role in stimulating innovation in wind power technologies, both at the intra and inter-sectoral levels (Braun et al., 2010), together with foreign direct investment (Kirkegaard et al., 2009).

All the three countries studied present a high degree of domestic content of the wind power installations indicating strong technological capability building. Certain components, such as control systems and bearings, are supplied by firms from a wide range of countries as is also the case with leading wind turbine producers around the world (Kirkegaard et al., 2009). In 2011, USA local industry supplied 67% of the turbines and components installed in the country-up from less than 25% before 2005 (Bolinger and Wiser, 2012). German domestic wind equipment manufacturers supplied over 77% of the domestic market in 2009, while it exported 80% of total German-made wind power equipment (Haščič, 2012). In China, since the adoption of a law on “local content requirements” in 2003, on average about 80% of all components of wind turbines installed in the country have been locally manufactured and assembled (Qiu and Anadon, 2012).

In global terms, the importance of German and Chinese wind technology manufacturers is also clear. In 2011, Chinese firms were responsible for 26% of global installations, followed by German ones with 16% (Figure 2.4). General Electric (GE), the only USA based firm among the main global players, had a reduced share of global installations, 7% of total. In contrast, GE accounted for 38.2% of USA market (DOE, 2012), pointing to the influence of national installations on building up global market players. Such a market share distribution (Figure 2.4) also indicates higher degree of internationalization of German and Chinese firms if compared to North-American ones. For example, from the 8% of global installations of turbines by Siemens in 2011, 20% took place in USA.

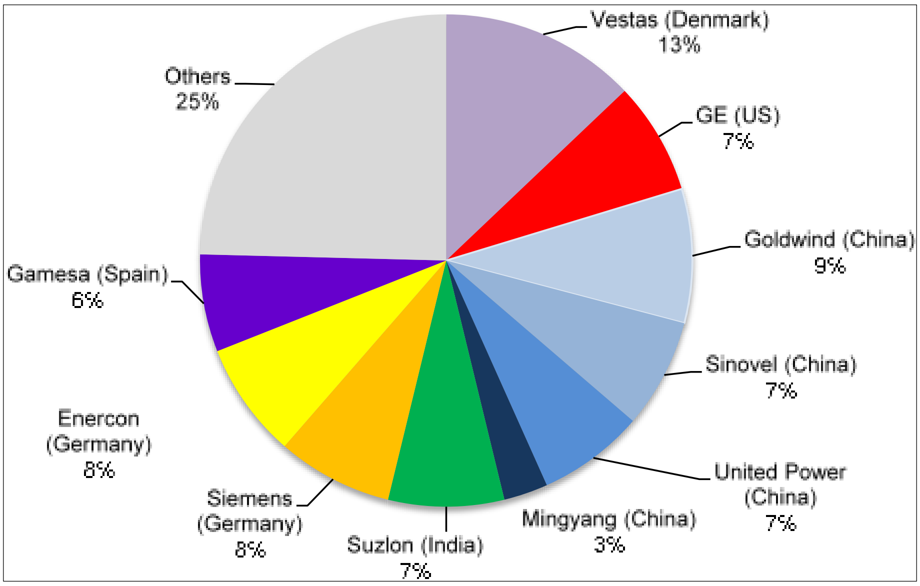

Figure 2.4: Turbine manufactures share of global installations; data from IEA (2013).

In contrast, turbine size shows a different pattern of change in technological capabilities. In 2006 the average size of turbines in China was 830 kW, with 600–850 kW turbines accounting for 80% of the market share. On the other hand, the average turbine size in Germany and USA was 1634 kW (Tan and Seligson, 2010). In 2011, the average turbine size had grown in all three countries, to 1.5 MW in China, 2.5 MW in Germany and 2 MW in USA (Fraunhofer - IWES, 2014; Wiser and Bolinger, 2013). Here Germany leads the technological development. Wind turbines with nominal powers above 3 MW are rapidly penetrating the German market and already represented 16.8% of newly installed wind power generating capacity in 2011–up from 6% in 2010 (GWEC, 2012). China and USA clearly lag behind. In 2011, the expansion of upgraded technology in China was still driven by 2 MW models, which accounted for 14.7% of newly installed capacity, and models with a power of over 2.5 MW accounted for only 3.5% (IEA, 2014a). In USA, turbines with 3 MW or above represented less than 8% of newly installed capacity (Wiser and Bolinger, 2013). Further reasons to consider the Chinese industry as lagging behind are problems with high levels of curtailment (up to 23% of wind energy production) and a below-average capacity load factor, the proportion of actual electricity produced compared to installed capacity (of 22% compared to 33% in USA). These figures indicate that China is still struggling to catch up with Germany and USA.

As wind power technologies are entering maturity, turbine model life cycles are becoming longer. In the German market, for instance, the wind turbines with nominal power up to 500 kW were dominant for 3 years, from 1990 to 1993, whereas the 1 to 2 MW class were dominant for almost six years, from 1998 to 2004, and current classes of wind turbines are dominating for even longer, since 2004 (Fraunhofer - IWES, 2014). This slowing-down of technological change may favour catching up by Chinese and USA industries, as it means more time for building up capabilities while past technological trajectories in other countries facilitate international knowledge spillovers.

2.3.5 Market Structure

The market structure as a lead market factor refers mainly to the degree of competition. We do not focus here on competition within electricity markets since previous research indicates that electricity market conditions have little effect on renewable energy innovation (e.g., Johnstone et al., 2010; Popp et al., 2010). Competition has been considered a crucial stimulus for innovation by researchers such as Schumpeter (1983) and Dosi et al. (1990). Based on the idea of creative destruction, the argument is that competition increases the pressure for technological change as innovations cause certain incumbent organizations, technologies, skills, and equipment to become obsolete which then creates opportunities for newcomers. Lead markets are usually highly competitive because competition speeds up technological development (Aghion et al., 2012) which enhances the adaptability of innovation to diverse market conditions (Cleff and Rennings, 2011).

Despite the fact that wind power is commercially deployed in 83 countries (IRENA, 2012a), it has a high level of market concentration in terms of geographical distribution: by the end of 2013, the top 10 countries accounted for 85% of the total global capacity, namely China (28.7%), US (19.2%), Germany (10.9%), Spain (7.2%), India (6.3%), UK (3.3%), Italy (2.7%), France (2.6%), Canada (2.4%), Denmark (1.5%) (WWEA, 2013). Market concentration at the geographical level is especially notable for competition in wind power, because of systems’ cost composition and companies’ organizational structure. 64% to 84%

of the investment cost of an onshore wind power system is the cost of the wind turbine (including turbine production, transportation and installation), of which raw materials respond for 60% to 90% (IRENA, 2012b). Of the remainder turbine costs, labour makes up 5% to 7%, while transportation costs 2% to 8%, depending on the wind turbine size (Cotrell et al., 2014; DOE, 2012). This combination of low labour input, internationally standard commodity prices and relatively high transportation costs create barriers for turbine producers to realize further cost reductions by shifting production sites to low-cost locations. Hence, investments in turbine production are expected to remain market-seeking, *i.e.*, to follow demand location, and remain geographically dispersed.

On the organizational level, the vertical integration of most wind turbine manufacturers, with internalized parts production and O&M services, spreads local competition to the supply chain. Geographical proximity of suppliers offers advantages of cost reduction through supply chain management based on techniques such as component commonality, just-in-time stocking and shorter lead times (IRENA, 2012a). In addition, local sourcing of wind power parts may benefit compliance of local-content rules and insulate from exchange rate fluctuation and customs duties.

Led by wind turbine manufactures, the supply side of the wind power industry is highly concentrated within China, Germany and USA (

Table 2.3). Market contraction due to declining prices of gas in USA and carbon in Europe and China, as well as a global reduction of public support, created a situation of over-capacity of supply and led the wind power industry to consolidation and higher concentration. Germany turbine makers experienced a decline in market share within China, where domestic suppliers constituted over 93% of the market in 2013, up from 28% just six years earlier, and some (e.g., Bard and Fuhrländer GmbH) filled for insolvency in late 2013 (IEA, 2013b). In the United States, there were factory closures and layoffs due to a shortage of new turbine orders (Wiser and Bolinger, 2013). China is expected to follow the same trend, with current predictions pointing to a reduction of two thirds in the number of wind turbine makers in the next five years (News, 2014).

Table 2.3. Renewable power capacity in 2013; data from REN21 (2014).

Technology/Power Generation in GW	China	USA	Germany
Bio-power	6.2	15.8	8.1
Geothermal power	0	3.4	0
Solar PV	19.9	12.1	36
Concentrating thermal power (CSP)	0	0.9	0
Wind power	91	61	34

Regarding a lead market advantage, the local production and companies’ headquarters location show important differences among the three countries. The German and the Chinese markets are dominated by national companies, which in both cases were responsible for more than 70% of the market. In contrast, only 40.3% of USA market was supplied by national players in 2013 (Table 2.4). A possible explanation is the difference in terms of policy support within the three countries. Whereas in Germany and China there was strong policy support for the initial stages of the innovation process (through R&D financing in the former and through technological transfer and acquisition in the later), USA policy was focused rather on the demand side (e.g., through Renewable Portfolio Standards). The lower degree of local production in USA probably follows the fact that most top 10 companies are of foreign origin, since the initial development of wind power manufacturing has historically been synchronized to domestic demand. On the other hand, USA market has an estimated 550 locally based manufacturers selling wind power equipment in the national market in 2012 (James and Goodrich, 2013). The large number of players in USA may be connected with the fact that the local industry benefits from a well developed financing system and from public incentives to wind power development, which foster entrepreneurship (Wiser and Bolinger, 2013) and mean a less risk-averse approach than in China and Germany.

In terms of competition with other renewable energy sources, wind power is the main renewable energy source by installed power capacity in China and in USA (Table 2.3). In Germany, even though with a slightly lower installed capacity than solar PV, wind power is ahead in terms of share in final energy supply with 16.2% compared to 6.4% for solar PV and 1.9% for solar thermal energy (Fraunhofer - IWES, 2014). These high shares of power capacity installed in all three countries give wind power technologies an advantage to compete with other renewable energy sources. For instance, the need to realize the forecasted return on investment of such installations builds up the pressure for priority of grid connections and adaptations suitable to wind power.

Table 2.4. Market share of 10 top turbine manufacturers (annual installations in 2012); data from BTM Navigant (2014); GWEC (2012); Wiser and Bolinger (2013)

Germany				China				USA			
Company	**HQ**	**LF**	**%**	**Company**	**HQ**	**LF**	**%**	**Company**	**HQ**	**LF**	**%**
Enercon	Germany	Yes	49.6	Goldwind	China	Yes	23.3	GE Wind	USA	Yes	38.2
Vestas	Denmark	Yes	20.0	United Power[2]	China	Yes	9.3	Siemens	Germany	Yes	20.1
Repower[1]	Germany	Yes	16.2	Ming Yang[3]	China	Yes	8.0	Vestas	Denmark	Yes	13.8
Nordex	Germany	Yes	8.4	Envision	China	Yes	7.0	Gamesa	Spain	Yes	10.2
Siemens	Germany	Yes	1.3	XEMC-Wind	China	Yes	6.5	Repower	Germany	No	4.5

GE Wind	USA	Yes	1.2	Shanghai Electric	China	Yes	6.3	Mitsubishi	Japan	No	3.2
Others			3.3	Sinovel	China	Yes	5.6	Nordex	Germany	No	2.1
				CSIC-Haizhuang	China	Yes	4.9	Clipper	USA	Yes	1.9
				Dong Fang	China	Yes	3.6	Acciona	Spain	No	1.5
				Zhejiang Windey	China	Yes	3.4	Suzlon	India	No	1.4
				Others			22.2	Other			3.0
Top 6 sum			***96.7***	***Top 10 sum***			***78.8***	***Top 10 sum***			***97.0***

Notes: HQ: Headquarters country. LF: Local factory; [1] Since 2014, renamed Senvion, subsidiary of Suzlon Group; [2] Before being restructured as a state-owned enterprise in 2007, United Power was Longwei Power Generation Technology Service, a joint venture with the US company Westinghouse between 1994 and 1998, and a joint venture with Siemens from 1998 to 2006; [3] A joint venture with German Aerodyn Energie Systeme Gmbh.

From the data analysed here, no clear lead market advantage for any of the three countries studied follows. In fact, quite the opposite holds for USA, where a lack of strong national players may mean little opportunities to compete with Germany and China since domestic investments in wind power expansion can be used to foster technological development of foreign companies. For instance, USA investment can increase the benefits gathered by German players from technological capabilities acquired through a long path of technological development, which occurred jointly with domestic market formation and the emergence of public support. German companies, despite being highly concentrated in terms of turbine production (the top 2 companies hold 65.8% of the national market - Table 2.4), are experiencing a trend towards outsourcing of manufacturing activities and increasingly focusing on O&M activities (IEA, 2013b). These provide steady revenues even when sales are falling, and can add value to turbine sales. For China, new benefits can possibly come from a global integration of wind industry value chains. With increasing components commonality, the production of some wind power system components (notably, those relatively easier to transport, such as bearings and gearboxes) can become more centralized, thus benefitting from economies of scale. As such, China has the advantage of comparatively lower costs, mainly in facilities for iron cast and forging (GWEC, 2012). Still, experts suggest that USA perhaps can build up a lead position in provision of financial services to wind power installations and grid infrastructure connection (IEA, 2015; Wiser and Bolinger, 2013). If this is true, it seems to suggest a situation with opportunities for the three countries to develop comparative advantages in different activities in the wind power value chain.

2.4 Comparison of Lead Market Factors

The analysis of lead market factors for wind power in China, Germany and USA delivers no clear “winner”. However, USA seems to have the weakest position. It has no clear advantage for any lead market factor relative to the other two countries. Advantages can be identified for China in terms of demand side of domestic market and policy mix, and for Germany in terms of supply side of domestic market and technological capability (Table 2.5).

Table 2.5. Summary of lead factors for each country.

Lead Market Factor	China	Germany	United States
Demand side of domestic market	++	0	+
Supply side of domestic market	+	++	0
Policy mix	++	+	0
Technological capability	0	++	+
Market Structure	+	+	0

Note*:* ++: strong advantage; +: low advantage; 0: no advantage.

In comparison to Germany, the demand side of domestic market advantage for China and to a lesser extent for USA, come with no surprise since these last two countries have larger energy markets (in total consumption), have higher CO_2 emissions rates in global terms and have started to scale up wind power energy more recently. Moreover, as discussed earlier (in Section 2.3.1), China has the highest growth forecast and the best conditions for cost reductions in the short run (due to competitive costs of inputs-mainly labour and raw materials transformation). Still, if China or USA will lead further wind power deployment remains an open question that seems to be better answered by policy support rather than by technological change. Reducing uncertainty of policy support for the wind power industry in USA could increase investment and technological innovation through risk reduction and better profit prospects.

At the same time, changes in Chinese policy design to optimize incentives for higher efficiency on power generation could fasten repowering and upscaling, adding a further impulse to domestic demand growth. Within this context, China’s stronger position in terms of policy can become a compounding advantage towards market leadership. In the last years, China not only made the largest amount of public investment, but also the largest expansion in foreign markets. Policy support for Chinese companies to adopt the so-called “Go Global” strategy have pushed foreign direct investment overseas from around USD 15 billion in 2005 to over USD 67 billion in 2011 (IEA, 2015). Chinese manufacturers invested more in electricity generation than in manufacturing bases or commercial subsidiaries, with 63% of the funds directed to the first (Tan et al., 2013). This strategy is aimed at securing markets for Chinese companies, which also started to suffer with oversupply in the global market and higher quality standards from foreign competitors. In the national market, Chinese companies enjoy an additional advantage with market reserve assured by the local content regulation and weak competition of foreign funded companies due to their comparatively higher price (GWEC, 2012).

In contrast, the German leadership in terms of supply side of the domestic market and technological capability seems to raise more promising advantages for leading the industry, especially in terms of innovation. The German wind power industry has been built upon stringent environmental policy, a strong industrial base and a high degree of integration in international trade (Ru et al., 2012), which are all difficult, if not impossible, to reproduce in the short to medium run. The German Wind Energy Association (BWE) has more than 20,000 members, making it the largest association of its kind in Germany and one of the world's largest associations in the field of renewable energies (REN21, 2014). Currently, the focus on modernizing transmission lines (Smith Stegen and Seel, 2013) and repowering (del Río et al., 2011) reinforces the German leading position on technological capabilities development. Moreover, the rapid pace of technological change in wind power technologies works as an additional barrier for China or USA to catch up with Germany. Even though lacking appropriated policy support, technological development in USA wind power industry is considered to be closely following the Germany in terms of wind turbines technologies (Bolinger and Wiser, 2012). Furthermore, powered by competitive energy as well as labour costs and exchange rates (Celasun et al., 2014), the recent trend of rebuilding of manufacturing activities in USA can be an additional push for wind power development in the country.

2.5 Assessment of Lead Market Potential

Altogether, the lead market factors analysed for China, Germany and USA show no clear indication of a stable lead market position for any of these countries. First-mover advantages seem to almost necessarily shift to different countries along the path of wind power diffusion. After all, the assumption of the lead market approach that a lead market is a development in a single country can be problematic in the case of wind power technologies. In the same way that previous studies concluded that technology learning in wind power is deemed to have both national and global components (Lindman and Söderholm, 2012), so does market dynamics. Hence, the difficulty of isolating factors in terms of geographical space to determine a country's competitive position within an industry and a market which work in a global scale.

The comparative analysis of the lead market factors in China, Germany and USA points rather to an international structure of the wind power industry, with countries occupying different lead positions within the supply chain. In line with previous studies, these results suggest that an international specialization within the production chain of wind turbines is under way, and that it is strongly connected to domestic policies supporting low-carbon technology diffusion(Dechezleprêtre and Glachant, 2014; Peters et al., 2012).

As a result, further diffusion of wind power technologies at the global scale tends to be led by countries that occupied lead markets positions in the early phases of diffusion. In this case, lead market factors can serve as indicators of future areas of specialization. As global diffusion brings wind technologies into maturity, the paces of change and of profitability growth are reduced. As a consequence, countries can increasingly benefit from competitive advantages formerly acquired to exploit the new market boundaries. The recent expansion of wind power in new markets such as in Brazil, India, Malaysia and Indonesia reinforce this perception. China and Germany have been playing a key role on the diffusion of wind power in these countries, notably in areas related to their respective lead market advantages. The German share in companies supplying grid connection equipment and grid management tools is growing, whereas China is becoming one of the main exporters of wind turbines and other wind power related components (IEA, 2014a; UNEP, 2014).

Interaction of wind power industries among countries may affect their performance on certain lead market factors and provide further impetus for shifts in competitive advantage of the wind power industry. If one country performs better in terms of any of the lead factors, this will have an impact on other countries. Within the last decade, the most significant interactions occurred between Germany and USA, and more recently between China and the previous two. Germany and USA have mutually benefited from different developments of the wind power industry at national and international levels. Advantages from demand growth in either market have spilled over between the countries generating cost reductions due to economies of scale and reduced times of product development (Section 2.3.1). Furthermore, in the middle 2000's, the installation by German companies of wind power systems in USA have reduced the domestic problem of supply shortages (see Section 2.3.5) and benefited Germany by increasing its return to scale of technological development. On another hand, China has benefited from diffusion of technological capabilities from Germany and market demand from the US (Sections 2.3.4 and 2.3.5). The later has been more recently explored through a strategy of going global from Chinese companies, as a reaction to limitations of demand in the national market. Technological capabilities previously developed by Germany have contributed to rapid cost reductions achieved by the Chinese wind power industry.

Chinese companies saved time and resources focusing on manufacturing and implementation, rather than on product development from the ground up.

Moreover, the turmoil promoted by the Chinese competition in the wind (and solar) markets in the last years points to the fallibility of lead markets as a policy goal. Efforts made by Germany, and other countries such as Denmark, to build up lead market advantages did not prevent a latecomer like China to dominate the market. Because manufacturers of Chinese wind technologies achieved batch supply capability, there was oversupply in the market and competition was intensified, leading to price decreases over the last years (GWEC, 2012). This resulted in a global restructuring of the wind industry, involving mergers and acquisitions, as well as companies going bankrupt. Foreign-funded companies located in China initially benefited from the emergence of Chinese wind power market, notably as it was characterized by a lack of severe competition due to insufficient supply of equipment. But these companies had to end their operations or were absorbed by other, mainly Chinese, companies when the prices started to fall in 2010. Previous advantages of lead market formation that, directly or indirectly, financed the internationalization of European and USA companies, were reversed into an over-capacity problem. From these companies, only the large ones survived, mainly because they benefited from a better reputation and were more trusted, both in terms of reliability of their products and O&M services.

Ambitious policy support for environmental innovation is expected to help industries to achieve technological leadership, thereby improving the competitiveness of the national economy. However, the innovation dynamic of environmental innovation in the energy sector is necessarily subject to international forces. At the supranational level, global climate policy informs the desired pace of energy system transformation by setting targets of GHG emission reductions. The innovation dynamics that follows takes place within the international competition for low-carbon technologies, based on national industrial policies. National suppliers in this sector are also usually exposed to international competition and the domestic markets are driven by this combination. Therefore, the difficulty of building domestic policies to achieve a lead market position at the industry level. Restricted to a national sphere and lacking control over costs (determined at the international level), governmental policies aiming at the creation of lead markets in low-carbon technologies, e.g., renewable energy, suffer of limited foresight and impact.

Despite the lack of a clear lead market formation, China, Germany and USA share some conditions that may have contributed for these countries to approach lead market positions within this last decade. From all five lead market factors analysed, two conditions seem pervasive on strengthening the three countries positioning: policy design and adaptation to different stages of wind power global technological trajectory. In all three countries policy was designed to support different elements of wind power technologies depending on the respective national industry characteristics and technological trajectory. For Germany, early market entrance and strong technological base made the initial focus on technological development and exports a rentable option. In USA, the stop-and-go cycles of policy support have pushed the industry towards a technology follower position, taking advantage of the combination of imitation and economies of scale due to its large domestic market. In China, the 10th and 11th Five-Year plans (2001–2005; 2006–2010) offered the initial support to build a national wind power industry, whereas the 12th Five-year plan (2011–2015) is expected to increase exports of goods with a higher value added, such as wind power system technologies. These cases offer further evidence to the literature in environmental policy where the technology aspect of policy support is increasingly recognized as a defining element of policy effectiveness.

2.6 Concluding Remarks

This paper has examined lead markets for wind power associated with three countries. This involved extending the existing framework for studying lead markets, and analysing the lead market potential of wind power in China, Germany and USA. The empirical analysis enables three types of conclusions. First, in response to our initial guiding questions: even though lead markets are difficult to be clearly defined at the country level, there is enough evidence that policy support for environmental innovation can help to create competitive advantages. The observed advantages for China and Germany in terms of particular lead market factors show a strong connection with policy support in each of these countries, while the comparatively weak position of USA appears to be closely connected to the lack of consistent policy support over time. In China and Germany, developing a lead market in wind power was clearly formulated as a policy goal, which served a broad policy framework encompassing objectives such as energy security and achieving international market dominance. Between 2008 and 2011, Germany (together with the European Commission, other member States and industry) have worked to carry out the action plans for six lead markets, one of them renewable energy, including wind power. The Lead Market Initiative (LMI) for Europe was launched by the European Commission following the EU’s 2006 Broad based innovation strategy. The scope of the LMI, the selection of the six markets and the action plans were approved in the Competitiveness Council of May 2008 [98,99]. Between 2010 and 2013, Germany also developed a project on lead markets sponsored by the funding initiative “Economics for Sustainability” from the Federal Ministry of Education and Research (Fraunhofer - IWES, 2014). China’s Twelfth Five Year Plan (2011–2015) defines renewable energy, including wind, as one of the strategic emerging industries (SEI) to be stimulated. One of the goals is to be an “international leader” by 2030, not only in terms of market share but also state of the technology [100]. This explains the long-term horizon of the policies implemented (e.g., contracts for feed-in tariffs for 15 to 20 years, Five Years Plan). Meanwhile, in USA, exploitation of gas intensified, fostering rapid growth of the related industry, and receiving increased policy support. Due to the strategic role of energy, the policy mix to support environmental innovation and competitiveness is often linked to a country’s geopolitical positioning.

A second conclusion concerns the impact of the policy mix in terms of environmental regulation and technology policy on technological trajectories. The assessment of lead markets for wind showed the relationship among the stage of wind power international diffusion, the technological trajectory at the country level, and policy design. In Germany, the diffusion of wind power coincided with early stages of its international expansion. At this moment, technological change and scaling up were occurring at a much faster pace than ever before. Benefiting from its already established supply capacity of technologies complementary to wind power, Germany was able to stimulate a rapid path of technological development in the industry. This involved building up advantages in terms of technological capability, knowledge flows and supply chain, while promoting domestic demand through strong subsidies for wind power generation. On the other hand, the diffusion of wind power in China started almost 30 years later than in Germany, at a moment when economies of scale had become more important and technological change started to slow down. The main lead market advantages of China–domestic market and policy mix–were developed in a context of rapid market expansion with high rates of growth and falling prices, strongly supported by policies stimulating deployment in national and international markets.

A third conclusion regards supranational interactions. The international dynamics of the energy markets, as well as the “race” for leadership in green growth, make innovation in renewable energy a necessarily supranational issue. In this case, interactions among countries have effects that go beyond the traditional risks of spillovers involved the innovation process. As demonstrated by the massive growth of the Chinese wind (and solar) manufacturing capacity, investment in diffusion can backfire. The rapid market expansion led to industry consolidation that has destroyed benefits of earlier (and more costly) investments, with the risk of an undesirable reduction in technological diversity and slowing down technological progress in the industry.

Striving for lead markets in wind power, although not clearly beneficial to any of the three countries studied, has contributed to the international diffusion of wind power technologies. As technology diffusion sets through, the cost gap between renewable and traditional fuel sources narrows, making renewable energy sources a more attractive option in countries where it so far was too expensive. The benefits of pursuing a lead market position by one country spill over to other countries, as renewable energy technologies become more affordable. In a similar way, the benefits of reducing emissions through higher renewable energy use also spill over to contribute with the global challenge of climate change mitigation.

The extended framework for lead market testing highlights the importance of spatial conditions to the international diffusion of renewable energy innovations. The differences among the lead factors for China, Germany and USA indicate the diversity of local characteristics relevant to wind power development. Therefore there is a need for a policy mix that addresses multiple goals. The position of a country’s wind power industry on the curve of innovation, its technological trajectory and knowledge base play a key role in defining the most suitable policy mix. In terms of future research, it would be good to have a clear understanding of how important different lead market factors are, what is their relative weight, and the extent to which they contribute to spur renewable energy innovation and to sustain competitiveness.

Chapter 3

Diversity in Solar Photovoltaic Energy: Implications for Innovation and Policy[*]

3.1 Introduction

The threat of climate change and peak oil is stimulating investments in renewable energy options as widespread deployment of low-carbon technologies is required to tackle these challenges (IEA, 2014a; IPCC, 2014). Solar photovoltaics (PV) is widely considered to be among the main options to play an important role in the long term. The reason is that it directly taps into solar energy, has no moving parts, and is consistent with decentralized and off-grid solutions (IEA, 2015). This suggests that solar PV has long-term competitive potential compared to traditional and other alternative energy sources (IEA, 2015, 2014a). Grid parity - equality of the production costs of electricity from solar PV and of conventional sources - is considered to have already been achieved for some very specific technical and geographical conditions, while a broader realization of grid parity is expected in the next five to ten years (IEA, 2015, 2014a).

Although the cost of solar PV has dropped by a factor of nearly 100 since the 1950s - more than any other energy technology in the same period (IEA, 2015; Nemet, 2006), a main concern is how to maintain a rapid rate of unit cost reduction. Past cost reduction has been driven by a combination of technological improvements and gains of specialization (IEA, 2015, 2014a).

From 2000 to 2014, solar PV was one of the fastest-growing renewable energy technologies worldwide, with an average annual growth of installed capacity of above 40% (IEA, 2015). Solar PV is moving in the direction of being a mature technology. This raises

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the question of which degree of diversity is desirable to ensure steady progress, avoid undesirable lock-in, while also enjoying a sufficient level of increasing returns of adoption. Diversity is considered here - from an evolutionary-economic perspective - as having benefits next to costs, because it fosters evolutionary progress through innovation (van den Bergh, 2008). Diversity stimulates recombinant innovation and technological spill-overs, which speed up technological development

This study aims to map diversity in the solar PV industry, as well as contribute to a better understanding of the role of diversity in stimulating an adequate pace of technical progress in terms of innovation and diffusion to mitigate climate change. By studying nine performance indicators, the various solar PV technologies are examined in terms of technology, market and actor (both country and firm) dynamics. Based on our findings, we draw policy recommendations for supporting solar PV development.

The structure of the paper is as follows. Section 3.2 introduces the framework and research method. Section 3.3 presents the results. Section 3.4 discusses the results and policy implications. Section 3.5 concludes.

3.2 Material and methods

3.2.1 An evolutionary economics’ perspective on diversity

In recent years, a significant body of literature has emphasized the potential of evolutionary economics to analyse environmental problems (van den Bergh, 2008), including those related to energy use and the energy sector (Costantini and Crespi, 2010). Evolutionary economics departs from the concept of population (of agents, technologies, products, strategies, organisations or institutions) which are subject to selection and innovation dynamics (Nelson and Winter, 2002). Selection generally reduces existing diversity, whereas innovation increases it, and their interaction leads to complexity and (phases of) progress.

In evolutionary economics, diversity is generally seen as positively contributing to technological progress in terms of the speed of innovation and cost reduction (Rosenberg, 1983). By maintaining variety within a resource pool, diversity facilitates spillovers among distinct technologies. Keeping options open is beneficial to innovation when it reduces the lock-in to incumbent, dominant technologies, which have a competitive advantage from auto-reinforcing increasing returns to scale (Dangerman and Schellnhuber, 2013). An example commonly seen in renewable energy technologies is the policy-driven creation of niche markets. Furthermore, by keeping options open, diversity enables higher system flexibility and increases the likelihood of finding good technical or organizational solutions in the face of high uncertainty about long-term (international) economic, political and social conditions (Stirling, 2010). Additionally, diversity increases the chance of recombinant innovation since it involves a larger number of different elements and therefore the likelihood of many possible connections to be created among them. In the case of solar PV, the diversity of technologies may spur innovation by allowing the combining of several pre-developed modules and components. Moreover, innovation (in such modules) benefits from diversity in system designs and regulations in different geographical areas around the world. Finally, diffusion of innovations can benefit from diversity since a pool of options improves system adaptability (Wilson, 2012). In the case of solar PV this is relevant because the conditions of installation and operation significantly change according to local circumstances, and in turn affect innovation and diffusion rates and direction.

Nevertheless, diversity seldom offers a ‘free lunch’ (Weitzman, 1992). Higher levels of diversity may entail higher costs through foregone increasing returns to adoption. The higher the technological diversity, the lower the share of each technology in the market, and, hence, the lower the returns to scale that can be enjoyed. These arise on both the demand and supply sides of markets, and include economies of scale in production, compatibility with other technologies via standardization, learning effects, network externalities, and information externalities (more common products are better known and more trusted by consumers).

The challenge is to find a balance between these various benefits and costs of diversity (van den Bergh, 2008). The complete evolutionary picture is that innovation forces generating diversity are complemented by selection through competition, regulation and institutions. Nevertheless, through the process of repeated selection among diverse technologies, path dependency results which may give rise to lock-in to suboptimal technological options.

When considering the desirable or even optimal level of diversity in energy policy making and sustainable innovation, it should be noted that diversity is multidimensional. It has been defined by three main properties: variety, balance and disparity (Stirling, 2010). Variety refers to the number of categories into which a population can be portioned and can be seen to reflect the number of options within a system. Balance can be defined as the distribution of frequencies of each category or option within the population. Lastly, disparity relates to the degree of difference among, or distance between, the options. *Ceteris paribus*, the greater the variety, the higher the balance, or the more disparate the options, the greater the diversity.

There are still few systematic frameworks to assess, empirically or conceptually, the value of diversity. One idea is to explore the notion of optimal diversity, which reflects balancing the various short- and long-term costs and benefits of diversity, taking into account its three dimensions (van den Bergh, 2008; van Rijnsoever et al., 2014).

3.2.2 Research Method

The framework of analysis used here to examine diversity and its role in the solar PV industry departs from the conceptualization of technological change in the solar PV industry by (Andersson and Jacobsson, 2000) and (van den Heuvel and van den Bergh, 2009).

This approach, as summarized in Figure 3.1, enables the study of selection and innovation processes involving the distinct technology options, their specific characteristics, strengths and weaknesses as well as their specific dynamics in the technology, market and actor dimensions.

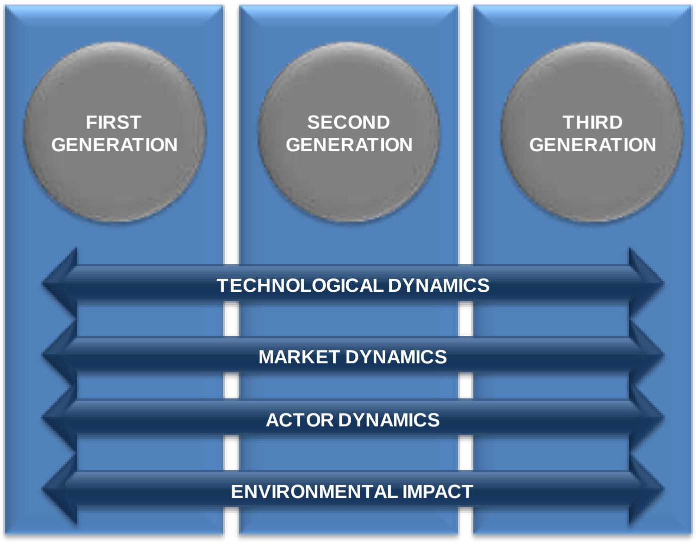

Figure 3.1: Analysis framework. Inspired by Weitzman (1992) and Anderssonand Jacobsson (2000).

For our analysis we proceeded in four major steps. First, to map the most relevant mechanisms of technological development in solar PV technologies, we performed an ample secondary data search of publicly available data on the PV industry. To this end we used information gathered from academic publications, industry associations, research organizations (such as energy agencies), and government and company reports. As a second step, we analysed the information gathered in step one to outline diversity in the solar PV industry. The third step was dedicated to the selection of indicators for technology, market and actor dynamics used to explore technological diversity in the solar PV industry. Here, technology dynamics refers to the rate and direction of technical change, market dynamics relates to the diffusion of solar PV technologies, and actor dynamics is associated with the number and type of firms that enter and exit the industry. We then analysed different solar PV technologies following the framework previously established.

We undertake a mainly qualitative analysis, which uses nevertheless some descriptive statistics to illustrate our arguments. By discussing recent changes in the solar PV industry, our aim is to provide a relevant analysis of its technological diversity and the underlying factors. Hence, in the following sections we are able to identify the qualitative nature, and in a few cases the statistical character, of certain trends associated with diversity in solar PV.

3.3 Results

3.3.1 Framing Diversity in Solar PV Technologies

For the period of 1940s to the early 1970s, research and development in photovoltaics was focused primarily on space applications and satellite power. With the oil crisis during the 1970s, development of terrestrial applications started and the solar PV industry was quickly established. Since then, the industry has experienced a continuous growth, characterized by a steady increase in installed capacity. World-wide, it surpassed 130 GW at the end of 2013, an increase from only 1.46 MW in 2000 (EPIA, 2014), with a steady decrease in prices - more than 80% cost reduction on a $/Watt peak basis for the period 1973 to 2011 (Algieri et al., 2011).

Photovoltaics (PV) is the direct conversion of sunlight into electricity, which is performed via photovoltaic cells. PV cells are built of layers of a semi-conducting material across which light creates an electric field, causing electricity to flow (IEA, 2015). Solar cells are coated with anti-reflective material in order to limit light reflection at their surface and to absorb the maximum amount of radiation possible (Chen, 2011). The intensity of light absorbed by a solar cell determines the amount of electrical power it generates.

Solar PV cells are arranged in series and in parallel to form a module. The modules can then be connected in parallel or serial configurations to form arrays. Complete PV solar systems are composed of two basic elements:

- modules, which contain solar cells;
- and a ‘Balance-of-System’ (BOS), which means the combination of electronic components, cabling, support structure, and for some devices, electricity storage, optics and sun trackers.

On the basis of previous studies, we decided to rely for our analysis on the classification of solar PV technology generations proposed by the European Photovoltaic Industry Association (EPIA). Following EPIA (EPIA, 2014), PV technologies are classified into three generations: the first includes devices that use silicon (Si) wafers; the second involves thin film technologies; and the third covers organic, dye-sensitized cells and other technologies that are emerging. Each generation refers to a plurality of technologies, which share technical and industrial complementarities. These technological generations represent the set of technological options currently in development.

3.3.1.1 First Generation PV Technologies: Silicon Wafers

Crystalline silicon (c-Si) is the most common and mature technology representing approximately 80% of the market today (IEA, 2014). The market dominance of crystalline silicon is related to several factors as explained in Table 3.1.

Table 3.1. Factors for c-Si market dominance.

Material characteristics	• Efficiency (as high as 25%) • Former shortage (has pushed rapid innovation in wafer production and cell manufacturing, lowering silicon consumption per W of module power produced – from 10 g/W in 2007 to current 7 g/W) • Current abundance (silicon supply is not expected to limit the production of Si-based solar cells even in the most aggressive scenarios of terawatt peak production per year) • Non-toxicity (easiness and cost of recycling)
Device performance	• Long term stability (25 to 30 years) • Reliability (low maintenance)
Manufacturing	• Learning curve of more than 80% (in terms of decrease of cost per watt peak) since the 1970s • Knowledge spillovers from the microelectronics industry

Source: Breyer and Gerlach (2012); Kerr et al., (2002)

The type of crystalline cells produced depends on how the wafers are made. The main types of crystalline cells are:

- Mono crystalline (mc-Si):
- Polycrystalline or multi-crystalline (pc-Si)
- Ribbon and sheet-defined film growth (ribbon/sheet c-Si).

Mono- and multi-crystalline cells have a similar production yield. The second type has an increasing market share. Ribbon c-Si, a third technology of crystalline cells, represents less than 5% of the market (EPIA, 2014). In terms of efficiency[3], mono-crystalline cells and modules lead with rates between 16-22% and 13-19%, respectively; whereas for multi-crystalline cells and modules the rates are between 14-18% and 11-15%, respectively (EPIA, 2014).

Despite the steady cost reductions of the first generation PV technologies described by the classical 20% learning rate (Breyer and Gerlach, 2012), there is still a strong potential for further cost reduction (IEA, 2014a). Two additional sources coming from outside the solar PV industry are believed to be promising, namely a reduction in material consumption, and an increase in device efficiency (Bolinger et al., 2015).

Today, the cost of a silicon module is dominated by the silicon substrate cost. For the period 1990 and 2010, wafers have decreased in thickness from 400 μm to 180 μm (IEA, 2014b). Similarly, the reduction of the solar cell thickness is expected to generate an increase in efficiency (Kerr et al., 2002). Furthermore, an increase of 1% in efficiency alone will cause a reduction in costs per W by 5-7% (IEA, 2014b).

3.3.1.2 Second Generation PV Technologies: Thin Film

Thin film modules are constructed by depositing extremely thin layers of photosensitive material on to a low-cost backing such as glass, stainless steel or plastic (IEA, 2015).

Thin film (TF) is currently seen as the main alternative to crystalline silicon for several reasons: its potential reduction of production costs, lower material usage, lower energy consumption, fewer processing steps, automated fabrication, possible use of flexible substrates and a shorter energy payback time (Lee et al., 2011). In addition, some TF technologies are considered disruptive as they involve innovations capable of shifting the learning curve towards higher learning rates (Bolinger et al., 2015). However, TF has lower efficiency rates, lower stability[4] and less durability[5] (IEA, 2014b). TF modules commercially available are differentiated mainly by the materials used and their efficiency rates (Table 3.2).

High-efficiency solar cells based on a multifunction technology using, for example, gallium arsenide and gallium indium phosphide, can have superior efficiencies. These cells currently have an economically feasible application for concentrating PV (CPV) systems (IPCC, 2014). CPV systems use concentrating optics to focus sunlight onto solar cells. An advantage of CPV is that with increased cell efficiency, the cell area can be reduced in

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[3] Efficiency defined as the percentage of incident light energy that actually ends up as electric power (IEA, 2015).

[4] Stability refers to different absorption rates for lights with different wavelengths (Lee et al., 2011).

[5] Durability is reduced mainly due to deformations after extensive sun exposure (Lee et al., 2011).

proportion to the concentration level. Yet, CPV requires direct-normal irradiation, which restricts its application to specific climate conditions with low cloud coverage. Moreover, CPV's require the use of a tracker to focus light into solar PV cells. This, however, causes particular problems and additional costs.

Table 3.2. Types of thin film modules.

TF module type	Module size; Layer thickness	Efficiency rate	Specifities
Amorphous silicon (a-Si)	5.7 m²; 1 µm	4-8%	• Lower manufacturing costs due to larger substrate size. • Light, flexible modules perfectly suitable for flat and curved industrial roofs.
Multi-junction thin silicon film (a-Si/µc-Si)	1.4 m²; 3 µm	7-10%	• Less instability due to smaller substrate size.
Cadmium telluride (CdTe)	1 m²; NA	10-11%	• Lowest manufacturing costs. • Is the most economical TF technology currently available.
Copper, indium, gallium, (di)selenide/(di)sulphide (CIGS)	1 m²; NA	7-12%	• Efficiencies of up to 20% achieved in laboratory. • More complex and less standardized manufacturing process.

Source: IEA (2015).

The market share of TF PV is approximately 15-20%, but could grow beyond 30% within the next decade (IEA, 2014b). Among the four types of module, Cadmium Telluride (CdTe) is currently the least expensive to manufacture, with module production cost of 0.76 US$/Wp (Raugei et al., 2012). The concerns regarding the use of cadmium, notably because of its toxicity, have been disproven. Life-cycle analysis has demonstrated that growth in the CdTe PV sector might reduce overall global cadmium-related environmental pollution as it facilitates recycling (Raugei et al., 2012).

3.3.1.3 Third Generation PV Technologies

Whereas first and second generation technologies strive to reduce costs through accumulated knowledge, third generation technologies refer to disruptive changes that seek to overcome the "Shockley-Queisser limit"[6] (IEA, 2014b).

These technologies are often categorised under two types following the focus of development: increases in conversion efficiency, and cost reduction. The former type focuses on technologies like "hot carriers", multiple electron-hole pair creation, and thermophotonics.

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[6] The Shockley-Queisser limit predicts that the existing technologies saturate at <25% efficiency on flat-plate modules unless novel features are included (IEA, 2014b).

The latter type focuses on low cost materials, low-temperature atmospheric processing, and high production volumes (Bolinger et al., 2015).

Following the guidance of the European Photovoltaic Industry Association (EPIA, 2014), third generation technologies that are already beginning to be commercialized can be classified as:

- Advanced inorganic thin films such as spherical CIS and thin-film polycrystalline silicon solar cells, which are low-cost (printed) versions of existing inorganic thin-film technologies.
- Organic solar cells which include both fully organic and hybrid dye-sensitized solar cells.
- Thermo-photovoltaic low band-gap cells which can be used in combined heat and power (CHP) systems.

Among third generation technologies, organic PV cells are seen as the most promising: they have constantly decreasing manufacturing costs (expected to reach 0.50€/W by 2020) and are already moving towards full commercialization (EPIA, 2014).

Organic PV cells involve fully organic PV (OPV) solar cells and the hybrid dye-sensitised solar cells (DSSC). OPV cells use stacked solid organic semiconductors, either polymers or small organic molecules. DSSC cells are made of dye molecules (the ‘sensitizers’) attached to a very large surface area of a nanoporous oxide semiconductor electrode, followed by injection of excited electrons from the dye into the oxide (Chen, 2011).

In 2009, 5 MW of OPV cells and 30 MW of DSSC cells were produced, and, in 2012, the production volume is expected to increase to 1 GW and 200 MW, respectively (IEA, 2014). The current efficiencies of OPV cells are about 6% for very small areas and below 4% for larger areas. For DSCC commercial applications still have efficiency below 4% (IEA, 2014).

3.3.1.4 Variety in solar PV technologies

The number of options among solar PV technologies has increased since the industry was established, as shown in Table 3.3. *Ceteris paribus,* the expansion of technological options means an increase in variety and, hence, higher diversity.

Table 3.3: Variety among PV solar technologies; data from: EPIA (2014).

PV solar generation	Technology alternatives	Year of first best research-cell efficiency reported
1st	Mono-crystalline	1954
	Multi-crystalline	1984
2nd	Amorphous silicon (a-Si)	1976
	Multi-junction thin silicon film (a-Si/μc-Si)	1976
	Cadmium telluride (CdTe)	1976
	Copper, indium, gallium, (di)selenide/(di)sulphide (CIGS)	1976
3rd *	Organic PV (OPV)	2001
	Dye-sensitised solar cell (DSCC)	1991

Note: *refers to cells.

The differences between technology generations are reflected by their distinct paths of technological development and market diffusion. The first generation, considered mature and with a dominant market share, is concentrated in two versions of the same cell technology. The second generation, thin-film, has higher rates of market share growth and increases in patent registration (as discussed in the following sections), and embraces various sources of materials, production processes and applications. Third generation technologies, although presented here as mainly comprising two alternatives, actually involve a broader set of approaches – based on new materials, devices or conversion concepts – which are still in incipient development stages. This diversity in terms of variety is relevant for the dynamics of technical change of solar PV, because it can increase the chance that unexpected spillovers and recombinant innovations take place (van den Bergh, 2008).

3.3.2 Diversity and dynamics in solar PV

Dominant designs are commonly selected through competition between different options. This then affects the direction and the rate of technical advance, as well as the industry structure and competition (Popp et al., 2013). The emergence of a dominant design usually means reducing uncertainty, promoting a shift in the R&D focus from product to process development, and enabling increasing returns of adoption and technology diffusion. A shift of technological opportunities for improvement occurs in the direction of incremental innovations. Many incremental changes, each promoted by a significant innovation, jointly form a discontinuous change that can unlock the system from the dominant design – whether this is fossil fuel based electricity or first generation PV (Ehrnberg, 1995). This illustrates the importance of technological diversity as it allows for many different incremental innovations to happen more often and at lower costs.

The idea that diversity contributes to technological development is broadly accepted in the literature on technology and innovation (Cooke et al., 2013; Grübler et al., 1999; Lechevalier et al., 2014; Lettl et al., 2009; Mohseni and Islam, 2012; Neij and Andersen, 2012; Skea, 2010; Stirling, 2010; Suzuki and Kodama, 2004; van den Bergh, 2008; van Rijnsoever et al., 2014; Wang et al., 2014; Zeppini and van den Bergh, 2013). Diversity is considered to play a crucial role in the development of emerging technologies (Dosi, 1982; Faber and Frenken, 2009; Nemet, 2012), such as renewable energy sources (Cooke et al., 2013; Dechezleprêtre et al., 2013; Noailly et al., 2013; van Rijnsoever et al., 2014). Knowledge accumulation together with the combination of diverse technologies can stimulate innovation required to accelerate a transition to renewable energy (Dechezleprêtre et al., 2015; Popp et al., 2011). Technological diversity of energy sources is further considered beneficial because it enhances security of supply and improves energy accessibility due to a wider geographical spread of energy sources. As explained in section 3.2.2, here we analyse a set of indicators for technology, market and actor dynamics to explore the state of technological diversity in the solar PV industry.

3.3.2.1 Technology dynamics

Two complementary forces drive technical change, namely "technology push" and "demand pull". The former cherishes technical change as a process driven by the supply-side and focus on radical innovations, whereas the latter involves (anticipated) market demand as a key determinant, and focuses on incremental innovations. In the framework proposed by Andersson and Jacobsson (2000), patents were used to indicate the size and orientation of technological activities among competing designs. We make use of their insights here.[7]

For the period 2002 and 2010, 442 patents were registered in the United States Patent and Trademark Office (PTO) for solar PV technologies, of which there were 116 in 2010. Data from the PTO is recognized as indicative of innovation worldwide since it enables inventors to avoid the publication of a patent while the granting is still under process as long as the applicant does not pursue patent protection in other countries (Popp et al., 2013). Comparing the distribution of patents between the three generations during this period (2003-

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[7] We are aware that there is debate in the literature on to what extent patents serving as a reliable indicator of technological progress. Andersson and Jacobsson (2000) use them merely to understand the direction of innovation. We interpret them here as a proxy of diversity.

2010), the first generation accounts for 29% of the total, the second for 41% and the third for 31%. This distribution is relatively even, which indicates balance. Seen as an indicator of technological development, a fairly equal number of patents can be interpreted as evenness in terms of effort being put into each technology which, in turn, contributes to diversity.

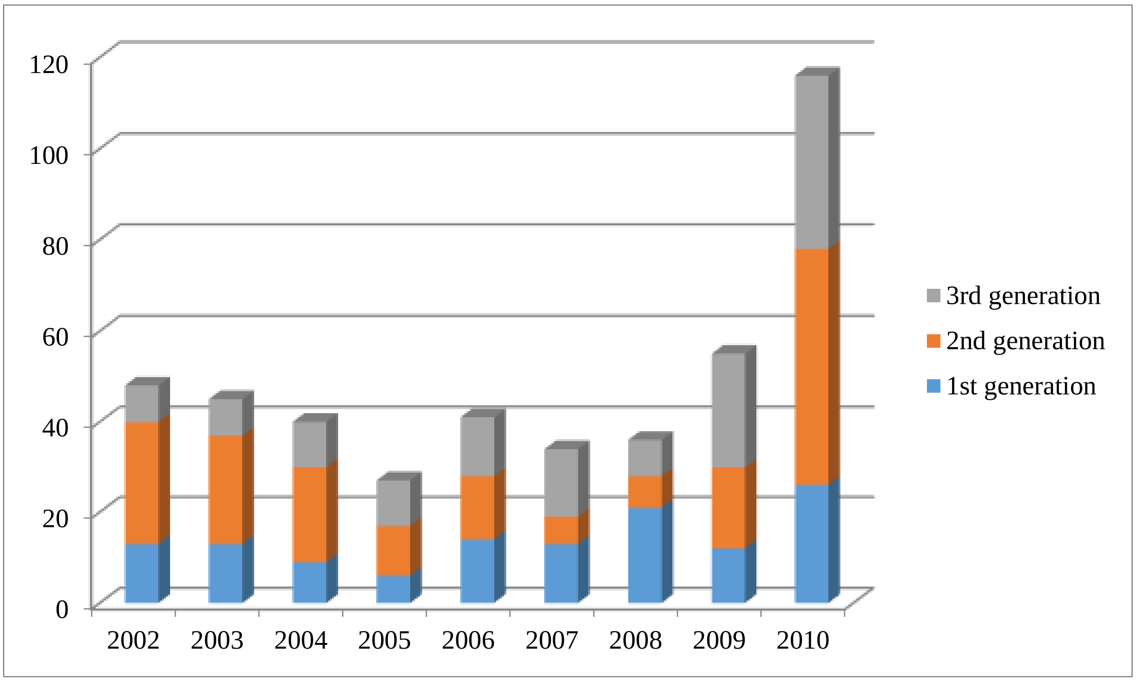

Figure 3.2. Number of patents per PV generation (2002-2010); data from Cleantech Group (2012).

Comparing patents registration per generation over time (Figure 3.2), the difference is more significant for the number of patents registered yearly for each generation than for the total along all years. For first generation technologies the largest difference between higher and lower yearly numbers of patents registered is 20 (6 in 2005 and 26 in 2010); for second generation, this is 46 (6 in 2007 and 52 in 2010); and for third generation, it is 30 (8 in 2008 and 38 in 2010). In terms of % growth, the diversity trend can be perceived in the last three years (2008-2010). For example, from 2008 to 2009, the number of patents for third generation technologies grew by over 200% whereas the one for first generation technologies shrank 43%. There is no clear pattern of fluctuation among the generations over the years. Generations can be seen as quite disparate in terms of patenting track and, therefore, diverse.

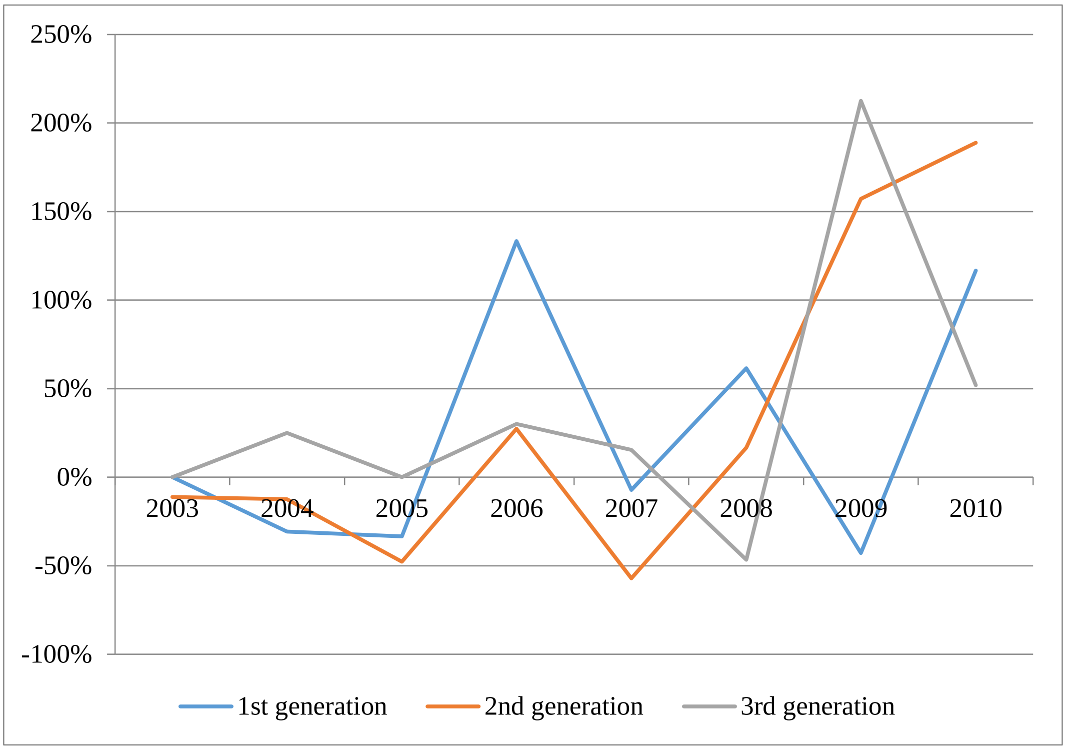

Figure 3.3: Evolution of number of patents registered; data from: Cleantech Group (2012).

The peak of patent registrations in 2010 is considered to be due to increases in R&D investment during previous years (Cleantech Group, 2012). In 2010, total patents in the solar PV industry[8] registered a record level of 339 (up 232% from 2009), second only to fuel cell patents, and far exceeding the level of wind energy patents which had been in second place in the clean energy sector since 2006.

The broad variety of photovoltaic technologies is expected to continue to make progress in terms of performance, reliability and cost (Raugei et al., 2012). Even though there is a loss of increasing returns from investment in R&D, diversity ensures gains derived from complementarities in knowledge bases (Wu and Mathews, 2012), technological capabilities development and the potential for technology breakthroughs from recombinant innovation.

In addition, market consolidation and growth are essential for the development of PV technologies; not only because R&D funding for solar PV comes mostly from private sources - 60% on average during the last decade (EPIA, 2011) - but also because it stimulates competition within the industry, which in turn will stimulate further innovation.

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[8] Patents registered for solar PV enhancement technologies (e.g., CPV, anti-reflective coatings), enabling technologies (e.g., racking systems, power conversion, heat sinks, bypass diodes, sun tracking) and PV applications (e.g., use of PV technology in a product) (Cleantech Group, 2012).

3.3.2.2 Market Dynamics

Market dynamics of renewable energy sources is characterized by strong environmental regulation and public funding. Market forces *per se* (i.e. uncontrolled by environmental regulation and technology support) fail to provide the incentive to develop or adopt renewable energy technologies, because these technologies have social benefits that are not captured in the private ones. Private investors tend to focus on the development of renewable energy technologies to the extent of complying with regulations designed to encourage it.

The different rates of technological progress of PV technologies affect market dynamics. Market forces promote selection among competing designs with distinct technological trajectories and rates of diffusion. For instance, the historical dominance of first generation wafer silicon cells, and the returns to scale it has already achieved, affect the impact of public regulation and funding on the other two generations of PV technology.

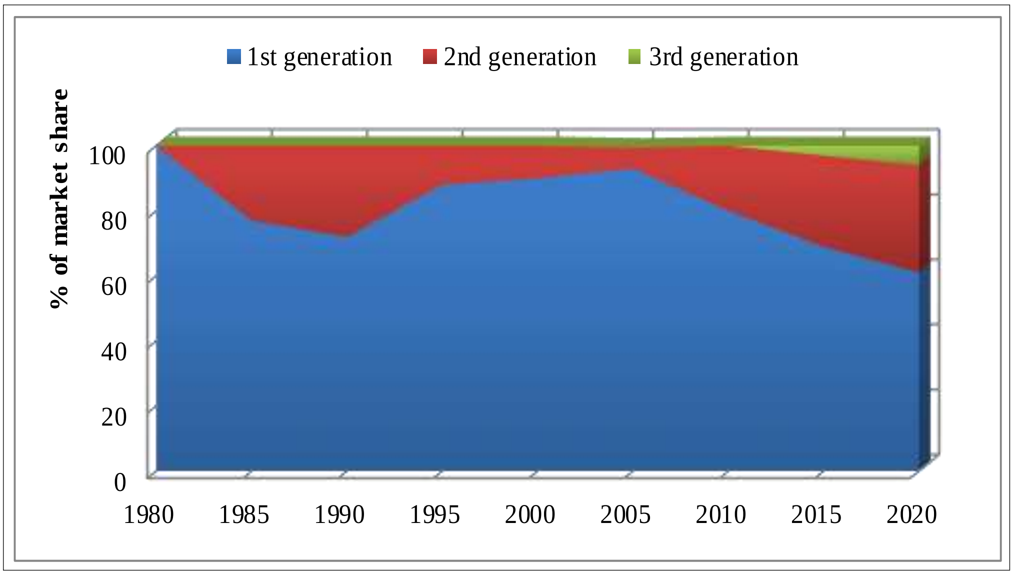

Figure 3.4. Market share evolution of solar PV generations in %; data from: EPIA (2011).

Analysing the rate of diffusion of each solar PV technology generation gives some insight into the level of diversity in the industry. As depicted in Figure 3.4, for the period 1980 to 2010, first generation technologies had a market share of 80% on average. Inconsistent with predictions of a growing market share for second generation PV technologies (to 28% and 33% in 2015 and 2020, respectively (EPIA, 2011)), data from 2013 show an even larger participation of first generation technologies with a 90% market share (ISE - Fraunhofer Institute for Solar Energy Systems, 2014).

The decrease of market concentration among the different technologies between 2005 and 2010 has not continued. Second generation technologies experienced a fall in market share from 16.5% in 2009 to 9% in 2013 (ISE - Fraunhofer Institute for Solar Energy Systems, 2014). With an increasing dominance of first generation technologies, the trend seems to be towards higher concentration and, consequently, a lower diversity.

Comparing the differences in cost trajectories between the solar PV technologies indicates higher diversity, as demonstrated in Table 3.4. In 2013, average costs ranged from 1 US$/Wp for second generation amorphous silicon cells to 3 US$/Wp for first generation monocrystalline silicon cells (Deutsche Bank, 2011). This shows a wide range, with the higher cost being triple the lower cost. The learning rate also shows a large difference, with 1% cost reduction for a doubling of cumulative installed capacity for the third generation compared with 90% for the first generation. These differences in terms of cost performance are indicators of diversity because they express how different the technologies are in terms of capability to compete in the market (e.g. Monocrystalline Si cells cost three times what Amorphous Si cost), as well as in terms of possible gains of scale (e.g. Monocrystalline Si cells' learning rate being up to 9 times higher than Amorphous Si, indicating that a doubling in the production volume of the first might lead to a 90% cost reduction compared to only 10% of the latter).

Table 3.4: Solar PV diversity in cost and learning rates.

Generation	Type of solar cell	Cost (US$/Wp[a])	Learning rate[c]
1st	Monocrystalline Si	3	85-90%
	Polycrystalline Si	2	
2nd	Amorphous Si	1	10-15%
	CIGS	1,5	
	CdTe-Cds	1,5	
3rd	Organic cells	2,83[b]	<1%

Notes: [a]The "peak watt" (Wp) rating of a solar module is the power (in watts) produced by the solar module under standard illumination conditions at the maximum power point. [b]Data from 2009. [c]Learning rate is the percentage cost reduction associated with a doubling of the cumulative installed capacity.
Source: IEA, 2014; IRENA, 2013.

The various solar technologies show differences between the costs of PV cells (Table 3.4), but not of power generation (Table 3.5). Despite particularities of deployment[9] (e.g., size and purpose of installations) and of cost composition (giving rise to differences in PV module costs and costs of BoS[10] elements) the ultimate differences in the cost of electricity

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[9] Each PV system requires a unique design based on site-specific characteristics.

[10] Since 2004, regardless of module prices, system prices have decreased steadily due to lower installation and maintenance costs derived from falling BOS costs (Deutsche Bank, 2011). BOS costs are viewed as critical for decreases in solar PV energy generation costs. Because they are dispersed among various components, they can be reduced through improvements coming from diverse industrial players, some not yet integrated into the PV supply chain.

production between different generations of solar PV may result to be moderate. This is illustrated by the case of commercial system cost in 2011 and the forecast up to 2016 (Table 3.5).

It should be added, though, that, the similarity of electricity generation prices is based upon different underlying components. Indeed, different combinations of gains of scale, capital costs, solar cells costs, learning rates and deployment arrangements result in similar overall prices, and thus competitive advantages. Moreover, rates of diffusion are expected to become more balanced too. The EPIA (EPIA, 2011) forecasts that crystalline silicon, thin film and other technologies will have equal shares in installed PV capacity around 2030. The cost of a typical PV system is expected to decrease from an average €2-3/Wp in 2011 to €1/Wp in 2030 and even €0.5/Wp in the very long term (ISE - Fraunhofer Institute for Solar Energy Systems, 2014). According to IRENA (2013), by 2016 solar PV is likely to generate electricity at a cost equal to or below the cost of grid-based electricity for at least half of US residential and commercial electricity consumers.

Table 3.5. Levelized Cost of Electricity (LCOE)[a] of Solar PV by Market Sector and Technology.

Year	**2011**		**2016[b]**		
Generation	**1st**	**2nd**	**1st**	**2nd**	
Solar cell technology	**Crystal. Si**	**CdTe**	**Crystal. Si**	**CdTe**	**CIGS**
US$/watt					
Module cost	1,12	0,75	0,63	0,48	0,50
Benchmark ASP[c]	1,43	1,28	0,73	0,63	0,70
Commercial BOS cost	2,10	2,25	1,50	1,60	1,53
Commercial all-in system cost	3,53	3,53	2,23	2,23	2,23
Residential BOS cost	3,80	n.a.	2,80	n.a.	2,83
Residential all-in system cost	5,00	n.a.	3,53	n.a.	3,53
US$/kWh					
Commercial LCOE	0,13-0,17	0,13-0,17	0,08-0,09	0,08-0,09	0,08-0,09
Avg. commercial power price	0,10	0,10	0,10	0,10	0,10
Grid parity	No	No	Yes	Yes	Yes
Residential LCOE	0,20	n.a.	0,13-0,17	0,13-0,17	0,13-0,17
Avg. residential power price	0,12	n.a.	0,13-0,17	n.a.	0,13-0,17
Grid parity	No	n.a.	yes	n.a.	Yes

Notes: [a]LCOE is calculated by dividing the aggregate cost of generation by the total kWh generated, using the mid points of the regions (Frankfurt Germany, and Naples Italy) and the nominal annual costs and output (kWh) over the 20 year useful life. [b]2016 projections assume 2-3% annualized increase in the U.S. average residential electricity price. [c]ASP is Average Selling Price.

Source: Deutsche Bank (2011).

3.3.2.3 Actor Dynamics: Countries[11]

The variety of energy policies and public support programmes, as well as the regulation of domestic electricity markets, mean that countries play the role of actors in the dynamics of solar industry. The case of Italy in 2011 makes this point clear. The release of new subsidies in the Italian solar PV industry increased its installed capacity from 3,500 MW to 12,500 MW (IEA, 2014a), an increase of almost 300% in a single year (from 2010 to 2011).

Comparing the distribution of cumulative installed solar PV capacity and the increase of new connected capacity in 2011 illustrates the trend of rising diversity among countries. In 2011, the increase in worldwide installed capacity was 66.8% (from 16.6 GW in 2010 to 27.7 GW in 2011), whereas the number of countries with more than 1 GW of additional capacity rose by 100%, from 3 to 6 - Germany, Italy and the Czech Republic, in 2010; Italy, Germany, China, the United States, France and Japan, in 2011 (IEA, 2014). Furthermore, there is also disparity of installed and newly connected capacity among the countries: in 2011, Germany had almost 33 times the installed capacity of the UK, despite the fact that the UK almost doubled its capacity in the same year. Explaining such differences among countries needs to take into account country size. For example, the entrance of China and the US in the pool of countries with more than 1GW of added capacity in 2011 involves fewer efforts (in economic and environmental terms) compared to France and Japan, due to, e.g., different total energy system size.

In 2013, Europe's role as historical leader in the solar PV market has come to an end. Europe's participation has fallen from 75% of new global installations in 2011 to 29% in 2013 (EPIA, 2014). Cumulative installed capacity outside Europe almost doubled from 30 GW in 2012 to almost 60 GW in 2013, demonstrating the ongoing rebalancing between Europe and the rest of the world. Solar PV market growth has shifted to Asia Pacific countries, with China and Japan being the leading players, accompanied by the US (IEA, 2014). China aims to raise its total installed solar PV capacity from the current 14 GW to 50 GW by 2020 (IEA, 2014a). This aim is not only motivated by cleaning its energy matrix, but also by reducing the problem of oversupply from its 1st generation solar PV companies. In Japan, changes in energy subsidies are fostering the diffusion of large-scale industrial PV systems with at least 100 kW installed capacity, which tends to favour second generation technologies. Also, in the US, all three grid-connected market segments – residential,

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[11] This and the following sections compare only the first and second technological generations of solar PV due to lack of data for the third. This might be explained by the fact that third generation technologies are still entering the market, which explains the absence of published unified information of the companies working in this field.

commercial and utility-scale – are experiencing robust growth, with demand being distributed among all three solar PV generations (Bolinger, Mark and Weaver, 2014).

The distribution of production capacity (in MW) per solar PV generation among countries leads to diversity in a different configuration. The global production capacity of first generation modules was estimated to be around 35.2 GWp in 2013, whereas production capacity for second generation (TF) modules was around 3.5 GWp (ISE - Fraunhofer Institute for Solar Energy Systems, 2014).

In 2012, China concentrated 78% of the total production of first-generation technology modules, followed by Japan and Korea with 5.8% and 5.4% (Figure 3.5). Production of second-generation modules was led by Japan (47.8%), and followed by Germany (29%) and the USA (22.6%) (Figure 3.6). Therefore, there are distinct differences in diversity between the two generations: the first has its production spread among a higher variety of countries with a high concentration in one producer (China), whereas the second displays a more balanced production among fewer countries.

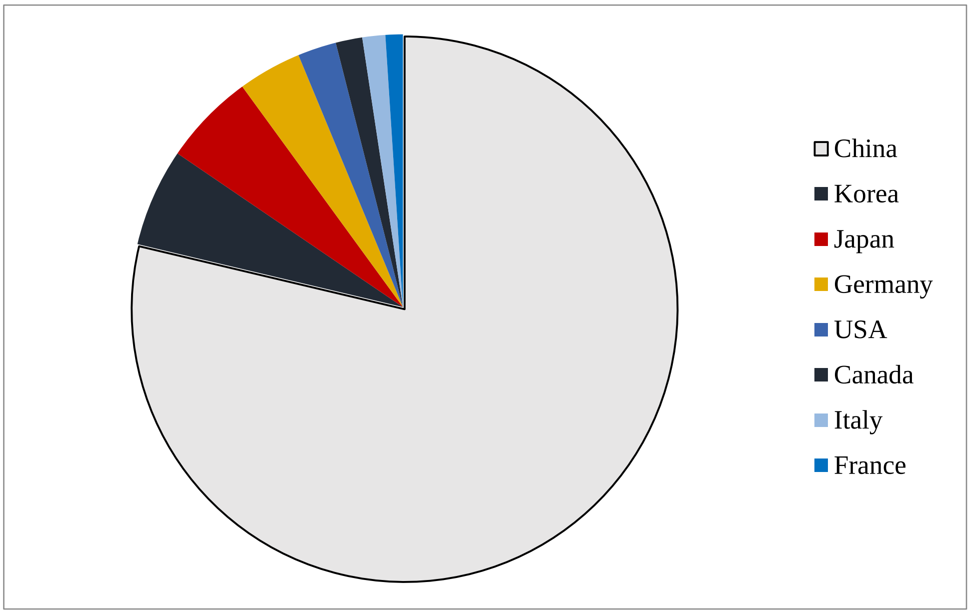

Figure 3.5: First generation module production per country in 2012; data from IEA (2014).

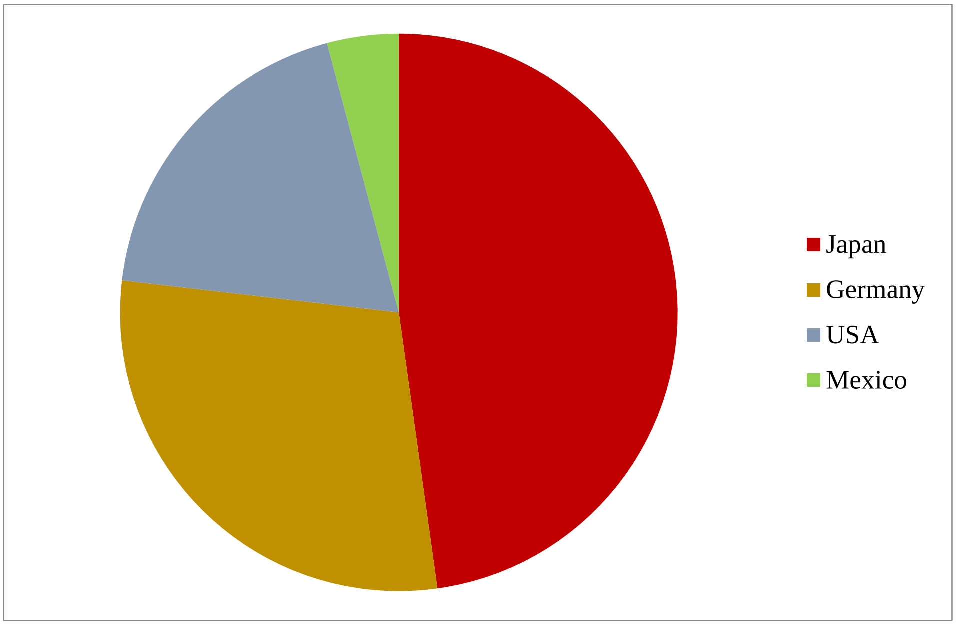

Figure 3.6: Second generation module production per country in 2012; data from: IEA (2014).

3.3.2.4 Actor Dynamics: Companies

Companies are also key actors in the solar PV industry dynamics. Besides the high degree of internationalisation and private funding of R&D in the solar PV industry, diversity within companies should be analysed because they articulate different and often complementary assets and behavioural patterns (Andersson and Jacobsson, 2000).

The majority of module makers produce their cells in house – in 2013 the highest outsource rate was under 30% (EPIA, 2014). The top 10 module producers, holding almost 70% of the global market share, are also cell manufactures. Hence, there is a predominance of overlap or integration between the two activities. For this reason, module producers are dealt with here, also because it allows us to capture broader aspects of diversity along the technology trajectory.

In 2013, around 1,000 companies produced first generation technology modules, totalling an estimated production capacity of 67.7 GW, but with only 47 GW of actual production (REN21, 2014), due to unfulfilled demand forecasts by some companies. The top 10 market players concentrated 48,1% of the first generation modules' total output (Bolinger, Mark and Weaver, 2014). Second generation technology modules were manufactured by about 160 companies: with a total production of 3.5 GW, where the top 2 market players responded for 71% of the total production (REN21, 2014). Therefore, there is an imbalance between the two generations. For the production of the first technology generation, there is a lower degree of market concentration than for the second generation. Even though a high level of variety of players (distinct in terms of size, output, revenue, strategy) may lead to higher technological diversity, the recent trend of consolidation of the largest market players as well as the concentration of production in China contribute negatively to diversity.

In the PV industry as a whole, there is a concentration trend driven by vertical integration and internationalization (IEA, 2015). It is triggered by price competition (and the consequent search for cost reduction), as well as the benefits of a multinational presence. This process might challenge the maintenance of diversity as the solar PV market becomes dominated by a few international companies. Market concentration can lead to a decrease in diversity in the absence of countervailing policies. Additionally, the lack of international agreements about how to set support schemes at a global scale endangers technological diversity by leaving the definition of a dominant design to a few market players.

3.4 Discussion and Policy implications

The results of the analyses in the previous section are summarized in Table 3.6. With the analysis of diversity based on the nine indicators examined here, our study contributes to the current literature in three ways. First, we show that diversity in the solar PV industry has different facets in distinct dimensions (technology and market) and actors (countries and companies). Second, we identify the mechanisms of solar PV technological development where diversity tends to remain constant or even grow. Finally we discuss the implications of technological diversity for policy aimed at supporting innovation and diffusion of solar PV.

In the *dimension technology* the growth in patenting activity for the distinct technologies can contribute to innovation as it stimulates diversity. Striving for specialization as the alternative to enjoy returns to scale and short-term efficiency (or cost-effectiveness) tends to hamper innovation. For the same reason, setting technological standards is not a wise strategy in an early stage of innovation because it poses a risk of inefficient lock-in. In addition, diversity serves to keep options open when there is uncertainty about which option will be best under future economic, social and technological conditions. The precise balance between short-term efficiency and diversity is likely to depend on the degree of uncertainty about successful innovations: the more uncertainty, the more diversity may be needed during some period of time.

Policy could promote the emergence of technologies that can be easily combined with others stimulating the creation of new technological options, such as modular designs. Modularization works at multiple levels and contributes to more complex and radical innovations. Knowing how related technologies and innovation processes affect each other increases R&D efficiency and enhances synergistic effects. This requires that policies are designed to foster modular innovations. Modularity also facilitates inter-sectoral spillovers which are especially beneficial for renewable energy technologies to overcome lock in to fossil fuels (Choi and Anadón, 2014; Delrio and Unruh, 2007). From a policy point of view, an additional advantage of diversity is that it avoids the 'picking of winners' by keeping technological options open (Popp and Newell, 2009).

With regard to the dimension *market* an important policy lesson is that promoting growth in market shares of very distinct, emerging solar PV technologies will contribute to a balance of disparate technologies, thus fulfilling two of the three diversity dimensions. This in turn contributes to long term technological progress. The recent development of solar PV in Japan serves an example, with Feed-in tariffs stimulating different installation technologies. In Japan, because solar PV installations were initially concentrated at residences, the new support scheme implemented since 2012 was designed to develop the non-residential market with, among others, the aim of increasing technological diversity, motivated by energy security (Muhammad-Sukki et al., 2014).

Table 3.6: Diversity trends

Industrial dynamics category	Indicator	Diversity trend[12]	Comments
Technology	Patents registered	Positive	The patenting activity among technologies paves the way for keeping and increasing diversity, which contributes to avoiding lock-in of first generation PV and increases the possibility of radical innovations leading to a faster diffusion of PV as an energy source.
Market	Evolution of market share	Negative	The increasing degree of market concentration hinders competition among technologies, raising the risk of technological lock-in due to increasing gains of adoption and diffusion.
	Cost	Positive	Diversity of costs contributes to technological development as it fosters efforts to improve efficiency. Yet, it also entails the risk of the cheaper design to become dominant.
	Learning rate	Fuzzy	It would be a positive trend if future developments of learning rates of second and third generation technologies follow the path of the first generation.
	Price	Positive	Price similarity tends to increase competition among the different technologies and, therefore, diversity of technological alternatives, which keeps options open.
Actor	Energy generation capacity	Positive	Reducing the concentration of installations among countries contributes to technological development as it allows for testing diverse deployment conditions.

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[12] A diversity trend is called positive when data analysis indicates a tendency to maintain or increase diversity level and negative in the case of decrease; fuzzy refers to the cases where contradictory trends for different performance indicators were found.

Increase of newly connected capacity	Positive	Diverse rates of diffusion contribute to further development of solar PV as it generates information about distinct policy and deployment schemes.
Distribution of production capacity	Negative	Concentration of production in a few countries threatens the evolution of PV as it may restrain technological development associated with specific characteristics of local industrial dynamics.
Number of manufacturers	Negative	Concentration of production by a few manufacturers hinders technological development as it increases market power and reduces the resource pool for further progress.

In terms of *actor dynamics*, distinct rates of diffusion of solar PV within (an increasing number of) countries contribute to diversity. Policy should take account of the scale of the market because maintaining a particular degree of diversity is costlier the smaller is the scale (e.g., a city or region). With a very large system scale like a sizeable country (e.g., Germany, the USA or China), or a supranational entity like the European Union, there are more opportunities for simultaneously realizing returns to scale and diversity benefits. This is especially true when regions specialize in the most suitable technologies given their climatic, industrial and knowledge (science) conditions. In this case, the conflict between scale and diversity becomes less pronounced. Improving electricity markets integration, such as at the European Union (EU) level, is a relevant strategy in this respect. Previous research shows that at high levels of EU market integration, solar PV can reduce the requirements of additional investment in grid infrastructure. For example, in a scenario of 15% solar PV penetration, solar PV installations close to dense consumption areas could reduce transmission capacity requirements by almost 75% (EPIA, 2012).

Additionally, a serious effort might be undertaken to stimulate knowledge transfer, dissemination and research cooperation between different countries (private and public sector, including universities), as is the case in the wind energy industry (Acemoglu et al., 2012; Gosens and Lu, 2014). In particular, this could lead to conducting research in larger international teams and more funding via international organizations.

We noted that diversity at the technological level only decreased moderately, as the large share of technologies remains silicon based. This suggests that radical innovations are still required, which calls for a stronger focus on fundamental research on solar PV. Public investment in R&D could therefore be aimed at stimulating ‘deviant’ technologies by subsidizing or funding risky R&D and facilitating the creation of technological niches. Since diversity is reduced by selection, public policy might further try to relieve or delay selection pressure for a while, so that alternatives are not too quickly disappearing from the market or the mix of R&D investments. This suggests to provide more subsidies per unit of investment the less developed and more promising is a solar PV technology. However, as recently shown by Kumar Sahu (2015), in the top ten solar producing countries policy support for solar PV is still very much focused on diffusion and less on innovation.

Many publications on stimulating renewable energy as a solution to global warming suggest a policy mix of environmental regulation and direct technological support (Acemoglu et al., 2012; Gosens and Lu, 2014). It has been stressed that such a package could effectively close escape routes like the green paradox (oil market responses), energy rebound and carbon leakage, which is critical for assuring global environmental effectiveness of policy (Dechezleprêtre et al., 2015).

The final message here is that diversity needs to be seriously considered as a separate or sub-criterion next to the traditional policy performance criteria like efficiency (cost-effectiveness), equity and sustainability, as well as next to the more pragmatic goals of security, accessibility and affordability. Probably it is best to see diversity as a sub-criterion since it affects long-term efficiency of energy strategies as well as security. More diversity can then best be seen as an insurance against uncertainty about technological and market developments.

3.5 Conclusions

The results of this study show that the dominant trend is an increase or maintenance of diversity among solar PV technologies. Diversity in solar PV favours its technological development and contributes to increasing its long run speed of diffusion. Especially in highly dynamic markets as is the case of solar PV, diversity works as a positive force by keeping options with potential long run success open, by reducing the chance of lock-in into one technological option, and by allowing for experimentation and spillovers. One should not think, however, in terms of maximizing diversity but striving towards optimal or desirable diversity, as diversity implies foregone increasing returns to scale (or gains of adoption).

It was argued that policy can try to stimulate relevant technological developments through stimulating modular innovations and deviant technologies. Moreover, policy makers could try to stimulate the coordination of specialization in specific technologies within large geographical areas (like the EU), to benefit from local market, expertise and climate conditions. In this case the conflict between diversity benefits and increasing returns to scale would become less pronounced. More generally, we have argued here that it is important for effective energy policy to recognize and take into account the value of diversity, and treat diversity as a separate policy selection (sub)criterion.

Chapter 4

Linking scientific knowledge evolution and environmental innovation: empirical evidence from wind turbines

4.1 Introduction

The literature on directed technological change has long argued that the process of innovation critically relies on the recombination of existing knowledge, ideas and artefacts. Yet, the growing importance of environmental innovation has raised new questions regarding the link between knowledge and innovation. On the one hand, environmental innovation is expected to offer a double advantage as it fosters competitiveness while also enhancing environmental sustainability (Ambec et al., 2013; Lanoie et al., 2011; Porter and Van der Linde, 1995; Stefan and Paul, 2008). On the other hand, environmental innovation suffers from a triple externality problem, since in addition to the common knowledge market failure, it faces drawbacks from environmental externality and lock-in (Acemoglu et al., 2012; Dangerman and Schellnhuber, 2013; van den Bergh, 2013). The problem of knowledge 'appropriability' hinders investment in environmental innovation in the same way that the environmental externality fosters over-exploitation of natural resources (Jaffe, 2012), whereas lock-in privileges further development of incumbent technologies (Heggedal, 2014). As a result, environmental innovation follows a distinctive dynamics compared to innovation in other realms.

A first and largely explored consequence is that environmental innovation is highly dependent on policy support (Jaffe et al., 2005; Johnstone et al., 2010; Popp, 2010; Popp and Newell, 2009). More recently, literature has emerged pointing to a particular knowledge dynamics of environmental innovation due to 'path dependency' in knowledge production

(Acemoglu et al., 2012; Noailly and Smeets, 2015). The idea is that knowledge builds on the 'shoulders of giants', i.e., that the prior knowledge base related to one technology strongly influences innovation in the same technology. Environmental technologies, because mostly newly developed, struggle with a reduced knowledge base compared to incumbent technologies. Accordingly, studies on various technologies converge to find that environmental innovations disproportionally benefit from heterogeneous knowledge sources when compared to incumbent technologies (Dechezleprêtre et al., 2013; Ghisetti et al., 2015; Horbach et al., 2013).

So far, research on the knowledge dynamics of environmental innovation has focused mainly on technological knowledge, usually looking at patents. Surprisingly, despite strong consensus on the close link between science and technological change, the role of scientific knowledge remains underexplored in the environmental realm. To fill this gap, this study extends the examination of the contribution of knowledge to environmental innovation developing a novel approach based on the analysis of scientific publications on wind turbines. By mapping the trajectory of scientific knowledge related to the advancement of wind turbine technologies, this paper addresses the following question: How scientific advances relate to the technological evolution of an environmental innovation? The answer to this question is relevant for the literature on environmental innovation, which needs to enhance the understanding of knowledge as driver of technological progress. Moreover, linking scientific knowledge and technological trajectory is relevant for policy making as it sheds light on the implications of technology-specific measures. Wind turbine is a suitable environmental innovation for our study because of its long trajectory of science-based development, technological complexity, widespread diffusion and quick up-scaling.

The remainder of the paper is organised as follows. Section 4.2 provides a short review of the empirical literature which attempts to map the links between science and technology, with a focus on the role of articles. Section 4.3 describes the dataset used and the methodological approach. The results are reported in Section 4.4. Discussion and conclusion follow in Section 4.5 and 4.6, respectively.

4.2 Conceptual framework

4.2.1 Linking science and technology

The relationship between science and technology has long been discussed as a main driver of technological change. At present, there is an emerging consensus that science and technology co-evolve and interact in rather complex ways (Balconi et al., 2010; Caraça et al., 2009; Dosi and Grazzi, 2010; Fleming and Sorenson, 2004; Murray, 2002; Rosenberg and Nelson, 1994; Trajtenberg et al., 1997). Furthermore, much empirical evidence on the emergence of major technological shifts during the last decades points to a tight link between new technologies and major scientific advancements in various sectors, where the most common examples are biotechnology (e.g. Magerman et al., 2015), ICT (e.g. Mazzucato, 2014), pharmaceuticals (e.g. Cockburn and Henderson, 1998) and semiconductors (e.g. Dibiaggio et al., 2014).

The fundamental implication is that closeness to science is expected to improve the rate of technological change. Science provides a guide to search and implementation of new knowledge, reducing trial-and-errors and therefore the overall time of development of a new technology. For instance, science can foster efficiency of private research activities by producing reports of successes and failures from previous research in a codified form of problem-solving (Dasgupta and David, 1994). Furthermore, access to scientific knowledge reduces search efforts by providing valuable information on technological opportunities and possibilities of re-combination of existing knowledge (Cassiman et al., 2008). Thus, scientific knowledge offers a map of technological domains thereby facilitating the optimal allocation of research efforts to the most promising technological opportunities.

At the same time, the impact of science is mediated by the level of technological complexity involved[13]. Highly complex artefacts tend to benefit the most of a tight link to science as the marginal gains of scientific guidance are larger if compared to simple systems. From a systemic point of view, the larger the number of parts and connections among these parts, the stronger the impact of scientific knowledge as avoidance of trials has an exponential effect over the final output. Moreover, the large rates of failure characteristic of highly complex products (Nightingale, 2000) render scientific knowledge guidance even more valuable. Additionally, from an organisational point of view, the use of scientific knowledge is advantageous as far as it facilitates understanding and foresight of the outcome of new (unfamiliar) knowledge combinations (Sorenson et al., 2006; Yayavaram and Chen, 2015).

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[13] Another mediator for the impact of science is absorptive capacity (see Cohen and Levinthal, 1990 and Zahra and George, 2002 for reviews). However, absorptive capacity is considered out of the scope of our study as we do not focus on the organisational or individual factors driving the impact of knowledge on technology, but rather on the relationship between scientific knowledge and technology evolution.

4.2.2 Knowledge dynamics and environmental innovation

Two main research strands have looked at the role of knowledge on the dynamics of environmental innovation. A first strand has been focused on the link between prior knowledge basis and resulting knowledge spillovers on current innovation. Studies show clear evidence of significant knowledge spillovers within environmental technologies (Popp, 2006; Verdolini and Galeotti, 2011), as well as between environmental and incumbent technologies (Johnstone et al., 2009; Noailly and Smeets, 2015). More recently, another research strand has focused on knowledge spillovers to investigate how knowledge flows among innovators. Here, patent citations (Aalbers et al., 2013; Noailly and Shestalova, 2013) and knowledge networks (Herstad et al., 2014; van Rijnsoever et al., 2014) are examined as representations of learning process among different agents.

Studies point to a high impact of knowledge spillovers on environmental innovation. An analysis of US patents granted between 1976 and 2006 by Nemet (2012) shows that knowledge originating in other technological areas has contributed to the most valuable advances in low carbon energy technologies. Popp and Newell (2012) demonstrate that clean energy patents have a higher chance of being cited than other patents. In a patent citation analysis comparing technologies from four sectors (namely, energy production, automobiles, fuel, and lighting), Dechezleprêtre et al. (2013) found that, on average, patents of environmental technologies receive 43% more citations than fossil fuel based ones. Furthermore, studies from Noailly and Shestalova (2013) and Aalbers et al. (2013) point to considerable heterogeneity among environmental technologies in terms of extension of knowledge spillovers and degree of path dependency.

Although research based on patents has greatly advanced our understanding of the role of knowledge for environmental innovation, its shortcomings are well known. First, not all knowledge is patented, so patent analyses tend to underestimate the actual extent of knowledge stocks and flows (Dechezleprêtre et al., 2013; Fleming and Sorenson, 2004). Highly technical and scientific knowledge are difficult to standardize and codify which works as a barrier for patenting (Cohen et al., 2002; Cohendet and Meyer-Krahmer, 2001). In particular, non-codified knowledge and know-how traditionally embodied in technological artefacts, interpersonal relationships and learning-by-doing are not captured by patent citations. Further limitations for using patents derive from: the cost of the patent application and the approval procedure (Nelson, 2009), interest on information disclosure (Bessen, 2005), institutional context of research (Agrawal and Henderson, 2002), market uncertainty (Kim et al., 2016) and level of IPR enforcement in the country (Cohen et al., 2002).

Arguably, scientific publications offer an alternative proxy to understand the relationship between knowledge dynamics and environmental innovation as discussed in the next section.

4.2.3 Knowledge dynamics and citation networks

Since the work of Garfield et al. (1964), citations among scientific publications have been increasingly used in studies to examine knowledge dynamics (e.g. Bhupatiraju et al., 2012; Epicoco et al., 2014; Hassan and Haddawy, 2015; Ponomariov and Toivanen, 2014). Citation analysis is advantageous because it escapes constrains characteristic of institutional boundaries where relevant data is maintained (Griliches, 1994). By mapping the most relevant research, citation networks can be valuable to inform policy makers about the balance between pull and push instruments of support to innovation in a specific area, as well as about the productivity of national investments (Newbery et al., 2011). Moreover, a global perspective over citations networks indicates changes occurring over time in the setting of knowledge generation and flows which influence technological trajectories (Leydesdorff and Zawdie, 2010). Citation networks have been used by recent studies based on scientific publications in order to identify the main technological or scientific trajectories that have characterized the evolution of specific research fields (e.g. Calero-Medina and Noyons, 2008; Epicoco, 2013; Mina et al., 2007).

Much of the empirical evidence points to a strong relationship between scientific publications and innovation. Previous studies indicate that publications have a positive impact on accelerating the rate of technological innovation essentially by fostering knowledge diffusion in time and space (Sorenson and Fleming, 2004). Researchers working at the industry consider scientific publications as a more effective knowledge source than academic patents (Breschi and Catalini, 2010). Likewise, a study with the MIT faculty indicates that scholars value publications to be two-and-one-half times more important than patents as a knowledge source (Agrawal and Henderson, 2002). In a survey with the US manufacturing sector, publications were identified as the main source of knowledge flows from the public sector (Cohen et al., 2002).

Studies combining the analysis of patents with scientific publications find that patent citations to scientific publications (as opposed to patent to patent citations) provide more comprehensive information about knowledge flows (Branstetter and Ogura, 2005; Hicks, 1995; Hicks et al., 2001). Furthermore, scientometrics evaluations indicate an important grow in the number and share of non-patent literature citations in patents (Bonaccorsi and Thoma, 2007; Popp, 2016). For instance, the analysis of citations to publications reveals that U.S.

patents in clean energy technologies cite more foreign than U.S. literature in contrast with patent to patent citations (NSF, 2014). This suggests that looking at publications enables to identify foreign links which would remain invisible in an analysis solely based on patents. Similarly, previous studies of pairs of patent-publications depict different scientific and technological networks (Murray, 2002). In addition, a combined study of patent citations to survey reports from R&D labs in the U.S. indicates publications to be a better measure of knowledge originating from public research than patent citations (Roach and Cohen, 2012).

There is wide agreement that scientometrics as a method to understand knowledge dynamics is advantageous because it enables the study of large amounts of data in a way that facilitates the identification of "hidden patterns" (Daim et al., 2006; Mina et al., 2007). Mainly two explanations arise. On the one hand, the number of citations has grown with the number of publications: in 1992, a publication in the areas of science and engineering received, on average, 1.85 citations, whereas in 2012 this number rose to 2.47 citations (NSF, 2014). On the other hand, the main alternative measure, patents, contain an increasing number of references to scientific articles (Jaffe and De Rassenfosse, 2016).

In fact, due to the consistent growth rate of journals and publications, bibliometric data has been gaining increasing prominence as indicator of knowledge dynamics (Hicks et al., 2015; Nelson, 2009; Sakata et al., 2013; van Eck and Waltman, 2014). Bibliometric data is considered the best standardized proxy to account for the overall evolution of knowledge systems (Abramo et al., 2012; Must, 2006), and offers the advantage of being defined by the research community itself and not by the analyst (Mina et al., 2007). With respect to research on wind turbines, articles can be considered as a fairly reliable indicator of the state of knowledge since the propensity to publish is relatively high in the field (EWEA, 2009; Quarton, 1998). In addition, the large number of observations minders the commonly indicated shortcomings of citation analysis (Agrawal and Henderson, 2002; Leydesdorff and Etzkowitz, 1998). This paper proposes to analyse citations among scientific publications as indicator of the knowledge evolution to understand technological progress. The idea is that in the same way that scientific citations are made to acknowledge the various contributions of prior research to the citing paper, citations portray knowledge stocks (cited articles) and flows (citing articles). At the aggregate, citations establish direct empirical connections to prior knowledge, and indicate the pattern of knowledge accumulation (Zhuge, 2006). In addition, we follow previous studies (e.g. Hassan and Haddawy, 2015) to use citation networks to map the distribution of scientific knowledge at the country level, looking at the information about authors' affiliations.

4.3 Data and methods

4.3.1 Wind turbines: rationale for case study choice and background information

Among all environmental innovations, wind turbines make one of the most interesting case studies to understand knowledge dynamics due to wind power long trajectory of science-based development, technological complexity, widespread diffusion and rich inter-sectoral connections (Bolinger and Wiser, 2012; Lindman and Söderholm, 2012). Wind power is the most widely diffused technology among modern renewables, responding to the highest share of electricity generation after hydropower - 2.3% worldwide in 2012 (IEA, 2015). In 2014, more than 24 countries had at least 1000 MW of wind power installed (GWEC, 2014). Since its early entrance to commercial power markets in the 1970s - initially in Denmark, following to California in the 1980s, and to Germany and Spain in the 1990s (NREL, 2012) - wind power technologies have quickly evolved and wind turbines have been found to be the largest single contributor for changes in power generation costs and upscaling (Bolinger and Wiser, 2012; Wiser and Bolinger, 2013). In 2014, wind turbines represented between 64% and 84% of total installed costs onshore and between 44% and 50% offshore (IRENA, 2015). Wind turbines evolution has been driven by several factors, of which two are especially relevant. First, in terms of power capacity, onshore wind turbines grew from an average of 10 kW to 30 kW in the 1970s, to new grid-connected turbines with an average size of 1.94 MW in 2014 (NREL, 2015). The largest commercial wind turbine currently available has 8 MW capacity (IEA, 2015). Second, capacity factors have mounted mainly due to larger rotors, improved design, and siting (Wiser and Bolinger, 2013). This technological evolution has a background of intensive research among diverse technologies. With more than 8000 components (Blanco, 2009), a typical wind turbine combines outputs from several research areas. Hence, the interest in investigating how scientific knowledge on wind turbines is related to its technological evolution and how it is distributed across countries.

4.3.2 Data

The dataset was extracted from the Web of Science (WoS) database by means of a keyword search “wind turbine” on titles, abstracts and author keywords of articles published from 1950 until 2015 (as the 23th of November of 2015). The keyword strategy was defined upon a review of previous studies and by interviews with three experts[14]. Only publications that are classified as “article” in WoS were considered to warrant scientific relevance to the data

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[14] The experts were engineers working in research on wind turbines design.

analysed. The final dataset (publications extracted by the keyword search) contained 13.344 articles. Next, we have cleaned the data for entries lacking information (such as authors or cited references) and for false positives (e.g. articles focusing on issues not related to wind turbine technological development, such as the impact of wind turbines on bats or birds). We checked for false negatives by running independent data retrievals with 11 alternative keyword strings (see Table A.1. in Appendix A for full list) and then using the string ‘wind turbine’ to refine the search. The database resulting from this alternative search summed up 8.986 articles, or 32% less articles than in the database initially recovered for the analysis. Hence, we consider the original database to encompass the majority of scientific research on wind turbines. The total number of articles in the final database is 7.028.

4.3.3 Citation network analysis

In this study, publications on wind turbines correspond to the vertices of a network and are connected to each other by a number of arcs, which symbolize citational links among articles. Here, each citation link represents a piece of knowledge that has been incorporated and to some extent further developed by the citing article. Citations among articles, by pointing epistemic links among the pieces of knowledge that have contributed for the technological trajectory of wind turbines, are taken as an indicator to map the pattern of knowledge dynamics. We have constructed 4 citation networks following different time periods (see Table 4.1). The full citation network, with articles published between 1954 and 2015, has 7.028 vertices (corresponding to the articles in the dataset) and 18.725 arcs (corresponding to the citations). Next, we applied two algorithms to the networks, the critical path method and the hubs and authorities, both implemented by the program Pajek[15]. Finally, we have applied a co-word analysis to code the content of the articles mapped in the networks (see Section 4.3.4).

Of course, this methodological approach has limitations. First, the use of bibliometric data involves intrinsic caveats as propensity to publish and to cite vary across countries, knowledge areas, authors and organizations. However, data on scientific articles remain the best standardized proxy to map the evolution of scientific knowledge related to a specific technology field (Mina et al., 2007; Poirier et al., 2015). In addition, compared to patents, scientific articles have the advantage of adding empirical evidence to the extant literature as an alternative data source which follows a distinct logic of production and appropriability.

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[15] Pajek is freely available at http://mrvar.fdv.uni-lj.si/pajek/. For a review of science mapping software tools see (Cobo et al., 2011).

Table 4.1. Citation networks characteristics

Network	A	B	C	D
Time period	1954-1990	1954-2000	1954-2010	1954-2015
Publications	121	404	2107	7028
Citation links	25	119	2813	18725
Length Critical Path	3	9	28	31

4.3.3.1 Critical Path

If knowledge flows through citations, a citation network can be seen as "a system of channels which transport scientific knowledge" (Nooy et al., 2011, p.256). The largest the number of citations an article receives the more redundant citations to previous articles become. As a result, such an article represents a network intersection marked by intense knowledge flows. The Critical Path Method (CPM), captures the dominant trajectory of knowledge accumulation that emerged over the analysed period. By computing the total number of paths linking the oldest vertices in a citation network to the most recent ones, the CPM algorithm maps all possible streams of knowledge accumulation, and identifies the most important one. Hence, the contributions selected by this algorithm are expected to capture the main scientific trajectory that paved the technological progress in wind turbines since its origin. The CPM algorithm[16] is based on the Search Path Count (SPC) method (Nooy et al., 2011), which calculates traversal weights on arcs following the main path analysis from Hummon and Doreian (1989). Main path analysis calculates the extent to which a particular article is needed for linking others, which is called the traversal weight (Nooy et al., 2011). It measures the weight of arcs, i.e., the paths linking entry vertices (articles not cited within the dataset) to exit vertices (articles not citing within the dataset). The CPM is the path from entry vertices to exit vertices with the largest traversal weights on its arcs. The intuition is that at each citation (arc) the paper (vertex) that has attracted the largest weight in the path represents one of the most important pieces of knowledge in the network (Verspagen, 2007).

4.3.3.2 Hubs and Authorities

Hubs and Authorities are formal notions of the structural prominence of vertices in a network (Brandes and Willhalm, 2002). Unlike critical path analysis, which identifies the most important streams of growth in a citation network, the Hubs and Authorities measures the

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[16] The main difference is that SPC computes weights in an acyclic network by calculating the number of paths running through each vertex and arc; whereas the CPM computes the global main path, i.e., the path with the overall largest sum of arc weights in the network. For formal explanations of the algorithm and method see Nooy et al. (2011).

prominence of articles by taking into account not simply the number of citations that it receives, but also the prestige (in terms of citations received) of the articles that cite it (Calero Medina and Noyons, 2008). In line with the PageRank algorithm first developed for the Google Search Engine (Brin and Page, 1998), the algorithm hubs and authorities selects the core articles that establish the grounds for further development of knowledge regarding wind turbines (authorities), and their best developments (hubs). Therefore, the authorities are the most prominent articles as citation source, whereas other articles act as focused hubs, directing citation to authorities. The nature of the linkage in this framework is asymmetric and mutually reinforcing (Kleinberg, 1999). Hubs link heavily to authorities, but hubs may themselves have very few incoming links, and authorities may well not link to other authorities. The authority of a paper is related to the number of strong hubs, and a strong hub is a paper citing several authorities (Calero-Medina and Noyons, 2008).

Hubs and authorities weights are calculated based on an iterative algorithm that maintains and updates weights for each article to build a centrality vector. The initial mapping of authorities (based on the number of citations received) is updated by the mapping of hubs (based on the number of citations of authorities an article makes). Then, these hub pages are considered to ‘pull together’ authorities and eliminate other articles. For formal explanations of the algorithm and method see Batagelj (2003) and Kleinberg (1998). Here, we use the algorithm hubs and authorities to map high-quality documents (the ones with high authority and hubs scores) and understand their roles in the citation network. The assumption is that the prominence of publications can serve an indicator of the knowledge trajectory and distribution among authors.

4.3.4 Content mapping: co-word analysis

Similar to co-citation analysis, co-word analysis seeks to identify patterns of co-occurrence, or co-absence, of pairs of objects (e.g., words, nouns) to establish relationships between ideas and concepts presented in the texts analysed (Leydesdroff, 1989; Nerur et al., 2008). Co-word techniques have been previously used to explain and map the development of scientific knowledge and concepts (e.g. Peters and van Raan, 1993; Ronda-Pupo and Guerras-Martin, 2012). Here, we use co-word analysis as an additional approach to establish the main research focus of each paper analysed. To do so, we used words in titles, keywords and abstracts of the articles of the critical path for each of the networks mapped. First, we analysed nouns, adjectives and verbs[17] to aggregate words with the same meanings (for example, singular vs. plural, diverse orthographies or misspelling) without adding up words with different meanings (this was checked manually). These words were then used as a reference framework for the analysis. Second, we established the word-frequencies for each critical path string. Third, we checked the co-occurrence of the most frequent words for each critical path string. The pairs of words with the highest co-occurrence have been used to identify the research topic of each publication in the critical paths and in Hubs and Authorities mapped (see Tables A.2 and A.3 in Appendix A).

4.4 Results

In this section, we start by drawing general trends from the descriptive statistics on the publications dataset (Section 4.1.). Next, the evolution of scientific knowledge is analysed in two steps: first, we use the critical path algorithm to understand the backbone trajectory of knowledge accumulation for the period 1954-2015 (Section 4.2.1.). Second, we use the Hubs and Authorities algorithm to analyse changes in the focus of scientific knowledge development along time (Section 4.2.2.).

4.4.1 Main trends

4.4.1.1 Accelerated expansion

The number of publications related to wind turbines grew sharply since the early 2000s. From the total number of articles in our dataset (7.028), 92% were published between 2000 and 2015. As shown in Figure 1, this trend follows the expansion on wind power installations: from the 369 GW of global capacity in the beginning of 2015, 96% were installed between the years 2000 and 2014 (GWEC, 2015). This can be understood as an indicator of the influence of the wind power industry over research activities and, consequently, over publications. Such a result is in line with the idea of beneficial effects from demand pull policies over R&D activities in the renewable energy sector (Dechezleprêtre and Glachant, 2014; Nemet and Kammen, 2007; Tang and Popp, 2014). Additional evidence of the close connection between industry and research activities comes from the simultaneous variation in the number of yearly publications among the five leading countries in terms of total publications (Figure 4.1).

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[17] Prepositions, pronouns and some verbs were excluded to the extent they had no specific relevance for the research topics analysed.

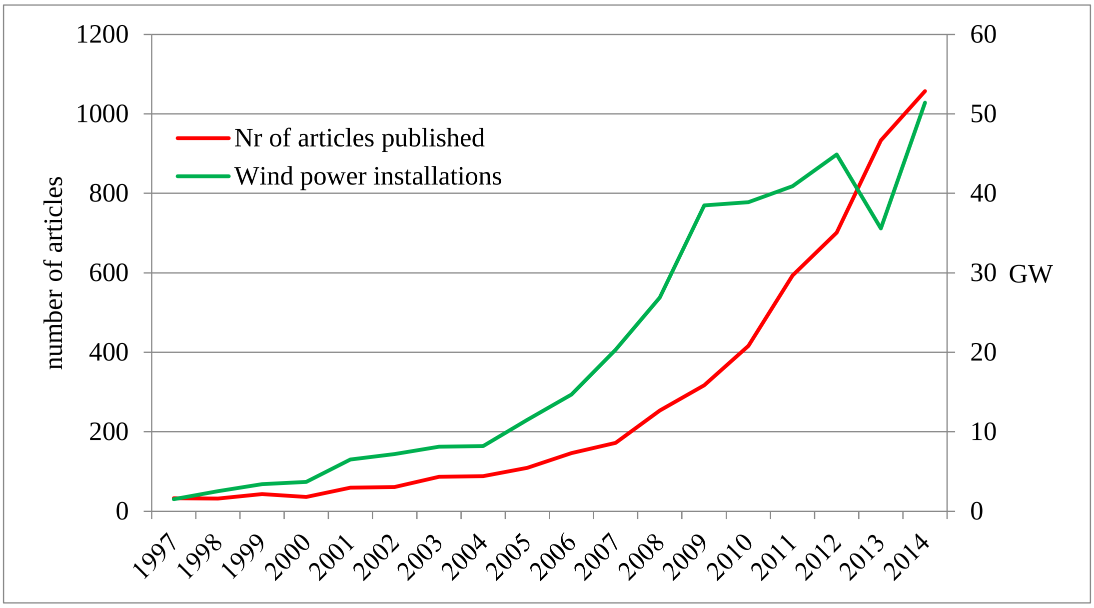

Figure 4.1. Variation of number of articles and wind power installed capacity

4.4.1.2 Geographical concentration

To capture the geographical distribution of research concerning wind turbines we mapped the countries of the organizations to which authors were affiliated. The articles in our dataset involve a total of 89 countries hosting at least one author. Publications are concentrated in a few countries: 52% of the total number of articles were published by authors with affiliations located within one of top five in total number of publications, respectively, the US, UK, China, Denmark and Canada (see Table 4.2). This concentration trend is quite consistent with that found for the wind power industry, however with a different pool of countries. By the end of 2014, only six countries had more than 10 GW of wind power capacity, altogether corresponding to 75% of the 369 GW in global installations, namely: China (114.6 GW), the US (65.8 GW), Germany (39.1 GW), Spain (22.9 GW), India (22.4 GW), and the UK (12.4 GW) (GWEC, 2014).

In addition, it is remarkable that two of the countries with the longest research trajectories in wind power technologies - namely, Denmark and Germany – have a lower than average share of articles taking the first author country of affiliation as indicator (dividing the numbers in column FA by those in TP), and above average share of articles written in international collaboration (CA/TP). This can be related to the catching-up process experienced by the wind turbine industry in China, which was based on the acquisition of foreign technologies (Qiu et al., 2013), as well as with the fact that both Denmark and

Germany host the currently largest turbine manufacturers, the Danish Vestas, and the Germans Enercon, Siemens and Nordex (REN21, 2014).

Table 4.2. Top 20 countries in number of publications from 1975 to 2015

Country	TP	TP/N	FA	FA/TP	CA	CA/TP
US	1003	19%	854	85%	237	24%
UK	509	10%	406	80%	181	36%
China	507	10%	454	90%	171	34%
Denmark	434	8%	328	76%	195	45%
Canada	273	5%	222	81%	80	29%
Japan	262	5%	230	88%	64	24%
South Korea	259	5%	218	84%	66	25%
Spain	252	5%	220	87%	59	23%
Iran	205	4%	165	80%	40	20%
Germany	184	4%	129	70%	94	51%
Italy	159	3%	128	81%	51	32%
India	148	3%	140	95%	18	12%
Netherlands	145	3%	114	79%	62	43%
France	136	3%	93	68%	57	42%
Turkey	133	3%	124	93%	15	11%
Norway	120	2%	89	74%	59	49%
Australia	115	2%	79	69%	50	43%
Sweden	114	2%	93	82%	41	36%
Taiwan	112	2%	112	100%	9	8%
Greece	110	2%	97	88%	25	23%

TP: Total number of articles published with at least one of the authors having an affiliation in the country. N: total number of articles in the dataset with information about authors' affiliations (i.e., 5.159). FA: Number of articles published with first author's affiliation in the country. CA: Number of articles with at least one co-author affiliated to another country.

4.4.2 Scientific knowledge evolution

4.4.2.1 Critical path: The backbone trajectory

The path formed by the 31 articles on the critical path[18] (Figure 4.2) which captures the trajectory of scientific knowledge evolution that emerged throughout the analysis of scientific publications on wind turbines. Six topics arise as dominant across different segments of the critical path and at different periods of time, namely: controller design and turbulence management, wake[19] modelling, wind farm design, large eddy simulations, offshore simulations, and ABL-wake modelling.

From the bottom of the figure and moving along the vertical axis, the longest string of articles is from the initial period analysed (1986-2010) and focuses on control systems,

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[18] For detailed information on the articles see Table A.4. in the Appendix A.

[19] Wind turbine wake refers to the downstream area of reduced wind speed behind the turbine.

namely controller design and turbulence management. This segment serves as a sink for the remaining of the network which, in 2011, is bifurcated into two strings (namely, wind farm design and wake modelling). In 2013 and 2014, two other strings of publications are developed, one focused on large eddy simulations and another one focused on offshore simulations. The most recent string of articles to emerge is combined ABL and wake modelling, which reflects the rising importance of these elements to optimise control systems.

The six strings of publications identified present a strong focus on modelling wind turbines and wind farm performance, whereas shifts on research topics along time refer to different frameworks and modelling techniques. Until 2010, analyses were directed at comparisons of wind turbines types (mainly horizontal and vertical axis), power generators and turbine power system design. From 2010 onwards the research *foci* have been diversified towards wake modelling and wind farm design. More recently, research has focused on three different issues: the use of large eddy simulations, offshore simulations and the development of models combining ABL-wake simulations. In fact, these three topics are seen as main drivers of wind power design optimization particularly for large and offshore wind farms (Ashuri et al., 2014).

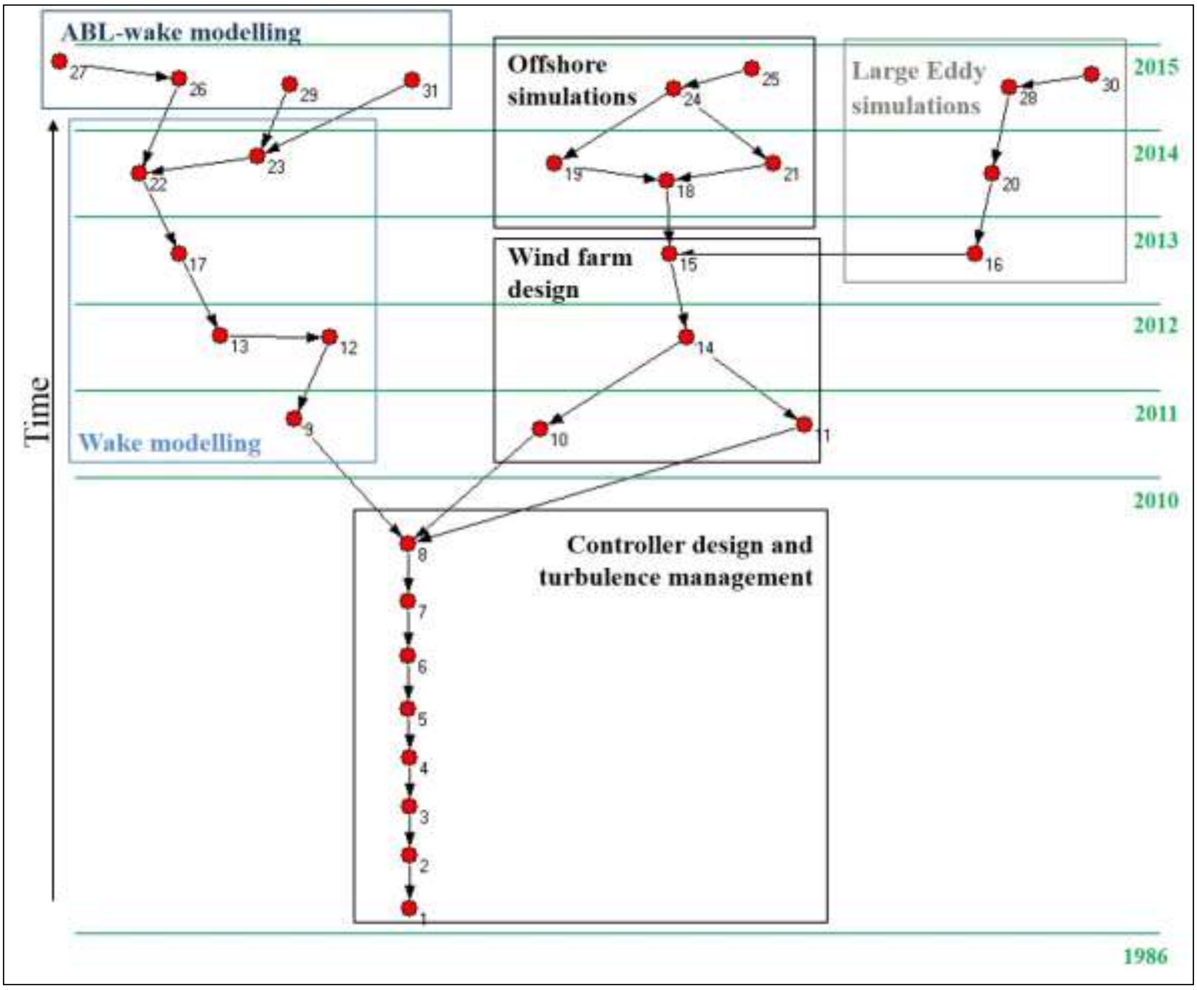

Figure 4.2. Critical Path of scientific knowledge development

4.4.2.2 Hubs and Authorities: Research focus development

We applied the algorithm Hubs and Authorities to analyse the research focus of the most prominent articles at different periods of time. The underlying assumption is that these articles can serve as indicators of the evolution of research *foci* along the development of scientific knowledge regarding wind turbines. In order to do so, we have selected the articles which summed up to 70%[20] of the weight of all hubs and authorities in each network, and then categorised them by topic following the co-word analysis previously done (see section 3.4). Next, we have summed up the weight of articles grouped around a same subject. Subjects with the highest share of total weight in the network are considered to be the most relevant research topics during the period. Authorities point to the most influential articles in

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[20] The 70% weight threshold was established because it enables to cut off articles that represent less than 0.1% of the total weight in the network. The aim is to increase the robustness of our analysis since articles with very little weight tend to generate noisy results in bibliometric analysis (Huang, 2014; Noyons, 1999).

terms of scientific advancement whereas hubs indicate the articles with highest impact in guiding further research.

As shown in Figure 4.4, research *foci* continuously changed over time towards increasing diversity. The number of research topics depicted by hubs and authorities articles grew from 8 for the period 1954-1990 to 17 for the period 1954-2015 (see Table A.2. in Appendix A for more details). In the 1990s and in the 2000s, articles were primarily focused on wind turbines design and control, and performance prediction. This is in line with the results from the critical path and indicates the initial phase of technology development which is commonly focused on defining a dominant design, in this case, by defining the main components characteristics, such as blades and control systems. Between 1990s and 2000s, the main change in terms of research focus is shown by hubs articles which include a new topic, namely controller design. Controller design refers to the load frequency controller[21] which development gained importance with the increasing need of wind power integration to the grid and the geographical variability of wind farm sitting.

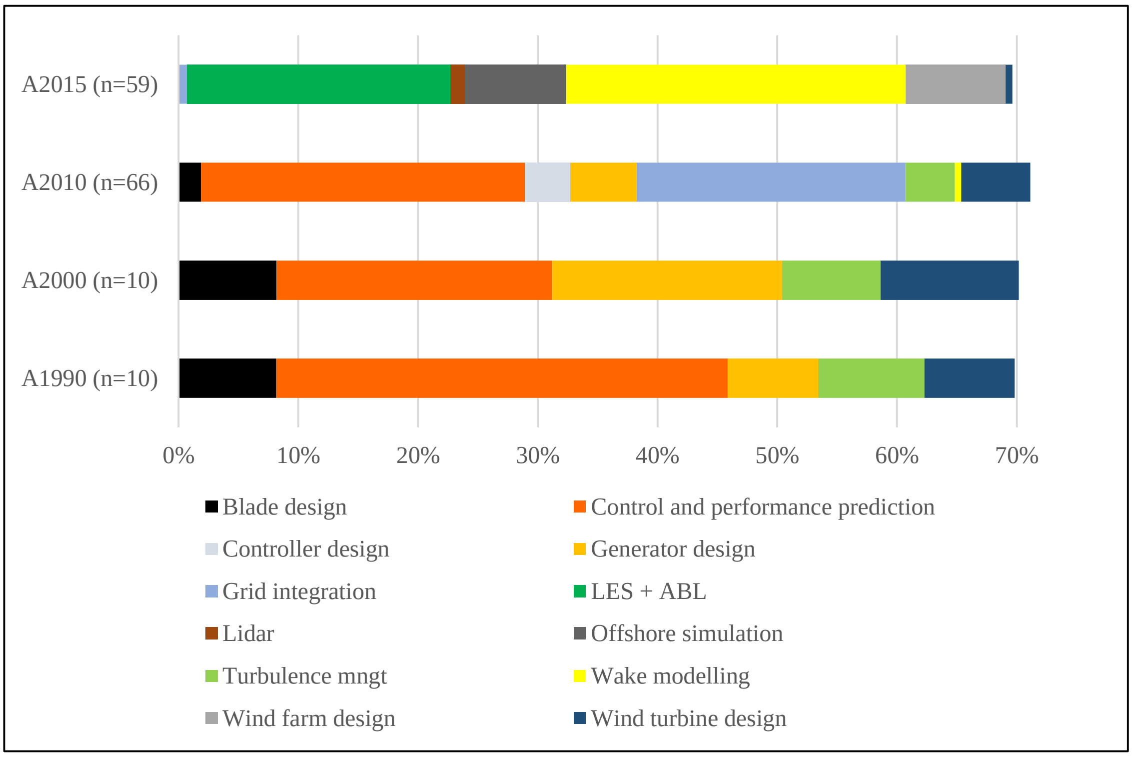

Figure 4.3. Authority articles by research topic and share of total weight in the network (n: number of articles summing up 70% of total weight in the network)

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[21] The controller starts up the turbine at predetermined wind speeds (generally of 8-16 mph) and shuts it off when winds are too high (see Goudarzi and Zhu, 2013 for a review).

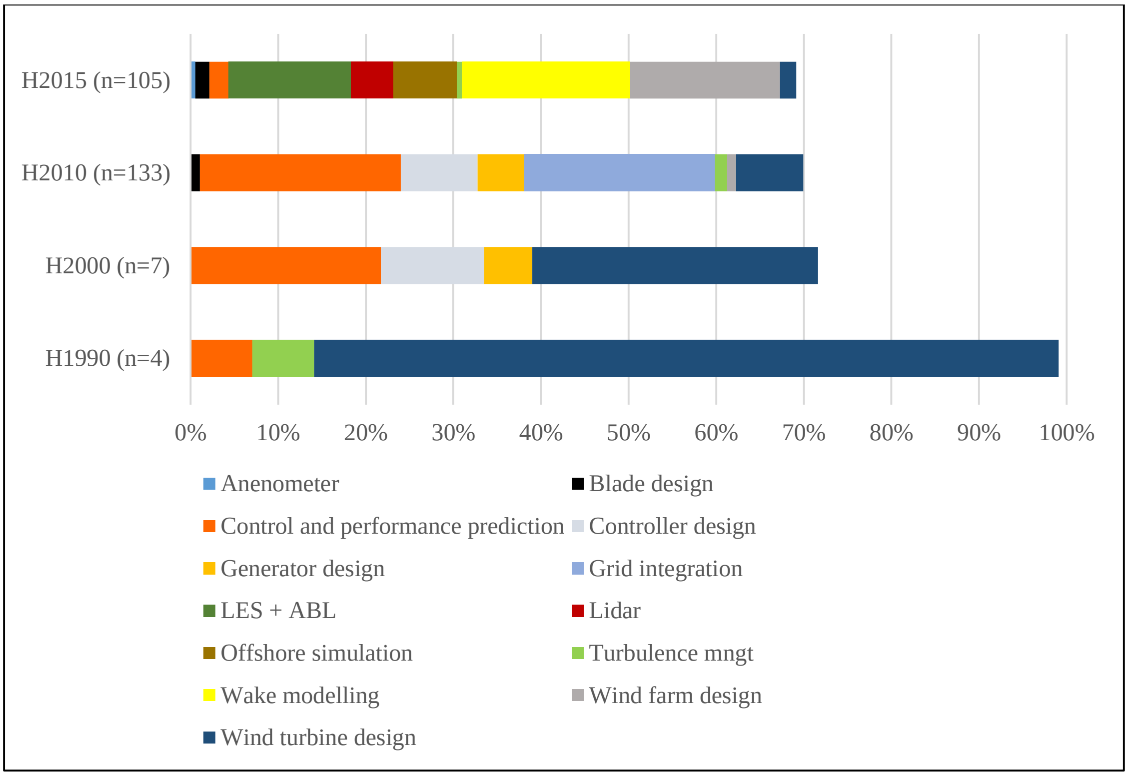

Figure 4.4. Hub articles by research topic and share of total weight in the network (n: number of articles summing up 70% of total weight in the network

The sharpest shift of research focus is seen in the more recent networks 1954-2010 and 1954-2015. For the 1954-2010 network, grid integration emerges as a central research subject. This can be explained by the fact that it was only in the mid-2000s that wind power installations started to respond for shares of electricity production large enough (over 10% of yearly total generation) to create significant challenges to grid integration (IEA, 2014). For the full network (1954-2015), other research subjects arise, all directly related to modelling and simulation for performance forecast, both onshore and offshore. Two topics, atmospheric boundary layer (ABL) and Large Eddy Simulations (LES) are closely related to the growing size of wind farms. Wind farms with horizontal extents over 10 to 20 km present a different dynamics of kinetic energy fluxes where the interaction with the ABL becomes crucial in determining the efficiency of each wind turbine. In this case, wind turbines deployed in large arrays suffer a decrease of their efficiency due to complex interactions among themselves and with the ABL (Calaf et al., 2011). The most common approach to dealing with the problems generated by this interaction is based on the use of Large Eddy Simulations (LES) since it enables to test a great variety of parameters characterizing the wind farm (Sanderse et al., 2011).

Other two ‘new’ research topics refer to related technologies directed to simulation and performance prediction: lidar and anemometer. Lidar (short for light detection and ranging) is considered a potentially breakthrough technology because of its capacity to improve wind turbine control and thereby reduce wind power cost (Davoust et al., 2014; Mikkelsen et al., 2013). Anemometers have been traditionally used to measure wind speed in the wind power industry, however the increasing height of wind turbines towers and the consequent difficulty in their maintenance has renewed the research interest on the topic. Recent studies have focused on measuring anemometers performance and comparing it to lidars (see Honrubia et al., 2010 for a review).

4.5 Discussion

In this section, we discuss the link between scientific knowledge evolution and the technological trajectory of wind turbines (Section 4.5.1) and then derive the implications for the literature on environmental innovation (Section 4.5.2).

4.5.1 Linking scientific knowledge evolution and technological trajectory

Overall, our results point to a close connection between scientific knowledge evolution and the technological trajectory of wind turbines. On the one hand, the analysis of scientific knowledge follows previous studies based on technological knowledge to confirm the importance of knowledge diversity for environmental innovation (e.g. Dechezleprêtre et al., 2013; Ghisetti et al., 2015; Horbach et al., 2013; Nemet and Johnson, 2012). As shown in the critical path (see Figure 4.2), scientific knowledge accumulation followed a trend of increasing heterogeneity with more distant knowledge areas combined and a larger diversity of research *foci* over time. This path of knowledge accumulation is well aligned with the technological changes on wind turbine design derived from up-scaling[22] (IEA, 2013; Wilson, 2012). The sequential shifts on the focus of scientific knowledge development reflect changes in operational dynamics and management methods mainly driven by increases in wind turbine size. Following up-scaling, simulation and calculation models (e.g. large eddy simulations, ABL and wake modelling) have evolved to capture the complexity of wind regimes, and improve the accuracy of performance forecasts and safety estimations (Quarton,

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[22] Upscaling refers to increases on the size of wind turbines and wind farms. The size of wind turbines has increased from an average of 75kW and 17m of rotor diameter in the 1980s to 2 MW and 100m in 2012 (EWEA, 2014). Wind farms have grown from an average nameplate capacity of 37 MW in the 1980s to 120 MW in 2012 (DOE, 2014), with offshore projects expected to reach capacities between 500-1000 MW (Sieros et al., 2012).

1998; Sieros et al., 2012). In fact, changes in wind power production derived from up-scaling have made the need for reliable control methods even more pressing (Garcia-Sanz et al., 2011).

On the other hand, the path of scientific knowledge evolution has shed new light on the focus of technological change where non-physical parts appear to have a prominent role in the technological trajectory of wind turbines. Next to the traditional components of wind turbine architecture, scientific knowledge puts a strong weight on technologies related to data collection and modelling (see Figure 4.5). Data collection and modelling are important research fields for product and project development (before wind turbine development and deployment) as well as for ongoing operational forecasting (after installation). Correspondingly, the analysis of hubs and authorities shows scientific knowledge around these topics to have recently gained weight – accounting for 30% in the network with cut year 2010 and 50% for the one with cut year 2015.

These results reinforce the idea that the focus of innovation changes in a sequential manner following a product's life-cycle. Previous studies mapping the technological trajectory of wind turbines point to shifts on the focus of innovation between components and sub-components of the product architecture (e.g. Arvesen and Hertwich, 2012; Huenteler et al., 2015). Yet, our results suggest a further step where the focus of innovation surpasses the limits of product architecture to move to a 'hidden structure' of complementary management and forecasting technologies. At least two facts related to the wind power industry help to explain this path. First, the fact that wind power has achieved maturity as an energy source which enables further development of modelling and simulations due to the availability of historical data on power production. Second, the expansion of wind power in terms of wind farms size and offshore installations which creates the need to adapt previous developed technologies to these new settings.

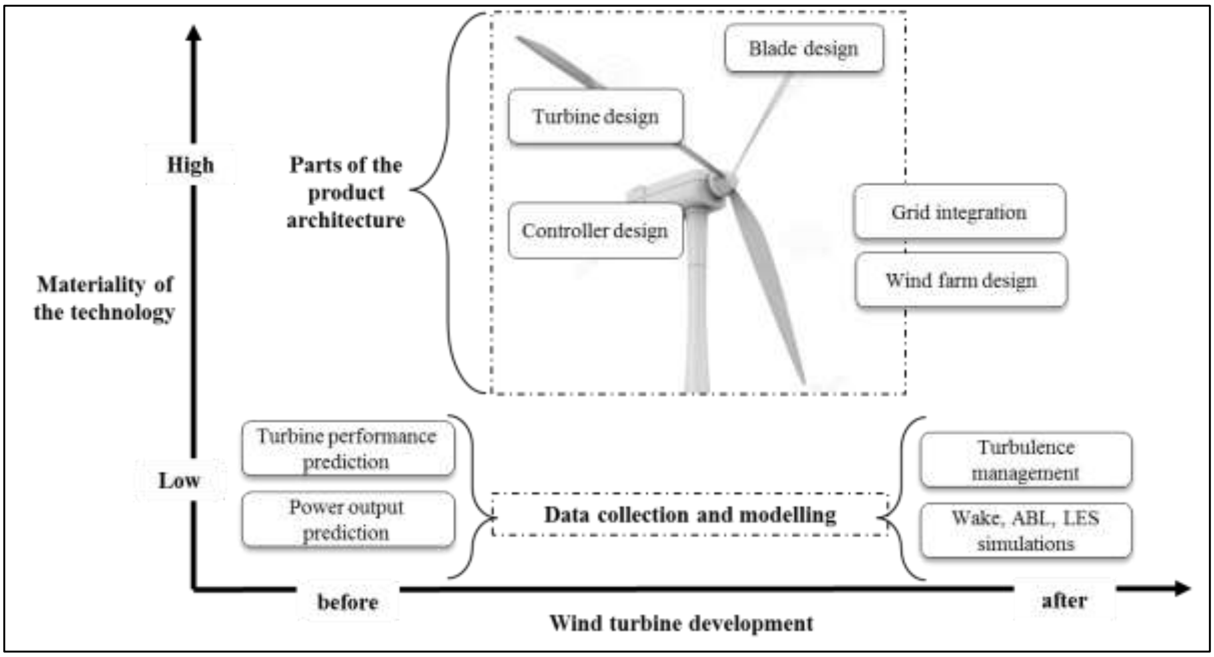

Figure 4.5. Research topics stylized distribution following development stage and materiality

Indeed, the advancement of modelling and simulation technologies is considered one of the most promising areas for further improvement of wind turbine performance. The main reason is their capability to enhance operation monitoring by facilitating (preventive) maintenance activities and early detection of catastrophic failures thereby improving turbine availability, power output and cost performance (Sheng et al., 2013). At the same time, product development is also favoured as accurate and reliable monitoring offers valuable data to improve component design, equipment operation and control strategies (García Márquez et al., 2012; Hameed et al., 2010). An additional incentive to invest in modelling and simulation technologies comes from the much lower upfront costs involved in their development when compared to the cost of parts replacement. In the U.S., for instance, wind turbine condition monitoring systems have an average market price of 16.000 USD, compared to parts replacement costs which can go up to millions – e.g. 2.3 million USD for a rotor (Yang et al., 2012).

4.5.2 Environmental innovation and knowledge dynamics: implications for the literature

The fact that data collection and modelling have emerged only after large scale diffusion of wind turbines suggests a particular dynamics of environmental innovation. Based on natural resources forecasting, such as solar irradiance and wind regimes, environmental innovation suffers with limited historical data on performance of comparable product designs. For wind turbines, a dominant design was established in the mid-80s and from there until the 2010s technological evolution had been focused on product architecture, essentially on improving components' design with the goal of reducing costs and improving power generation performance (Bergek and Jacobsson, 2003; Bolinger and Wiser, 2012; Braun et al., 2010). From the 2010s, wind turbine technologies matured and the innovation focus shifted, at least partially, towards increasing performance through complementary, non-material parts, i.e., data gathering and simulation (Hameed et al., 2010; Yang et al., 2012). This seems to be specific of such an emergent technology as the reciprocal interdependence between modelling and changes in wind turbine design are dependent on their previous deployment to generate real data to feed modelling. Moreover, the need of simulation accuracy gained force mainly with the unfolding grid integration issues (Holttinen et al., 2011; IEA, 2014; Peihong et al., 2012). A possible explanation is that, as it is characteristic of environmental innovations, wind power was developed upon strong policy support. For countries with the largest wind power capacity, subsidies have guaranteed a minimum return on wind power investment which in some cases has weakened the link between power output and profitability (Hitaj et al., 2014; Mir-Artigues and del Río, 2014). Arguably, this might have worked to reduce market pressure to develop technologies dedicated to wind forecast and monitoring.

Two additional characteristics of environmental innovations in the energy sector may have contributed for this path of technological development in wind turbines: the strong link to external knowledge and the high complexity of deployment. Modelling techniques as well as data gathering mechanisms are dependent on breakthrough innovations from basic science and not necessarily directly related to wind power or the energy sector in general (Davidsson et al., 2014). This entails a further hurdle as basic science is concentrated in a few countries and the disconnection with the energy system hinders efficient policy support targeting. These conditions add dependence of environmental innovation on external research areas, as well as of the importance of inter-sectoral knowledge spillovers. At the same time, wind turbines functioning needs to have harmonized interactions with a number of external systems (e.g. natural environment, grid standards, mix of energy sources, demand characteristics, market structure). This variety of interfaces creates exceptional challenges in performance forecasting as deployment takes place in highly diverse terrains, and is connected to largely diverse power systems.

Last but not least, an additional lesson from our study comes from a methodological standpoint. The focus on scientific publications had a crucial role in the results found here due to appropriability issues particular to wind turbines. Current modelling techniques to assess wind turbine behaviour and impact on the power system are proprietary and manufacturer specific and mostly restricted by wind turbine manufacturer's non-disclosure agreements (Singh et al., 2011). Hence, most modelling techniques are not patented as it is common practice among wind turbines manufacturers to avoid releasing the information required to patent[23]. By contrast, the scientific publications analysed here have provided access to enough data to map the evolution of modelling and data gathering technologies related to wind turbines. Mainly two factors are important to explain the difference of contents between patents and scientific publications in this case. First, publications tend to reveal information before it is patented as the process of publishing is less costly and quicker than patenting (Hicks, 1995; Nelson, 2009). Second, since less than 15% of the authors of the articles analysed here were affiliated to a wind turbine manufacturer, the non-disclosure agreements from such companies may have had limited impact on this study. A main implication is that using scientific publications may entail a strong advantage compared to patents depending on the appropriability system around the technology studied. Thus, future research on knowledge dynamics could benefit from adapting data sources to different appropriability regimes, as well as from combining scientific publications and patents.

4.6 Conclusion

Largely driven by technological change on wind turbines, wind power has become one of the most widely diffused environmental innovations. By mapping the evolution of scientific knowledge underpinning wind turbines technological trajectory, this paper has investigated how advancements in science relate to the development of an environmental innovation. To this end, we have built and analysed an original database of scientific publications covering the period between 1950 and 2015. We have used two different network citation algorithms to analyse the path of knowledge accumulation and the most prominent knowledge areas related to the development of wind turbines. The results show a close link between science and innovation, and shed new light on the importance of complementary, non-material technologies. The process of knowledge accumulation depicts scientific knowledge evolution as closely connected to technological changes driven by wind turbine up-scaling. The strong

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[23] A main reason for secrecy is the sensitivity of wind turbine and wind farm performance to accurate modelling and forecasting. In the U.S., for example, current wind forecasts typically have errors in the range of 15% to 20% for a single wind plant; whereas a 10% improvement in wind generation forecasts could reduce the national power system operating costs by about 140 million USD per year (at 14% wind energy penetration) (Lew et al., 2011).

influence of modelling and simulation technologies on recent scientific developments on wind turbines suggest that an extended view of technology trajectory is needed to include important complementary technologies. These findings help extend the understanding of environmental innovation drivers by providing new empirical evidence of its link with scientific knowledge.

Appendix A

Table A.1. Alternative search strings

Search Keyword	Nr of papers retrieved	Nr. of papers after refining by “wind turbine”
wind + rotor	7738	2912
wind + power train	26	14
wind + nacelle	348	258
wind + tower	3942	964
wind + foundation	1861	427
wind + transformer	4170	173
wind + substation	303	37
wind + cabling	3113	136
wind + grid	11919	2606
"wind farm"	4769	1449
"wind farm integration"	69	10
Total	38258	8986

Table A.2. Summary of research topics by network derived from co-word analysis

Time period	1954-1990	1954-2000	1954-2010	1954-2015
Total number of papers in the network	121	404	2107	7028
Citation links	25	119	2813	18725
Nr of critical path papers	3	9	28	31
Nr of authority papers	10	10	66	59
Nr of hub papers	4	7	133	105
Nr of research topics	8	9	16	17

Table A.3. Coding for research topics

Research topic	Content	Key terms for co-word analysis
ABL and LES simulation	Simulations and modelling focusing on the impact of adding Atmospheric Boundary Layer (ABL) and Large Eddy Simulation (LES) to the measurements.	Atmospheric Boundary Layer; ABL; Dynamic-Model; Large Eddy Simulation; LES; Model; Modelling; Turbulence.
ABL and wake modelling	Simulations and modelling focusing on the impact of adding Atmospheric Boundary Layer (ABL) and wake effects as a new variables.	Atmospheric Boundary Layer; ABL; Aerodynamics; Dynamic-Model; Flow; Model; Modelling; Simulation; Turbulence; Wake.
Anemometer	Anemometer is a device for wind speed measurement and transmission of wind speed data to the controller. Topics in this category focus on atmospheric stability assessments with different types of anemometers and various geographical and technical conditions.	Anemometer tests; Atmospheric Conditions Assessment; Incoming Flow; Measurements; Predictions with anemometers.
Blade design	Performance assessment of different blade designs under diverse operational and testing conditions (e.g. wind turbine design, wind farm layout, wind regime).	Blade Diameter; Blade Edges; Blade Suction; Blade-element theory; Blade Surface; Rotating Blade; Vortices.
Control and performance prediction	Assessment of models and measurement techniques to estimate wind turbine performance in terms of power output and stability.	Aerodynamic Models; Aerodynamic Loads; Computation Fluid Dynamics; Horizontal-Axis Wind Turbine (HAWT) models; Measurements; Performance comparison. Power prediction.
Controller design	The controller is the part responsible for starting up and shutting down the wind turbine at predefined wind speeds. Topics in this category focus on testing different types of controllers under various conditions (e.g. wind turbine design, power system components).	Controller; Frequency Control; Load Frequency Controller; Modified Load; Pitch Controller; Power Tracking; Small Power System.

Generator design	Performance assessment of different types of generators (e.g. synchronous/asynchronous) under various conditions (e.g. wind turbine design, wind farm layout, wind regime).	Generators; Generators Stability; Induction Generators; Synchronous Generators; Simulation.
Grid integration	Assessment of control strategies for grid integration. Performance simulation of different system designs (e.g. combination of inverters, generators, wind turbine models, wind farm sizes).	Doubly Fed Induction Generator (DFIG); Inverter; Grid; Grid Integration; Low Voltage Ride Through (LVRT); Power System; Voltage Stability.
LES (Large Eddy Simulation)	Application of a LES technique to assess wind turbine and wind farms performances.	Aerodynamics; Dependent Dynamic-Model; Measurements; Model; Modelling; Simulation; Surface-Layer; Turbulence; Large-eddy simulation; LES.
Lidar	Assessment of measurements using different types of lidar (short for light detection and ranging) under various conditions (e.g. wind turbine design, wind farm layout, wind regime).	Light detection and ranging measurements; Lidar; Error quantification; Lidar data; Measurements.
Offshore simulation	Measurement and simulation techniques of wind turbines and wind farms offshore.	Wakes; Offshore; Offshore Wind Farm; Modelling; Measurements; Simulation; Wind Farm Layout.
Turbulence management	Assessment of turbulence under various conditions (technical, geographical, meteorological) using different testing and simulation techniques.	Fatigue Problems; Modelling; Measurements; Simulation; Turbulence-Induced Flux; Turbulent Flows.
Wake modelling	Assessment of wake effects under various conditions (technical, geographical, meteorological) using different testing and simulation techniques.	Flow; Measurements; Model; Modelling; Simulation; Turbulence; Wake; Wake Effects; Wake Merging; Wake-Turbine Interaction; Wind-Turbine Wake.
Wind farm design	Assessment of different options for wind turbines sitting (or wind farm layout) for optimising power output, land use and cost performance.	Wind Farm; Optimal Wind Turbine Spacing; Land Surface Costs; Turbine Wakes; Placement; Stability; Tunnel.
Wind turbine design	Assessment of different wind turbine designs (e.g. vertical or horizontal axis, different hub heights and rotor diameters; fixed-speed or variable slip) for optimising power output, stability and cost performance.	Hub height; Power fluctuations; Wind turbine design; Horizontal-Axis Wind Turbine (HAWT) models; Vertical-Axis Wind Turbine (VAWT); Small Size Turbines.

Table A.4. Details of papers in CPM

Nr. CPM	Authors	Year	Title	Journal
1	Garrad, A.D.; Quarton, D.C.	1986	Symbolic computing as a tool in wind turbine dynamics	Journal of sound and vibration
2	Ekelund, T	2000	Yaw control for reduction of structural dynamic loads in wind turbines	Journal of wind engineering and industrial aerodynamics
3	Stol, K; Balas, M	2001	Full-state feedback control of a variable-speed wind turbine: A comparison of periodic and constant gains	Journal of solar energy engineering-transactions of the asme
4	Wright, AD; Balas, MJ	2003	Design of state-space-based control algorithms for wind turbine speed regulation	Journal of solar energy engineering-transactions of the asme
5	Hand, MM; Balas, MJ	2007	Blade load mitigation control design for a wind turbine operating in the path of vortices	Wind energy
6	van Wingerden, JW; Hulskamp, AW; Barlas, T; Marrant, B; van Kuik, GAM; Molenaar, DP; Verhaegen, M	2008	On the proof of concept of a 'Smart' wind turbine rotor blade for load alleviation	Wind energy
7	Lackner, MA; van Kuik, G	2010	A comparison of smart rotor control approaches using trailing edge flaps and individual pitch control	Wind energy
8	Roy, A; Kedare, SB; Bandyopadhyay, S	2010	Optimum sizing of wind-battery systems incorporating resource uncertainty	Applied energy
9	Wang, L; Hsiung, CT	2011	Dynamic Stability Improvement of an Integrated Grid-Connected Offshore Wind Farm and Marine-Current Farm Using a STATCOM	IEEE transactions on power systems
10	Chamorro, LP; Porte-Agel, F	2011	Turbulent Flow Inside and Above a Wind Farm: A Wind-Tunnel Study	Energies
11	Calaf, M; Parlange, MB; Meneveau, C	2011	Large eddy simulation study of scalar transport in fully developed wind-turbine array boundary layers	Physics of fluids
12	Wharton, S; Lundquist, JK	2012	Assessing atmospheric stability and its impacts on rotor-disk wind characteristics at an onshore wind?farm	Wind energy
13	Vanderwende, BJ; Lundquist, JK	2012	The modification of wind turbine performance by statistically distinct atmospheric regimes	Environmental research letters
14	Markfort, CD; Zhang, W; Porte-Agel, F	2012	Turbulent flow and scalar transport through and over aligned and staggered wind farms	Journal of turbulence
15	Wu, YT; Porte-Agel, F	2013	Simulation of Turbulent Flow Inside and Above Wind Farms: Model Validation and Layout Effects	Boundary-layer meteorology journal
16	Abkar, M; Porte-Agel, F	2013	The Effect of Free-Atmosphere Stratification on Boundary-Layer Flow and Power Output from Very Large Wind Farms	Energies
17	Dufresne, NP; Wosnik, M	2013	Velocity Deficit and Swirl in the Turbulent Wake of a Wind Turbine	Marine technology society journal

18	Stevens, RJAM; Gayme, DF; Meneveau, C	2014	Large eddy simulation studies of the effects of alignment and wind farm length	Journal of renewable and sustainable energy
19	Yang, WX; Tavner, PJ; Crabtree, CJ; Feng, Y; Qiu, Y	2014	Wind turbine condition monitoring: technical and commercial challenges	Wind energy
20	VerHulst, C; Meneveau, C	2014	Large eddy simulation study of the kinetic energy entrainment by energetic turbulent flow structures in large wind farms	Physics of fluids
21	Yang, D; Meneveau, C; Shen, L	2014	Effect of downwind swells on offshore wind energy harvesting - A large-eddy simulation study	Renewable energy
22	Bastankhah, M; Porte-Agel, F	2014	A new analytical model for wind-turbine wakes	Renewable energy
23	Iungo, GV; Porte-Agel, F	2014	Volumetric Lidar Scanning of Wind Turbine Wakes under Convective and Neutral Atmospheric Stability Regimes	Journal of atmospheric and oceanic technology
24	Sorensen, JN; Mikkelsen, RF; Henningson, DS; Ivanell, S; Sarmast, S; Andersen, SJ	2015	Simulation of wind turbine wakes using the actuator line technique	Philosophical transactions of the royal society a-mathematical physical and engineering sciences
25	Failla, G; Arena, F	2015	New perspectives in offshore wind energy Introduction	Philosophical transactions of the royal society a-mathematical physical and engineering sciences
26	Stevens, RJAM; Gayme, DF; Meneveau, C	2015	Coupled wake boundary layer model of wind-farms	Journal of renewable and sustainable energy
27	Sarlak, H; Meneveau, C; Sorensen, JN	2015	Role of subgrid-scale modeling in large eddy simulation of wind turbine wake interactions	Renewable energy
28	Yang, XL; Howard, KB; Guala, M; Sotiropoulos, F	2015	Effects of a three-dimensional hill on the wake characteristics of a model wind turbine	Physics of fluids
29	Abkar, M; Porte-Agel, F	2015	Influence of atmospheric stability on wind-turbine wakes: A large-eddy simulation study	Physics of fluids
30	Howard, KB; Hu, JS; Chamorro, LP; Guala, M	2015	Characterizing the response of a wind turbine model under complex inflow conditions	Wind energy
31	Hancock, PE; Zhang, S	2015	A Wind-Tunnel Simulation of the Wake of a Large Wind Turbine in a Weakly Unstable Boundary Layer	Boundary-layer meteorology journal

Chapter 5

The role of external knowledge sourcing in environmental innovation: Empirical evidence for solar and wind power[24]

5.1 Introduction

Environmental innovations such as energy efficiency and renewable energy are essential for meeting ambitious climate change goals as agreed to by all countries in the Paris Climate Agreement of December 2015. Knowledge creation and diffusion are key enabling factors to achieve such environmental innovations. New knowledge is required to promote breakthroughs in technological change so as to speed up the transition to a low carbon economy. By stimulating the continuous development of environmental innovation, knowledge openness reduces the risk of an economy getting 'locked-in' to technologies that are not the most efficient ones, as well as escaping potential future 'lock-in' of inefficient technologies. Yet, empirical evidence on the link between external knowledge sourcing and environmental innovation performance is scarce.

The present paper intends to fill this gap by analysing the relationship between innovation performance and external knowledge sourcing strategies, focusing on the cases of solar and wind power. Renewable energy technologies are particularly well suited to this study as previous research indicates their technological development to be highly dependent on external knowledge sources (de la Tour et al., 2011; Dechezleprêtre et al., 2015; Dechezleprêtre and Glachant, 2014; Glachant et al., 2013; Kirkegaard et al., 2009; Nemet, 2012; Noailly and Smeets, 2013; Rexhäuser and Löschel, 2015). Arguably, the high levels of novelty and complexity characteristic of renewable energy push organisations to search for

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[24] A version of this paper was submitted to Research Policy in July, 2016.

complementary knowledge areas, thereby strengthening the impact of external knowledge sources on innovation.

The impact and suitability of different strategies on searching and accessing external knowledge remains controversial. On the one hand, accessing external knowledge is expected to improve innovation output as it enables organisations to take advantage of specialized knowledge that is complementary to their own expertise. On the other hand, exploring external knowledge involves transaction costs of searching and management, as well as the risk of undesirable knowledge spillovers. In addition, some recent studies point to ambiguous evidence regarding the role of channels through which organisations access external knowledge. It suggests that impacts of knowledge search depend on the particular strategies and its interaction with organisational and environmental factors (Cassiman and Valentini, 2015; Ferreras-Méndez et al., 2015; Ghisetti et al., 2015). A recurrent question is how to structure a knowledge sourcing strategy so that it combines a broad number of knowledge sources with in-depth external knowledge search. From a time and effort angle there is a trade-off between these characteristics, in an ideal case resulting in an optimal strategy of external knowledge sourcing. Our study provides insight on this for the case of renewable energy.

Based on a survey with research groups (henceforward referred to as RGs) located in 35 different countries, here we analyse the link between external knowledge sourcing and innovation performance in two technology fields. In this way, our study makes three main contributions to the current literature. First, our study provides empirical evidence on the role of external knowledge sourcing at a global scale, while previous research has been limited to a single country or a small set of countries mainly belonging to the OECD (Ferreras-Méndez et al., 2015; Ghisetti et al., 2015; Laursen and Salter, 2014). Second, by comparing two environmental technologies, namely solar and wind power, our study can assess whether external knowledge sourcing is contingent on the technology field and the search strategy adopted in it. Third, our findings suggest that a trade-off is needed to balance the best of different knowledge search strategies.

The paper is organised as follows. In Section 5.2, we present a review of the literature on the link between knowledge and innovation, and focus on particular aspects of this regarding environmental innovation and renewable energy. Section 5.3 explains sampling and data collection procedures, as well as the variables measurement adopted. Section 5.4 presents and interprets the results. Section 5.5 concludes and derives policy implications.

5.2 Theoretical perspective and hypotheses

5.2.1 Knowledge sourcing as innovation driver

Successful innovations depend on the creation and integration of new knowledge – technological, strategic and market related. An extensive theoretical and empirical literature deals with the determinants of internal and external knowledge sourcing, and their effects on innovation performance. Evolutionary economic theory, for instance, highlights the interactive learning and cumulative processes among actors involved in innovation (Jensen et al., 2007; Nelson and Winter, 2002). Within this perspective, the combination of diverse knowledge sources, such as inter-sectoral knowledge, is especially valued as a means to generate radical innovations (Nemet, 2012; Rosenberg and Nelson, 1994). More recently, one strand of literature has gained attention by encouraging an ‘open innovation model’, which advocates the use of external knowledge sources to accelerate innovation and market diffusion (Chesbrough and Crowther, 2006; Gassmann et al., 2010). Similarly, management studies provide evidence that a wider and more diverse pool of knowledge sources fosters innovation as it enables building new competences through the combination of complementary knowledge sets from internal and external sources (Bergek et al., 2013; Teece and Pisano, 1994).

A commonly shared idea is that internal and external knowledge sourcing activities are simultaneously carried out and complementary, i.e., mutually beneficial as their returns are positively correlated. Internal knowledge sources strengthen the impact of external knowledge sources by improving knowledge assimilation and optimising the focus or intensity of external knowledge search, which is usually known as absorptive capacity (Cohen and Levinthal, 1990; Zahra and George, 2002). At the same time, external knowledge sources enhance the impact of internal knowledge by introducing new knowledge and practices, and by creating the possibility of innovative combinations of knowledge. These contribute to preventing inertia and obsolescence (Cockburn and Henderson, 1998; Kogut and Zander, 1992; Leonard-Barton, 1992; Nelson and Winter, 2002). Previous studies have also built up empirical evidence both for the positive impact of accumulated knowledge when tapping external knowledge (Arora and Gambardella, 1994; Escribano et al., 2009; Hansen and Birkinshaw, 2007; Wu and Shanley, 2009), as well as on the benefits of external to internal knowledge sources (Cassiman and Veugelers, 2002; Cohen et al., 2002; Tether and Tajar, 2008; Vega-Jurado et al., 2009). Yet, next to the potentially positive effects on innovation of combining knowledge sources, comes the risk of inhibitory effects due to path dependency (Acemoglu et al., 2012; Sydow et al., 2009), search myopia (Levinthal and March, 1993) or core rigidities (Leonard-Barton, 1992).

The impact of complementarity between internal and external knowledge sourcing on innovation performance remains controversial due to mixed evidence from the few empirical studies done so far. Beneficial effects of complementarity have been found for the combination of internal R&D and suppliers as knowledge sources for process innovations (Reichstein, 2006), internal R&D and knowledge flows from research institutes and universities (Cassiman and Veugelers, 2006), and between absorptive capacity and external knowledge flows in sectors marked by knowledge breakthroughs and tight intellectual property rights (Escribano et al., 2009). In contrast, other research has pointed to a substitution effect between internal R&D and external knowledge sources, as well as decreasing returns of the benefits from the latter. (Laursen and Salter, 2006). Further research indicates that internal R&D has a weak effect on promoting exploitation of external knowledge sources and a negative relationship with knowledge sourced from competitors (Lhuillery, 2011). Along the same lines, Vega-Jurado et al. (2009) indicate a significant variation of knowledge sourcing complementarity between product and process innovation, but still no positive effect in terms of innovation output.

5.2.2 Knowledge sourcing for environmental innovation

External knowledge sources play an especially important role in environmental innovation for several reasons. First, empirical evidence suggests that external (inter-sectoral and international sources) have a higher impact on innovation in environmental technologies than on other technologies (Acemoglu et al., 2012; Cruz-González et al., 2015; De Marchi, 2012; Ghisetti et al., 2015; Lanjouw and Mody, 1996; Leoncini et al., 2016). Hence, if environmental innovation is comparatively more dependent on external knowledge sources than incumbent technologies, external knowledge sourcing strategy gains relevance. Second, incumbent technologies have a much larger knowledge base and thus enjoy increasing returns to scale in generating further innovations (Acemoglu et al., 2012; Dangerman and Schellnhuber, 2013; van den Bergh, 2013). This means that optimising knowledge sourcing for environmental technology involves a double challenge, namely to compete with incumbent technologies while also seeking to explore them as external knowledge sources. Third, the use of external (competing) knowledge sources can backfire by feeding further development of the knowledge base of the incumbent technologies.

Among all environmental innovations, extensive research has been gathered for renewable energy on the impact of external knowledge sources on innovation. Previous studies focused on renewable energy innovation have sought to identify, trace and assess the mechanisms capable to induce or hamper the impact of external knowledge. This has involved examination of the link between knowledge and innovation in renewable energy with a focus mainly at the technology and country levels. At the technological level, a key element is comparing the benefits of investment in knowledge production across technologies and sectors. The underlying argument is that resources should be aimed at the alternatives with best return on investment, for example, by focusing on technologies with larger extent of knowledge spillovers, broader applications, and limited crowding-out effects (Noailly and Shestalova, 2013; Popp et al., 2010; Popp and Newell, 2012). At the country level, studies have concentrated on the relative influence of domestic and foreign knowledge production in renewable energy. Empirical evidence points to an important impact of international knowledge flows on renewable energy innovation, not only through traditional market channels, but also through knowledge spillovers (de la Tour et al., 2011; Glachant et al., 2013; Kirkegaard et al., 2009; Popp, 2009). Nevertheless, despite the central role of external knowledge in fostering renewable energy development, empirical investigation of the impact that different knowledge sourcing strategies have on innovation remains underexplored.

5.2.3 Knowledge sourcing strategy and renewable energy innovation

Renewable energy innovation depends on a broad range of knowledge sources as it usually involves the combination of diversified and complex knowledge areas (Garrone et al., 2014; Nemet, 2012; Noailly and Smeets, 2015; Popp, 2016). This explains the importance of external knowledge sourcing as a means to increase the likelihood of gathering complementary knowledge capable of fostering innovation.

Two core features of knowledge sourcing strategies are “breadth” and “depth” (Aharonson and Schilling, 2016; Ferreras-Méndez et al., 2015; Ghisetti et al., 2015; Laursen and Salter, 2006, 2014; Leiponen and Helfat, 2009; Love et al., 2014). The first component, “breadth”, refers to the range of knowledge sources upon which an innovator draws in order to access external knowledge. The basic assumption is that a larger number of knowledge sources improves innovative performance as it means access to a more diverse knowledge base. Early research showed that the likelihood of uncertain innovation success can be enhanced by increasing the variety of technological sources (Nelson, 1959; (Kogut and Zander, 1992). More recently, the idea of open innovation further emphasized the value of external knowledge sourcing by arguing it is a necessary strategy to increase R&D productivity in the face of growing competition and faster technology development cycles (Cassiman and Valentini, 2015; Chesbrough, 2003; Chesbrough and Crowther, 2006). In the context of renewable energy technologies, the role of external knowledge sources is particularly relevant as they require a systemic change, including not only technological innovations but also organizational (e.g., grid management) and institutional ones - e.g., specific regulations (Popp et al., 2010; Trancik, 2015).

The second component of knowledge sourcing, “depth”, denotes the intensity of use of external knowledge sources. Innovative organisations often draw deeply from only a restricted number of external knowledge sources (Bodas Freitas et al., 2013; Cassiman and Veugelers, 2006; von Hippel, 1994). The development of each of these intensively used knowledge sources involves the construction of an interaction pattern, where shared communication channels, goals and working routines are built over time. Despite the additional costs involved, this knowledge sourcing strategy is expected to pay-off as it grants access to more distant and complex knowledge, and spurs virtuous cycles of exchanges with external knowledge.

Motivated by the foregoing arguments, we will test if the following hypotheses are supported for renewable energy innovation:

H1: Breadth of external knowledge sourcing has a positive effect on innovation performance of research groups focused on renewable energy.

H2: Depth of external knowledge sourcing has a positive effect on innovation performance of research groups focused on renewable energy.

Building on previous studies (Cruz-González et al., 2015; Ghisetti et al., 2015; Laursen and Salter, 2006, 2014), we further examine whether some organisations ‘over-search’, leading to a negative impact on their innovation performance, or become too deeply dependent on external sources for innovation. Moreover, as external knowledge sourcing has a cost in terms of money, resources and attention, one may expect decreasing returns to set in at some stage (Ghisetti et al., 2015; Laursen and Salter, 2006). These considerations give rise to a third hypothesis that will be tested:

H3: Breadth and depth of external knowledge sourcing have an inverted U-shape effect on innovation performance of research groups focused on renewable energy.

An issue particularly relevant to renewable energy innovation is the impact of public support to innovation in the form of government funding of private or public R&D, given that there is broad empirical evidence of its impact on innovation in general (Arnold, 2012; Defazio et al., 2009; Jaffe, 2002; Jaffe et al., 2015). For innovation in renewable energy, public support in the form of direct or indirect subsidies has played a key role in the emergence and deployment of new technologies (Bettencourt et al., 2012; Johnstone et al., 2009; Popp and Newell, 2012; Rodríguez et al., 2015). Still, to our knowledge, little work has been carried out to investigate the relationship between the degree of public support for R&D (henceforward referred to as 'public support) and the impact of external knowledge sourcing on innovation. Given the combination of the importance of basic, scientific research for renewable energy innovation and the broadness of the knowledge basis for it, we expect to find public support to have a moderating effect on external knowledge sourcing. Organisations that enjoy greater public support may be able to multiply the innovation benefits of external knowledge sourcing, for example, by reducing the costs of knowledge management. We therefore investigate whether, conditional on hypothesis 1 and 2, the interaction of breadth and depth with public support is associated with greater innovation success. Accordingly, our hypothesis can be stated as:

H4: Public support to R&D positively moderates the impact of breadth and depth on innovation performance of research groups focused on renewable energy.

5.3 Study design

5.3.1 Case selection

Several factors justify the choice of solar and wind power as case studies to analyse the contribution of external knowledge sources to environmental innovation. First, among environmental technologies, solar and wind power have the highest potential to become cost competitive with incumbent energy sources (Dale, 2013; Hirth et al., 2015; IEA, 2014a), and therefore are the most likely to quickly contribute to climate change mitigation. Second, both technologies have enjoyed wide diffusion in the last decades. This is important considering that the time frame to consolidate new knowledge is long, especially in view of path dependency and cumulative causation (Jacobsson and Bergek, 2004). Moreover, the diversity of countries and settings where solar and wind power are developed and implemented will allow us to draw general insights from the analysis. Third, these technologies involve different levels of complexity and have had distinct technological trajectories (Huenteler et al., 2015). Their development entails the integration of activities (e.g. design, engineering, production) and of components and sub-systems from different industrial areas (Baker et al., 2009; Blanco, 2009), and hence the combination of a diverse set of knowledge bases and capabilities. Such a variety of knowledge adds importance to external knowledge sourcing, which is the focus of our analysis.

5.3.2 Data collection approach

Original data was collected through a web survey from June to July 2015. The sample of respondents was constructed by collecting email addresses of "corresponding authors" in scientific articles published between 2005 and 2015, obtained from the Scopus database. The initial selection through a keyword search[25] for solar and wind power technologies resulted in 84,330 publications, from which 42,817 email addresses were retrieved. After checking for false positives[26] (i.e., publications that were not related to solar and wind energy technologies), we excluded all publications that had fewer citations than the mean number of citations for all publications in its publication year. This was motivated by the aim of identifying the most significant publications and associated authors (Garfield et al., 1964; Leydesdorff et al., 2009). Next, the database was cleaned of duplicate email addresses.[27] The final database included 7,601 email addresses. A pilot study[28] was performed to test the questionnaire, and the final survey was sent out: 6,134 emails were delivered and 1,467 bounced. We collected 508 valid responses[29], which corresponds to a response rate of 8.3%[30].

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[25] The keywords search involved two steps: first, a list of keywords was defined based on a literature review and validated with two experts; second, the search was performed independently for wind and solar energies, combining the words 'solar' and 'wind' with the list built in the previous step.

[26] This procedure was based on the analysis of the publication source, title, keywords and abstract.

[27] Duplicate email addresses were due to people being author on multiple publications, or to different email addresses existing for a single author. In the latter case, the email address of the most recent publication was used.

[28] Several revisions of the questionnaire were tested (both electronically and through personal contacts) with experts on different energy technologies, survey techniques or innovation studies, in order to improve formulations, definitions and question formats. The pilot study was made with a subsample of 50 emails randomly selected.

[29] We only considered responses from researchers working as head of the research group or in senior positions (at least 5 years of experience).

[30] This response rate is consistent with previous studies based on different web survey tools (e.g. Dillman, 2007; Sánchez-Fernández et al., 2012; Sauermann and Roach, 2013).

5.3.3 Variables

5.3.3.1 Dependent variable

Innovation output is measured by patents as this indicator is recognised to be among the most effective measures of industrial innovation (Cohendet and Meyer-Krahmer, 2001; Hicks, 1995; Meyer, 2000; Nelson, 2009; Poirier et al., 2015). Patents have historically figured as one of the main indicators of innovative performance, and knowledge stocks and flows (Archibugi, 1992; Corredoira and Banerjee, 2015; Jaffe et al., 1993; Johnstone et al., 2009; Lanjouw and Schankerman, 2004). Furthermore, patent counts are also considered a reliable indicator of the level of innovative activity, since patent applications are mostly started in the beginning of the research process (Popp, 2009). Patent data offers several additional advantages: it is publicly available and combines detailed information about inventors, technology, institutions and interpersonal links (Griliches, 1990; Jaffe and Trajtenberg, 2002; Popp, 2005; Watanabe et al., 2000). However, using patents also has drawbacks: patent values are highly heterogeneous, some inventions are not patentable, and the propensity to patent strongly varies across sectors and countries (Malerba and Orsenigo, 1996; Nelson, 2009). In this study, these limitations are addressed by focusing on specific technology fields (namely solar and wind power), rather than aggregate patent statistics for whole countries, as well as by using a set of control variables as explained in section 3.3.3.

5.3.3.2 Explanatory variables

The explanatory variables relate to the knowledge sources the research group relies upon. Building up from the long lasting tradition of innovation surveys realised by the European Commission, OECD, and ZEW[31], we study 12 types of knowledge sources, namely scientific publications, non-scientific publications (e.g. industry reports), patents, personal contacts, staff exchange, facilities sharing, research partnerships, PhD financing, suppliers, customers, competitors and consultancy (please see Table 5.1 for full descriptions). Respondents were asked to report the use and evaluate the importance of each knowledge source for innovation in their research group. To investigate the relationship between knowledge sourcing and innovative performance, we follow previous studies and use breadth and depth as variables reflecting openness of external knowledge sourcing (Cruz-Cázares et al., 2013; Ghisetti et al., 2015; Kafouros et al., 2012; Laursen and Salter, 2006). Breadth is constructed as a combination of the 12 sources of knowledge (for details, please see B.1. in Appendix B). As a

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[31] Namely: the Community Innovation Survey (CIS) from the European Commission, the OECD innovation microdata project, and Mannheim Innovation Panel (MIP) survey yearly organised by ZEW.

starting point, each of these sources is coded as a binary variable, 0 meaning no use and 1 use of the given knowledge source. Subsequently, the 12 sources are summed up to obtain an index of the degree of openness of each research group. In line with previous studies using this construct, the variable has a high degree of internal consistency (Cronbach's alpha coefficient = 0.8255).

Depth reflects the intensity of use of knowledge sources. Here, we create binary variables to reflect the knowledge sources to which the research group attributes a high degree of importance, where those ranked as very important (i.e. 5 on a Likert scale 1-5) are coded as 1, and the others 0. Then we add up these binary variables to obtain an index of how many knowledge channels a research group intensively exploits. Again, the degree of internal consistency of this variable is high and comparable to previous empirical studies (Cronbach's alpha coefficient = 0.8273).

Table 5.1. Variables description.

Variable	Description
Dependent variable	
Innovation output	Number of patents or patents applications where the research group was listed as an inventor between 2005 and 2014
Independent variables	
Breadth	Number of knowledge sources the research group relies upon
Depth	Number of knowledge sources the research group values as highly important
Control variables	
Size	Number of PhD holders working full time in the research group
Start-up	Research group established in 2010 or later
Organisation type	Type of organisation the research group is or is affiliated to
Country	Country of location of the research group
R&D investment	Average yearly budget of the research group between 2005 and 2014
Collaboration intensity	Research partnerships resulting in patent between 2005 and 2014
Propensity to patent	Patenting as a highly important goal for the research group
Focus on basic research	Share of resources dedicated to research not motivated by an immediate application
Focus on applied research	Share of resources dedicated to research geared towards a specific application
Government-funded R&D	Share of government-funded R&D in the research group total budget between 2005 and 2014

5.3.3.3 Control variables

The control variables include factors that have been shown to influence or moderate innovation performance in previous studies focused at knowledge sourcing, namely: organisational characteristics (i.e. size, type, year of foundation and country of location), propensity to patent, collaboration intensity and level of R&D investment (Bekkers and Bodas Freitas, 2008; Cassiman and Veugelers, 2006; Czarnitzki et al., 2009; Jaffe, Adam B., 2000; Laursen and Salter, 2006; Roper and Hewitt-Dundas, 2015; Tether and Tajar, 2008; Wu and Shanley, 2009). As for organisations, research group size is considered to be an important predictor of innovation output, even though with heterogeneous impact (Galende and de la Fuente, 2003; Rothwell and Dodgson, 1994; von Tunzelmann, 2003). Large organisations tend to have more research personnel and funding, enjoy higher economies of scale in research, and have better access to diverse knowledge channels. In contrast, small organisations tend to take larger risks, develop research activities more efficiently, and implement technological and organisational changes more quickly. We control for organisation size by using the number of people holding a PhD and working full time in the research group as a proxy.

In addition, respondents were asked to identify the type of organisation to which their research group belongs, or is affiliated to; the year of foundation, and the country of location. We control for the type of organisation to account for differences in terms of innovation purpose and knowledge sourcing strategy depending on institutional character (public or private) and focus of activity (e.g. firm, research institute, university, NGO). As is common in innovation studies, we also control for country of location with 35 dummies corresponding to OECD countries plus the largest emerging economies (e.g. China, Brazil, Russia). Furthermore, we control for whether the research group has been recently established, as this reduces the likelihood of having had any patents granted. We used the dummy variable 'start-up' to indicate groups founded after 2010.

A second set of control variables is used to account for factors particular to each technology and sector dynamics: R&D investment, collaboration intensity, propensity to patent, degree of research novelty and share of public support. We control for R&D investment by the research group as its impact on innovation output is widely recognised in the literature (Dosi and Soete, 1988; Freeman, 1998; Freeman and Soete, 1997; Griliches, 1994). Next, collaboration intensity is controlled by a dummy variable indicating that the research group has already had formal research partnerships resulting in a patent. Together, these two control variables work as a proxy for absorptive capacity (Cassiman and Veugelers, 2002; Escribano et al., 2009; Fosfuri and Tribó, 2008). Propensity to patent is controlled by using a dummy variable that assumes the value of '1' if patenting is considered as a main goal of the research group. Degree of novelty is controlled by the extent to which the research group is dedicated to basic or applied research, where the former indicates higher degree of innovation radicalness than the latter. Finally, the impact of public support received by the research group is also considered as environmental innovation is highly dependent on public funding. We control for the share of public support in the total budget of each research group.

5.3.4 Method of estimation

We use a negative binomial regression model as estimation method since our dependent variable, innovation performance, is measured as a count variable, namely the number of patents. Negative binomial models are suitable to studies with samples characterised by overdispersion and many independent variables (Cameron and Trivedi, 2013), as is the case here. In order to check for multicollinearity, we calculated both pair-wise correlations and variance inflation factors (VIFs). An examination of the correlation tables (see Tables B.2 and B.3 in Appendix B) reveals that correlations are low, with 0.49 as the highest, found between one pair of control variables (namely size and R&D investment). We observe that all tolerance statistic values are much higher than the recommended threshold of 0.2, and that the maximum VIF is 1.35, well below the recommended ceiling of 10 (Randolph and Myers, 2013; Tabachnick and Fidell, 2013; Winkelmann, 2008). Together, these results indicate that there is no serious multicollinearity. Due to the relatively small size of our samples for each technology studied, standard errors can be large in the regression analysis, so we consider ‘$p<0.1$’ as the threshold for statistical significance in our analysis (Lavrakas, 2008).

5.4 Linking renewable energy innovation and knowledge sourcing: empirical results

5.4.1 Descriptive statistics

Before analysing the link between openness of knowledge sourcing and innovation, we use descriptive statistics to obtain an overview of the main characteristics of the RGs studied (Table 5.2). The results show a fairly similar profile of RGs focused on solar and wind power. Only 17% of the RGs are start-ups (i.e. have been founded after 2010), the average number of full time researchers is 14 for solar and 15 for wind, and the average yearly R&D investment is between 220-235,000 Euros (for the period 2010-2014). Most RGs in our sample are affiliated to either a university (74% for solar and 82% for wind) or a public research institute (18% for solar and 12% for wind). In terms of country of location, our sample has a balanced participation of OECD and non-OECD countries with the former hosting 49% of the RGs focused on solar and 58% of RGs focused on wind. The main differences between the RGs arise from their innovation performance, propensity to patent and collaboration intensity (see Table 5.2). Among the RGs focused on solar, 74% produced at least one patent in the period 2010-2014, whereas for RGs focused on wind this number drops to 64%. At the same time, RGs working on solar put a comparatively stronger focus on patenting with 63% of the RGs considering patents as a main goal, compared to only 44% of those RGs focused on wind. Similarly, 30% of the RGs working on solar have had at least one patent resulting from a formal research partnership, whereas the same holds for only 21% of the groups working on wind.

Table 5.2. Descriptive statistics

Variable	Variable format	Solar (n=341)		Wind (n=167)	
		Mean	SD	Mean	SD
Innovation output	Numeric	4.49	3.99	3.92	4.19
Breadth	Scale (0-12)	11.27	1.48	11.18	1.46
Depth	Scale (0-12)	2.37	1.96	2.18	1.87
Size	Numeric	14.32	27.73	15.20	36.66
Start-up	Dummy	0.18	0.38	0.19	0.39
R&D investment	1000 Euros	105.9	89.2	103.1	86.9
Collaboration intensity	Dummy	0.30	0.46	0.21	0.41
Propensity to patent	Dummy	0.63	0.48	0.44	0.50
Basic research focus	Scale (1-5)	2.22	1.33	2.06	1.24
Applied research focus	Scale (1-5)	3.06	1.21	3.31	1.20
Public support to R&D	%	54.68	29.25	53.25	27.32

5.4.2 Results

Estimation results of the negative binomial regression analysis are presented in Table 5.3. Model 1 is the baseline in which only knowledge sourcing strategies (*breadth* and *depth*) and control variables are included. Model 2 adds to the baseline model the squared terms of *breadth* and *depth* in order to investigate the presence of non-linear effects of external knowledge sourcing. Model 3 accounts for the moderating role of *public support to R&D* on the knowledge sourcing strategies by including the interaction terms between external search *breadth* and *depth* and *public support to R&D*. The models show that the distinct knowledge sourcing strategies have significant impact on the innovation produced by RGs focused on solar and wind power, however divergent between the two technology fields.

Hypothesis 1 is confirmed only for solar, indicating that for research on this technology a broad number of external knowledge sources (*breadth*) has a positive impact on innovation performance. In contrast, our results indicate a negative effect of *breadth* on the innovation performance of research on wind. This suggests that RGs focused on wind technology explore a too large number of knowledge sources in view of their managerial and/or financial capacity. Hypothesis 2 is validated only for wind, supporting the idea that more intensive exploitation of external knowledge sources (*depth*) has a positive impact on innovation performance. For RGs working on solar power, *depth* appears to have a negligible effect as it is not statistically significant.

H3 is only partially supported. For RGs focused on solar power the coefficient of *breadth*^{2} is significant and negative, suggesting that the benefits of adding new knowledge sources start falling beyond a certain level of *breadth*. For RGs working on wind power the results show that the coefficient of *breadth*^{2} is significant and positive, which means there is a U-shaped effect on innovation performance of breadth for this technology field. In other words, the benefits of additional knowledge sources increase after a certain threshold. For *depth*, our results do not indicate limits to its effect on innovation (as *depth*^{2} actually is not significant for both technology fields). All in all, the 'take home message' is that the effects of *breadth* and *depth* are distinct for solar and wind power over the studied period (2005-2014). We explore this further in subsequent analyses (see Figure 5. 1 and Figure 5.2).

Table 5.3. Impact of knowledge sourcing strategies on innovation.

Research group focus	Solar power technologies			Wind power technologies		
	Model 1	Model 2	Model 3	Model 1	Model 2	Model 3
Breadth	0.130**	1.925**	2.026**	-0.008*	-2.388***	-3.221***
	(0.059)	(0.883)	(0.902)	(0.074)	(0.809)	(0.960)
Depth	-0.001	-0.198*	-0.055	0.088*	0.357**	0.132
	(0.024)	(0.113)	(0.122)	(0.051)	(0.176)	(0.242)
Breadth^2		-0.075**	-0.079**		0.110***	0.128***
		(0.037)	(0.037)		(0.037)	(0.039)
Depth^2		0.011	0.009		0.027	0.023
		(0.006)	(0.006)		(0.012)	(0.012)
Breadth*Public Fund.			0.000			0.007*
			(0.002)			(0.004)
Depth*Public Fund.			-0.002*			-0.003
			(0.001)			(0.002)
Public support to R&D	0.116**	0.118***	0.334**	-0.093	-0.133	-1.238*
	(0.042)	(0.041)	(0.346)	(0.115)	(0.111)	(0.668)
R&D investment	0.230***	0.217***	0.214***	0.151*	0.187*	0.148*
	(0.052)	(0.052)	(0.051)	(0.110)	(0.102)	(0.106)
Collaboration intensity	0.350**	0.384**	0.348**	0.750***	0.993***	1.020***
	(0.145)	(0.143)	(0.140)	(0.301)	(0.310)	(0.302)
Start-up	-0.128	-0.106	-0.105	-1.142**	-1.503**	-1.505**
	(0.194)	(0.194)	(0.191)	(0.513)	(0.533)	(0.542)
Size	0.007*	0.007**	0.007**	0.003*	0.005*	0.007**
	(0.004)	(0.004)	(0.003)	(0.004)	(0.003)	(0.003)
Propensity to patent	0.419**	0.409**	0.464***	0.660**	0.307*	0.117*
	(0.150)	(0.148)	(0.147)	(0.296)	(0.278)	(0.289)
Basic Research	0.066	0.063	0.070	0.281*	0.181	0.120
	(0.056)	(0.055)	(0.054)	(0.149)	(0.136)	(0.135)
Applied Research	-0.068	-0.055	-0.036	0.143	0.081	0.080
	(0.056)	(0.056)	(0.055)	(0.128)	(0.117)	(0.116)
Constant	-1.719*	-11.556**	-13.098**	1.539**	12.926***	20.446***
	(1.043)	(5.191)	(5.555)	(1.530)	(4.416)	(6.367)
Country dummies	Yes	Yes	Yes	Yes	Yes	Yes
Org. type dummies	Yes	Yes	Yes	Yes	Yes	Yes
Pseudo R^2	0.117	0.124	0.131	0.152	0.185	0.192
p-value	0.000	0.000	0.000	0.000	0.000	0.000
Log-likelihood	-439.732	-436.08	-432.437	-200.783	-192.972	-191.464

Standard errors in parentheses. *$p<0.1$, **$p<0.05$, ***$p<0.01$

For solar power, the marginal effect of *breadth* on innovative performance tends to decrease and get close to zero after a certain threshold is achieved (i.e., 9-10 knowledge sources out of 12). For wind power, *breadth* has a considerably higher threshold than for solar - respectively, 6 and 3 as minimum number of knowledge sources. This limited range of variation of *breadth* for the sample of RGs focused on wind power (6 to 12) may explain the lack of confirmation of decreasing returns in the model. For *depth*, our graphs point to decreasing marginal returns for both technologies to a similar degree. The marginal return of *depth* tends to sharply decrease when more than 5 knowledge sources are intensively used for innovation. Altogether, we may conclude that both the variety (*breadth*) and the intensity (*depth*) of the search for external knowledge have a non-linear impact on innovation performance.

Turning to the impact of public support on innovation performance (Model 3), our results lead to different outcomes for RGs focused on solar and wind power (see Table 5.3). For innovation in solar power, the results indicate *depth* to be negatively moderated by *public support to R&D*, suggesting a trade-off between the share of public support of research and the intensity of exploitation of external knowledge sources. For innovation in wind technology, *breadth* is found to be positively moderated by *public support to R&D*. This positive impact of *public support to R&D* on *breadth* is in line with the idea of a positive correlation between the availability of public research support and *breadth* of external knowledge search.

The effect of the control variables is consistent for all the models presented, with only a couple of differences between solar and wind power. As expected, *R&D investment*, *collaboration intensity*, *propensity to patent* and *size* are positively correlated with innovation performance for both technology fields. Our results also support the idea that being a *start-up* has a negative impact on innovation in wind power (effects on solar power have a negative coefficient, however not statistically significant). For *public support to R&D*, our data indicates a positive effect only for RGs focused on solar power, whereas effects on wind power are negligible (*Depth*Public Fund* is not statistically significant).

Finally, as robustness checks, the same models in Table 5.3 have been tested by dropping the main country of location for the most innovative RGs, namely, Spain for solar power and Denmark for wind power. This aims to reduce possible biases of strong innovators on the sample. Coefficients' signs and significance levels of the main regressors are consistent along all the models. Appendix B (Table B.4) presents the table with the validation estimation results for Model 1 to 3.

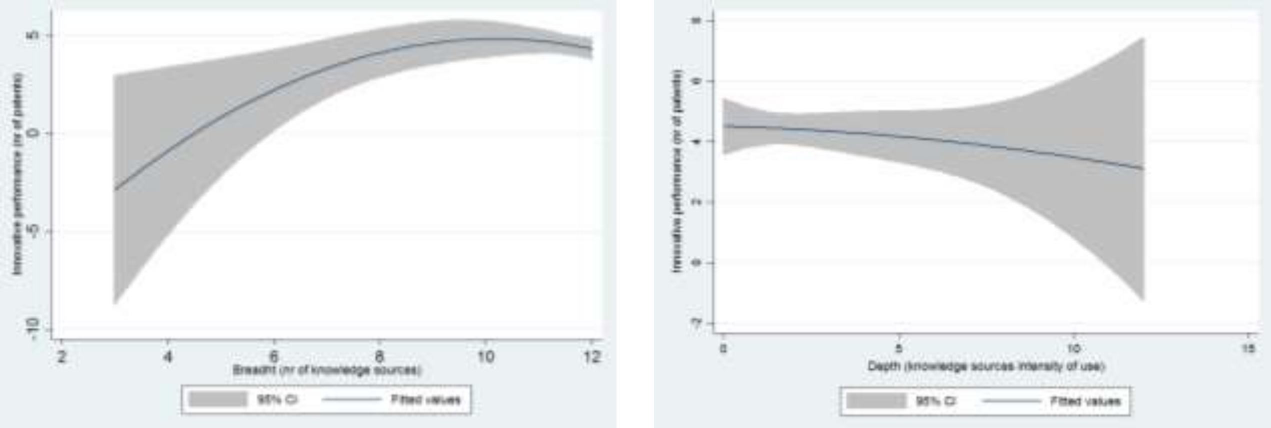

Figure 5. 1. Breadth and depth effects on research on Solar power technologies.

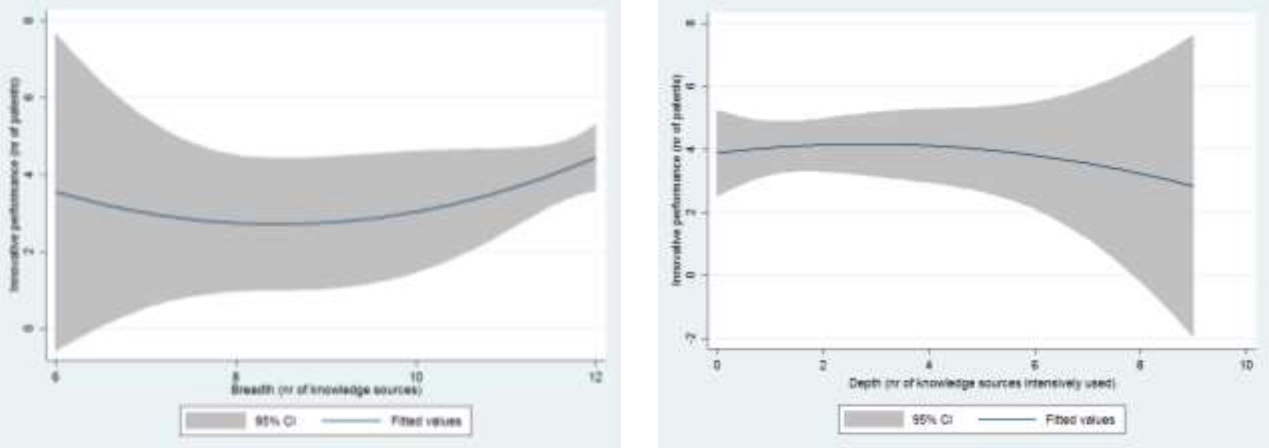

Figure 5.2. Breadth and depth effects on research on Wind power technologies.

5.4.3 Discussion

Overall, the empirical results highlight that the effect of external knowledge sourcing is contingent on the search strategy adopted, as well as on the technological area (see Table 5.4). Similarly, our findings suggest public support to have mixed moderating effects on the impact of knowledge sourcing strategies on innovation. Below we discuss these findings in detail.

Our results show that the two knowledge search strategies have a significant, yet ambiguous, impact on innovation performance. External search breadth fosters solar power innovation while external search depth has a positive impact on wind power innovation. In line with the literature on open innovation, these findings confirm previous studies indicating positive effects of external knowledge sourcing (Berchicci, 2013; Cassiman and Valentini, 2015; Chesbrough, 2003; Escribano et al., 2009; Leiponen and Helfat, 2009; Leoncini et al., 2016). By contrast, our results suggest a negative effect of breadth on wind power innovation, as *breadth* is found to be negative and have a U-shaped impact on innovation (*breadth2* is positive and statistically significant). In fact, the benefits of external knowledge sourcing have already been disputed by previous studies reporting similar results, pointing at possible disadvantages of an open knowledge sourcing strategy (Berchicci, 2013; Cassiman and Valentini, 2015; Cruz-González et al., 2015; Hung and Chiang, 2010). This can be explained by the fact that organisations have to go through a learning process to attain important benefits from external knowledge sources, overcoming several limiting factors[32], such as absorptive capacity, resources allocation, market timing, technology and market turbulence, to reference empirical studies (Hung and Chou, 2013; Laursen and Salter, 2014; Leoncini et al., 2016; Love et al., 2014).

In this regard, our results suggest that optimising benefits from a knowledge search strategy involves a trade-off. Specifically, they suggest that there is a limit to the integration of breadth and depth. At odds with the widely accepted assumption of complementarity between breadth and depth (Cassiman and Valentini, 2015; Chesbrough, 2003), our findings indicate a rather asynchronous relationship where only one of the two knowledge search strategies was found to benefit innovation, depending on the technology field (solar or wind). Innovation in solar power is found to be positively related to knowledge search breadth and negatively related to depth, while innovation in wind power is found to be positively related to depth and negatively related to breadth. Two determinants of the effect that knowledge search strategies have on innovation help to explain the possible underlying causes of this trade-off: technological turbulence[33] and innovation novelty.

Technological turbulence is considered to have a moderating role on the impact of knowledge search strategies. Previous research has shown that an environment characterised by high levels of technological turbulence negatively moderates breadth and positively moderates depth (Cruz-González et al., 2015; Hung and Chou, 2013). Accordingly, our findings point to a positive impact of depth on innovation in wind power, which has been characterised by profound technological transformation due to changes in product design (Lindman and Söderholm, 2012), rapid grid integration (Baritaud, 2012) and continuous price fluctuations (Bolinger and Wiser, 2012) for the period studied (2005-2014). In the same way, the positive impact of breadth on solar power innovation can be connected to a less dynamic technological environment as most turbulent changes in this technology field took place in the late 1990s, thus before the period studied (Candelise et al., 2013; Subtil Lacerda and van den Bergh, 2016). The underlying reasoning is that the extra costs involved in external search

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[32] Please see (Huizingh, 2011; West and Bogers, 2014) for reviews.

[33] Technological turbulence refers to the rate of technological change and uncertainty, which at high levels speeds up knowledge and technology obsolescence (Jansen et al., 2006).

depth pay off only in the face of quick knowledge obsolescence, characteristic of highly technologically dynamic environments. In this case, investments in external search breadth do not increase profitability, or are even counterproductive depending on the amount of resources allocated, as they divert attention from deep exploitation of more distant knowledge. Alternatively, within more static technological environments, knowledge search breadth is advantageous as a strategy to widen an organisation's knowledge base thereby fostering future recombinant innovation (Nemet, 2012; Wu and Shanley, 2009). Moreover, knowledge search breadth enhances the chances for an organisation to enjoy emerging technological opportunities by mapping new products and services, as well as by adding distinct new variations of knowledge (Teece, 1998; Zucker et al., 2007).

Table 5.4. Summary of effects on innovation

	Solar	Wind
Breadth	+	-
Depth	ne	-
Breadth^2	-	+
Depth^2	ne	ne
Breadth*Public support to R&D	ne	+
Depth* Public support to R&D	-	ne
Public support to R&D	+	ne
R&D investment	+	+
Absorptive capacity	+	+
Start-up	ne	-
Size	+	+
Propensity to patent	+	+

Note: "ne" means no effect

Innovation follows particular dynamics depending on the degree of novelty involved (see (Garcia and Calantone, 2002). In the same vein, the impact of knowledge search breadth and depth on innovation has been related to diverse degrees of innovation novelty. Prior empirical evidence indicates that the more radical an innovation is, the more beneficial depth and the less effective breadth of external search are in fostering it (Cassiman et al., 2010; Hsieh and Tidd, 2012; Laursen and Salter, 2006; Leoncini et al., 2016). External search breadth is considered more suitable to foster incremental changes because it involves a rather superficial exploration of a broad number of sources. Depth, by contrast, is considered to serve best for gathering knowledge from distant domains, thus it is more likely to spur radical innovation. Correspondingly, our results point to a positive effect of breadth on solar power innovation and a positive effect of depth on wind power innovation, which can be considered to have focused, respectively, on incremental and radical innovations in the period analysed (IEA, 2014a). For solar power, the rapid diffusion and strong market instability that characterised its dynamics during the 2000s are considered to have reduced incentives to radical innovation and fostered incremental changes required by adaptation to new markets (Eleftheriadis and Anagnostopoulou, 2015; Quitzow, 2015). For wind power, more radical innovation has been promoted by soaring shares of wind electricity supply, which have increased the pressure to rapidly increase efficiency and integration into the electricity grid (Barthelmie and Pryor, 2014; Wiser and Bolinger, 2013).

Turning to the moderating role of public support, our results also show mixed effects for breadth and depth. Public support is found to positively moderate the effect of breadth on wind power innovation, and to negatively moderate the effect of depth on solar power innovation. This indicates that higher shares of public support enhance the benefits of breadth on wind power innovation but reduce the benefits of depth for solar power innovation. The positive effect of the interaction between public support and breadth for wind power innovation is remarkable since public support does not have a direct effect on innovation in this technology[34]. However, this result supports the idea that public support fosters knowledge diversity (Lyall et al., 2013; van Rijnsoever et al., 2014) as it can be understood to provide additional resources which, compared to private ones, are more freely allocated (Czarnitzki et al., 2015). As a result, public support may stimulate organisations to explore a wider number of knowledge sources. For solar power, depth is negatively moderated by public support, suggesting that their combination weakens innovative performance. This can be at least partially explained by the fact that public support is commonly associated with the utilization of traditional scientific sources and institutional frameworks, which have a lower incentive to patent compared to private funded research (Hottenrott and Lawson, 2014). In addition, the rapid expansion of research on solar power in the last decade has struggled with the limited availability of specialized human capital (IEA, 2014b), which may explain the negative effects of growing public support on innovation performance when it involves deep, time consuming, interactions as in the case of depth. Indeed, if organisations seek to deeply draw on too many knowledge sources but have limited human resources, they may lose much time in communication and building new relationships, which might be counter-productive in terms of the net, overall impact on innovation.

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[34] *Public support to R&D* is negative and not significant which indicates a strong effect of private funding (see Table 5.3).

5.5 Conclusions

Effective sourcing of external knowledge is a key driver of environmental innovation. To better understand how the search for external knowledge affects environmental innovation, this study has examined its impact on innovation in two renewable energy sources, namely solar and wind power. Two different components of knowledge sourcing strategies, namely breadth and depth, were identified from the literature as relevant, and thus studied in terms of their effect on environmental innovation performance. We empirically tested hypotheses regarding the effects of these two components of external knowledge search on the innovative performance of two technology fields. Our findings add to the recent literature (Cassiman and Valentini, 2015; Cruz-González et al., 2015; Hung and Chou, 2013) by drawing attention to a contextual dependency of external knowledge effects on innovation. More generally, our study contributes to the literature by offering new empirical insights about the suitability of the open innovation framework in an environmental realm. This has relevant managerial and policy implications.

Our results confirm that external knowledge sources have an impact on innovation, however, with mixed effects. In fact, we find that the assumed complementary relationship between breadth and depth of knowledge sourcing does not hold for the environmental innovations studied. Instead, our analyses suggest a trade-off between knowledge search breadth and depth with inverse effects for solar and wind power innovations. For solar power innovation, only breadth appears to be advantageous while *depth* has a negative sign but is not statistically significant. By contrast, for wind power innovation, only depth has positive effects, whereas *breadth* is negatively associated to innovation performance.

Furthermore, our findings confirm two recurrent arguments regarding policy support to environmental innovation in general, and to renewable energy in particular. First, there is a necessity for policy design to account for the complexity inherent to the systemic dynamics of environmental innovation (Crespi, 2015; Rogge and Reichardt, 2016). Hence, public support to R&D should not only foster external knowledge sourcing, but also the development of the ability to identify and implement the most suitable knowledge search strategy within a changing technological environment. As shown by our findings, the interaction of misplaced public support and external knowledge sources may have negligible or even negative effects on innovation (see Table 5.3 for details). Second, the significant differences between the impact of external knowledge sources on solar and wind power innovation shown in this study confirm the need of technology-specific policies to stimulate environmental innovation (Azar and Sandén, 2011; Sandén and Azar, 2005; van den Bergh, 2013). This is at odds with the common practice of ‘one-size-fits-all’ instruments, such as feed-in tariffs for all types of renewable power, or common emission reduction targets for different energy efficiency technologies. Our results suggest that policies aimed at fostering environmental innovation should account for the technology-specific set of incentives and environmental dynamics capable of catalysing positive effects of external knowledge sourcing. For technology fields characterised by low technological turbulence and a focus on incremental innovation, incentives to broaden knowledge sources (i.e. enhancing breadth) can be an effective means of improving innovative output. Conversely, in the face of high technological turbulence and more radical innovation, incentives to strengthening ties among a reduced number of diverse actors (depth) are likely more effective in fostering innovation.

Finally, our results strongly suggest that by simultaneously searching widely and deeply across a variety of knowledge channels an organisation may trigger negative effects of external knowledge search on innovation. Hence, besides the risk of over-searching due to decreasing returns of openness, our findings point to a trade-off between search breadth and depth. Rather than seeking to fully develop both search modes simultaneously, organisations should, according to our findings, tailor their external knowledge search to best fit the specific level of environmental technological turbulence and technological novelty involved. Of course, this brings in additional managerial challenges as the best combination of breadth and depth requires some degree of technology analysis and forecasting capacity of an organisation. Thus our findings echo previous studies (Cassiman and Valentini, 2015; Cruz-González et al., 2015; Huizingh, 2011; Knudsen and Mortensen, 2011) that call for a more cautious interpretation of the advantages of external knowledge sourcing. Further research is needed to understand how organisations focused on environmental innovation can design effective external knowledge sourcing strategies, as well as when and how to switch the focus between external search breadth and depth.

Appendix B

Table B.1. Importance of knowledge sources by technology

Research group focus	Solar					Wind				
Importance*	1	2	3	4	5	1	2	3	4	5
Knowledge sources	Percentages					Percentages				
Scientific publications in journals or books	0.29	1.17	3.79	22.74	72.01	0	2.42	5.45	30.3	61.82
Other publications, including professional publications and reports	2.96	7.69	26.63	45.86	16.86	0.6	5.42	21.08	55.42	17.47
Patent texts as found in the patent office or in patent databases	9.25	21.19	34.63	29.55	5.37	20.13	20.75	38.99	14.47	5.66
Personal contacts	1.2	4.49	19.46	48.2	26.65	0.61	5.52	22.7	49.08	22.09
Staff exchange with other research groups	6.19	14.75	29.79	40.71	8.55	7.83	13.86	34.94	34.34	9.04
Facilities Sharing (e.g. laboratories, equipment, housing) with other research groups	3.59	12.57	27.84	42.22	13.77	9.76	22.56	25.61	31.71	10.37
Research Partnerships as formally established agreements	0.59	1.76	19.41	48.24	30	2.41	3.61	21.69	46.99	25.3
Financing of PhD projects	2.66	3.85	9.47	43.79	40.24	4.27	3.05	15.24	41.46	35.98
Suppliers of services, equipment, materials, components, or software	5.39	17.07	29.94	38.02	9.58	11.11	23.46	37.04	20.99	7.41
Customers or clients	13.35	19.58	35.01	24.63	7.42	9.94	22.98	34.16	21.12	11.8
Competitors	11.75	21.39	34.34	29.52	3.01	8.7	24.22	35.4	27.33	4.35
Consultancy	14.16	24.1	30.72	27.11	3.92	12.96	32.1	34.57	14.2	6.17
Average	5.95	12.47	25.09	36.72	19.78	7.36	15.00	27.24	32.28	18.12

*1:‘Not important at all’, and 5: ‘very important’.

Table B.2. Correlation matrix and collinearity analysis for RGs focused on Solar

Variable	1	2	3	4	5	6	7	8	9	VIF	Tolerance
1. Innovative performance	1.00									1.20	0.70
2. Breadth	0.12	1.00								1.05	0.91
3. Depth	0.02	0.16	1.00							1.04	0.93
4. Public support to R&D	0.19	0.05	0.08	1.00						1.03	0.94
5. R&D investment	0.47	0.00	-0.09	0.10	1.00					1.20	0.69
6. Start-up	-0.06	-0.10	-0.01	-0.05	0.01	1.00				1.02	0.95
7. Size	0.31	0.06	0.11	0.15	0.39	-0.16	1.00			1.13	0.78
8. Collaboration intensity	0.28	0.12	0.09	0.03	0.17	0.04	0.12	1.00		1.06	0.89
9. Propensity to patent	0.12	0.21	0.10	-0.08	0.07	0.00	0.03	0.15	1.00	1.04	0.92

Table B.3. Correlation matrix and collinearity analysis for RGs focused on Wind

Variable	1	2	3	4	5	6	7	8	9	VIF	Tolerance
1. Innovative performance	1.00									1.21	0.68
2. Breadth	0.12	1.00								1.06	0.90
3. Depth	0.04	0.06	1.00							1.04	0.92
4. Public support to R&D	0.05	-0.14	-0.10	1.00						1.11	0.81
5. R&D investment	0.29	0.09	0.03	0.24	1.00					1.35	0.55
6. Start-up	-0.30	-0.21	0.00	0.07	-0.31	1.00				1.12	0.79
7. Size	0.35	0.11	-0.01	0.23	0.49	-0.32	1.00			1.35	0.55
8. Collaboration intensity	0.37	0.10	-0.19	-0.11	0.14	-0.09	0.15	1.00		1.14	0.77
9. Propensity to patent	0.30	0.23	-0.03	-0.25	-0.07	-0.12	0.03	0.27	1.00	1.13	0.78

Table B.4. Robustness checks
Impact of knowledge sourcing strategies on innovation: negative binomial excluding Spain and Denmark.

Research group focus	Solar power technologies			Wind power technologies		
	Model 1	Model 2	Model 3	Model 1	Model 2	Model 3
Breadth	0.110*	2.190*	2.283*	-0.124	-1.965**	-3.718***
	(0.070)	(1.372)	(1.384)	(0.095)	(0.835)	(1.052)
Depth	0.002	-0.190	-0.055	0.145**	0.189*	0.022
	(0.026)	(0.126)	(0.134)	(0.053)	(0.202)	(0.205)
Breadth^2		-0.085*	-0.091*		0.086**	0.130***
		(0.056)	(0.056)		(0.039)	(0.041)
Depth^2		0.011	0.009		0.019	0.022*
		(0.007)	(0.007)		(0.013)	(0.012)
Breadth*Public support to R&D			0.001			0.011***
			(0.002)			(0.004)
Depth*Public support to R&D			-0.002**			-0.005**
			(0.001)			(0.003)
Public support to R&D	0.088**	0.090**	0.257	-0.053	-0.045	-1.888***
	(0.044)	(0.043)	(0.399)	(0.110)	(0.122)	(0.622)
R&D investment	0.290***	0.275***	0.262***	0.156*	0.180*	0.133
	(0.057)	(0.057)	(0.057)	(0.105)	(0.107)	(0.096)
Collaboration intensity	0.400**	0.463***	0.422**	0.680**	0.876***	1.032***
	(0.160)	(0.162)	(0.158)	(0.275)	(0.308)	(0.292)
Start-up	-0.132	-0.118	-0.080	-1.284**	-1.423**	-1.484***
	(0.207)	(0.206)	(0.203)	(0.478)	(0.514)	(0.462)
Size	0.007*	0.007**	0.007*	0.003	-0.002	0.002
	(0.004)	(0.004)	(0.003)	(0.007)	(0.007)	(0.006)
Propensity to patent	0.420**	0.384**	0.454**	0.832***	0.656**	0.281
	(0.169)	(0.168)	(0.167)	(0.267)	(0.259)	(0.253)
Basic Research	0.119**	0.114**	0.123**	0.484***	0.409**	0.298**
	(0.060)	(0.059)	(0.058)	(0.1659	(0.164)	(0.152)
Applied Research	-0.052	-0.042	-0.019	0.210*	0.182	0.157
	(0.062)	(0.061)	(0.061)	(0.129)	(0.127)	(0.120)
Country dummies	Yes	Yes	Yes	Yes	Yes	Yes
Org. type dummies	Yes	Yes	Yes	Yes	Yes	Yes
Pseudo R^2	0.1388	0.1445	0.1531	0.2388	0.2585	0.2826
p-value	0.000	0.000	0.000	0.001	0.000	0.000

Chapter 6

Mismatch of wind power capacity and generation: Causing factors, GHG emissions and potential policy responses [*]

6.1 Introduction

A transition of renewable energy is crucial for making our economies environmentally sustainable. With adequate policy support, renewable energy sources have the potential to meet up to 80% of the world‘s energy supply by 2050 (IPCC, 2014). In the last decade, renewable energy has experienced a very high rate of expansion. Between 2004 and 2013, power generation capacity of renewables[35] grew by more than 600%, from 85GW to 560GW (REN21, 2014). Renewable energy sources have recently surpassed fossil fuels in terms of global capacity additions and investment per year[36]. Nevertheless, the renewables share of total primary energy supply has increased only 0.4% from 2006, when its share was 10.6%, to 11% in 2013 (IEA, 2015). Most discussions of this rather disappointing development focus on stimulating further diffusion and associated investment in capacity. Nevertheless, the

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[35] The data presented hereafter on renewable energy exclude hydropower since the focus is on intermittent renewable energy sources.

[36] In 2013, renewables contribute 58% to total global (net) capacity added. For the third consecutive year renewables surpassed fossil fuels and nuclear in terms of investment in new power-generation capacity, comprising US$ 214.4 billion – almost double the net investment in fossil-fuel power, namely US$ 148 billion. This excludes replacement of electricity plants (BNEF, 2014; IRENA, 2014).

increase of power generation from renewables has traditionally lagged behind the expansion of capacity installation.

Largely due to policy support in the form of subsidies or green certificate systems, renewable energy sources have shown high expansion rates of installations. However, at the same time, there is a serious mismatch between installed capacity and actual power generation of renewable energy. This is a somewhat overlooked issue in the literature, which is surprising as it suggests a missed opportunity to contribute effectively and relatively cheaply (cost-effectively) to a reduction in GHG emissions.

The mismatch applies particularly to electricity generation from wind power. Wind power has the largest installed capacity among the intermittent renewable energy sources with 318 GW by 2013 (REN21, 2014). Between 2000 and 2012, its globally installed capacity has grown at an average rate of 24% per year (IEA, 2014c). In contrast, electricity generation from wind started to rise only from 2008 on, at an average 0.3% per year, resulting in a share of 2% of global electricity production in 2012 (IPCC, 2014). Yet, if all generation capacity then installed had been used, wind power could have supplied 14.7%[37] of the global electricity consumption in 2012. At the same time, in 2013 alone, an estimated 212 GWh of electricity generated by the existing capacity of wind power were not transmitted to the grid (Li et al., 2015). This is partly explained by the falling prices of coal and gas, but also by low capacity factors[38] and barriers to integration with the broader energy system (Baritaud, 2012; Volk, 2013). So the past decades of policy support have led to extensive deployment of wind power but its capacity of electricity generation has remained under-exploited.

This paper analyses electricity generation from wind power[39] in order to shed light on the mismatch between installed capacity and power generation. In addition, it qualitatively evaluates the consequences for GHG emissions. The study focuses on the four countries with the largest wind power installations in the past decade, namely China, the United States, Germany and Spain. The main contributions of this paper are three: mapping the main drivers of wind power capacity utilisation within the current energetic system; assessing foregone opportunities in terms of GHG emissions reduction; and identifying potential policies to narrow the gap between electricity capacity and generation from wind power.

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[37] Full capacity refers to maximum power output. The calculation is based on 1625 Mtoe of electricity consumption (IEA, 2015) and 318 GW of installed capacity (REN21, 2014).

[38] The term “capacity factor” denotes the ratio of average power delivered in a given period compared to the theoretically maximum power that can be generated (further details are provided in section 2.2).

[39] The analysis is focused on electricity generation from onshore and grid connected wind power installations because this setup is the most widely deployed. Offshore wind power is mentioned whenever relevant for the discussion.

The remainder of this paper is organized as follows. Section 6.2 reviews the factors determining electricity generation from wind power within the current system. Section 6.3 estimates wind power capacity utilisation in the four countries studied, identifies drivers of the gap between capacity and generation, and explains differences found among countries. This is followed in Section 6.4 by a discussion of foregone opportunities to reduce GHG emissions, and policies to improve wind power generation with given capacity. Section 6.5 concludes.

6.2 Wind power: driving forces of capacity utilisation

In this section we examine the main features of electricity generation from wind power followed by discussion of the determinants of its capacity utilisation.

6.2.1 Electricity generation from wind power

Wind power systems produce electricity by harnessing the kinetic energy of wind and converting it into electric energy. For electricity generation, the dominant design of wind power systems is the utility-scale, the so-called "wind farms". Normally built in geographical areas characterized by consistent wind flows, wind farms combine several wind turbines with a balance of system of electrical components (such as transformers and grid interconnectors). Each wind farm has a peculiar dynamics that defines its power generation capacity. This dynamics is based on several features, such as the wind farm's capacity factor and connectivity to the power grid[40]. Electricity generated by wind farms is introduced into electric grids by transmission system operators (TSOs) and delivered to consumers by distribution system operators (DSOs)[41]. Since electricity cannot be stored cost-effectively in large quantities, supply and demand must be balanced in real time at all times. This task is normally performed by a grid management system that coordinates TSOs and DSOs. Because electricity networks are highly interconnected, any imbalance between supply and demand in one location may affect the entire network. Hence, electricity provision to consumers depends on the system operators' capacity to guarantee that supply evens demand across the whole network at all times. To this end, a platform is used to allow all electricity producers to communicate in real time with the system operator. In a competitive electricity market, this central platform works also as a bidding market, where the cheapest offers can be identified and dispatched.

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[40] For a comprehensive discussion on wind farms see Chowdhury et al., 2013 and Herbert et al., 2014.

[41] The focus on transmission and/or distribution operators, rather than on vertically integrated utility structure, is given by the fact that these play key roles in markets with significant shares of wind power generation.

Electricity networks are complex systems, with many complementary components and feedbacks. Moreover, each location and each market have different energy mixes, network structures, levels of wind penetration, etc. Here we focus on the current electricity system to analyse the factors considered determinant of the capacity utilisation of wind power installations. Instead of looking at the conditions enabling a future all-renewables system, we recognize fossil fuels as a complementary energy source, and acknowledge the need for redundant capacity of wind power upon this current hybrid system. The following sections briefly review the main determinants of capacity utilization of wind power installations, namely: capacity factors, system flexibility, and market integration.

6.2.2 Capacity factor

The capacity factor is an indicator of electricity-generating capacity that specifies the percentage of time that a wind farm produces electricity during a representative year. It is calculated as the ratio of average power delivered in a given period compared to the theoretical maximum power, for a single turbine, a wind farm (covering several turbines) or an entire country (with several wind farms). Capacity factors vary following location and the design of wind turbine and wind farms. The local wind resource is considered the most important factor affecting the performance of wind energy systems (Blanco, 2009). Location influences the capacity factor due to wind conditions. These are rated by capacity of kinetic energy generation (derived from the weather conditions), but also by transmission enabling factors, such as: correlation with peak demand; proximity to end-consumers; and variability and predictability of wind blow (Baritaud, 2012; IEA, 2014d).

Design of wind turbines influences the capacity factor by nameplate capacity (maximum power generation capacity) and suitability to the wind regime.

Recently, turbine design has evolved towards higher power capacities by increasing the height of the tower and the length of the blades (IEA, 2013b). On average, however, the average height and rotor diameter of turbines has grown more rapidly than average power capacity. This decrease in the specific power, or ratio of capacity over area, has pushed up capacity factors for the same wind speeds (Wiser and Bolinger, 2013). For lower wind speeds, rotors with high masts and long blades in relation to generator size are the most suitable, and sometimes present even higher capacity factors than high speed designs (Bortolini et al., 2014). Moreover, because lower-wind-speed areas are often closer to consumers than the best wind locations, this offers additional advantages as lower transmission losses and higher flexibility of dispatch. While several designs are in use today, new grid-connected turbines had an average size of 1.8 MW in 2012, up from 1.6 MW in 2008 (Navigant, 2014). The largest commercial wind turbine currently available is 7.5 MW, whereas turbines with a rated capacity between 1.5 MW and 2.5 MW respond for the largest market share (IRENA, 2012b). Onshore wind has a capacity factor ranging from 20% to 40% (IPCC, 2014), depending on the turbine design (see Table 6.1).

Table 6.1: Capacity factors for different wind turbine designs

Onshore turbine nameplate capacity	Capacity factor projected	Standard deviation
<100kW	18%	75.4%
100kW – 1MW	22%	75.1%
>1MW	31%	77.5%

Source: Arvesen and Hertwich, 2012.

In the last decade, the expansion of wind power installations generated information about realized capacity factors that were in general lower than the originally assumed ones, namely with an order of magnitude of 35% (Arvesen and Hertwich, 2012). This has significant consequences for investors since the average capacity factor over the 20 years lifetime of a turbine defines the electricity produced and, hence, the return on investment. For example, for the EU15, the average capacity factor realized in 2003-2007 was 21%, rather than the initial projected 35%. This resulted in a 66% increase[42] of average levelised cost of wind power generation (Boccard, 2009). Even though oscillations across time and regions make capacity factors difficult to forecast precisely, the industry has now assembled experiences in highly diverse contexts, which offer relevant information to improve the decision about future installations, as well as to better forecast electricity production from current installations.

6.2.3 System flexibility

Competitive operating costs or merit-order effects make electricity from wind to have priority of being dispatched into the grid, thereby displacing the use of other electricity sources (Jónsson et al., 2010; Pereira et al., 2014). This results in electric system operators and markets using other generators to meet demand minus any available wind energy. Larger shares of intermittent wind-generated electricity lead to higher variability in the electric system.

Due to this higher variability, further integration of intermittent renewable energy, as wind, requires additional flexibility of a network, i.e. increased capacity to receive variable

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[42] Levelized cost is the ratio of fixed cost to capacity factor. In this case, the ratio of projected to realized capacity factor is 35/21=1.66, so that the cost is 66% above the initial estimate.

and uncertain power flows. The impact of intermittency of renewable energy sources usually becomes noticeable beyond 2% to 3% of total electricity generated, but is expected to create technical or cost barriers to integration only with penetration levels above 20% (GEA, 2012). Several countries (e.g. Denmark, Germany and Spain) have electric systems expected to support intermittent power inputs at annual shares between 25% and 40% of total electricity supply (IEA, 2014d).

Without additional flexibility, a system is unable to absorb increasing shares of wind-generated electricity, leading to higher curtailment[43] rates. In this case, the capacity utilisation of a wind farm would be maintained at levels below what the wind regime enables, rather constrained by the grid capability. This is of major concern since it limits the capacity of a wind farm to achieve, or increase, net energy generation. This results in a lower rate of return on investment and less GHG emissions being reduced.

To improve network flexibility, the main approaches currently used in the electricity sector involve changes in four areas, namely network infrastructure and management, portfolio diversity, storage and demand side management. These are briefly discussed.

6.2.3.1 Network infrastructure and management

Network infrastructure can be strengthened by reinforcing the physical structure and extension of transmission and distribution lines. This allows the system to support wider and sudden power input variations, as well as to connect with more distant power generation and consumption centres (Benatia et al., 2013). Grid management can enhance flexibility essentially by improving the accuracy of wind forecasts and by reducing response and communication times between generators and system operators (Denholm and Hand, 2011; Li et al., 2015).

An additional mechanism to increase a network capacity to absorb wind power is to dynamically regulate transmission capacity with relation to wind and temperature. This technique is known as "dynamic line rating" (DLR). For example, a wind of 1m/s can increase line rating as much as 44% due to the cooling effect of wind on the transmission lines (IEA, 2014d). Further benefits from applying DLR are reduced congestion and re-dispatch operations (Cochran et al., 2012).

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[43] Curtailment refers to reductions of power dispatch into the grid in response to a transmission capacity shortage, with the aim to secure system reliability.

6.2.3.2 *Portfolio diversity*

Portfolio diversity refers to the geographical expansion of wind farms and grid infrastructure, as well as to complementary and non-intermittent energy sources, known as dispatchable plants. The first type of diversity offers two advantages: enhanced demand-supply balance as within larger geographic areas variations of supply by individual wind farms tend to cancel out (Neuhoff et al., 2013); and higher forecast accuracy for the electrical system since geographical dispersion reduces the impact of forecasting errors associated with individual wind farms (Albadi and El-Saadany, 2010). Dispatchable plants increase a system capability to cope with variability of wind-generated electricity either by attending peak demand or by guaranteeing minimum supply. Here, the most suitable electricity sources are hydro and gas-fired plants due to their fast ramp up (Jacobson and Delucchi, 2011).

6.2.3.3 *Energy storage*[44]

Storage technologies have the potential to increase network flexibility required for wind-generated electricity. Because storage functions as both an electricity producer and consumer it can smooth electricity flows, absorbing power during peak generation and returning it to the grid during peak demand (Zhao et al., 2014). Through this mechanism of quick adaption to intermittence, it offers additional advantages such as: increased reliability by neutralizing forecast errors; and lower network requirements in function of reduced stress over transmission and distribution lines and operators (Luo et al., 2014).

Unfortunately, all storage technologies currently available have considerably higher costs compared to other flexibility options. Storage has a cost of about US$ 1200/kW for typical projects (IEA, 2014d). By 2010, electricity storage capacity amounted to 125GW worldwide, corresponding to about 3% of global electricity generation capacity (Luo et al., 2015). To date, pumped hydroelectric (pumped hydro) is the most mature and cost-competitive storage option. It accounts for 99% of installed capacity by 2012, with Japan (23 GW) and EU-15 (13 GW) as the main markets (IEA, 2014d). Furthermore, recent studies indicate that storage can become cost-effective only within specific technology mixes and with wind-generated electricity responding for at least 48%-51% of the total (Tuohy and O'Malley, 2011).

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[44] Storage refers to technologies that absorb electricity at a given time and return it at a later date. Technologies based on seasonal storage capability (days or weeks), such as hydrogen storage and power to gas, are not considered here because they are still in a very early stage of development.

6.2.3.4 Demand side management

Demand side management (DSM) refers to a mix of measures to improve flexibility by controlling consumption. The main objective is to change a system or utility's load shape, reducing or avoiding peak demand and peak generation. An incentive is often offered to customers in return for participation. Programmes focus on customers’ voluntary responses, mainly by setting smart energy prices that incentivize targeted consumption behaviour (Finn and Fitzpatrick, 2014). The overarching goal is to assure that prices reflect real-time availability of electricity, thereby providing the adequate incentives to drive consumers’ behaviour (Clastres, 2011). DSM is considered one of the most promising low cost instruments for additional flexibility. It enables short-term redistribution of electricity demand without many additional infrastructure requirements (Yang et al., 2014).

6.2.4 Market integration

Integration of wind power in electricity markets is still evolving and shows variation across countries. So far, wind-generated electricity has been remunerated by support schemes at the margin of competitive electricity markets. Further market integration depends on a system capable of securing reliability and security of supply at least cost while using the largest amount of wind-generated electricity possible. Because of intermittency and lack of storage options, increasing the volume of wind-generated electricity challenges the system to balance generation and consumption at all times. This requires synchronous coordination between power generators, system operators, and consumers. The use of market-based solutions, such as price signals, to push for timely and efficient responses, is here complemented by technologies that shorten communication and response times and increase control over power flows (IEA, 2014d). Market integration has been promoted by a number of instruments. Below, we discuss the most widely employed ones.

6.2.4.1 Balance of dispatch

The maintenance of electricity supply depends on the balance of dispatch among all generators, of wind power and all other energy sources present in a system. Trade integration among dispersed wind power generators and use of complementary and non-variable sources (e.g. hydro or gas-fired power plants) have proved to be the most cost-effective solutions so far (Baritaud, 2012; Jacobson and Delucchi, 2011; Volk, 2013). Due to variability and uncertainty characteristics of wind power, short-term bidding is considered more suitable than the current pattern of long-term contracts (Neuhoff, 2011; Rubin and Babcock, 2013).

The closer to generation time a purchase contract is arranged the more accurate in terms of the amount and timing of wind power generation it tends to be. With higher accuracy, larger amounts of wind power can be dispatched to the grid without reducing security of supply or increasing system costs (Wang, 2014). This also entails further benefits by reducing the need of reserve capacity as well as curtailment risks.

At the same time, because a higher penetration of wind electricity tends to lower electricity prices (Ketterer, 2014; Twomey and Neuhoff, 2010), conventional electricity generators may become uneconomic over time. However, these non-intermittent plants are necessary to guarantee system supply in situations of too little or too strong wind. Hence, there is a need to provide incentives to maintain a safe level of conventional power generation. So-called markets for ancillary services[45], where remuneration is based on tasks other than power effectively delivered, are an option. In this case, conventional power generators could be rewarded by capacity available and operation capabilities such as fast ramping, ramp rate control, quick-start, low turn down, and inertial response (Cochran et al., 2012).

6.2.4.2 Reduced time of response

Reducing the time intervals of system operation better reflects wind power generation. Dynamic markets that function on intervals of minutes, rather than hours, are more suitable for integrating wind power because they allow to better track actual generation and net load, without the need to rely on reserves (Clastres, 2011). Furthermore, dispatching in shorter intervals enhances coordination among different wind farms, and with conventional generators, improving overall system efficiency (IEA, 2014d). Currently, the best practice dispatch interval is five minutes – namely, at ERCOT[46] in Texas, US (Zarnikau et al., 2014); but one hour tends to be the rule. Another mechanism for reducing time of response is to shorten gate closure times[47], so that trading can happen as close as possible to real-time operations. This increases capacity use in two ways: reductions of forecast errors to a

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[45] Ancillary services refer to operations required to warrant continuous electricity supply, such as scheduling and dispatch, reactive power and voltage control, power loss compensation, load following, power balancing and curtailment control. Historically, these services have been provided mainly by conventional power sources. With large penetration of wind, these conventional power generators may need to continue generating electricity above required levels just in order to be available to provide ancillary services (IEA, 2014d).

[46] ERCOT refers to Electric Reliability Council of Texas, the system operator responsible for the electric grid and 75 percent of the state's electricity market.

[47] Gate closure time refers to the future time at which the market commits to deliver electricity. After gate closure, it is not possible to change electricity supply or demand offers. Most markets are based on a day-ahead trading, which closes at mid-day on the day before power generation. The second most common market is the intra-day, where trading takes place on the same day as physical delivery of electricity (IEA, 2014d).

minimum; and dispatch planning closer to actual generation, which tends to be superior to figures from long-term forecasts (Wang, 2014).

6.2.4.3 Local marginal pricing

Local marginal pricing (LMP), or nodal pricing, refers to the practice where grid constraints are considered in market clearing at the local level. With LMP, demand and supply are cleared at several points in the network, so that each generator adapts its power load to the local limits of the grid (Cochran et al., 2012). In the short-run, this enables the market to be co-optimised following grid constraints. Simulations of an integrated European network using LMP found that it could promote an increase of power transfers among countries of up to 34%, depending on the level of wind penetration (Neuhoff et al., 2013). In the medium and long-run, LMP builds up accurate system information about the need, or excess, of resources in particular locations, as well as profitability (Lewis, 2010). This information about resources needs is also useful to identify and promote optimal balance between network improvements and generation costs, since it enables generators to factor future transmission costs into decisions about location (Volk, 2013).

6.2.4.4 Curtailment control

Electricity system operators have to be capable of curtailing wind-generated power. In periods of low demand, negative pricing can stimulate generators to curtail power, reducing the pressure on the grid and on average prices (Cochran et al., 2012). In periods of peak generation, curtailment can shave off output peaks reducing the need for additional infrastructure and increasing wind power overall utilisation factor (Holttinen et al., 2011). Hence, a trade-off between curtailment level and network infrastructure influences overall system performance. In general, optimal levels of curtailment are necessarily low due to the fact that power generation costs rise exponentially after a certain curtailment threshold (Burke and O’Malley, 2011).

6.2.4.5 Cross-border trade

Electricity trade between national markets helps pooling the expensive capacity resources required to maintain electricity supply and adds overall flexibility to the energy system, facilitating wind power integration in different ways. First, market integration of larger geographical extensions reduces peak demand. As a consequence, the need for balance of supply is diminished, as well as the costs related to capacity reserve and grid management services (Neuhoff, 2011). At the same time, large wind areas tend to reduce uncertainty about electricity production since forecast errors at different locations cancel each other out (Böckers and Heimeshoff, 2014). In addition, by promoting more intensive and less uncertain transmission flows, cross-border trade can enhance the value of the transmission network and reduce system operation costs (Baritaud and Volk, 2014).

6.3 How much electricity is generated from wind?

Wind energy is the most variable, unpredictable, and widely deployed of the intermittent renewable energy sources. Therefore any factor that negatively affects capacity utilisation of wind plants today is likely to be a constraint for other technology options, such as solar PV. Here we examine electricity generation from wind power in the four countries with the largest shares of wind power capacity installed between 2005 and 2011, namely China, the United States, Germany and Spain (Table 6.2). Power capacity installed has been chosen as the main criterion to select the countries studied here, for two reasons. First, market size has been recognized as a main driver of wind power development (Lewis and Wiser, 2007; Neuhoff et al., 2013). Second, there are various unresolved challenges associated with the integration of large amounts of wind-generated electricity (as discussed in sections 6.2.3 and 6.2.4), which are especially relevant for a transition to a low-carbon system. In the next sections we present the estimation of capacity utilisation for each of the four countries studied. A discussion of possible explanations follows.

Table 6.2: Renewable power capacity: top countries in 2013

Technology	Power generation capacity in GW				
	World	China	US	Germany	Spain
Bio-power	88	6.2	15.8	8.1	1
Geothermal power	12	0	3.4	0	0
Hydropower	1,000	260	78	5.6	17.1
Solar PV	139	19.9	12.1	36	5.6
Concentrating thermal solar power (CSP)	3.4	0	0.9	0	2.3
Wind power	*318*	*91*	*61*	*34*	*23*
Total renewable power capacity	1560	377	171	84	49

Data from: REN21 (2014).

6.3.1 Capacity utilisation

Capacity utilisation refers to how much electricity is actually produced by wind power compared to installed generation capacity. Here we refer to the ratio of annual electricity output to installed capacity as “realized capacity factor” and use it as an indicator of capacity utilisation. Annual realized capacity factors are calculated for the four countries in the period 2005-2011, using data on electricity output (in GWh) and installed generation capacity (in

GW) from the International Energy Statistics of EIA (2014). The analysis focuses on the period 2005 to 2011 because it showed the highest growth rates of wind power installations since the industry achieved maturity.

A formal expression for the realized capacity factor of a country in a year t ($RCF(t)$) is as follows:

$$RCF(t)=\frac{WEG(t)}{IGC(t)\,x\,H}$$

Here $WEG(t)$ is the total wind electricity generation in year t (in GWh), $IGC(t)$ is the total installed generation capacity of wind power in the corresponding year (in GW), and H is the number of hours in a year, which we set equal to 8760 (i.e., 24 hours times 365 days). Electricity generation and capacity data are for December 31 of each year. Installed capacity data is based on the maximum-rated output of a wind power generator. Table 6.3 shows data on electricity generation from wind in the four countries studied. In spite of the diversity in terms of scale and growth rates, the *RCF* values for the four countries fall in a very narrow range. Increases in installed capacity and electricity generation contrast with the maintenance of realized capacity factors for wind under a 30% ceiling (DOE, 2010). Compared to *RCF*, *WEG and IGC* growth rates are largely superior in the period. In the U.S., where *RCF* improved the most, it rose 30%, whereas *WEG* and *IGC* increased by factors of 5 and 4, respectively. The Chinese experience shows a much wider gap with *RCF* falling by 38% while *WEG* and *IGC* growing by factors of 30 and 40, respectively. Germany and Spain had lower, reverse, *RCF* variations (+6% and -8%, respectively), and also lower expansion rates of *WEG* and *IGC* (around 60% in Germany and 100% in Spain).

The previous numbers indicate a bias of development towards capacity installation rather than towards improvements in the efficiency of electricity generation. Of course, building additional capacity involves much shorter lead times than developing new technology or electricity infrastructure to improve capacity factors. However, the four countries analysed here share a trajectory of consistent capacity expansion for the last decade. Still, within this period, average capacity factors of wind farms built after 2005 have been stagnant (IEA, 2013b). Advances in wind turbine design, such as an increase of nominal capacity factors from an average 25.5% in 2000–2005 to an average 29% in 2006–2012, have not been enough to overcome the fall of electricity generation due to the expansion towards low wind quality sites and a lack of network adaptation (IEA, 2014a).

Wind power expansion has been stimulated by cost reductions realized through increasing returns to adoption obtained from rapid growth in the last decades (Blanco, 2009; Lewis and Wiser, 2007). But this has been focused on capacity building. Evolution in electricity production and generation efficiency is lagging behind as shown by RCF levels (see Table 6.3). Consequently, performance of wind power systems is not entirely satisfactory. In financial terms, a low efficiency of electricity generation reduces profitability and enlarges payback times of investment. In environmental terms, idle wind power generation capacity represents foregone opportunities to reduce GHG emissions.

Next to the technological limits of wind turbines, wind quality determines capacity utilisation. Higher wind speeds generate higher energy output and blow more consistently. Previous studies indicate that a doubling of wind speed can increase power output of a wind turbine by a factor of eight (EEA, 2009), whereas a more consistent wind blow facilitate transmission scheduling and grid integration (Rahimi et al., 2013). To account for these differences in terms of wind quality, we calculate the share of capacity utilisation of wind power (WCU) considering the wind regimes of each country studied, as follows:

$$WCU(t) = \frac{WEG(t)}{IGC(t) * FH(t)}$$

Here FH corresponds to a factor of wind quality calculated as the percentage of the number of hours in a year when wind power was available to run turbines at full capacity. Hours are measured for onshore wind turbines with on average 80m hub height.

The percentage of capacity utilisation, as shown in Table 6.3, is based on wind turbine nameplate capacity and estimated wind regime. The differences between the realized capacity factor (RCF) and the wind regime (FH) indicate that not all the available wind power was used, that is, wind farms have not worked at full power during all possible hours.

Table 6.3: Wind power capacity installations and utilisation

Country	*WEG* in 2005 (GWh)	*WEG* in 2011 (GWh)	*IGC* in 2005 (GW)	*IGC* in 2011 (GW)	*RCF* in 2005	*RCF* in 2011	*FH* in 2005	*FH* in 2011	*WCU* in 2005	*WCU* in 2011
China	2028	73200	1.3	62.4	18%	13%	23%	22%	80%	62%
US	17811	120177	8.7	46.0	23%	30%	30%	34%	78%	88%
Germany	27229	46500	18.4	29.1	17%	18%	26%	28%	65%	66%
Spain	21176	42374	9.9	21.7	24%	22%	27%	25%	91%	89%

Data from CWEA (2013), EEA (2009), EIA (2014), GWEC (2012), IEA (2014c), IWES (2014), Schwabe et al. (2011), Wiser and Bolinger (2013).

Even though the performance of wind turbines depends on location (Chowdhury et al., 2013), there is wide agreement that modern onshore wind turbines in mature markets can achieve a working hours rate of 97% or more (Blanco, 2009; IEA, 2013b). As a matter of fact, the restrictions to electricity generation imposed by wind regimes can be overcome by adequate wind turbine designs, system operation technologies and market integration mechanisms. These will be discussed in following section.

6.4 Possible explanations for capacity utilisation of wind power

Among the various factors that condition wind electricity generation, here we focus on the most important ones for the current rates of capacity utilisation, namely: capacity factors, system flexibility and market integration (as summarized in Table 6.4). The goal is to identify factors that affect capacity utilisation, and thus explain the variation found among the countries studied. The analysis uses data from relevant energy agencies in each country, as well as insights from studies in the scientific literature.

Table 6.4: Summary of determinants of capacity utilisation

		China	United States	Germany	Spain
Capacity factor	Turbine design	Low nameplate capacity	High nameplate capacity	Mixed nameplate capacity Repowering in place	Medium nameplate capacity
	Location	Average wind country Expansion towards low wind regime sites	Average wind country Expansion towards low wind regime sites	Low wind country Expansion towards sites with similar wind regime	High wind country Expansion towards sites with similar wind regime
System flexibility	Network infrastructure and management	Low capacity of transmission lines Inadequate wind turbine technology	Large investment in transmission lines High accuracy of wind generation forecasts Nodal dispatch control	Large investment in transmission and distribution lines Early network adaptation to wind power	Real-time communication Centralization of grid operation
	Portfolio diversity	Coal and hydropower	Decentralized wind power Gas and hydropower	Coal, gas, solar PV and hydropower	Coal, gas, solar PV and hydropower
	Demand Side Management	NA	Yes	Yes	Yes
Market integration	Balance of dispatch	Market for ancillary services non-existent	Market for ancillary services partially developed	Market for ancillary services base developed	Market for ancillary services developed
	Time of response	Long term contracts	5’ for some spot markets	45’ for spot markets	15’ for spot markets
	Local marginal pricing	NA	ERCOT (Texas)	EpexSpot market	EpexSpot market
	Curtailment control	At power generator level	At the wind turbine level	At the wind turbine level	At the wind turbine level

Cross-border trade	Among ‘regional markets’	Among system operators (mostly at the State level)	CWE region and the Northern region	Mainly with Portugal

Information in this table is based on CWEA (2013), DOE (2010), EEA (2009), EIA (2014), IEA (2014a, 2014b, 2014c, 2014d), EC (2014), IWES (2012), IPCC (2012), NREL (2013), Wiser and Bolinger (2013).

6.4.1.1 Wind turbine design evolution

Between 2005 and 2011, variations in *RCF* values differed among the countries studied. Germany and Spain showed narrow ranges, while China and the US showed wider ones. The lower *RCF* variation in Germany and Spain can be explained by the small range of variance of wind regime in these countries. With relatively small territories, additions of wind power installations in Germany and Spain take place in locations with similar wind conditions than in the ones previously exploited. The improvement of *RCF* in Germany is mainly explained by repowering[48], a trend that is yet to start in Spain. In 2011 only, repowering had accounted for approximately 17.8% of new installations in Germany, increasing average output by a factor of 2.5 in the renewed wind farms (GWEC, 2012). In Spain, the estimated potential for repowering is 2.3 GW, corresponding to wind power installed capacity in commercial operation for a period of at least 13 years (Colmenar-Santos et al., 2015). However, repowering is expected to play a role in the industry only after 2016, when public funding is expected to become available (del Río et al., 2011).

China and the US show very different cases characterized by large and opposite *RCF* variations. Such a disparity comes as a natural consequence of the exponential rates of growth experienced by wind power in these countries. Whereas Germany and Spain roughly doubled their installations and generation capacity within the 7 years analysed, in the US these have grown by over 400% and in China by more than 350% in the same period. The fact that the Chinese *RCF* decreased over time while the North-American increased can be explained by differences in the wind power technology and the electricity system of each country.

China’s capacity factor has historically been among the lowest in the world. In the last years, capacity factors continued to fall mainly for three reasons. First, the long distance between sites with best wind quality, mostly located in the North of the country, and main consumption centres concentrated in the southeast, has limited wind power generation through transmission losses and forecast errors (Yang et al., 2012). Second, wind farms expansion turn towards low wind speed locations which has pushed full load hours further down since 2010 (Zhao et al., 2013). And, third, faulty wind turbine design. On the one hand,

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[48] Repowering refers to the process of replacing existing wind turbines with new turbines that either have a larger nameplate capacity or higher efficiency of electricity generation.

Chinese installations are dominated by turbines with medium to low capacity: 1.5MW turbines respond for 64% of total installations, followed by 2MW and 2.5MW with 26.1% and 6.6%, respectively (Li et al., 2015). On the other hand, the majority of the wind turbines operating do not meet the technical requirements to be connected to the grid which have reduced the share of wind installations connected to the grid from 84.48% in 2005 to 75.36% in 2011 (Zeng et al., 2015).

In contrast, the increase in *RCF* in the U.S. can be attributed mainly to technological improvements in wind turbine design and better wind farm siting. The design of the average wind turbine installed in the US evolved from 1.4MW turbine nameplate and 70m hub high in 2004-2005 to 2MW and 100m high in 2011, resulting in larger and more constant energy output (Wiser and Bolinger, 2013). For example, 26.5% of installed capacity in 2011 corresponded to turbines with rotor diameters of 100 meters or larger, compared with only 10% in 2010 (AWEA, 2012). Additionally, the ratio of nameplate capacity to swept area declined, which improved energy capture. In the last decade, annual energy production per square meter of swept rotor area (MW/m2) has shown yearly increments of 2 to 3% (EEA, 2009). At the same time, wind farm siting has also positively contributed to improve capacity factors. With more accurate knowledge about wind regimes and turbine design adequacy, wind farm layouts have been refined, leading to capacity factor improvements of up to 6.4% (Chowdhury et al., 2013). As a result, the US has achieved higher capacity factors for wind farms – in spite of the recent expansion towards lower-quality wind resource sites.

6.4.1.2 Flexibility of network infrastructure and operation

In terms of system flexibility, the most important barriers for increasing wind power capacity utilisation in the countries studied are related to network infrastructure and operation. A problem common to the four countries is the speed of networks expansion. Building transmission and distribution infrastructures requires much more time than building wind farms. One reason is that creation of transmission lines involves extended land acquisition (Fernández Fernández et al., 2013; Yang et al., 2012). Network issues differ among countries due to geographical features, technologies implemented and electricity market structure.

In China, the combination of this time delay to build grid infrastructure and a high level of investment in installations is a main cause of a low (and even falling) rate of capacity utilisation. In addition, low technical standards for generators to connect to the grid also play an important role in limiting wind power capacity utilisation. The lack of grid control and management technologies not only decreases the input of wind-generated electricity but also reduces the overall reliability and security of the electricity system. As a result, China has the highest curtailment rates worldwide, 17.5% in 2011 and 21.7% in 2012 (Li et al., 2015). Between 2010 and 2011 only, 273 major incidents of turbines unexpectedly going off-line from the grid were registered, increasing losses in the amount of electricity fed into the grid (Schuman and Lin, 2012). One of the main difficulties is the absence of "Low Voltage Ride Through" (LVRT)[49] technology in most wind turbines installed in China, which further reduces the overall network resilience to the common variations in wind-electricity flows (GWEC, 2012).

In contrast, in the US, expansion of installation capacity occurred simultaneously with capacity utilisation growth. This was pushed by two big forces to overcome network barriers to wind power integration: investment in transmission lines and improved operations management. Between 2007 and 2012, more than 2,300 miles of new transmission lines were added yearly, compared to less than 1000 miles between 2000 and 2006. This was the result of a conjoint effort of States, grid operators, utilities, regional organizations, and DOE (Wiser and Bolinger, 2013). In Texas, for example, addition of transmission lines helped the main electricity system operator, ERCOT, to reduce curtailment levels from 17% in 2009, to 8% to 9% in 2010 to 2011 (NREL, 2014). Regarding operational barriers, US system operators are in the forefront of development of grid management technologies. Built upon the information of wind farms and grid operation assembled during the last decade, these management technologies enable significant improvements in forecasting accuracy and dispatching control (Porter, 2013). With higher forecast and control accuracy, system operators can increase the volumes of wind electricity dispatched by reducing response times. For instance, regions with fast energy markets might change the dispatch schedule within a 5 minute period, while other regions often use hourly schedules (Gil et al., 2012). Shorter times of response in electricity markets can decrease the number and quantity of curtailments, maintaining the quality and security of the electricity supply, and at the same time maximizing wind power dispatch.

Network adaptation to wind power in Germany started already in 2003 with the introduction of a Grid Code aimed at adapting grid requirements to wind turbine characteristics as well as to specific control and protection rules. This involved setting basic rules to assure network flexibility, including: technological standards for wind turbines (e.g. embedded LVRT technologies and provision of ancillary services like voltage and frequency

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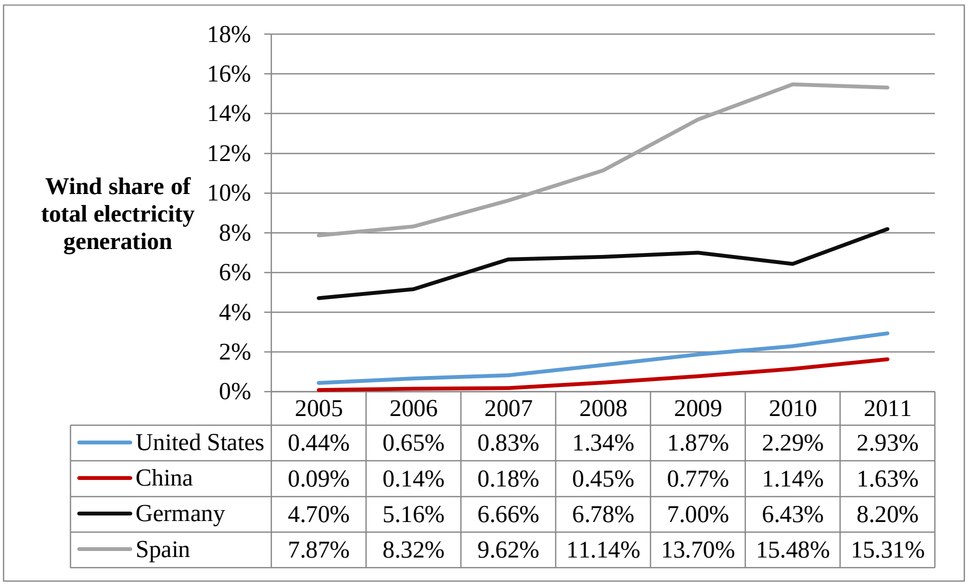
[49] LVRT is a technology that enables wind turbines and large wind farms to remain online when system voltage drops, instead of tripping offline; it is a requirement for grid connection in the US and Europe (IEA, 2013b).

control), and intelligent system protection devices to ensure a minimum loss of wind power and to guarantee fast recovery of normal operation (Erlich et al., 2006). These ended up influencing the wind power industry worldwide through the exports of German turbines and returns to scale from the quick expansion of the domestic grid. Germany has consistently amplified transmission and distribution lines with investments of more than 27 billion between 2007 and 2011 (Groebel, 2013). As a result, curtailment levels have been kept remarkably low, namely 0.2% in 2009 and 0.34% in 2010 (IWES, 2012).

With the highest levels of capacity utilisation among the countries studied, Spain is considered a benchmark of network flexibility. This achievement is mainly due to electricity system operations. Since 2006, transmission system operators (TSO) require real-time communication with wind farms so that the relevant conditions of operation can be observed and generation can be controlled at all times (Holttinen et al., 2011). 99% of the high voltage transmission lines in Spain are controlled by the Red Elétrica Española. This TSO centralizes the operation of renewable energy sources in the country, receiving information from wind parks, while controlling 96% of wind generation capacity installed. It allows for adaptations of power generation within 15 minutes (De La Torre et al., 2012). This degree of precision to change wind power dispatch at different points of the grid enables the operator to avoid curtailment and energy transmission losses, thus leading to optimization of capacity utilisation.

6.4.1.3 Penetration level, price signals and ancillary services

Market integration becomes increasingly difficult with higher levels of wind power penetration. In this regard, Germany and Spain are considered to have achieved high penetration levels with wind power responding to at least 4% of the total net electricity supply since 2005; however, China and the US markets are still in their infancy, with penetration levels around 2% (Figure 6.1). Even though penetration levels have risen in all four countries, the gap between installed power and capacity utilisation remained wide.



	2005	2006	2007	2008	2009	2010	2011
United States	0.44%	0.65%	0.83%	1.34%	1.87%	2.29%	2.93%
China	0.09%	0.14%	0.18%	0.45%	0.77%	1.14%	1.63%
Germany	4.70%	5.16%	6.66%	6.78%	7.00%	6.43%	8.20%
Spain	7.87%	8.32%	9.62%	11.14%	13.70%	15.48%	15.31%

Figure 6.1. Wind as share of total electricity generation; data from EIA (2014).

There are many approaches that can explain the markets' ability to efficiently absorb high levels of wind power. Markets positively contribute to managing larger balancing areas and sources, pooling bids and bridging different regions and countries. For wind power, two aspects of market integration are important: long-term market signals must be able to induce system adaptation to be built; and the market must generate sufficient revenue to guarantee financial viability (Benatia et al., 2013; Holttinen et al., 2011). This depends, among other mechanisms, on price signals to wind power generators as well as to conventional generators. Markets that warrant priority to wind power generators to sell electricity while providing backup for shortages from conventional sources accommodate the natural characteristics of wind while reflecting the cost of overall system reliability.

Within the period studied, Germany and Spain have used the merit order effect to grant priority of dispatch to wind-generated electricity. Wind power is delivered to the grid whenever produced, regardless of demand. Curtailment is allowed for security reasons, such as to avoid grid instability. Feed-in tariff payments are maintained when electricity losses are caused by constraints of grid infrastructure. So far, this experience in Germany and Spain has led to a decrease in average wholesale electricity prices. The reason is that the merit order effect, by prioritizing subsidised low marginal cost wind power, tends to push out of the most expensive electricity generators (Holttinen, 2012; Ketterer, 2014).

Another positive characteristic to increase capacity utilisation is the fact that both these countries benefit from flexible backup energy sources and established ancillary markets (Nicholson et al., 2010). Cross-border trade has increased in Germany specially since 2009 with the creation of the European Market Coupling Company, and since 2010, with the electricity market coupling between countries in the so-called CWE region (Belgium, France, Luxembourg, and the Netherlands) and the Northern region (Denmark, Sweden and Norway). Electricity flows among these countries are now jointly optimised with electricity exports from lower-price to higher-price regions (BMU, 2012). Spain enjoys a highly responsive backup system due to the centralized operation (as discussed in the previous section). Moreover, it also counts with good exchange capability with Portugal (De La Torre et al., 2012).

Limitations to market integration in China arise from the regulatory framework. The lack of separation between the political and regulatory authorities submits market efficiency to political compromises. The National Development and Reform Commission (NDRC) controls China’s macroeconomic policy and regulates energy prices, mainly to control inflation, make Chinese exported goods more competitive pricewise, and ensure domestic social stability (Qiu and Li, 2012). Government driven, wind farm constructions are, in several cases, planned regardless of transmission capacity (Zeng et al., 2015), driven by factors disconnected to energy output, such as GDP growth, tax revenues or even achieving the necessary wind capacity required by local regulation to build new coal-fired power plants (Lam et al., 2013).

Unlike the centralized market regulation, the electricity transmission network is fragmented with the physical grid divided into regional grids managed independently (Kahrl et al., 2011). Hence, the Chinese market has very low levels of integration among regions, almost completely missing the benefits of balancing dispatch among different locations. Until 2009, prices of wind power in China were determined case by case through a bidding policy. But by privileging the lowest bidding prices this mechanism has exacerbated competition and reduced investors’ enthusiasm. Subsequently, a policy based on a fixed price was introduced involving setting four types of wind power benchmark prices across the country (Li et al., 2015). This has created new barriers to increasing capacity utilisation since it blocks trade among different “price regions” (Yuan et al., 2014).

In the U.S., wind power markets are regulated at the state level. However, these are highly integrated and flexible since more than 60% of the total electric output at the country level is managed through markets that operate on 5-minute response time (Milligan et al., 2011). This inter-state integration brings several positive contributions to higher capacity utilisation of wind power, such as: the enlargement of balancing area; the provision of ancillary services due to short dispatch intervals; and the potential of inter-regional scheduling as shorter response times enable more efficient dispatch planning for importer and exporter (Milligan and Kirby, 2010). Nevertheless, only a minor share of wind power is typically traded in short-term spot markets in the U.S.. Historically, around 60% of wind energy has been sold through long-term Purchase Power Agreements (PPAs) for an average period of 20 years. These have performed well as a hedge against price variations from fossil fuels, a mechanism that reproduced a merit order effect stimulating the maximization of capacity utilisation. Nevertheless, this is a contribution to capacity utilisation with variable effectiveness. As shown by the recent fall of wholesale electricity prices (driven by lower natural gas prices), average wind PPA prices have suddenly gone out of the wholesale power price range on a nationwide basis (Wiser and Bolinger, 2013). This undermines the financial benefits of wind electricity, potentially reducing its input into the grid.

6.5 Implications for GHG emissions and policy recommendations to narrow the capacity-generation gap

Wind power generates environmental benefits primarily from displacing the emissions from fossil fuel-based electricity generation. Wind-generated electricity entails 28.1 times[50] less emissions than coal, currently the first source of electricity generation worldwide (IEA, 2015). However, these potential environmental benefits of wind power have not been realised because power generation capacity is only partially used (as shown in section 6.3). This becomes more problematic as wind power participation in electricity supply grows. Present prospects point to at least 20% of electricity supply from wind in the countries studied. Hence, the capacity-generation gap, if maintained, will increase the amount of missed reductions of GHG emissions.

Our findings, as summarized in Table 6.3, indicate that capacity-generation gaps of wind power are country specific. Next to geographical conditions and technological limitations, electricity generation from wind is determined not only by direct subsidies for deployment, but also by balancing and grid regulations (Holttinen et al., 2011; Klessmann et al., 2008; Van Hulle et al., 2009). Policy solutions to narrow this gap need to simultaneously tackle three barriers to capacity utilisation, namely: low capacity factors, insufficient system flexibility and limited market integration (see Section 6.3 for details). Without addressing these barriers, further expansion of wind power installations will tend to enlarge capacity-generation gaps. Analysing the four countries with the largest wind power installations

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[50] Given that the average life cycle GHG emissions for wind energy is 34.1g CO2-eq/KWh (Nugent and Sovacool, 2014) and for coal to be 960g CO2-eq/KWh (Sovacool, 2008).

(2005-2011) has allowed us to identify regulations that have successfully improved wind power capacity utilisation (Table 6.5), and derive policy recommendations to reduce the capacity-generation gap.

Table 6.5: Examples of policy measures to reduce capacity-generation gap of wind power (2005-2011)

Policy Focus	Policy measures	Examples
Capacity factor	Regulation of wind farms' location	None of the countries studied have regulated wind farm siting specifically in relation to the quality of wind regimes.
	Standards for wind turbines technologies	Germany and Spain: wind turbine certification and grid code[51] standards as requisites for approval of wind power projects.
System flexibility	Alignment between expansion of wind power installations and electric system development	US (ERCOT): definition of areas as competitive renewable energy zones, where grid infrastructure building takes place before full potential of wind power installations is realised.
	Demand-side management mechanisms	Spain: regulation establishing technical obligations (e.g. production forecast, fault-ride through capability) to improve control of wind power generation and dispatch into the grid.
Market integration	Incentives to geographical expansion of market for balancing services	Germany and Spain (Europe): since 2009, Germany and Spain benefit from the European Network of Transmission System Operators (ENTSO-E), which co-ordinates 41 national transmission systems operators (TSOs) from 34 countries.
	Harmonization of regulations	Spain: creation of a specific national control centre for renewable technologies (the CECRE - Control Centre for the Special Regime), with mandatory connection for all wind power generators.

Information in this table is based on Abbad (2010), Brunes and Ohlhorst (2011), del Río (2012), DOE (2008); ENTSO-E (2012); EWEA (2010); Hull et al. (2009); IEA (2014c); IRENA (2012); Lew et al. (2010); Milligan et al. (2015); RD (2004); RD (2007) and Wu et al. (2014).

Capacity factors can be improved by better locations in terms of wind regime and network operation, and design of wind turbines and wind farms. Regulation of locations of wind farms can help by directing wind farms towards sites with best wind regimes and most suitable network connections (Boccard, 2009; Burke and O'Malley, 2011). Next to increasing electricity output due to better wind resources, optimal location can improve network operation, e.g. reduce electricity flow congestion. In relation to wind turbines and wind farms design, subsidies based on generation efficiency rather than installed capacity can stimulate power generators to opt for the most energy efficient option rather the cheapest one. Since the early development of their wind power industries, Germany and Spain have stimulated high capacity factors by establishing minimum standards for wind turbines technologies (Erlich et al., 2006) and, more lately, repowering programs to replace low performing wind turbines (del Río et al., 2011). An additional, recent instrument used by these countries is to set payments of feed-in tariffs in proportion to wind regime quality. This is aimed to stimulate investors to optimize location and avoid problems with lack of grid connection or wind

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[51] Grid code typically includes technical specifications for power load such as voltage and frequency.

turbine shadowing due to low quality wind regimes (del Río, 2012; Nordensvärd and Urban, 2015).

To improve system flexibility, policy needs to enhance coordination among wind power generators, system operators and grid infrastructure. An initial requirement is to align the expansion of wind power installations with overall system development. Auction mechanisms[52] may provide an attractive solution since they enable to control the volume of additional installations while keeping prices competitive (del Río and Linares, 2014). Auctions also facilitate information about the location of future generators which optimizes investments in grid infrastructure. Among the countries studied, the ERCOT in the US is one of the best examples of successful regulation resulting in a balanced expansion of wind power installations and transmission infrastructure. The Public Utility Commission of Texas has defined five areas as competitive renewable energy zones, where the building of transmission lines precedes the full development of wind power capacity. Here, one of the enabling factors is that policy design has facilitated financing by allocating all transmission costs to load (Milligan et al., 2012). As a result, a plan to construct new transmission was developed to guarantee the dispatch of additional 18.5 GW of wind power while reducing the volume of curtailments (IEA, 2014d). In parallel, electricity market regulation can facilitate system operation by stimulating the use of demand-side management mechanisms and creating an incentive for conventional generators to provide ancillary services (see section 6.2). In Spain, for example, regulation has contributed to shorten response times by: establishing mandatory hourly output forecasts from generators with installations over 10MW; as well as an economic incentive to acquire fault-ride through capability of up to 5% for kWh generated for 4 years[53] (RD, 2007).

In terms of deepening market integration, policy can provide an immediate contribution by increasing the area size over which the system is balanced in real-time. This can increase the utilisation of wind power capacity, namely through geographical smoothing and higher economies of scale (Benatia et al., 2013). At the country or region level, the harmonization of regulations, such as protocols and procedures across different system operators, would extend and improve coordination among different areas (Baritaud, 2012). At the international level, similar type of benefits could be achieved through integration of national renewables policies and system operation regulations. This can be illustrated by the

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[52] In auction mechanisms, both price and quantity are determined in advance of the decision to build a wind farm, namely under a public bidding process.

[53] Based on the estimated average total system cost, which includes all the costs of the system in a year (such as costs of generation, transmission, distribution, retail, etc.).

European regulation creating the European Network of Transmission System Operators (ENTSO-E) in 2009. Since then, the ENTSO-E has improved the coordination among the electricity markets of the 34 member countries, promoted further standardisation of regulations, and increased market transparency and integration.

Large-scale deployment of wind power leads to more volatile, real-time power flows which add requirements to the energy system in order to secure electricity supply. Ancillary services, network infrastructure and market remuneration need to be adapted to wind power dynamics in a cost and time effective way. So far, because wind penetration levels have been maintained at an upper limit of 10% to 15% of total electricity generation (for certain countries and period analysed here, namely Germany and Spain), managing the technical operation of power systems has been possible without major changes on the energetic system and without using its full installed capacity. But with continuous growth of wind power installations and more pressing need to reduce GHG emissions, a full adaptation of the electricity system is required. It is clear that the challenges created by wind power intermittency and dispersed geographical distribution can only be resolved with policy support. Yet, no single policy solution has emerged until now, arguably because of the specific and changing dynamics of the each energy system.

6.6 Conclusions

This paper has analysed the mismatch between installed capacity and actual electricity generation of wind power. It studied the evolution of wind power installations and electricity generation in China, US, Germany and Spain. Levels of capacity utilisation of wind power installations were estimated and its drivers were identified. Despite differences in terms of development of wind turbine design, flexibility of network infrastructure and operation, and the level of wind power penetration, all four countries studied show a constant, if not rising, capacity-generation gap in wind power.

With the largest additions in capacity installations, China and the US showed distinct performances in capacity utilisation. In China, constraints on grid connection and lack of market incentives to integration led to a decrease in capacity utilisation, from 80% in 2005 to 62% in 2011. In the US, increasingly advanced wind turbine technologies and grid management techniques improved capacity utilisation, from 78% in 2005 to 88% in 2011. Germany and Spain represent more mature markets. In Germany, repowering of wind farms has contributed to maintain capacity utilisation stable at around 65%. In Spain, development of system operation techniques and advances in wind forecasting have been responsible for sustaining capacity utilisation at a very high level of about 90%.

Several policies can contribute to a better balance between power generation capacity and capacity utilisation of wind power. Electricity market regulation and policies promoting system flexibility play a key role. Policy support to wind power should focus not only on expanding capacity installation, but also on increasing the efficiency of electricity generation. This can be achieved through the development of better performing technologies (wind turbines, system operation techniques, wind forecast methods) as well as extended integration of wind power electricity into the (inter)national electricity system. In this way, the net electricity generation from the overall system could be increased, contributing to further and cost-effective reduction of GHG emissions.

Chapter 7

Conclusion

7.1 Summary and main conclusions

This dissertation has examined drivers of low-carbon innovation that underlie the necessary and urgent transition towards a climate friendly energy system. It offers a perspective on key factors capable of speeding up low-carbon innovation in the energy sector so that it effectively contributes to climate change mitigation. The research presented in this dissertation is motivated by a combination of theoretical constructs and concepts from innovation studies and evolutionary, environmental and ecological economics. The underlying rationale is that innovation is essential for further development of low-carbon energy with the primary aim to reduce GHG emissions.

In order to contribute to the investigation on optimal policy design to support low-carbon innovation, Chapter 2 examined the formation of lead markets in the wind power industry in China, Germany and the USA. By developing an extended framework to analyse such formation, it has shown that lead market positions at the country level strongly benefit from national policy support. However, at odds with the original idea of conquering a stable leading advantage at the sector level, the findings indicate that competitive advantage tends to shift among countries and along the supply chain of the wind power industry. Due to the international nature of energy markets, the unavoidable interaction among industry players from different countries adds ‘investment leakage’ to the traditional risk of knowledge spillover involved in innovation. As shown by the rapid growth of the Chinese wind (and solar) manufacturing capacity, the benefit of investment in diffusion can shift to foreign countries. Indeed, the quick scaling-up of wind power capacity in Germany and the USA has largely benefited the Chinese industry. In addition, it has speeded up the consolidation of the global wind power industry, thereby reducing advantages of earlier (and more costly) investments in innovation, notably in other countries, as well as fostering a dominant design, which reduces technological diversity and may hinder further innovations and even lead to an early, undesirable lock-in.

The particular dynamics of low-carbon innovation are characterised by a strong impact of technology recombination as well as intra and inter-sectoral knowledge spillovers. This raises interest in the role of diversity for technological change in this realm. Chapter 3 was devoted to this. It studies the link between low-carbon innovation and diversity by developing a framework of nine indicators, covering technologies, markets and actors (countries and firms). This is then applied to the solar photovoltaic (PV) industry. Looking at the evolution of solar PV technologies for the years 2000-2010, the dominant trend was an increase of diversity in terms of patents, international markets, cost and pricing among the different technologies available. Such trajectory of increasing diversity was then contrasted with the fact that policy support has shown a lack of direct or specific incentives to stimulate an increase in the production of alternative solar PV technologies. This has important implications as diversity is key to keeping options open to be flexible and able to adapt to different economic and technological trajectories in the long run. Moreover, a higher diversity offers additional benefits to innovation by reducing the chance of lock-in into one technological option, and by fostering experimentation and spillovers. Hence, accounting for diversity as a relevant stimulus to technological change offers an important path to increase the effectiveness of policy support to low-carbon innovation.

The contribution of low-carbon innovation to climate change is highly dependent on the pace of technological change. Speeding up innovation is crucial since the transition to a low-carbon energy system needs to happen in the next decades. As a result, deepening the understanding of the knowledge dynamics underlying low-carbon innovation becomes essential. Chapter 4 offered a contribution to this literature by linking the development of scientific knowledge to the technological trajectory of wind turbines. In contrast to the dominant literature using patents as proxy for knowledge dynamics, this study makes a novel contribution by developing a new approach based on the analysis of scientific publications. A dataset based on bibliometric information was built up, using two algorithms for the analysis of citation networks which map the evolution of scientific knowledge underlying the technological trajectory of wind turbines. The results show a synchronous pattern between scientific research and wind turbine up-scaling. Moreover, the citation networks unravel an extended view of technology trajectory to highlight the importance of accessory technologies such as modelling and simulation. In addition, this study suggests that using scientific publications may entail a strong advantage compared to patents depending on the appropriability system around the technology studied. As the case of wind turbines has shown, secrecy agreements may reduce or even prevent patenting, but have less impact on publications.

Another challenge involved in speeding up low-carbon innovation is the problem of ‘path dependency’ in knowledge production. Mostly newly developed, low-carbon technologies strive to overcome the limitations imposed by a reduced knowledge base compared to the incumbent technologies. Hence the importance of external knowledge sources as a mechanism of accessing new knowledge in quick and costly efficient way. Against this background, Chapter 5 analysed the results of a survey involving 508 research organisations to compare the impact of external knowledge sourcing on innovation in solar and wind power. The results show that the effect of external knowledge sources differs between sourcing strategies and technology fields. A broad knowledge search strategy drawing on a large number of external knowledge sources is found to be more suitable to innovation on solar power, while the intensive use of a more limited number of external sources is found to be more beneficial for wind power. Hence, optimising external knowledge search seems to involve a trade-off between perusing the largest number of sources available and deepening knowledge obtained from a reduced number of sources. Two main characteristics of the technology field are found to be relevant to establish the suitability of different knowledge sourcing strategies: technological turbulence and innovation novelty. Highly turbulent technological environments and radical innovation by speeding up knowledge obsolescence tend to favour deeper knowledge sourcing, whereas a larger pool of knowledge sources is more suitable for stable technological environments and incremental innovation.

Finally, Chapter 6 had the aim to assess the current contribution of low-carbon innovation to GHG emissions reductions, a comparison is made between installed capacity and actual power generation of wind power in four countries that have led its diffusion during the last decade: namely, China, the United States, Germany and Spain. The results unravel a considerable mismatch between installed capacity and power generation for the case of wind power. Significant shares of untapped capacity of wind power generation are found for all countries studied. This suggest that relatively cheap opportunities to reduce GHG emissions are not seized. Comparing potential causing factors among the countries indicates the need to account for the risk of underutilisation of wind power capacity in decision making about, and policy support of, expanding capacity installations. Further innovation to create more efficient technologies (e.g. wind turbines, system operation techniques, wind forecast methods) as well as extended integration of wind power electricity into the (inter)national electricity system are key factors to improve wind power output.

7.2 Closing remarks and suggestions for future research

In the past decade, low-carbon energy sources have shown an exponential increase in installed capacity, led mainly by solar and wind power which had annual growth rates of respectively 46.8% and 24.9% between 1990 and 2012 (IEA, 2016). Such growth has been largely focused on scaling-up of power generation capacity, based on an underlying assumption that returns to scale and learning from deployment would enable further innovation as required to significantly contribute to climate change mitigation. Yet, the share of low-carbon sources in total energy production remains small. In 2012, low-carbon sources[54] were responsible for just 2.8% of global electricity supply, which is less than 1.1% of total primary energy supply (IEA, 2014a). Several reasons abound to explain this discrepancy. Solar and wind power facilities have not always been placed in the best locations in terms of potential power output efficiency, due to technical factors (e.g. poor solar and wind resource forecasts, insufficient adaptation of the electricity grid) or regulatory issues (e.g. restrictions on the positioning of power systems, availability of subsidies). Rapid scaling-up and concentration in some geographical regions has created additional challenges for grid operators to deal with intermittency of power production. These issues have contributed to increase low-carbon power curtailment, as well as the investment needed to create the operational and economic conditions for incumbent power generators to secure balancing services. In addition, the extended deployment of some early technological options for solar and wind power has led to a movement towards repowering (replacement of wind turbines or solar PV panels for technologically superior ones). As a result, further low-carbon innovation is urgently needed to create better performing technologies capable of tackling the challenge of increasing low-carbon output of the current installed capacity.

In contrast with the rapid scaling-up of low-carbon energy installations seen in the last decade, further innovation in this domain still involves several challenges beyond those studied in this thesis. First, the energy sector directs only a small share of investment to innovation, as reflected by its R&D intensity being among the lowest of all major industries (Jamasb and Pollitt, 2011). Estimates of total public and private investment in energy RD&D

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[54] Includes geothermal, wind, solar and tide power.

tend to be conservative, around 0.5% of the global expenditure in energy and 0.03% of world GDP (Holdren, 2006). In the US, energy firms reinvest less than 1% of their revenues in RD&D, whereas in sectors such as IT, semiconductors and pharmaceuticals firms reinvest considerably more, namely between 15% and 20% (Chazan, 2013). Hence, strong policy support directed specifically to low-carbon energy innovation could provide additional stimulus to private and public R&D.

In particular, the development of technologies to address intermittency and power grid management need to receive more attention. A foreseen large scale integration of low-carbon energy requires a system-wide effort for which technologies granting higher flexibility to energy flows and higher accuracy of power output forecasts are crucial (IEA, 2014b). In fact, as the share of variable renewable sources grows, further development of energy storage and other technologies, such as long-distance transmission and demand-side management will be needed to grant reliability of energy supply while minimising energy losses. Moreover, with the emergence of dominant designs among low-carbon technologies, non-physical artefacts – such as software – need to respond to an increasing share of the costs of a transition towards a low-carbon system and can work as both an enabler or a barrier to the emergence of new technologies. Still, these technologies remain understudied.

Last but not least, considering the pressing requirement for GHG emissions reduction and the unused potential of low-carbon energy production, further investment on low-carbon innovation could put a stronger accent on its environmental consequences. Lessons learned from developing solar and wind power should be applied to introduce the actual capacity of reducing GHG emissions within different time frames as a main factor to evaluate low-carbon innovation.

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