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Mechanisms that accelerate the diffusion of renewable technologies in new markets: Insights from the wind industry in Portugal

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Mechanisms that accelerate the diffusion of renewable technologies in new markets: Insights from the wind industry in Portugal[1]

Abstract

The spatial diffusion of sustainable innovations and the importance of local absorptive capacity in early adoption are studied through the comparison of the diffusion of wind energy in Denmark and Portugal. The novelty of this research consists in revealing patterns of spatial growth and explaining them with the help of concepts issued from the sustainability transitions literature. In particular, the technological innovation systems approach and the actor-oriented analysis focusing on the role of organizations and networks in the emerging innovation systems. An acceleration of diffusion was found in the case of wind technologies in Portugal in comparison with the "core". The analysis permitted to identify some key drivers of this process. In a first exploratory stage, science and technology policies emerged as initial "motor" of change supporting the fulfillment of critical functions of the innovation system (e.g. knowledge development, experimentation). In the implementation stage, the market took off induced by an attractive feed-in-tariff that enabled the formation of expectations. This attracted key actors whose advocacy coalitions have gradually got the capacity to influence policy making, which contributed to further speed up market formation. Diffusion acceleration was possible thanks to a series of partnerships with international manufacturers for the transfer of state-of-the-art technology from "core" countries, and to the enhancement of absorptive capacity that permitted to better assimilate transferred knowledge and integrate it with local competences.

Keywords: Spatial diffusion; functions of innovation systems; formative phase; up-scaling; absorptive capacity; wind energy

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1. INTRODUCTION

The magnitude of the problems caused by climate change requires a global action against its main cause, which has been clearly identified in the last review of the IPCC (2013) with the augmentation of carbon dioxide emissions since the industrial revolution.[2] The energy and transport sectors had an important share in this increase; however, emissions from those sectors are expected to keep growing in the next decades, driven by economic growth in the emerging countries (IEA, 2012a; Riahi et al., 2012). For instance, in 2012 coal reached the highest share of global primary energy consumption (29.9%) since 1970 and this despite the reduction of consumption in the US (BP, 2013).[3] Hence, there is an urging need for a major technological change in both energy and transport sectors. Some positive signs have already been given by the former. In the last decade, the electricity sector has witnessed a spectacular increase in the investment in renewable energy sources, especially wind energy. In fact, the global cumulative installed capacity of wind power has reached 282 GW in 2012 (GWEC, 2013), generating 521 TWh, or 2.3% of total gross electricity consumption (BP, 2013). Even though China leads in terms of installed capacity (around 70 GW), the majority of wind plants are still located in OECD countries. This case illustrates the importance of diffusing low carbon technologies like wind power across different regions, especially those where energy demand is expected to increase the most in the next decades.

The objective of this paper is exactly to contribute to our understanding of the process of spatial diffusion of wind energy technologies and how it can lead to the development of more sustainable energy systems. It addresses a case of diffusion from a pioneer country (Denmark) to a fast follower one (Portugal), comparing the development of wind energy in both countries and analyzing the processes that enabled fast technology growth and the development of a wind energy system in the latter.

In order to conduct this analysis, the paper draws on the literature that addresses the emergence and growth of new technologies and systems, in particular recent literature that gives an increasing attention to the spatial dimension of these processes. Thus, it combines contributions from historical scaling dynamics analysis (Wilson 2009; Grubler, 2012) with those from the technological innovation systems literature (Bergek et al., 2008a; Hekkert et al., 2007), adhering to the view that it is necessary to bring space more decisively into the latter (Markard et al., 2012; Coenen et al., 2012). This integration is a promising avenue of research.

[2] The 2013 IPCC's report deemed "extremely likely" (with a probability of over 95%) that human action causes climate change. This represents an increase in comparison with former reports. For instance, that link was considered "very likely" (90%) in the 2007 version.

[3] This figure compares to oil share (the world's leading fuel) with 33.1% of global (primary) energy consumption and to 2.4% of the part of renewables. See: BP, 2013.

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On the one hand, because it allows the contextualization of the technology transition process in different institutional settings, such as local structures and global networks (Coenen et al., 2012). On the other hand, because it takes in consideration the stage of development of technological innovation systems in different regions, and permits to identify the strategies to be pursued to foster technology transfer (Markard et al., 2011)[4].

Recent empirical research on the spatial diffusion of several energy technologies, focusing on the effect of scaling in growth dynamics (Wilson 2009; Wilson and Grubler, 2011), identified some international patterns of diffusion. It namely uncovered an acceleration of growth as innovation penetrates into new regions (Wilson, 2012; Grubler, 1998). This was explained by the fact that technology enters in new markets in a more mature stage, benefitting from development and market deployment in the first ("core") region. Wind power was found to be a good example of the acceleration of international adoption. Thus, given the fact that wind is the most mature renewable energy technology and the one that is effectively achieving a wide diffusion, it emerges as a relevant empirical setting to address the mechanisms of spatial technology diffusion.

However, despite the number of studies about the development of wind power, some of them based on international comparisons, this issue is still largely underexplored. In fact, those comparisons tend to be made between early developers, usually between Denmark and another pioneer country which invested significantly in wind technologies without similar success (e.g. United States, Netherlands, Norway). These studies offer several insights into the processes at work in the development and early diffusion of the technology, which may still be useful, when analyzing other spatial settings. Some of them highlight the value of firms' experience-based knowledge and "bricolage", i.e. incremental improvements obtained by "trial and error" processes that will accumulate and become major ameliorations of the technology (Garud and Karnøe 2003; Karnøe and Garud, 2013). Others emphasize the role of "learning from interacting" between the actors involved in the innovation process (i.e. suppliers, regulator, users) to enable learning micro-processes that will spur innovation dynamics (Kamp et al, 2004; Kristinsson and Rao, 2008). Still others reveal the role of "learning from searching" for the development of wind power in particular contexts (Bergek et al., 2003; Nemet, 2009) and namely in the crucial phase towards large-scale turbines (Hendry and Harborne, 2011). The role of technology and other incentive policies have also been analyzed by researchers from different perspectives, including comparisons of institutional frameworks (Toke et al, 2008; Breukers et al, 2007; Lewis and Wiser, 2007), emergence of a global technological innovation system

[4] The need to go beyond the focus on the national level was equally acknowledged by the proponents of other analytical models in the transitions literature, such as the Multilevel Perspective (MLP) (Raven et al., 2012).

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(McDowall et al., 2013) and econometrical analysis of the performance of support mechanisms (Jenner et al., 2013; Zhang, 2013). The importance of the combination of both demand-pull and supply-push instruments is also supported by some empirical studies (e.g. Nemet, 2009). Nonetheless, the international diffusion of wind technologies have received much less attention, and even so, the existing studies have focused more on the strategic relationships between wind turbine manufacturers and local producers (e.g., Kristinsson and Rao, 2008) than on technology transfer and on the technical needs of receiving countries.

This paper intends to fill this gap by comparing the case of Denmark with that of a fast follower, rather than with another pioneer. In fact, the transfer of wind energy technology from a "core" country to a fast follower can provide a valuable field of study on the determinants of spatial diffusion. In this context, Portugal is an interesting case study, not only for the speed of penetration but also for the modes assumed by such diffusion. Firstly, wind power growth was fast and very intense. Portugal is a country without oil or natural gas resources and with an historical dependence on energy imports. However, in 2011 the country generated 45.3% of electricity out of renewable energy sources (RES).[5] In the past decade wind energy registered a spectacular growth, becoming the second most important RES after hydropower. In 2011, it produced 17.2% of total electricity consumption, the second highest share among OECD countries, only surpassed by Denmark (EWEA, 2013; DGEG, 2013). Secondly, promotion of wind power was based on a mix of demand "pull" and supply "push" policies. A very generous feed-in tariff was implemented in early 2000s, resulting in a strong increase on the demand for wind farm connections. In 2005, overwhelmed by the requests for capacity installations, the government decided to organize public tenders for the attribution of capacity rights. Local production requirements were tied to those rights, revealing the will of the country to "catch up" (industrially) with up-to-date wind turbine technology (Martins et al., 2011). As a result, an industrial cluster was formed, and national incorporation of inputs rose from 20% to 100%, while exports absorbed more than 60% of production, in 2011 (Público, 2011). More than 2,000 direct jobs were created at the new industrial sites, harnessing local engineering and industrial competences and helping to recover a depressed industrial area in the Minho-Lima region (ENEOP, 2013). A better understanding of the mechanisms at work behind this process can offer some insights on the determinants of fast adoption and system building and thus contribute to extend our knowledge on the process of spatial diffusion of sustainable technologies. Lessons can also be derived for countries that are considering the adoption of renewable energy technologies (e.g. wind power) with the objective to reduce emissions and boost their economy.

[5] The third highest share in UE15 and the fourth among OECD countries. Still, current plans aim to raise that share to 60% by 2020 (DGEG, 2013).

So, the spatial diffusion of sustainable innovations and the importance of local absorptive capacity in early adoption are studied through the comparison of the development of wind energy in Denmark and Portugal. The paper starts from a generic research question: How do energy technologies evolve spatially? In order to contribute to answer it, the article focuses on the diffusion of wind energy from a technology pioneer to a fast follower and formulates a more specific question: Which were the main drivers of the transfer and adoption of wind energy in the case of a fast follower country as Portugal? The patterns of international diffusion are investigated with the focus on technological innovation systems' formation and industry up-scaling. The theoretical and empirical literature discussed above raise the hypothesis that fostering knowledge spillovers between regions through technology transfers and reinforcing local innovation capacity (e.g. knowledge development, creation of networks) may accelerate the formation of the local innovation system and consequently the spatial diffusion of new technologies.

The article is organized as follows. Firstly, the conceptual framework is presented. Secondly, the methodology and data sources are explained. Thirdly, the process of spatial diffusion of wind energy from Denmark to follower countries is examined, taking the case of Portugal. The paper ends with the discussion of the main findings. The understanding of the determinants of spatial growth allows a better design of strategies that can be used to foster the widespread adoption of low carbon technologies.

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2. EMERGENCE OF INNOVATIONS AND SPATIAL DIFFUSION: CONCEPTUAL FRAMEWORK

Two approaches have recently appeared in the literature that aims to understand the process of emergence and growth of new technology systems (Markard et al., 2012; Grubler et al., 2012). The first is the technological innovation system (Bergek et al., 2008a; Hekkert et al., 2007) that comes from the more theoretical field of socio-technical transitions (Markard et al., 2012). The second is the recent historical scaling dynamics analysis (Wilson, 2012, 2009) which comes from the tradition of more applied systems analysis (Grubler, 2012, 1998).

2.1 Technological innovation systems

2.*1.1 Conceptual model*

The model of Technological of Innovation Systems (TIS) focuses on the emergence of novel technologies and the institutional and organizational change that is needed to technology development (Markard et al., 2012). Innovation is understood as an interactive process involving a network of actors (e.g., firms, users), who act within a particular context of institutions and policies that influence technology development, adoption behavior and performance, and who bring new products, processes and organization structures into economic use (Carlsson and Stankiewicz, 1991; Bergek et al. 2008a; Jacobsson and Bergek, 2012). This definition highlights the three main elements constituting the structure of the new technology system (Bergek et al., 2008a; Jacobsson and Bergek, 2004): actors, networks and institutions. *Actors* include firms and other organizations (e.g. universities, industry associations) along the value chain (Bergek et al., 2008a). *Networks* are the result of links established between fragmented components to perform a particular task (e.g., learning and knowledge creation and diffusion, standardization and market formation, political and advocacy coalitions). *Institutions* consist of formal rules (e.g., laws and property rights) and informal norms (e.g. tradition and culture) that structure political, economic and social interactions (North, 1990, 1991). Institutions have three roles in innovation systems (Edquist and Johnson, 1997): to reduce uncertainty by providing information; to manage conflicts and promote cooperation; and to provide incentives for innovation.

The emergence of new technological innovation systems faces many challenges. Actors need to get the technology ready and aligned with the relevant institutions (Jacobsson, 2008). The literature on technological innovation systems focuses on the processes that are required for the TIS to start, grow and gain momentum. Bergek et al. (2008a) distinguish between a formative phase and a growth phase. The formative phase is when "… constituent elements of the new TIS begin to be put into place, involving entry of some firms and other organizations, the beginning of an institutional alignment and formation of networks." (p. 419), while in the growth phase "… the focus shifts to system expansion and large-scale technology diffusion through the formation of bridging markets and subsequently mass markets; hence the need for 'resource mobilization' increases by orders of magnitude." (p. 420). Thus the formative phase is central in the emergence of the TIS. New technologies face high uncertainties and financial needs in combination with low institutional support and small (if any) markets (Kemp et al, 1998). The early stage is then crucial to build the supportive structure that allows the innovation system to move into the next stage and develop in a self-sustaining way. This process is particularly important in the case of new and radical innovations, for which almost every component must be put in place.

One of the main advantages of the TIS approach is that it highlights a number of processes or *functions* that need to be carried out, for the innovation system to grow and gain momentum (Bergek et al., 2008b; Hekkert et al., 2007; Markard et al., 2012). The literature identified eight key *functions of innovation systems* that are necessary to fulfill for a successful maturation of the innovation (Bergek et al., 2008b):

- Development of formal knowledge
- Entrepreneurial experimentation
- Materialization
- Influence on the direction of search
- Market formation
- Resource mobilization
- Legitimation
- Development of positive externalities.

However, one major limitation of the technological innovation system approach is that it tends to focus at national level, overlooking the interactions established between the emerging TIS and the TISs from other countries (Markard et al., 2013; Binz et al., 2012).

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2.1.2 Spatial dimension

The recent integration of the spatial dimension in the TIS analysis opens a promising research avenue in many ways (Markard et al., 2012; Coenen et al., 2012). Firstly, it allows the contextualization of transition studies at different spatial and institutional levels (e.g. local structures or global networks) (Coenen et al., 2012). Secondly, it permits to take into account differences between regions in what concerns the stage of development of the TIS, and to assess how this affects the process of technology transition. Thirdly, it enables the analysis of actors' strategies (e.g., creation of networks) to stimulate the transfer of a successful innovation (Wieczorek et al., 2013; Markard et al., 2011). For instance, Garud and Karnoe (2003) compare the emergence of wind energy in Denmark and in the United States, explaining how producers, users and evaluators interacted differently in each case. The analysis shows how the Danish incremental approach was more effective to enable micro-learning processes that lead to the emergence of a successful path, than the more high-tech "breakthrough search" strategy of the US. In particular, it is emphasizes the role of the Danish Wind Turbine Test Station (which provided the required certification) in the development of wind turbines in Denmark, by promoting interactions between actors, as well as enabling knowledge development and diffusion. Kamp et al. (2004) point at the importance of "learning from interaction" in the success of the Danish approach. User and producer interactions allowed the incorporation of users' experience from technology's behavior in use, what was absent in the US case. Hendry and Harborne (2011), however, criticize the perspective that explains the success of the Danish technological path as the triumph of "bricolage" and experience-based learning. The authors show the significant part that played formal science-based R&D in the step-change to large megawatt wind turbines beyond those commercially available at the 500kW level in the mid-1990s.

The spatial dimension has been integrated in the TIS analysis in at least two different ways. On the one hand, through the analysis of national TIS as a subsystem from the international TIS, which includes globally operating actors, as in the "geography of transitions" (Binz et al., 2012). On the other hand, by focusing on transnational linkages, involving technology, actors, knowledge, etc., which allow the mobilization of local as well as international capabilities (Wieczorek et al., 2013). The comparison between these two approaches shows that the inclusion of space can be very helpful in the identification of key "prime movers" (Jacobsson and Johnson, 2000; Markard et al., 2011), who were decisive for the formation of the local TIS, namely by solving *imitability* and *transferability* issues. This leads us to conclude that an actor-oriented analysis focusing on the role of actors and networks for the development of system resources can improve the understanding about the formation of local innovation systems (Markard et al., 2011).

2.2 Drivers and patterns of the historical growth of technologies

A more empirical literature analyzed the historical diffusion of energy technologies focusing on the effect of scaling to draw lessons about technology development (Wilson 2009; Wilson and Grubler, 2011, Grubler, 2012). It has shown that growth typically evolves in a three-phase sequential process (cf. Wilson, 2009):

i) a formative phase consisting on the experimentation and production of many small scale units in order to establish the first production base;

ii) an up-scaling phase by constructing ever larger units (e.g., steam turbines or wind power plants) to gather technological economies of scale at unit level;

iii) and a growth phase characterized by mass production of large-scale units, reaping economies of scale (and also learning economies) at the manufacturing level.

Therefore, the scaling approach brings more clarity to the link between the formative and the growth phase. In the formative phase both technology and structures of the innovation system co-evolve and prepare the up-scaling that is necessary in order to move into the large-scale diffusion. This perspective highlights some important mechanisms for the development of the technology such as experimentation and learning (Hendry and Harborne, 2010), as well as legitimation which usually precedes institutional alignment with the needs of the emerging innovation system (Bergek et al., 2008b).

The analysis of international patterns of diffusion pointed to the acceleration of growth rates as innovation reaches new regions (Bento, 2013; Wilson, 2012; Grubler, 1998). The penetration of the innovation becomes faster as new technology transits from initial to subsequent markets. One of the reasons for this acceleration is the fact that technology is more mature when it starts to develop in other regions and a significant part of the learning costs have already been supported in the initial markets (Nemet, 2009). In fact, other regions may benefit from knowledge and technology spillovers created during the previous diffusion in the core (Jaffe, 2005). Keller (2010) emphasizes the role of international trade and FDI in the capture of

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technology spillovers.[6] In this perspective, the local capacity to exploit these externalities can be enhanced by importing technology or with the physical presence of international companies.

However, international technology diffusion is not automatic from the existence of a knowledge base in the core, but requires the recipient to have the capacity to absorb and assimilate such technology in order to take the maximum benefit from it (Mowery and Oxley, 1995; Teixeira and Fortuna, 2010). The term "absorptive capacity" was coined by Cohen and Levinthal (1989, 1990) in order to designate the ability of organizations (and ultimately their countries) to exploit external knowledge[7]. At the macro level, enhancing local absorptive capacity refers to the institutional and organizational changes that are needed to adopt more rapidly new technologies (Fagerberg and Godinho, 2006; Mowery and Oxley, 1995). In particular, the ability to absorb external knowledge and the efficient use of imported technology in laggard countries, such as Portugal, depends on a minimum level of human capital and local R&D efforts (Teixeira and Fortuna, 2010). It is also subject to non-technological factors related with the social and institutional set-up of the country, and the way these enable or constrain the development of a coherent and integrated innovation system. These socio-technical processes are extensively dealt with by the TIS literature, as we saw above.

This suggests that a complete understanding of the process of diffusion and adoption of sustainable energy technologies requires an analytical framework that combines the empirical contributions from the historical analysis of technology diffusion with the explanatory potential of a "spatialized" technological innovation systems approach.

[6] The typical channels for international technology transfer after the post-war have been capital imports, foreign direct investment (FDI) and licensing (Mowery and Oxley, 1995; Mowery et al., 1996; Keller, 2010).

[7] The authors point out that "…while R&D obviously generates innovations, it also develops the firm's ability to identify, assimilate, and exploit knowledge from the environment…" (Cohen and Levinthal, 1989, p.565). See Todorova and Durisin (2007) and Zahra and George (2002) for more refined models of firms' absorptive capacity comprising recognition of the value, acquisition, transformation /assimilation, and exploitation of external knowledge.

3. METHODOLOGICAL ISSUES

This research aims to reveal patterns of spatial diffusion and technology up-scaling and explaining them with the help of concepts issued from the sustainability transitions literature. In particular, the technological innovation systems approach and the actor-oriented analysis focusing on the role of organizations and networks in the emerging innovation systems. Instead of studying the strategies pursued in Core countries (e.g. Garud and Karnoe, 2003; Kamp et al., 2004; Hendry and Harborne, 2011), our analysis focus on the conditions of rapid transfer of technology from the center to fast follower and peripheral regions, because of its importance for global sustainability.

The paper focuses on the case of wind development in two countries: Denmark (representing the “core” of the innovation) and Portugal (a “fast follower” country). The comparison of the dynamics of growth of wind energy in Denmark and Portugal may reveal historical patterns, providing a ground for discussion on the determinants of spatial technological diffusion.

Quantitative and qualitative data was collected from official statistics such as IEA, Danish Energy Agency, Portuguese national statistics, Portuguese Directorate-General for Energy and Geology (DGEG). It was also used information published in secondary sources (e.g., scientific articles, policy documents, laws, newspaper, documents). Key actors of the wind and energy sector in Portugal were interviewed from industry (e.g. equipment manufacturers, developers, electricity producers), academia and policy making.

On the basis of the documents and interviews, the paper provides a short historical overview of the evolution of the wind system in Portugal, identifying the main events and the key actors. Drawing on this data, the paper uses the TIS framework as an analytical structure to investigate the processes at work over time, and attempts to provide an explanatory account of the fast diffusion, documented by the data on wind capacity development. In addition, the analysis use logistic growth models to fit actual numbers in order to identify historical patterns (Grubler, 1998, 2012; Marchetti and Nakicenovic, 1979; Fisher and Pry, 1971). Specifically, it is applied the historical scaling methodology developed in Wilson (2009) and Wilson and Grubler (2011). The term ‘scaling’ as used in this context represents the technological growth that is both rapid and extensive and occurs at multiple levels: the technology unit and the industry as a whole (Wilson, 2012).

4. SPATIAL DIFFUSION OF MODERN WIND ENERGY: THE CASE OF PORTUGAL

4.1 The diffusion of wind power in Portugal

This section examines the growth of wind technologies in Portugal. It starts to review the most relevant events during the diffusion. The main drivers are discussed next, before comparing the rhythm of penetration of wind in subsequent markets with the growth in countries from the center of innovation.

4.1.1 Brief history of the development of wind energy in Portugal

After the two oil shocks, many countries increased the investments in domestic sources of energy. Portugal was no exception, and in 1988 approved two laws (Decreto-Lei no. 188/88 and DL no. 189/88) to support independent generation from renewable sources up to 10 MW. Initially, this legislation was only applied to small-hydro projects, and it was not before half a decade later that it is also extended to other renewable energy sources (DL no. 313/95). However, the majority of the investments were still in small-hydro power plants with only half a dozen projects on small wind turbines mainly in the Azores and Madeira islands (Castro, 2011). These projects were undertaken by public research institutes, national utility and foreign investors (Estanqueiro, 2013). Wind power was still a technology under development, with little experience of deployment in Portugal. There was also limited knowledge of wind resource potential. Therefore, in the late 1980s and early 1990s, a large part of research activities concentrated on wind characterization and the evaluation of Portugal's wind resources (Matos, 2013). The situation started to change with the evolution of the international context, particularly with the technology progresses made in the core markets in the 1980s and 1990s.

The wind power has a long story of development and experimentation of prototypes in niche markets.[8] The energy shocks of the 1970s led a group of pioneer countries (United States, Denmark, Germany and the Netherlands) to devote large amounts of resources to R&D activities in wind technologies (Neij and Andersen, 2012). In particular, the United States invested in large size turbines searching for major breakthroughs that would turn wind energy

[8] The first wind power systems were already created in the 1880s (the first automatically operated was the 12kW Brush wind turbine installed in Ohio, in 1888). Small wind turbines were used to power rural communities in the 1920s and 1930s until the electricity grid came to displace them. Meanwhile several large models were experimented, of which two are of particular relevance: the Smith-Putnam turbine installed in Vermont in 1941, the first wind turbine over 1MW; and the 200kW Gedser turbine installed in 1957 in Denmark which was the first horizontal axis, three-bladed rotor oriented upwind, later known as the "Danish style". However, the early large scale wind turbines were very expensive to build and not very practical to operate. See: Neij and Andersen, 2012; McDowall et al., 2012.

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competitive, whereas Denmark pursued a more bottom-up strategy focusing on experimentation and production of smaller scale wind turbines (Garud and Karnoe, 2003). A generous tax incentive in California created a wind “boom” in the 1980s that had significantly increased the installation of wind turbines, from national and foreign producers (e.g. from Denmark). This was followed by a drop, caused by the reduction of subsidies and reliability problems experienced by the more advanced, though un-proven, US turbines (Neij and Andersen, 2012). Still, the early “boom” enabled knowledge and skills formation, which were important for Danish producers to continue technology development and, later on, to create a local market for wind. In the early 1990s, the conditions were finally set in Denmark for up-scaling wind turbines, as the industry started building units larger than 22kW up to 500kW. In the following years, the market for wind turbines knew an enormous development in other European countries, such as Germany and Spain, guided by the success of the Danish experience.

The diffusion of wind power kicks-off in Portugal in the second half of the 1990s, when better and cheaper turbines became available. The decision to invest in wind was influenced by the developments in energy policy in Europe. After the Chernobyl accident, many European countries, such as Denmark, Germany and Spain, enacted market deployment incentives to promote the growth of alternative energy sources (McDowall et al., 2012). By that time, wind turbine technology in service had proved its readiness to contribute to the power mix. The experience gained from its increasing implementation allowed significant performances improvement and cost reductions (Neij and Andersen, 2012). The first wind farms were installed in Portugal between 1996 and 1997 by Enernova (affiliate of the Portuguese utility EDP), with promising indications. These projects allowed the main Portuguese utility to get the first experience with the technology. The company was later actively involved in the lobby for the implementation of wind energy schemes in late 1990s.

4.1.2 Factors influencing the take off of investments

The development of wind power in Portugal was driven by two main determinants: the changes occurred in the political and regulatory context; and the favorable evolution in the economics of wind technologies.

Firstly, the context of investments was influenced by changes that intervened at both national and international levels. On the one hand, the restructuration of the national electricity system in 1995 established the distinction between a public electricity system (SEP) and an independent electricity system (SEI). As a consequence, it ended the monopoly of the Portuguese utility EDP and opened the market to new investors. On the other hand, the signing of the Kyoto Protocol and the subsequent European Directive (2001/77/CE, 27 September),

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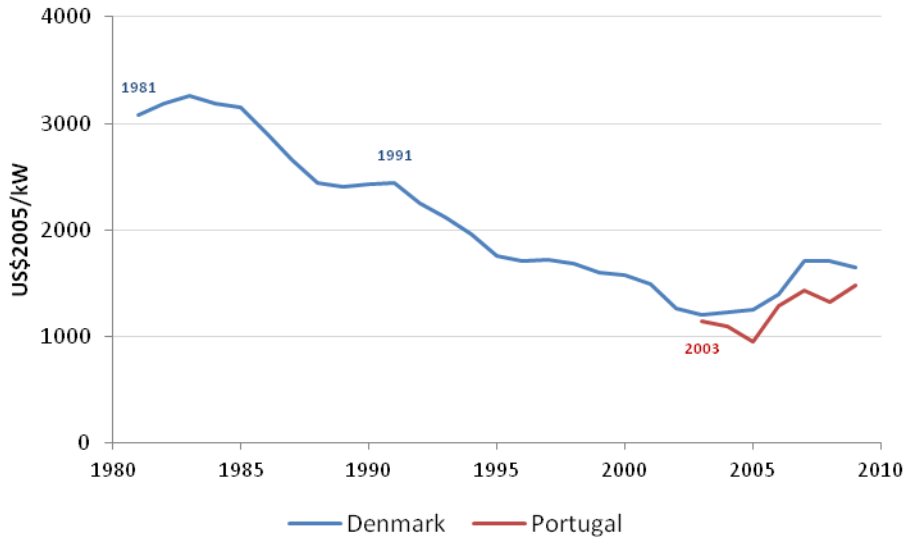
known as the "Renewables Directive", triggered a wave of investments in renewable energies. The directive established the overall target of 21% for electricity produced from renewable energy sources in the gross electricity consumption by 2010. It also fixed specific targets by member-states, such as 39% for Portugal. In 2001, the E4 Program (Energy Efficiency and Endogenous Energies) was approved (Resolution of the Council of Ministers No. 154/2001 of 19 October) that aimed to double the installed capacity of endogenous energies in Portugal in a horizon of 10 to 15 years. This included the installation of 2500 - 3000 MW of wind capacity by 2010. To achieve this goal, legislation was published that introduced a very attractive remuneration for renewable sources (DL no. 339-C/2001) and simplified the administrative procedures for the connection of new capacity (DL no. 312/2001).

Secondly, the progresses made by wind technology during the 1890s and 1990s prepared it for widespread diffusion. Danish manufacturers were already commercializing 3 MW wind turbines by the end of the 1990s. The new models had significantly improved their efficiency and performances over the previous ones, registering important reductions in the average downtime rates (to less than 2%) and turbine noise (Neij and Andersen, 2012). At the same time, investment costs in wind turbines were cut by half between 1980 and 2000 (Fig. 1). Wind energy thus became a mature technology, ready to supply important amounts of energy at a competitive cost, not only in the first markets but also abroad.

Figure 1. Average costs of installed wind capacity in Denmark and Portugal between 1980 and 2010



Sources: (Portugal) IEA Annual Wind reports - various years; (Denmark) Grubler et al., 2012.

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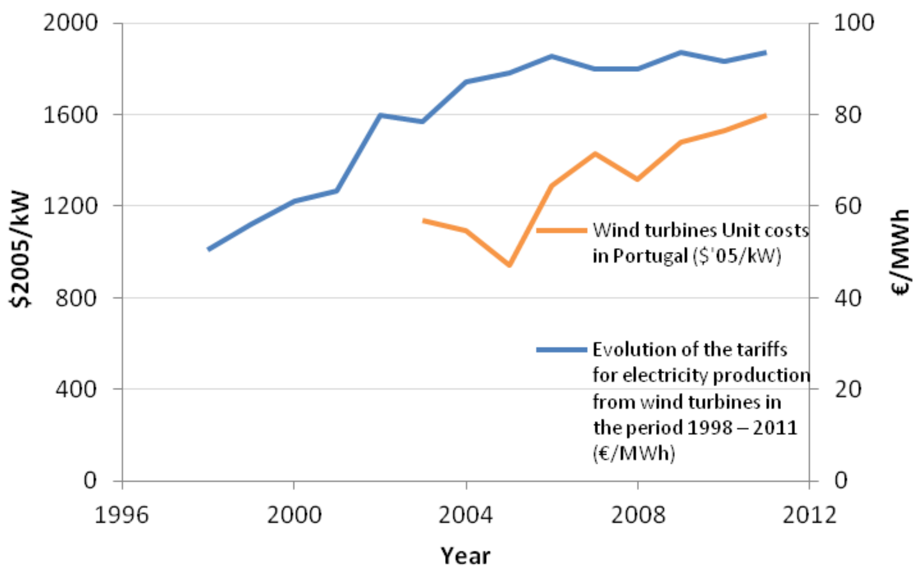
The favorable evolution of the economics of wind technologies was decisive for the Portuguese decision to invest in this renewable energy source. The country adopts the technology after the up-scaling and when it became a mature innovation in the core. In the late 1990s, wind technologies were much more advanced and cheaper than alternative renewable technologies, such as solar photovoltaic. The average cost of building wind capacity in Portugal was close to the one in Denmark. Figure 1 shows that investment costs are very well correlated in both countries, even if in absolute terms there are some differences between them which may be explained by the different sources used to construct the graph.

In spite of the declining cost trajectories predicted by the learning curve theory and observed in the previous decades, the price of wind turbines increased in the years 2000. This reflected a general movement at international level that was due to the joint effect of a surge in demand for wind turbines with the raise of production costs motivated by increasing labor and materials prices and profit margins (Bolinger and Wiser, 2012). In recent years, wind turbines prices have tended to converge around 1.2 to 1.6 million Euros.[9] Nevertheless, the increase in the remuneration of electricity generated from wind in Portugal in early 2000s more than compensated that increase in costs, guaranteeing the profitability of wind farms (Fig. 2). This strongly contributed to the rapid increase in the installed capacity of wind power.

Figure 2. Evolution of average wind turbines costs and tariffs for wind power in Portugal between 1998 and 2011



Sources: IEA Wind annual reports for Portugal <http://www.ieawind.org/countries/portugal.html>

[9] According to an anonymous source from a component supplier company.

4.1.3 Growth of installed capacity and international comparison

The diffusion of wind power in Portugal was rapid and impressive as most of the wind turbines were deployed after 2000. The growth in wind capacity kicks-off in 1999, when it was as low as 58 MW, doubling in average every other year. The installed capacity reached 4,364 MW (21% of total capacity) in 2011 (DGEG, 2013). As a result, the part of wind in total electricity consumption has been increasing to reach 18% in 2012 (DGEG, 2013). This was decisive to raise the share of renewable energies in final electricity consumption from 21.1% in 1999 to 45.3% in 2011, one of the highest shares in Europe (Fig. 3). The spectacular increase of wind power in Portugal can be further assessed by comparison with other top wind countries in Europe (i.e., Denmark, Germany, Spain, and United Kingdom). Portugal has the second highest share of wind energy in total electricity consumption (only surpassed by Denmark), and it is expected to stay in the same position in 2020 according to current plans. The Portuguese government maintain an attractive feed-in tariff (€ct. 9 per kWh in average) for onshore wind electricity that is in line with the support mechanisms in practice in other countries.

Figure 3. Shares and targets of renewable electricity and wind in gross final electricity consumption and support schemes for wind power in top wind countries in the EU

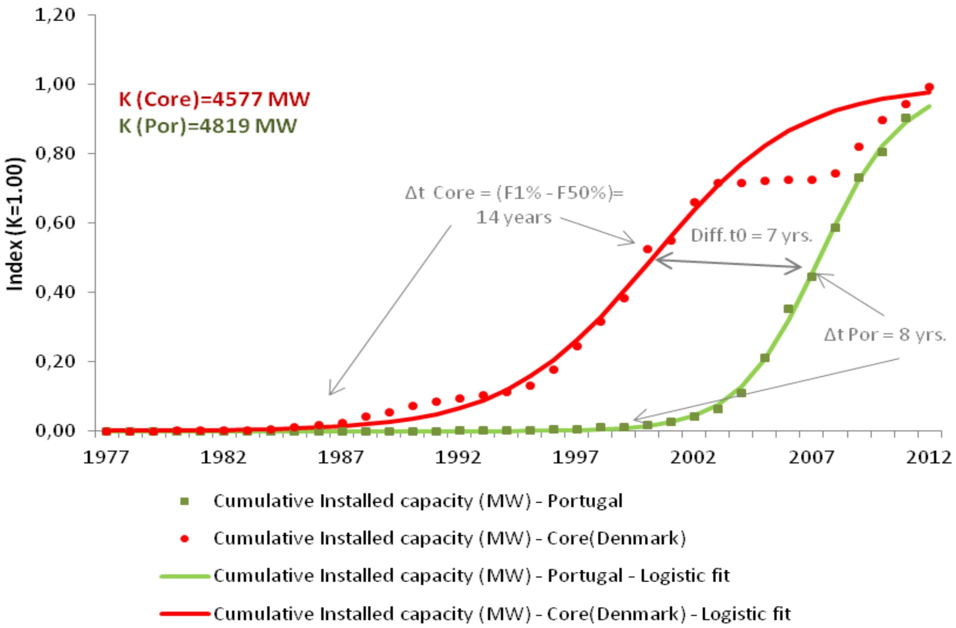
(in %)	Share of Renewable Electricity in Gross Final Consumption in (1999) 2011[i]	Renewable Electricity Targets in 2020[ii]	Share of Wind Electricity in Gross Final Consumption in 2011[i]	Wind Electricity Targets in 2020[ii]	Onsite Wind Power Support Scheme (Feed-in/Premium) in 2013[v]
Denmark	(13.3) 38.7	52	27.0	50[iii]	Premium above market price Guaranteed bonus of 0.25 DKK (approx. €ct 3) per kWh for 22,000 full load hours + 0,023 DKK (€ct 0,3) for covering the balancing costs. Different for plants financed by utilities
Germany	(6.7) 19.8	38.6	7.6	19	Feed-in tariff €ct 4.87 – 8.93 per kWh (according to duration of payment) + repowering bonus of €ct 0.5 per kWh and plant service bonus of €ct 0.48 per kWh
Portugal	**(21.1) 45.3**	**60**	**17.2**	**23**[iv]	**Feed-in tariff** **€ct 7.4-9.8 per kWh for 20 years**
Spain	(14.3) 30.3	40	14.8	21	Feed-in tariff[vi] €ct 8.1270 per kWh; from the 21st year onwards: €ct 6.7921 per kWh
UK	(3.4) 9.5	31	4.3	21	Feed-in tariff (GBP per kWh) 100kW - 500kW: 0.1804 500kW - 1.5MW: 0.0979 > 1.5MW: 0.0415

Sources: [i] DGEG (2013, p.12); [ii] data directly collected from the National Renewable Energy Action Plans (NREAPs) of the European Member States: Beurskens et al. (2013, Table 3 and 10a/b); [iii] Ren21 Map <http://map.ren21.net> (accessed in September 17, 2013); [iv] Plano Nacional de Acção para as Energias Renováveis (PNAER 2012) published by the Resolução do Conselho de Ministros n.º 20/2013, April 10; [v] RES-legal at <www.res-legal.de> (accessed in September 17, 2013), and for Portugal Peña (2013) citing Erse; [vi] the new energy reform announced by the Spanish government in July intends to significantly reduce the remuneration of renewable energy sources, namely from wind technologies.

How does this process compare with what happened in the "core"? Figure 4 compares the diffusion in Denmark and in Portugal. The growth of total installed capacity takes off in the latter when diffusion was well advanced in the former (i.e. around 40% of saturation). However, the speed of deployment accelerates when the technology enters into the Portuguese market. The adoption lag can be measured by the difference in the inflection points (F=50% coinciding with the year of maximum growth) of the logistic curves fitting actual growth in the two countries. In these terms, technology transfer from Denmark (Core) to Portugal took only 7 years, which is very fast comparing to the spatial diffusion of other energy technologies in developed countries in the past (Grubler, 2012). In addition to the speed of penetration, more than 500 MW of wind power were installed annually in Portugal between 2004 and 2009 while wind turbine prices were raising everywhere (Fig. 1-2). This is an intriguing finding and, thus, it is worthwhile to investigate what were the reasons that lead the country to maintain the investment plans in an increasingly expensive technology.

It is therefore relevant to try to understand what can explain the spectacular increase of wind capacity in Portugal. Our argument is that it was possible thanks to the successful formation of a local technological innovation system. The conditions that enabled the emergence of the local TIS based on wind technologies are studied in point 4.2. Also, the acceleration of wind diffusion as innovation transits from the core to other countries is an interesting finding that deserves to be further exploited. Section 4.3 examines more in-depth the rhythm of wind growth in Portugal in comparison with Denmark, and takes this case to discuss about mechanisms that speed up spatial diffusion.

Figure 4. Historical evolution of total cumulative installed capacity of wind power in Portugal and Denmark (1977-2012), indexed to saturation (K=1.00)



Source: DGEG, 2013; Spliid, 2013.

4.2 The emergence of a local TIS based on wind energy: the most influential functions of innovation system by stage of growth

This section analyses the emergence and growth of a local innovation system based on wind technologies in Portugal with the help of the technological innovation system theoretical approach (Bergek et al., 2008a,b; Hekkert et al., 2007, 2009). As pointed out above, this literature has identified several key functions of innovation systems that are required for a successful maturation of the TIS: development of formal knowledge, entrepreneurial experimentation, materialization, influence on the direction of search, market formation, resource mobilization, legitimation and development of positive externalities. The history of wind in Portugal is examined stage by stage - formative, up-scaling and growth stage - through the presentation of key facts that influenced the fulfillment of the most relevant functions of the innovation system.

4.2.1 Formative phase: Knowledge creation and experimentation

The first exploratory activities in wind technologies begin in Portugal in the 1980s. Internationally, the conditions were already created to scale-up wind turbines in Denmark as the industry started to build units larger than 22kW up to 500kW (Neij and Andersen, 2012). In the early 1990s, the Danish industry was already preparing for the construction of turbines with capacities above 500 kW. In Portugal, this period lays down the basis for the emergence of the new technological innovation system. Two main functions of innovation system were particularly important in the embryonic and formative phase: knowledge creation from the participation in international research projects, and entrepreneurial experimentation with small wind projects.

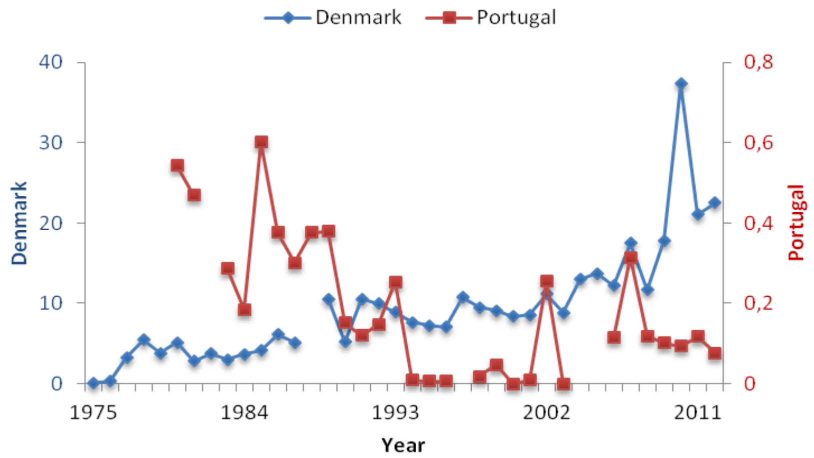
a) Knowledge creation

The first relevant activities in the field of wind power in Portugal were related with *formal knowledge development*. In the 1980s, the energy policy in Portugal is still under the influence of the two oil shocks of the previous decade. There is an official desire to diversify the energy sources of the economy, which is very dependent on energy imports, particularly fossil fuels. In this context a few national research groups get involved in European projects in the wind energy field, in particular after the country joined the EEC in 1986. The research laboratory INEGI starts to collaborate with international centers (e.g. Risø in Denmark) in European research projects on wind characterization, in the late 1980s (Matos, 2013). In the early 1990s, INETI, a public research center, publishes a detailed evaluation of the wind resource potential in Portugal

(IRENA-GWEC, 2012). The participation in several international research projects has enabled the creation of local knowledge on the characterization of wind resources and on wind technologies (Estanqueiro, 2013; Matos, 2013). In the mid-1990s, studies on wind potential began to be financed by private funds, particularly by the main utility - EDP (Costa, 2004). As a result, the installation of the first wind farms was done without the need for hiring international consultants, only the turbines were imported (Matos, 2013).

The creation of formal and applied knowledge can be assessed by the amount of investments in innovative activities over time. Figure 5 presents the total expenditure in research, development and demonstration (RD&D) activities on wind energy in Portugal and Denmark, respectively, between 1974 and 2012. Unsurprisingly, the amount of RD&D in the former is always one to two orders of magnitude lower than in the latter. A comparison of the evolution of the expenditures in the two countries is more interesting: RD&D peaks in Portugal in the 1980s and again in the 2000s, before a major growth in the installed capacity (Fig. 4), whereas it is steadily increasing in the case of Denmark. This might be also indicator of the RD&D orientation in Portugal towards a more applied type of knowledge, directed to solve practical problems associated with the adoption of wind technology. This comprises research activities related to: wind assessment, management of the penetration of intermittent renewable energy into the grid, and development of small urban wind turbines (IEA, 2012b).

Figure 5. Total expenditure in research, development and demonstration (RD&D) activities on wind energy in Denmark and Portugal 1974-2012, in Million Euros (2012 prices an exchange rates)



Source: IEA, 2013.

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b) Entrepreneurial experimentation

The second most important function in the emergence of the local innovation system based on wind technologies was *entrepreneurial experimentation*. The first trials began in 1985 in Lisbon (with a 20 kW turbine) and in the islands (Azores and Madeira), during the late 1980s and early 1990s, allowing the first contact with early prototypes of wind turbines. The following years saw a number of small turbines (around 100 kW) being tested and experimented in different parts of the country, both mainland and in the islands (Table 1). However, the first significant capacity installation occurred in Sines in 1992, with 12 machines of 150 kW of unit capacity in a total of 1.8 MW. This “exploratory” phase lasts until 1996 when the first 500kW and higher capacity turbines start being deployed in Portugal.

The experiments contributed to the development of applied knowledge and permitted to follow the progresses that the technology was undergoing abroad. They were also decisive for the main actors to acquire experience on wind technologies, which reduced uncertainties on these projects. The major role played by the utility EDP in the trials as well as the benefits in terms of “learning by using” for wind farm operators were similar to those observed previously in pioneer countries (Harborne and Hendry, 2009).

The early trials were also important to create resources and promote social change, in parallel with technology improvement (Hendry and Harborne, 2010). The demonstration trials in Portugal were not just able to address the problem of the “uncertain middle” between the technology transfer and early commercialization, but also the “uncertain context”, by laying down the foundations for the development of a community of firms and users that helped to legitimate the technology later on.

Table 1. Wind power scaling at both industry and technology levels in Portugal betwen 1985 and 1998

	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	19
Total capacity													
Installed power (MW)	0,29	0,29	0,29	0,53	0,53	0,53	0,93	3,83	8,93	9,08	9,08	20,03	20
Wind turbines (no.)	10	10	10	18	18	18	22	42	76	77	77	106	1
Sites (no.)	2	2	2	3	3	3	4	7	11	11	11	13	
Average capacity (MW)													
Farms	0,15	0,15	0,15	0,18	0,18	0,18	0,23	0,55	0,81	0,83	0,83	1,54	1
Aerogenerators	0,03	0,03	0,03	0,03	0,03	0,03	0,04	0,09	0,12	0,12	0,12	0,19	0
Aerogenerators - annual additions	0,03	-	-	0,03	-	-	0,10	0,15	0,15	0,15	-	0,53	

Source: INEGI - APREN (2011).

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c) Other critical functions

In addition, other functions of innovation system were gradually fulfilled during the exploratory period. The government promoted renewable energy as part of the future electricity generation mix, immediately helping to establish its *legitimacy*. It removed technical and legal barriers to the interconnection of renewable energy generators, namely by setting a "special regime" with priority dispatching (cf. DL 189/88).[10] The *financing* of early projects was supported with direct investment subsidies (cf. DL 188/88) whose funds came from the public budget and, to a substantial extent, from European programs (e.g. VALOREN) (Table 2). On the other hand, the attention given to renewable energies, such as wind power, *influenced the direction of search* and attracted supply-side actors to enter into the TIS. The first actors active in the field beyond the aforementioned public research laboratories (e.g. INETI, INEGI) were public utilities (e.g., EDA - Azores, EDP) and international developers who financed several early experimental projects. Finally, the *dynamic of positive externalities* was further boosted with the creation of the network of renewable energy producers (Associação Portuguesa de Energias Renováveis - APREN) in 1888, and the new renewable energy division of the incumbent EDP, i.e. Enernova, in 1993. The action of these two organizations was decisive for the implementation of support schemes in the late 1990s that precedes the take off of wind energy (IRENA-GWEC, 2012).

Table 2. Policies supporting the development of renewable energy positioned within the respective European & National Framework Programmes *(European programmes marked with an asterisk)*

RTD Framework programmes *	QCA (Country Framework Programmes)	Generic Operational Programmes at country level	Energy specific operational programmes	Support measures for energy (or including substantial number energy projects)
FP1 - 1984-1987	Pre QCA (1982-1988)			
FP2 - 1987-1991				SIURE (DL.188/88) subsidized by the European VALOREN*. JOULE* Introduction of a "special regime" for renewable energies (DL 189/88)
FP3 - 1990-1994	QCA I (1989-93)	PEDIP, CIENCIA		
FP4 - 1994-1998 FP5 - 1998-2002	QCA II (1994-1999)	PEDIP II, PRAXIS XXI	Operational Programme for Energy (DL.195/94)	ALTENER*
FP6 - 2002-2006	QCA III (2000-2006)	POE / PRIME , POCTI / POCI	Programa E4, ENE2010	MAPE (DL.70B/2000)
FP7 - 2007-2013	QREN (2007-2013)	COMPETE, POHP	ENE2020, PNAER,	Public tender for the attribution of rights connection (DR.144/2005), Fund to Support Innovation, SIMEI&DT, DEMTEC

[10] The national electricity system is composed by the public electricity system and the independent electricity system. The first comprises the regular activities to ensure the electricity supply in the country, including public service obligations and universal delivery. The second comprises the special regime producers and the non binding electricity system according to the legislation.

4.2.2 Up-scaling and growth phases: Legitimation, institutional alignment and market formation

The next stage corresponds to a period of hard market development of wind power in Portugal, encompassing both the up-scaling and growth phase. The former roughly comprises the years between the installations of the first 500 KW aerogenerators in 1996 until the deployment of the 3 MW turbines in 2003, whereas the latter starts around 2004 and coincides with the increasing rhythm of deployments. This happened after the publication of stimulating policies and the organization of a public tender in order to award connection rights to new wind power installations. This section examines how legitimacy was built around wind power, allowing the institutional alignment with the needs of the technology that fostered the development of the market.

a) External factors

At the international level, the focus of technology development in the 1990s was on up-scaling wind turbines in order to improve performances and grasp economies of scale at unit level (Wilson, 2012; Hendry and Harborne, 2011). Many economic and logistic challenges had to be solved during this process, such as the availability of cranes for the erection of larger turbines (Neij and Anderson, 2013). The technology progressed enormously and by the end of the 1990s the Danish manufacturers were already commercializing 3 MW wind turbines. The new models had significantly improved performances and reduced costs by half between 1980 and 2000 (Neij et al., 2003; Nemet, 2009). A number of other European countries got inspired by the technological achievements in Denmark. This was the case of Germany which re-oriented the technology policy to replicate the conditions of success of the Danish wind turbines. German manufacturers start to focus on smaller 3-blades turbines and benefited from the contacts with Danish companies for transfer of knowledge (Neij and Anderson, 2013). Another case was Spain which took advantage from the joint venture established between the local turbines manufacturer, Gamesa, and the most important Danish manufacturer, Vestas, to start producing the latter's technology under license for the domestic market (Lewis and Wiser, 2007). Meanwhile, Germany and Spain introduced investment and production incentives to promote market formation (Jacobsson and Lauber, 2006; del Río and Gual, 2007). The former set up a feed-in law paid by the electricity utilities to wind energy producers in 1990, while the later approved a similar law four years later.

Technology improvements in core countries opened a "window of opportunity" for the development of wind power in Portugal. The success of diffusion in Denmark, Germany and Spain, *influenced the direction of search* that lead to the entry of main actors into the sector. The first wind farms were installed in 1996/97 by Enernova (the EDP affiliate). This prepared the conditions for the intense growth of capacity installations that followed after the turn to the new millennium.

The interest on wind power was strongly influenced by the obligations signed in the Kyoto Protocol and the subsequent European Directive for Renewable Energy (2001/77/EC), which required Portugal to meet the target of 39% (later revised to 45%) of its gross national electricity consumption with renewable energy sources by 2010. In 2000, the share of renewable energy in electricity production was 25%, almost exclusively from hydropower which had a limited potential of growth because of the difficulty to construct new large dams.[11] By that time, wind energy had become a more mature technology and offered a credible alternative to invest in renewable energy. Hence, the Portuguese government launches the E4 program (Energy Efficiency and Endogenous Energies), which preceded the publication of a series of laws and the introduction of several incentives between 2001 and 2003 (Table 2).

b) Legitimation and institutional alignment

The maturity of the technology and the need to invest in renewable energy was crucial for the legitimation of wind power. This created the conditions for the fixation of targets for capacity growth and institutional alignment with the implementation of a favorable regulation.

Inspired by the success of wind power in other countries, in particular Spain, the Portuguese government sets up ambitious targets for capacity installation (Fig. 6). In 2003, the country plans to install 3,750 MW by 2010, raising this objective to 4,500 MW in 2006. More ambitious goals were set in 2010 when the government aimed to increase wind capacity to 8,500 MW by 2020. However, the financial crisis obliged the executive to lower its expectations to a more realistic 5,300 MW.[12] The definition of targets was decisive to create expectations about the development of the sector and about profit opportunities that encouraged the entry of newcomers and, thus, the growth of the innovation system.

[11] Shares of energy sources estimated from the DGEG online database available at http://www.dgeg.pt/ under the title "Produção / Consumos (1994-2011)", last accessed in October 3, 2013.

[12] Cf. Plano Nacional de Acção para as Energias Renováveis (PNAER 2012) published by the Resolução do Conselho de Ministros n.º 20/2013, April 10. This goal may be reviewed in the next years and more capacity can be installed depending on the financial situation of the country.

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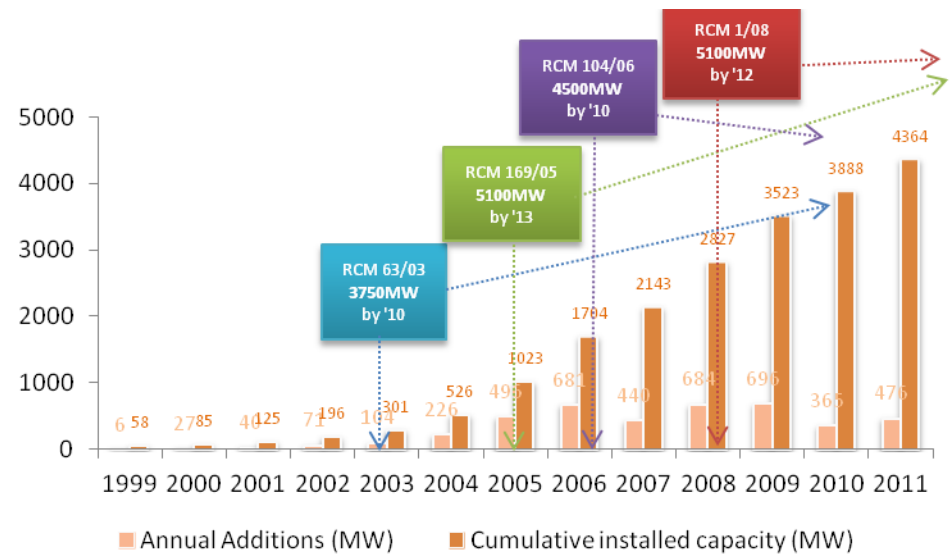
Figure 6. Cumulative and annual installed capacity of wind energy and official goals (in megawatts)



Source: DGEG, 2013

The *legitimation* of wind energy was also important for the institutional alignment with the needs of technology, which took the form of market regulations (e.g. the connection to the grid) and support mechanisms. A new "feed-in" tariff (FIT) was introduced in 2001 (Decree-Law n°339-C/2001) that substantially increased the remuneration for producers, encouraging the investment in wind power (Fig. 7). It was equally established that 2.5% of cash flows must be paid to the municipalities where wind farms are located. This decision was effective in lowering local resistance to the installation of turbines and in reinforcing legitimation (Delicado et al., 2013; Matos, 2013).[13] The FIT was revised in several occasions in 2005, 2008 and 2013, limiting both the value and duration. In 2005, for instance, new changes restricted the application of the FIT to the first 33 GWh produced per MW installed or 15 years, whatever is reached first (DL no. 33-A/2005). Nevertheless, the average tariff paid remained stable and high, as a large part of the installed capacity was approved under the more attractive tariff (Fig. 2).[14]

[13] Despite of fact that the Portuguese public opinion has been one of the less supportive of renewable energy among the European countries according to the Eurobarometer (cf. Delicado et al., 2013).
[14] Currently, the wind farms licensed after 2005 get € 74/ MWh, whereas projects contracted before 2005 receive around €85-€ 94/MWh (IRENA-GWEC, 2013; GWEC, 2013b; Ferreira and Araújo, 2007). However, one-half of total wind generation is still receiving the more generous tariff (Peña, 2013; IEA, 2009).

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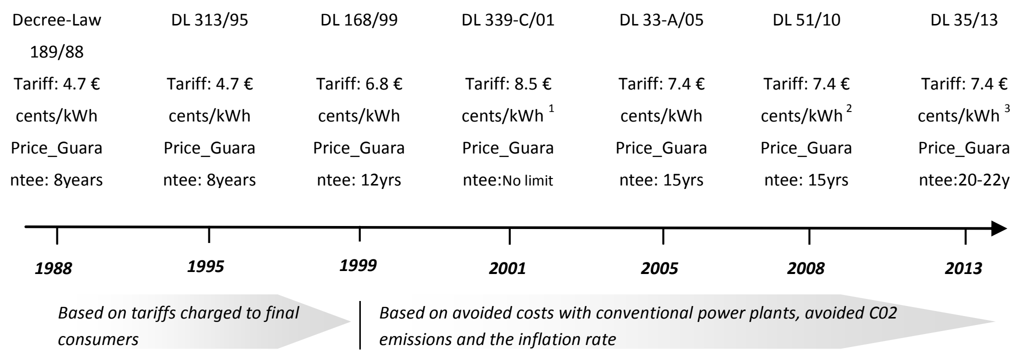
Figure 7. Evolution of the legal framework on wind energy feed-in tariff



Assumption: 12 MW wind farm, producing in average 2,640 hours equivalent per year. The values represent the feed-in tariffs that would be expectable with wind conditions in April 2005, according to the Decree-law in force.
([1]) Tariffs by output blocks: first 2,000 hours: 9.1 € cents/kWh; 2,000-2,200h: 7.8 € cents/kWh; 2,200-2,400h: 6.6 € cents/kWh; 2,400-2,600h: 5.6 € cents/kWh; beyond 2,600h: 4.7 € cents/kWh.
([2]) This DL allows the installation of 20% more capacity, in return for a reduction on the feed-in tariff proportional to the power increase up to 2.4%.
([3]) Wind independent power producers can extend the feed-in tariff period by five or seven years upon the payment of an annual compensation of 5,000 €/MW or 5,800 €/MW, respectively. In the first case, the feed-in tariff is extended by five more years and they can select either a tariff between 74 - 98 €/MWh or a guaranteed minimum of 60 €/MWh, starting 2020. In the second case, the additional period extends for seven years maintaining the alternatives as in the previous case.

Adapted from Ferreira and Araújo, 2007. Other source: Peña, 2013.

c) Market formation

The tariff approved in 2001 sparked hard *market formation* for wind in Portugal. In fact, the new attractive remuneration for wind power was followed by a strong interest in the technology (Fig. 6). The DGE (Directorate General of Energy) received applications for 7,000 MW of new wind capacity at the beginning of 2002, after the publication of the law (IEA, 2003). Also, the size of the turbines installed in Portugal was rapidly scaling up to 1.8 MW in 2002 and 3 MW in 2003. These two factors strongly contributed to a jump in total installed capacity, from 125 MW in 2001 to 1,023 MW at the end of 2005. The diffusion accelerated after 2004 with the installation of 500 MW per year in average until 2010 - despite the raising costs of investment. Consequently, the part of wind in total electricity consumption passed from 2% in 2002 to 19% in 2012 (DGEG, 2013). This is almost an order of magnitude increase within a decade, which shows clearly the transformation that wind energy operated in the Portuguese electric system.
In summary, this case demonstrates how institutional alignment with the needs of the innovation can trigger the development of a large market for a new technology.

d) Resource mobilization

Capital became more available for *financing* the development of new farms as the market for wind energy developed. This was reinforced by government incentives that were implemented in order to promote investments. Before 2005, the major investment support came from

"Incentive Scheme for Rational Use of Energy" (SIURE) and the "Measure of Support to Energy Potential and Rationalization" (MAPE) (DL. 70B/2000), in the framework of the PRIME operational program, which provided grants for new installations. These schemes were managed by the Ministry of Industry and Energy and the funds were partly supported by the European Union under the Country Framework Programme (QCA III) (IRENA-GWEC, 2012).

Since 2005, the government decided to organize auctions for the attribution of connection rights to new wind power stations, which were tied with requirement for local equipment production. A public tender for the allocation of 1,800 MW was released in three phases in 2005. The largest phase (A) of 1,200 MW was won by the consortium Eolicas de Portugal (ENEOP) led by the utility EDP in alliance with a foreign industrial partner (Enercon). This project involved the creation of an industrial cluster with a total budget of € 1.750 million (Martins et al., 2011). The economic crisis delayed the implementation of the wind farms: the capacity contracted only begun deployment in 2008 and is expected to be concluded in 2014; and, in 2011, the installation of new farms was stopped and production had to be re-orientated to exports (initially projected to start in 2013) with more than 60% of turbines produced being shipped abroad (Público, 2011). The second largest phase (B) of 500 MW was won by the consortium Ventivest, formed by the energy company Galp, the engineering company Martifer and the foreign manufacturer REpower – in which Martifer owned an important share of the capital. However, difficulties in access to finance as a consequence of the economic crisis affected the rhythm of installation of phases (B) and (C).[15] [16]

e) Development of positive externalities and co-evolution of the institutional design

The attractive remuneration and the subsequent market growth had implications for the development of other functions of innovation system. It significantly influenced the *guidance of search* and the entry of new supply-side actors from several connected activities (e.g. construction, metallurgy and engineering industry). In the same way, the development of the market contributed to the formation of *networks and externalities*. The public tender organized in 2005 spurred the creation of an industrial cluster of wind technologies, materialized in the setting-up of blades, towers and turbines factories located in Viana do Castelo and Vagos. The development of the cluster benefitted from the presence of strong metalomechanics, construction and electronics sectors, with qualified engineers and specialized workers. It also

[15] The reference tariffs for the three phases A, B and C of the tender was € 73/MWh under the DL no. 33-A/2005. However, the winner projects of phase A and B gave discounts of 5% and in the case of the several small projects that won phase C the discount reached a maximum of 23% (i.e. a bid of € 57/MWh). See: IRENA-GWEC, 2013; GWEC, 2013.

[16] Until mid-2013, for instance, Ventivest had only one wind farm in operation of the eight attributed in the auction (Público, 2013).

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contributed to the revitalization of depressed areas, creating new jobs in regions where some traditional industries were in decline. This had an important role in the local *legitimation* of the emerging system besides.

The incentives and support mechanisms were an important factor for the development of the sector in Portugal, which in turn strengthened its political influence as new players entered the field. The multiple (upward) revisions of the targets (see Fig. 6) are indicator of the increasing political strength of the coallition formed by the key TIS actors. Moreover, the connections with the political sphere intensified, with some cases of "revolving door". For instance a former Minister for the Economy (Luís Braga da Cruz, 2001/02) assumed the presidency of the board of Enernova (2002/05) after having implemented the FIT - turning wind business into a "safe bet"[17]. One of the key responsibles for the elaboration of the National Strategy for Energy (ENE 2010) (João Talone, 2003) become subsequently CEO of the historical incumbent EDP in 2003 and later CEO of Iberwind, the second largest promoter and operator of wind farms in Portugal. He was followed in EDP, in 2006, by a former Minister of Public Works, Transport and Communications (António Mexia, 2004/05). Before getting into the government both politicians had passed in the largest private banks BCP and BES, the latter being the second largest shareholder of Iberwind.[18]

The creation of rents was ineluctable with total funding provided by the government amounting approximately €3.6 billion up to 2010 ($2012 values) (Peña, 2013). This contributed to increase final residential electricity prices and led to a national electricity system's deficit of over € 2 million, thereby raising the opposition to wind power in the media (Delicado et al., 2013). In 2013, a new legislation was approved that pushes to 2020 the end of the "special regime" and thus, the transition of wind energy production into the liberalized market. It also gives renewable energy producers the possibility to receive the guaranteed tariff for an additional period of 5 or 7 years, in exchange for the payment of an annual compensation for the reduction of the tariff deficit. Nonetheless, the benefits for the electricity system in terms of deficit reduction may be crowded out by the extra payments generated through the extension of the FIT period.[19]

[17] We thank Frank Geels and the participants of the IST 2013 conference in Zurich for drawing our attention to this point.
[18] For more details in the relations between former political leaders and energy companies, see Bianchi and Viana (2012).
[19] Peña (2013) estimated between €0 and €12 per MWh ($0-$16 per MWh) the net present value of those extra payments. For instance, a 3MW wind turbine working 2,000 hours per year generates 6,000 MWh/year at €74 ($100) per MWh gives a revenue of €444,000 ($600,000). This number compares with the annual payment for compensation of the tariff deficit of €5,000 ($6,700) per MW (5 years of extension) or €15,000 ($20,100) per turbine, between 2013 and 2020. The total compensation paid during these eight years amounts to €120,000 ($160,800) which is roughly a quarter of the revenue guaranteed per year.

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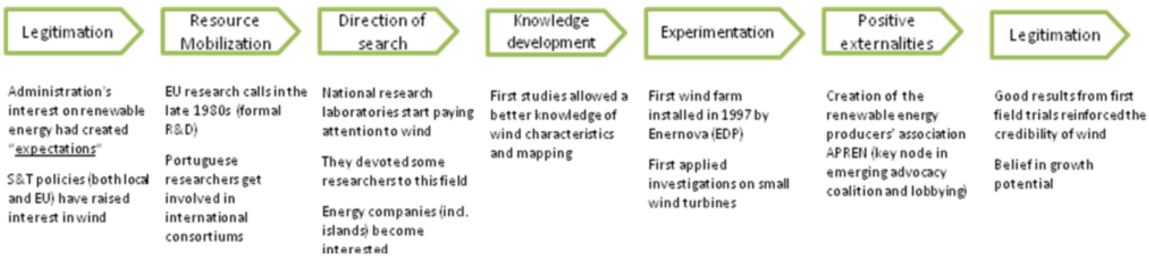
4.2.3 Synthesis of the role of the functions in the emergence and growth of the local TIS

This last point summarizes the processes that contributed to the spatial diffusion of wind power and the formation of a local technological innovation system. It particularly highlights the fulfillment of the functions of innovation system and the interactions established between them as the innovation system emerges and grows.

Previous researches on the formation of energy technology innovation systems in the past (e.g., wind, solar, biomass) have shown three important features of change. Firstly, they revealed a small number of functions particularly relevant for sparking system dynamics. Hekkert et al. (2009) highlights the value of “legitimacy”, “influence on the direction of search” and “market formation”. The authors argue that the first one helps to align institutions to the need of agents and technologies, whereas the second and the third ones are important for raising entrepreneurial activities. Secondly, key system functions are likely to change over the process with knowledge development and direction of search being crucial in the earliest formative period, whereas market formation become important in a more advanced stage of the TIS formation. Thirdly, interactions between functions may lead to “virtuous cycles” that accelerate system emergence and growth (Hekkert et al., 2009). This is likely to happen later in the formative phase when more functions are fulfilled, leading to stronger internal dynamics and to system growth.

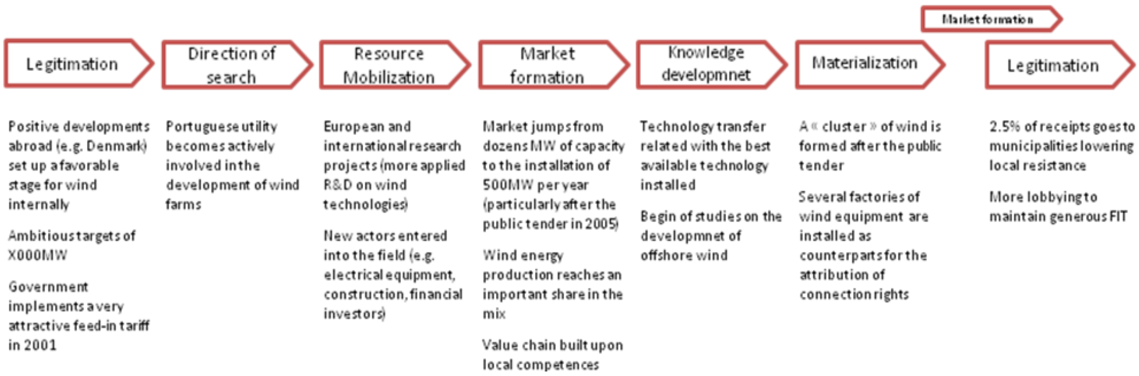
Two periods can be distinguished in the development of wind power in Portugal: the “exploratory” and formative stage; and the implementation stage. The former begins with the exploratory activities in the 1980s and goes on until the installation of the first wind farm, while the latter comprises the up-scaling phase of turbines between 1996 and 2003, and the capacity growth that followed.

Figure 8. « Exploratory » and formative stage of wind energy in Portugal



The “trigger” for the exploratory stage of wind technology in Portugal were conventional science and technology policies, both at national and European levels (Fig. 8). On the one hand, the government’s interest on renewable energies after the oil shocks created “expectations” about the development of alternatives that *influenced the direction of search*. On the other hand, the country joins the European Community at the moment when EC programmes provide *resources* for R&D and demonstration projects on wind energy, which began to displace nationally funded projects (Hendry and Harborne, 2011). Portuguese researchers, mainly from national laboratories and universities, get involved in international projects on the physical mapping of wind profiles and resources already in the 1980s. This contributed to increase the productivity of turbines as well as to form local knowledge on wind modeling and wind technologies. At the same time, the *experimentation* of several imported small wind turbines, particularly in the islands, generated applied knowledge that was helpful in the installation of the first wind farm by Enernova in 1997. The creation of the renewable energy producers' association (i.e. APREN) in 1988 was the key point in the emergence of an advocacy coalition. It had many *positive externalities* for wind growth in the early years, in particular for the implementation of the wind support schemes. The good results from the first trials reinforced the credibility of wind as an alternative to incumbent technologies. Meanwhile, a community of actors was formed (e.g. universities, national laboratories, firms) that contributed to *legitimate* wind power and disseminate the belief in its growth potential.

Figure 9. "Implementation" stage of wind energy in Portugal



The innovation system enters into a new stage of implementation in late 1990s (Fig. 9). The development of commercially viable multi-MW turbines and the successful market diffusion in core countries, such as Denmark and Germany, have set a favorable context for wind energy growth internally. The obligations imposed by the European Directive on Renewable Energies opened a "window of opportunity" to invest in wind energy. These factors worked together to *legitimate* wind energy and helped to align institutions to the need of the emerging innovation system. The government setting-up of a new tariff, in 2001, *influenced the direction of search* of main actors, starting with the energy utility. It also attracted new investors (e.g., private

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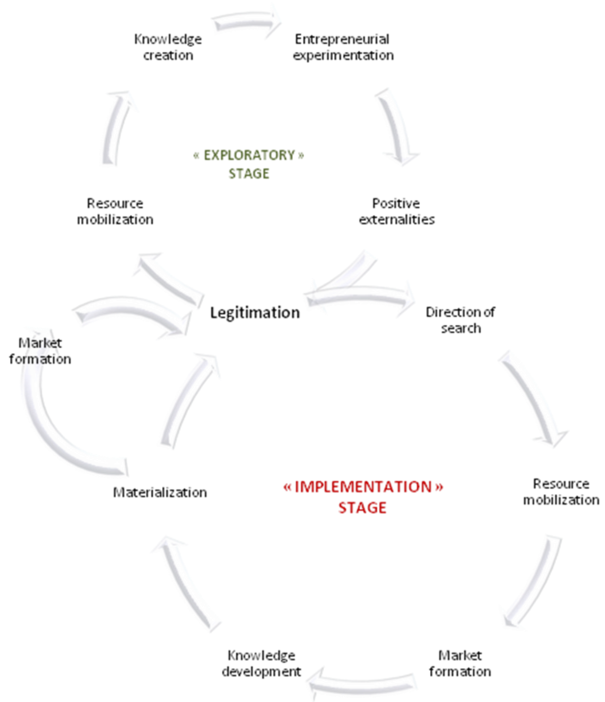
financers, financial institutions, engineering industries and electrical equipment companies) who brought more *resources* to the TIS in the form of capital or complementary knowledge. That decision was critical for the development of wind energy in Portugal as it enable hard *market formation*. During the next years, total installed capacity jumps from dozens to thousands MW. Good remuneration of production and high land costs contributed to the adoption of large, multi-MW turbines (IEA, 2003). Technology transfer was possible thanks to the establishment of joint-ventures between the incumbent and engineering companies with international equipment manufacturers, allowing the *development of local knowledge* on wind technologies. The public tender has also brought a series of investments in the emerging "cluster" based on wind technologies. It *materializes* in several factories of blades, towers and turbines to equip the new wind farms and increase exports. This reinforced the general positive perception concerning wind power, which has globally showed low resistance to the installation of turbines mainly thanks to the requirement that obliges producers to pay 2.5% of the revenues to the local municipality. As more and more capacity is added and the best sites onshore are exploited, the focus of the research starts to shift towards the development of the offshore potential. More recently, the financial crisis raised questions about the *legitimacy* of the rents in the sector; generators are nowadays actively involved in lobbying activities to preserve their benefits.

Hence, the development of wind energy in Portugal showed the importance of science & technology policy as an initial "motor" of change (Hekkert et al., 2007, 2009) by fulfilling sequentially other functions of the innovation system, such as: the direction of search, resource mobilization (e.g. R&D), knowledge development, experimentation and legitimation. The latter is of upmost importance, especially in the early years of innovation adoption, in order to shape expectations and increase the social acceptance of the innovation as a credible substitute for the incumbent technology. In other words, it is the "politics of shaping expectations and of defining desirability" (Bergek et al., 2008b). Legitimacy is necessary for the formation of protected market spaces – i.e. niches - which are crucial for the emergence of "packs of entrepreneurs" that contribute to increase experience and trust in the technology, as well as advocacy coalitions (Kemp et al, 1998; Bergek et al., 2008b). In Portugal, the EC projects had a decisive role to enable the first contact with technology developments abroad; later on, technology maturity and previous positive experiences helped entrepreneurs to deal with the formation of expectations and visions about wind power. The development of the sector reinforced the political influence of actors and networks which played an important role to preserve the incentives and targets for wind energy even when the prices of the technology were increasing.

The sequential order presented in Figures 9-10 highlights the most important links established between the functions during the formation and implementation phase of wind in

Portugal. Nevertheless, this process has happened in a less linear way than suggested in the previous figures. The reality was much more complex with functions being fulfilled simultaneously (e.g. influence in the direction of search and legitimation raising expectations) and with feedbacks back and forward (e.g. turbine experimentation enlarging the knowledge base, materialization of investments in equipment plants allowing further markets formation). Figure 10 gives a more systematical account of the emergence of the innovation system in Portugal by stage of development.

Figure 10. Interactions between functions of innovation system in the exploratory and implementation stages of wind power in Portugal



4.3 Spatial diffusion and local absorptive capacity

The analysis turns now to the geographical issues related with technology diffusion. The first section examines the patterns of spatial diffusion observed in wind technologies by comparing the growth in a lead ("core") country and in a fast follower. The second section investigates the channels through which wind technology was transferred, in order to discuss possible strategies that may speed up the international dissemination of new low-carbon innovations.

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4.3.1 Comparing the patterns of wind diffusion across countries

This section analyzes the spatial diffusion of wind power by comparing the growth in a well-known lead country in the field (Denmark or "DK"), and a recognizable fast follower (Portugal or "PT"). The analysis looks particularly at the scaling dynamics observed in these two countries.

The importance of scaling in the historical diffusion of energy technologies has been widely demonstrated in Wilson (2012, 2009) and Wilson and Grubler (2011). Firstly, it has been shown that the speed of diffusion is influenced by market size so that innovations with a higher potential should take longer to diffuse. Secondly, previous researches have revealed that growth rates typically evolve in a three-phase sequential process (cf. Wilson, 2012): formative phase, unit scaling and growth phase. During the formative phase, the structure and functions of the innovation system emerge in order to prepare for the up-scaling stage that is needed before large-scale diffusion becomes possible. Wilson (2012, p.89) suggests that this period "runs from first commercial application to the point at which new units reach 10% of the eventual maximum unit scale". Thirdly, the analysis of international patterns of diffusion pointed to the acceleration of growth rates as innovation penetrates into new areas (Bento, 2013; Wilson, 2012; Grubler, 1998). In other words, the rhythm of penetration becomes faster as the new technology transits from initial to subsequent markets. As pointed out above, this may be explained by the fact that new technologies (get out from the core and) start to diffuse abroad when they become sufficiently mature. Therefore, adoption is faster in the subsequent markets because they benefit from the investments previously made by the lead countries in the development and early deployment of the technology.

The dynamics of growth of wind power in Denmark and Portugal are shown in Figure 11. The sequencing of unit and industry scaling is faster in the follower country (PT) than it is in the Core (DK). Comparing the three-stages of growth in the two countries: the «formative phase » is much longer in the Core than in the follower, because of the need of experimenting with more units in the former; the « unit scaling » is much more rapid in the follower, which presents a faster growth in the size of average and maximum unit additions; and, finally, the « growth phase» reaches saturation more rapidly in the follower (steeper slope of the light blue curve) than in the Core. In all, the steeper curves in the case of Portugal indicate the acceleration of growth once technology leaves the core market.

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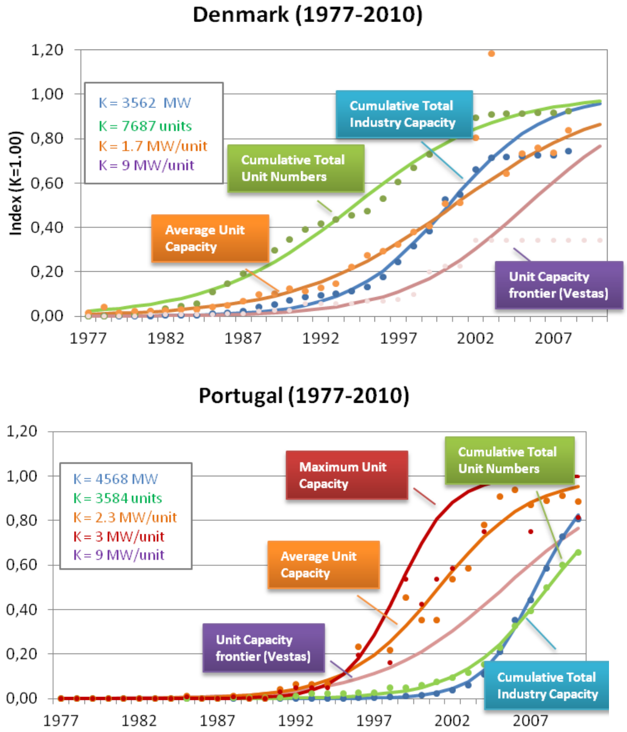
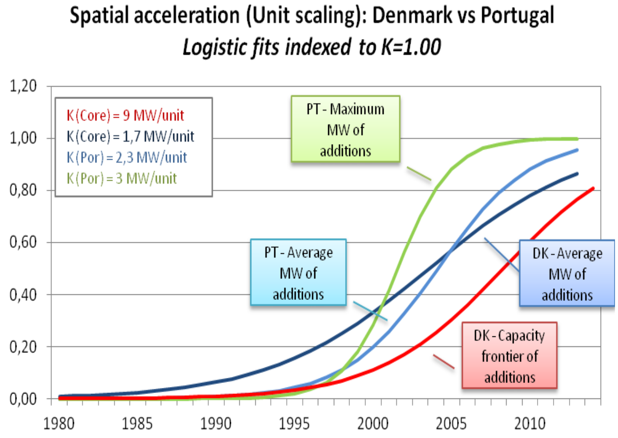
Figure 11. Unit and industry scaling: known data (dots) and logistic fits (lines) indexed to K=1.00

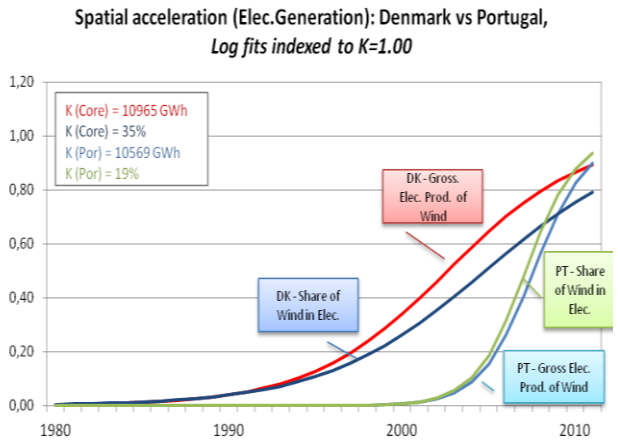


Source: DGEG, 2013; Spliid, 2013.

A more detailed analysis of turbines scaling and growth of wind electricity production in these two countries gives further information about the spatial diffusion of wind power (Fig. 12). The top graph compares the evolution of average and maximum (or capacity frontier for DK) unit additions in the Core (DK) and in Portugal. The graph reveals that growth was again much more rapid (steeper curves) in the second than in the first, showing clearer the acceleration of unit scaling in the next market. The diffusion of larger size turbines was quicker in the follower because much of the technical problems had been previously solved in the Core, i.e. due to the existence of knowledge spillovers - we come back to this in the next point.

Figure 12. Comparing unit scaling (top) and the share of wind in the electricity mix (bottom) in Denmark and Portugal, logistic fits only





Source: DGEG, 2013; Danish Energy Agency, 2013.

The second graph (Fig. 12, bottom) shows how capacity growth translates into higher electricity production. The figure presents the increase in gross electricity production from wind (in GWh) as well as the progress of its share in the overall electricity mix. Both indicators follow a close path, particularly in Portugal. In this case, wind production takes off well within the 2000s – thus with a great delay as compared with its beginning in the late 1980s in Denmark - and a few years later than unit scaling. The evolution is particularly fast when compared with the trend of average unit additions (i.e a growth rate or "ΔT" of 13 years vs. 6 years for the increase of the share of wind). Nevertheless, the share of wind power in the electricity-mix is larger in Denmark: it is currently 28% and can potentially reach 35% if the present trend continues in the next decades. These figures compare to 18% and 19%, respectively, for Portugal. Still, the growth potential falls shorter of the 2020 target in both countries (i.e. 50% for Denmark and

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23% for Portugal). This means that action must be taken (e.g. policy, electricity demand) to alter existing trends, in order to meet the objectives for the share of wind in electricity production.

In summary, the evidence surveyed for wind power in Denmark and Portugal confirms our initial hypothesis, according to which growth accelerates when the technology moves over from the Core and reaches new markets. The data also corroborates that diffusion starts in other regions when the new technology is sufficiently mature in the Core. The next point discusses the mechanisms that contribute to accelerate growth in subsequent markets.

4.3.2 Mechanisms of spatial diffusion: knowledge spillovers and absorptive capacity

What are the main processes that accelerate growth as the innovation gets out from the core market and starts diffusing in new markets? This phenomenon may have *internal* and *external* causes, which are connected with the context where the innovation takes place.

The existence of external *knowledge spillovers* from the diffusion in the core is a major factor for growth acceleration in the subsequent markets. Other regions benefit from external knowledge and technology spillovers created during the early innovation stages in the leader country (Jaffe, 2005). Technology starts to develop abroad when it is more mature and a significant part of the learning costs have already been supported by the pioneer markets (Nemet, 2009). In fact, wind power only takes off in Portugal in the beginning of the years 2000s, when turbines had already scaled up to 3-MW and diffusion is well into the growth phase in the core.

The typical channels for international technology transfer after the post-war have been capital imports, foreign direct investment (FDI) and licensing (Mowery and Oxley, 1995). Keller (2010) particularly emphasizes the role of international trade and FDI in the capture of technology spillovers. The follower countries can, on the one hand, accelerate the speed of adoption by importing the new technology from the core (Davies, 1977) and, on the other hand, strengthen local capacity to exploit spillovers thanks to the physical presence of international companies (Keller, 2010, Mowery et al., 1996).

The main technologies that needed to be imported were turbines and blades, while towers and other ancillary equipment could rely on local competences in methalomechanics, electronics and construction. The development of wind power in Portugal benefited since the beginning from the import of best available technologies, i.e., multi-MW turbine models.[20] Further technology transfer occurred when international manufacturers entered in joint ventures with local companies to invest in the local production of turbines and blades as required by the

[20] For many reasons, such as the high cost of the land or the attractive feed-in tariff (IEA, 2003).

public tender for the attribution of connection rights. This was the case of Enercon, which set-up new production facilities in Portugal, namely to supply the wind farms being installed through its consortium with EDP (Eneop), and that of the joint-venture established between REpower and the engineering company Martifer, that also involved local manufacture of some equipment. Towers and other ancillary equipment were provided by local firms, since the early stages.

However, the effective diffusion of the imported technology requires the recipient country to have the capacity to absorb and assimilate the new technologies (Mowery and Oxley, 1995; Teixeira and Fortuna, 2010). That is, a number of internal factors – technological, organizational and institutional - are required to create and reinforce *local absorptive capacity*, enabling the country to take the maximum benefit from the imported technology (Fagerberg and Godinho, 2006). In the case of the adoption of wind power in Portugal, the reinforcement of the absorptive capacity took three different forms.

Firstly, the participation in international R&D projects contributed for the formation of knowledge in the early years which reinforced the absorptive capacity, enabling a more rapid technology transfer and growth of wind power. As pointed out above, after the 1980s, national research laboratories (e.g., INEGI, INETI) were implicated in several European projects about the physical mapping of wind profiles and resources. This participation was decisive to form a local knowledge base on wind modeling and evaluation, which proved useful later on, when the market took off. In fact, the diffusion of wind power has unfolded almost without the need to hire any international consultant (Matos, 2013). The Portuguese case corroborates the theory which suggests that by collaborating in basic R&D activities, organizations (and ultimately countries) can improve the rate technology transfer and effectiveness in its use (Fabrizio, 2009).

Secondly, the development of the value chain was important to support the implementation of the technology. It drew on local engineering and industrial competences in non core technologies (i.e., beyond wind turbines) such as tower technologies and electrical components. As a matter of fact, national incorporation was relatively high since the beginning of hard market formation. Almost all towers, as well as transformers and other electrical equipment, were built in Portugal (Wind Directions, 2004). In addition, the emergence of the wind innovation system benefited from available knowledge on hydroelectric power and the conversion of activities from declining sectors (e.g., shipbuilding). The sharing of elements with other innovation systems enlarged the knowledge and resources at the disposal of the new innovation system, contributing to raise the social consensus around wind power.

Thirdly, the establishment of strategic alliances with foreign companies allowed to overcome weaknesses in indigenous technical capacity regarding the core technologies and fostered knowledge transfer (Mowery et al., 1996; Lewis and Wiser, 2007). The joint ventures

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established between international turbine manufacturers, such as Enercon and REpower, and local promoters (e.g. EDP, Galp, Martifer) enabled the access to state of art technology and the creation of a competitive industrial cluster. These alliances were established in reaction to the public tender organized in 2005, which required the bidders to produce equipments for wind farms locally, in exchange for the right to connect new capacity and to receive the regulated tariff (Martins et al., 2011). The tendering process provided enough stability and perspectives of domestic market growth to encourage global actors to delocalize full turbine manufacturing plants (Lewis and Wiser, 2007; Jenner et al., 2013). Therefore this scheme was successful in creating collective resources and ensuring that some benefits (i.e. value-added creation, jobs) reverted to the country.

In short, the story of the development of wind power in Portugal reveals how important are knowledge spillovers from the previous diffusion in the core as well as local capacity to capture those effects in order to implement rapidly the new technology. These two channels should be made clearer in future revisions of the content of functions of innovation systems. Similarly the interactions with other TIS, which in this case clearly helped to fulfill the functions accelerating the emergence of the innovation system, may be subject to more studies.

5. CONCLUSIONS

The international diffusion of energy technologies and the formation of institutional capacity in the receiving country were studied through the comparison of the growth of wind energy in Denmark (core) and Portugal (fast follower). The very short delay with which wind technologies were adopted in Portugal relatively to the leader and the scope of market penetration make this an interesting case of study, which may highlight the factors that contribute to a rapid spatial diffusion. It was found that diffusion accelerates when it transits from the core to the follower country. The new technology enters the latter when it has already up-scaled and is in the growth stage in the former. The main mechanism for technology transfer during the early years of market formation was imports of state-of-the-art equipments, which allowed the very rapid scaling of turbines, boosting the penetration of wind energy in the follower. Knowledge spillovers from the previous development of wind power in the core and a more mature technology have enabled the acceleration of spatial diffusion. However, this was only possible thanks to institutional and organizational changes in the receiving country which have supported growth.

The development of wind energy in Portugal showed the importance of science & technology policy, which was an initial "motor" of change (Hekkert et al., 2007, 2009) and also fulfilled sequentially other functions of the innovation system, such as the direction of search, resource mobilization (e.g. R&D), knowledge development, and experimentation. This raised confidence in the technology and established legitimacy, helping to align institutions with the needs of the emerging local innovation system. In a more advanced stage, the regulatory change was decisive to allow the take off of the market by creating expectations and attracting new actors. The dynamics of growth accelerated also thanks to the capacity of actors and networks to influence policy making. The new tariff fueled the penetration of wind power in the market, even though the prices of the turbines were increasing internationally. But it also generated rents for the producers which enlarged the deficit of the public electricity system, leading to the emergence of some hostility towards renewable energy producers. The fast development registered by the sector has nevertheless experienced a slowdown, given the current economic situation, which reduced significantly the investment opportunities in the local market, forcing some companies to search for foreign markets and/or diversify their activities. While some of them have been relatively successful in their foreign market expansion, they face a growing international competition which, combined with the shortage of local opportunities and with threat of future reduction in rents, raises some questions regarding the sustainability of the industry.

A couple of lessons can be drawn from this case which may contribute for technology policy design elsewhere - even though the efficacy of policies might change slightly depending on the country and the timing. The development of wind power took advantage of the assimilation of knowledge spillovers from abroad, through an improved local absorptive capacity. On the one hand, the diffusion of wind power benefited from the available competences in engineering and industrial activities. On the other hand, local companies had access to the best available technology through the establishment of strategic alliances with international turbine manufacturers for the installation of production factories in Portugal, which were essential in the process of formation of an industrial cluster. This was done in reaction to the new incentive scheme, based on public tenders for the attribution of connection rights and feed-in tariffs, which explicitly required the promoters to produce their equipments locally. Therefore the successful development of wind power in Portugal may give interesting insights to other follower countries aiming to adopt new energy innovations more rapidly.

The use of theories and concepts from the TIS literature to explain patterns of international technology diffusion has proven pertinent and has an enormous potential in future analyses. However, some improvements can be made in order to enhance the explanatory power of the theoretical framework in relation to spatial diffusion. We see at least two possible refinements. Firstly, by highlighting the most relevant functions in each stage of development of

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the innovation system in the follower country. In the case under analysis, the formative period allowed the fulfillment of functions that strengthened the absorptive capacity (e.g., knowledge creation, experimentation). This enhanced the exploitation of technology spillovers and the completion of other functions of innovation systems (e.g., resource mobilization, legitimation, market formation) during the more advanced stage of implementation. Secondly, by better integrating in the (functional) analysis some capacity-building activities (e.g. education and research expenses) that are likely to improve the absorptive capacity of new technological systems. This point may lead to reconsider the relationships between the TIS and competing TISs, as well as the links with the literature on national innovation systems and sectoral innovation systems in terms of assets creation at a more regional and local levels.

SUPPLEMENTARY MATERIAL

The spreadsheets containing the data series and all the analysis can be found at:
http://dinamiacet.iscte-iul.pt/wp-content/uploads/2013/11/Public-data-wind.xlsx

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