Technological Forecasting & Social Change xxx (2015) xxx–xxx

Contents lists available at ScienceDirect

Technological Forecasting & Social Change

The capacity for adopting energy innovations in Portugal: Historical evidence and perspectives for the future

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ARTICLE INFO

Article history:
Received 14 May 2014
Received in revised form 14 July 2015
Accepted 1 September 2015
Available online xxxx

Keywords:
Diffusion
Technological innovation systems
Up-scaling
Energy technologies
Portugal

ABSTRACT

This paper investigates the speed of adoption of energy technologies in a traditionally innovation importing country, Portugal, as compared with countries where these technologies first started. Data were collected on the growth of eight energy-related technologies, both energy supply (e.g. natural gas plants, wind turbines) and end-use (e.g., motorcycles). The analysis is done in terms of the evolution of the number of units and installed capacity, indicating possible scale effects. The results show an average adoption lag of one to two decades relatively to "Core" countries. However, the growth rate increases when a technology arrives at Portugal, confirming the hypothesis that adoption accelerates when technology reaches new markets. Additionally, the duration of diffusion in Portugal is less constrained by the final scale of diffusion, contrasting with previous observations for the Core. The data also uncover the successful diffusion of wind energy in Portugal, showing that growth took off less than a decade after the diffusion in the Core, and achieving similar levels of intensity. The analysis suggests that this was supported by the improvement in the adoption capacity, associated with the development of a wind energy innovation system. These findings open new perspectives for the spatial diffusion of sustainable innovations.

1. Introduction

The deployment of new energy technologies in large scale is needed in the next decades in order to overcome current societal challenges (e.g. environmental problems, security of supply) (IPCC, 2014). Historical experience reveals that the emergence and diffusion of energy technologies are slow and marked by a series of barriers (Grubler et al., 2012; Grubler, 2012; Fouquet, 2012). One of the reasons for this slowness is the extent of institutional and organizational changes that are often necessary for the emergence and dissemination of a new technology (Bergek et al., 2008; Jacobsson; Bergek, 2011). However, the analysis of international patterns of technology diffusion shows an acceleration of growth as the technology moves from pioneer countries and reaches new regions (Grubler, 2012, 1998; Bento, 2013). A possible explanation for this empirical regularity is the presence of externalities (i.e., "spillovers") from the technology development in pioneer countries, which supports its faster dissemination in subsequent markets (Jaffe, 2005; Perkins and Neumayer, 2005). The positioning of each country in the sequence of international diffusion depends on internal conditions, including the ability to absorb and use new technologies (Cohen and Levinthal, 1989, 1990).

The adoption of foreign technology is a key element in the convergence of the less developed economies with more advanced countries (Fagerberg and Godinho, 2008; Godinho, 1995). The notion of "latecomer advantage" has been put forward to explain the technological dynamism of less advanced countries over more developed ones (Gerschenkron, 1962). It is argued that the technological backwardness of the former allows them to absorb the most recent innovations developed in the latter, without having to bear the high initial costs of development (Perkins and Neumayer, 2005). In addition, they are not encumbered by the so-called vintage capital, which is known to be a factor that delays the transition to new technologies in pioneer countries, by creating stranded costs due to the previous investments in human capital and infrastructure (Unruh, 2000; Clark and Wrigley, 1997; Frankel, 1955). This line of reasoning can explain why the transition to new energy systems tends to take less time in follower countries, which benefit from both the experience gained from the diffusion in pioneer countries and a cheaper technology (Grubler, 2012). Wilson (2009) shows evidence of the acceleration of diffusion in late adopters for several energy supply and end-use technologies. The marketing and management literature also finds the same effect of faster diffusion in countries that adopt a given product innovation later, what has been called the "lead-lag effect" (see a review in Peres et al., 2010).

Portugal is an intermediate economy and a typical case of "follower" of technological changes initiated in the more advanced economies (Godinho, 2007; Godinho and Caraça, 1988). A few studies analyze the

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http://dx.doi.org/10.1016/j.techfore.2015.09.003

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recent evolution of innovative and institutional capacity in Portugal (e.g. Conceição and Heitor, 2005; Fagerberg and Godinho, 2008). In general economic terms, there is evidence of convergence (i.e. "catching up") with the most advanced economies, given the low initial levels of innovation as well as a growing dynamics in some areas (Lains and Silva, 2013; Lains, 2003). But, this process has been associated with a persistent deficit in the technological balance of payments, which can be seen as an indicator of investment in the adoption of foreign technology. This emphasizes the role of technology transfer[1] in the convergence process (Godinho, 2007, 1995). In fact, technology transfer, in its various forms (trade, foreign direct investment or licenses), is an instrument that allows absorbing knowledge spillovers from abroad (Keller, 2010). However, the conditions that permit to absorb eventual spillovers and how the evolution of these conditions relates to the rate of diffusion more recently are still poorly understood, particularly in the case of energy technologies.

It is therefore important to assess the pace at which energy technologies have historically diffused in new markets and understand the mechanisms at work in the cases in which such diffusion was faster. Portugal is chosen as the case study because of the spectacular progression that new renewable energy technologies knew lately. Instead of assuming that an eventual acceleration in the import and adoption of foreign technologies is an automatic result of technical progress (driven by some external influence), the article examines how technology characteristics affect the rate of diffusion and to what extent the diffusion is influenced by factors related to changes in the adoption context. The latter concerns particularly the role played by internal factors ("enablers") associated with changes in the country's institutional environment that improved the technological capacity to adopt more recent innovations such as wind power.

The paper starts by presenting the analytical framework that summarizes some lessons from the theoretical and empirical literature on the dynamics of innovation systems. Then it compares the adoption of energy technologies in Portugal with their diffusion in the countries where the technology was first developed, in terms of the timing of adoption, pace and scale. This approach not only provides a measure of the innovative performance of the energy sector, but also provides an empirical ground for discussion on the factors that accelerate technology adoption. The results of this analysis can contribute to inform the formulation of more empirically-based strategies to stimulate the diffusion of sustainable energy in follower contexts.

2. Technology formation in the core and the process of spatial diffusion: theoretical framework

2.1. Determinants of the rate of diffusion of technologies

Empirical research on the drivers of past technological transitions have identified a set of factors that influence the market penetration of new technologies and are likely to accelerate or delay their rate of diffusion (Grubler, 2012, 1998; Rogers, 2003): relative advantage, size of potential market, disruptiveness and existence of antecedent markets, technological complexity and infrastructure needs.

The relative advantage of a technology refers to the way it performs better a particular task, is more efficient or cheaper than rival technologies. The higher the relative advantage, the faster the market penetration (Fouquet, 2012). The size of the potential market (scale of diffusion) is another important factor, as high market penetration is likely to require more time to prepare the technology and organize the production (Wilson, 2012, 2009; Wilson and Grubler, 2011). The existence of antecedent markets determines the disruptiveness of the innovation. Technology disruptiveness can be assessed on the extent to which its diffusion depends on novel service provision, new supporting institutions or user practices (Rogers, 2003). The prior existence of a market and the nature of innovation — incremental or substitute vs. radical or rupture — imply different levels of uncertainty and therefore can introduce specific constraints in the rate of diffusion (Freeman and Perez, 1988).

The complexity of the technology, i.e. the extent to which its commercialization depends on challenging unit scaling or on the development of other technologies, also slows down the diffusion process (Grubler et al., 1999). For instance, the development of steam locomotives was only possible when more powerful steam engines became available in the 19th century (Rosenberg and Trajtenberg, 2004). Finally, the needs in terms of infrastructure may severely delay the market introduction and growth of a certain technology. This was the case of transportation systems, such as railways, or energy sources, such as natural gas, which took several decades to develop and reach the current extent (Geels, 2005).

The factors listed above may also impose contextual requirements that affect the duration of the diffusion process. For example, new environmental technologies that are not yet competitive are likely to have longer diffusion times, because of the need to create internal conditions, such as supportive regulatory frameworks or education and R&D investment. The more contextual points are discussed next.

2.2. Formative phase and mechanisms of spatial diffusion

The processes at action in the emergence of new technologies are addressed by two streams of literature. A more empirical approach that studies the regularities of technology diffusion and of systemic technological change (e.g. Grubler, 1998; Wilson, 2009; Wilson and Grubler, 2011a), and a more theoretical approach that examines the emergence and growth of technological innovation systems through the constitution of the structure and fulfillment of key innovative processes or functions (e.g. Markard et al., 2012; Bergek et al., 2008; Hekkert et al., 2007; Jacobsson and Lauber, 2006).

Recent empirical research analyzes the diffusion from the standpoint of the increase in the scale of production as well as the commercialization of even larger technologies (Wilson, 2012, 2009; Wilson and Grubler, 2011). Historical evidence has shown that the expansion of energy technologies depends on both factors and that the diffusion has evolved in a process of three sequential phases (cf. Wilson, 2012): the establishment of a productive base during the formative stage; upscaling at unit level; and the growth and generalization of the technology. Furthermore, the innovation was found to occur first in the central countries ("Core"), where it is developed and begins to be experimented in order to reach sufficient maturity for market commercialization, and then spills over to other geographic areas (Grubler, 1998, 2012).

The analyzes of international diffusion patterns suggest that diffusion accelerates as technology reaches new regions (Bento, 2013; Grubler, 2012; Wilson, 2009). This acceleration may reflect the existence of external effects ("spillovers") from earlier technology deployment in the Core (Jaffe, 2005; Cappelli et al., 2014). In fact, follower countries do not bear the original R&D costs, and can take advantage of the learning processes previously conducted by firms from the center, who have invested to improve performances and reduce costs — by increasing cumulative installed capacity when this was more expensive in order to advance in the "learning curve" (Perkins and Neumayer, 2005). This permits to solve the main technical problems and refine the technology, generating knowledge that is potentially available to other countries (except when protected by patents). Consequently, the access to cheaper and superior models boosts the rate of diffusion in

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[1] We follow the definition of international technology transfer proposed by Keller (2010) who considers technology as "knowledge required for production" and thus technology transfer as the deliberated movement of technological knowledge between different countries. Technology diffusion is only one element of this general movement. This concept refers to the impact of a new technology on the national level which is likely to be measured in quantitative terms (units or equivalent capacity, MW). The form taken by this transfer (FDI, acquisition or licensing) is important for the final result, but it is not the focus of our investigation.

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subsequent markets (cf. Section 2.1) — often to the detriment of developing an internal industry.

However, not every country benefits from external effects to the same extent. Local capacity to absorb innovations strongly determines the rate of technology adoption in a particular geographic area and *in fine* the position that this area occupies in the sequence of spatial diffusion. In particular, the existence and quality of local competencies are essential factors for the establishment of a critical mass capable of absorbing knowledge spillovers and adopting emerging technologies (Cohen and Levinthal, 1989, 1990).[2] Several case studies have shown that these local competencies are likely to be extended and improved through investment in education and R&D (Teixeira and Fortuna, 2010; Fagerberg and Godinho, 2008; Godinho, 2007). These internal factors are needed to create a favorable context for the diffusion of the technology.

Another strand of recent research, more theoretical, looks at the development of innovation systems as the result of a coevolution of institutional and technological processes. The literature on technological innovation systems considers that invention, development and diffusion occur along an iterative process involving a network of actors who act within a context of institutions and policies that influence the innovation process (Jacobsson and Bergek, 2011). In this perspective, the successful development of a new technology depends on the creation of a structure (i.e. actors, networks and institutions), as well as on how the system fulfills a number of key processes, referred to as "functions of the innovation system": development of formal knowledge; entrepreneurial experimentation; materialization; influence on the direction of search; market formation; resource mobilization; legitimation; and development of positive externalities (Bergek et al., 2008; Hekkert et al., 2007).

During the formative phase, the structure of the new innovation system has to be established and the main functions of the system have to be fulfilled. In successful cases, this triggers a "virtuous" cycle that sustains the growth of the new technology (Jacobsson and Bergek, 2011). In these terms, a dynamic innovation system that supports the development of new ideas and the rapid adoption of innovations is critical for fast technology diffusion (Jacobsson and Johnson, 2000).

By identifying important attributes of the technology, it is possible to investigate the requirements in what concerns more contextual factors associated with the development of the innovation system, in both structural and functional terms. For example, disruptive technologies may require longer formative phases in order to align supporting institutions (i.e. legitimation) and stimulate market formation (Hekkert et al., 2007). Other factors like technology complexity may impact on the risks and resource requirements for experimentation, namely in the case of larger (more costly) demonstrators which require the convergence on a dominant design that shows a clearly articulated demand.

Applying this rationale to the particular case of adoption, by follower countries, of technologies developed in the Core, it can be argued that: i) followers' capacity for absorbing knowledge spillovers from the learning processes that took place in the Core, requires internal efforts, i.e. the performance of the key processes that enable the growth of the technology and lead to the formation of an innovation system around it; b) if these conditions start being fulfilled, the experience gained in the Core can accelerate the process – in particular for key functions such as knowledge development and technology experimentation – thus enabling a faster formation of the local technological innovation systems.

The technological innovation system approach thus stresses the need to combine factors that are intrinsic to the technology, and context-related elements that create favorable conditions for its development and adoption, i.e. are enablers of diffusion—including "transnational linkages" which, as suggested by Wieczorek et al. (2015, p.138), "complement for missing resources and capabilities at the national level". This combined approach provides a more encompassing framework to address the processes that take place when a technology moves from the Core to follower countries; and thus provides a more far-reaching explanation for the acceleration of diffusion identified by the empirical literature.

3. Empirical model and data sources

The evolution of the adoption capacity in Portugal is assessed through the analysis of the diffusion of several energy technologies. One of the main steps of this research is to adjust logistic curves to actual data in order to identify historical patterns of technology diffusion. There is a wide range of evidence supporting the use of the three-parameter logistic function in the representation of technological diffusion, particularly in the field of energy and transportation systems (Grubler, 1998; Marchetti and Nakicenovic, 1979). This function is inspired by the logistic model of Fisher and Pry – a simple S-shaped curve assuming symmetry around the inflection point – which can be represented as follows:

$$y(t) = K/[1 + exp(-b(t - to))]$$

where:

K saturation level (asymptote)
to inflection point at $K/2$
b diffusion rate (slope of the S-curve)
Δt period of time during which y grows from 10% to 90% of its saturation level (K), and
Δt = (1/b).log 81.

The usual procedure consists of fitting a logistic curve to the variable y representing the cumulative number of units produced or the cumulative installed capacity (measured in megawatts, MW). In previous work, two criteria were established to validate the parameters found by the logistic functions (Wilson, 2009; Debecker and Modis, 1994): i) goodness of fit (adjusted R^2) greater than 95%; and ii) historical data covering at least 60% of the estimated asymptote (K).

In order to examine the behavior of energy technologies, a sample of technologies whose diffusion has had a great impact on the energy system was selected. Temporal series were compiled on the historical diffusion of several technologies, not only of energy supply (refineries, steam engines, coal power plants, natural gas power plants, hydro power plants, wind power plants), but also of end-use technologies (domestic production of passenger cars and motorcycles). The fact that these are all mature technologies ensures that enough data is available to estimate the logistic parameters. In addition, the diffusion of these technologies can be fitted with logistic curves with very high coefficients of determination (higher than 95%, not shown). Therefore the data respect the two criteria (minimal "reliable" coverage and goodness of the fit), which validates the parameters found in the logistic fits and enables their comparison.

The spatial diffusion of technology is analyzed globally and for three regions – "Core", "Rim" (distinguishing Former Soviet Union "Rim 1" from the diffusion in other fast followers "Rim 2"), and "Periphery" – which are identified according to their entry in the sequence of spatial diffusion. In other words, regions are defined according to the timing in which technology penetrates into different geographic spaces. Historically, technologies disseminate from the "Core", typically situated in OECD countries, to the remaining developed OECD countries, before reaching other parts of the world (Wilson, 2009; Grubler et al., 1999). However, each technology is a specific case and the criterion for the organization of countries in regions is always the moment of their entry into the technological diffusion.

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[2] 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 Narula (2004) and Criscuolo and Narula (2008) for an attempt to extend the concept to the national and "innovation system" level.

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Table 1
Energy technologies included in the analysis: units, time series and spatial disaggregation.

Technology		Data & units	Time series	Other regions	Main sources (Portugal)[a]
Supply-side energy technologies	Oil refineries	Total capacity[b] (#, MW)	1940–2007 (Portugal: 1940–2012)	*Core*: OECD ("Former Soviet Union") *Rim2*: Asia (excl.China), Mid.East,Lat.America *Periphery*: China, Africa *Global*	Galp (2013)
	Power—coal	Cumulative capacity (#, MW)	1908–2000 (Portugal: 1889–2010)	*Core*: OECD *Rim1*: FSU *Rim2*: Asia, South Africa *Periphery*: Africa (exl.SouthAfr), Lat.Am. *Global*	DGEG (2013), APA (2013), REN (2013), Museu da Electricidade (2013), Guedes (2001)
	Power—natural gas	Cumulative capacity (#, MW)	1903–2000 (Portugal: 1997–2010)	*Core*: OECD *Rim1*: FSU *Rim2*: Asia *Periphery*: Africa, Lat.Am. *Global*	REN (2013), ERSE (2007, 2013)
	Power—wind	Cumulative capacity (#, MW)	1977–2012 (Portugal: 1985–2011)	*Core*: Denmark	INEGI-APREN (2011), DGEG (2013)
	Power—hydro	Cumulative capacity (#, MW)	1900–2012 (Portugal: 1927–2010)	*Core*: OECD *Rim1*: FSU *Rim2*: Asia *Periphery*: Africa, Lat.Am. *Global*	DGEG (2013), REN (2013)
	Steam engines	Total capacity (#,hp/MWeq.)	1710–1930 (Portugal: 1819–1946)	*Core*: UK, US *Rim2*: Continental Europe *Periphery*: Rest of the World(RoW) *Global*	Tann and Berckin (1978), Woytinsky (1926), Pedreira (1990), Serrão (1971), INE (1945)
End use energy technologies	Passenger cars	Cars produced (#, hp/MWeq.)	1900–2005 (Portugal: 1960–2012)	*Core*: US *Rim1*: FSU *Rim2*: OECD (excl.US) *Periphery*: RoW *Global*	UN (2013), OICA (2013), AIMA/ACAP (1997), 2002, 2013), Selada and Felizardo (2004)
	Motorcycles	Motorcycles produced (#, MWeq.)	1900–2008 (Portugal: 1948–1994)	*Core*: UK, France, Germany, Italy *Rim1*: FSU *Rim2*: US, Japan *Periphery*: China, India, Indonesia *Global* (incl.RoW)	UN (various years)

[a] Main sources for remaining regions (described in detail in Wilson (2009) and Bento (2013)): Oil refineries — Oil & Gas Journal, BP, Enos; Power-Coal — Platts; Power — Natural Gas — Platts; Power-Wind — DEA, BTM Consult (data updated from Spliid (2013); Power — hidro — Platts; Steam engines — Kanefsky, Woytinsky, US Census; Passenger Cars — AAMA, US NHTSA, ACEA; Motorcycles — UN (2008). Data is freely accessible at: http://www.iiasa.ac.at/web/home/research/researchPrograms/TransitionstoNewTechnologies/Scaling-Dynamics-of-Energy-Technologies1.en.html.

[b] Installed capacity (not cumulative capacity).

The research uses the best available statistical information contained in the databases of international organizations and national statistical agencies, data provided by sectoral actors or obtained from the literature. Table 1 summarizes information about the data sources used, the spatial disaggregation and time series.

4. The adoption of energy technologies in Portugal

4.1. Historical evolution of the technological diffusion

The evolution of the installed capacity of energy technologies over time is an important indicator of the capacity of technology adoption in a given country. Diffusion processes can be understood by studying the way technology disseminated and the average time required for growth, i.e. timing, scale, and pace of adoption.

The literature reviewed in Section 2 suggests that local absorptive capacity has an important influence in the rate of technology diffusion. An improved ability to adopt can translate into i) a greater impact of the technology on the market, ii) an acceleration of growth, or iii) a shorter time lag between the introduction of the technology in the country and its previous diffusion in the Core. This section will mainly address the first point, the others being discussed in the following section.

The market impact of the diffusion of various types of energy technologies in Portugal over the last century (using as indicator the cumulative total capacity) is presented in Fig. 1. The figure shows some technologies starting at a higher capacity level (e.g. natural gas power plants, hydro power plants, oil refineries, and motorcycles) because of the characteristics of the diffusion that begun with the deployment of a large capacity (e.g. power plant) already in the first year.[3] The analysis of the historical data reveals some features of the processes of diffusion in Portugal. Firstly, end-use technologies such as motorcycles can reach similar levels of penetration, i.e. cumulative capacity equivalent, as energy supply technologies of a larger unit size like hydroelectric power plants. This result coincides with the findings of studies undertaken for other regions and globally (Grubler et al., 2012), reasserting that end-use technologies are as important (in terms of market impact) as supply technologies in the energy system.

Secondly, the data suggests that the rate of diffusion is influenced by the characteristics of the technology. Comparing technologies of the same type such as the three electricity production technologies (hydro, natural gas, and wind power), it appears that the rate of diffusion is relatively slower in the case of technologies whose diffusion requires the construction of a dedicated infrastructure. This explains the slow progression of hydroelectric capacity whose growth required the construction of more dams, which also depended on lengthy

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[3] The first natural gas power plant opens in Portugal relatively late, in the second half of 1990s. That is why the curve departs from hundreds of MW (more exactly, 237.4 MW). For the same reason, the first modern oil refinery is installed in Cabo Ruivo (Sacor), in 1940, with an equivalent capacity over 300 MW. In the case of Motorcycles, the first data point in 1948 corresponds to the year of first continuous production in Portugal in the factory of Alma, in Vila Nova de Gaia. See Section 3.2 for more details about the sources.

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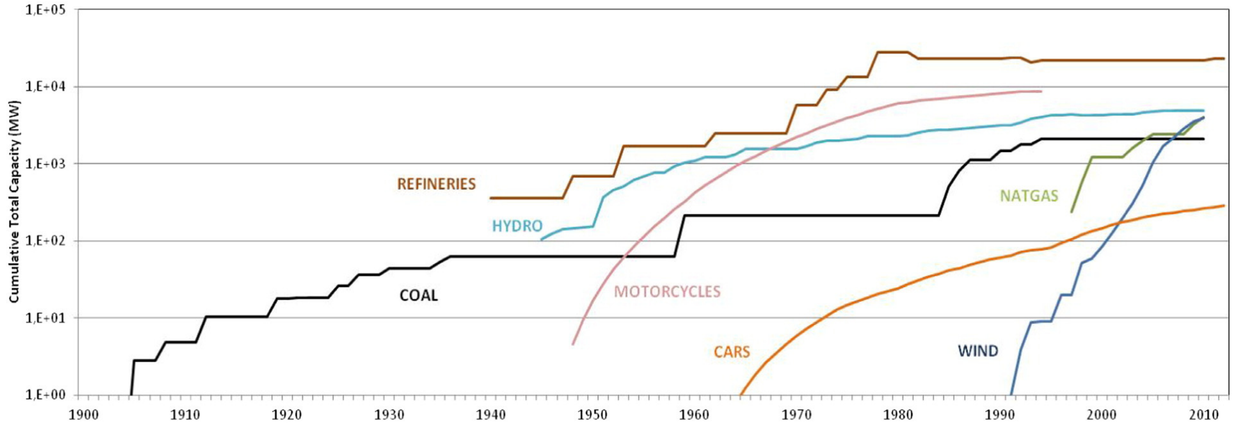

Fig. 1. The historical diffusion of energy technologies in Portugal in the 20th century — cumulative total capacity (MW), known and interpolated data, log scale y-axis.

authorization processes. Or even the delay in the introduction of natural gas for electricity production (when compared with other European countries), which was due to the need to build a costly infrastructure practically from the scratch, in the absence of a gas network.

Finally, it is worth noting the speed of penetration of wind energy, whose capacity has progressed quickly, reaching about 4000 MW in just two decades. In this case, it can be argued that the requirements in terms of infrastructure were less constraining than in the case of other energy production technologies such as natural gas. The integration of wind power into the existing electrical system was relatively straightforward, although requiring some adjustments, due to the intermittency of wind and the more dispersed nature of production. Other factors, related to the dynamics of the local innovation system, have also contributed for that performance, as will be discussed later.

4.2. Comparative performance with other regions

The capacity for adopting energy technologies can also be measured by the average time delay relative to other geographic areas. The rate of diffusion is likely to differ depending on whether the country is involved in the development of the technology (i.e., is part of the center or "Core") or is a follower, more or less rapid (Nelson, 2007; Lall, 2001). Empirical research suggests that a new technology takes time to disseminate in the "Core", but the process tends to accelerate when the technology moves into the subsequent markets. Yet the technology typically reaches lower saturation levels in the latter in comparison with the Core (Grubler, 2012; Bento, 2013).

The average delay in the adoption of energy technologies in Portugal, in relation to the countries of the center, is analyzed for a number of energy technologies by comparing the parameters of diffusion. These parameters are obtained from the logistic curves fitted to the actual data on growth of several technologies in their respective markets. In particular, the inflection point (*to*) — which represents both the midpoint in the S-curve ($F = 50\%$) and the moment of fastest growth — serves as a reference for this comparison. Hence, the delay in the adoption of new technologies is measured by the difference between the inflection points in Portugal and in Core countries. The smaller that difference, the shorter the time it takes for the technology to start diffusing in Portugal. Fig. 2 illustrates the parameters obtained in the case of the diffusion of wind power in Portugal and in the Core, here represented by the Denmark, a world reference in modern wind energy technology (Neij and Andersen, 2013).

Table 2 shows the results for the lag in the diffusion of several technologies in Portugal relative to other geographical areas. To simplify the

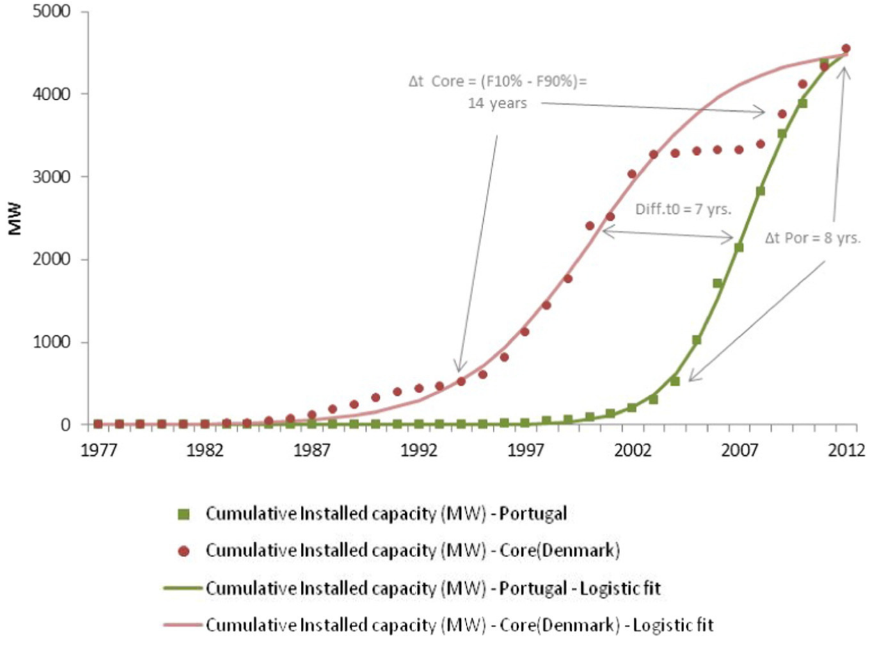

Fig. 2. Illustration of the fitting process with the logistic model to obtain the diffusion parameters — cumulative capacity (MW) of wind power between 1977 and 2012.

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Table 2
Time lag of the historical diffusion of several technologies in Portugal vs. other regions.

Technology/region	Core (a)	Rim1	Rim2	Periphery	Portugal (b)	(b)-(a) (years)
Oil refineries	1969*		1970	1977	1975	*6*
Power – coal**	1973	1975		1987	1988	*15*
Power – hydro	1971	1973			1986	*15*
Power – gas (1st. phase)	1971	1976	1985	1982	2006	*35*
Power – wind	2000				2007	*7*
Passenger cars	1989	1998	1995		2006	*17*

* Refineries of the type fluid catalytic cracking (FCC).
** "POWER" means that the technology is dedicated to the generation of electricity. For instance, "POWER-COAL" refers to coal power plants.

analysis, countries are divided into three groups of regions, according to their entry in the sequential process of spatial diffusion: countries where the technology emerged and diffused for the first time compose the center or "Core" of diffusion; fast followers of the pioneer areas are grouped in the "Rim", whereas former Soviet Union countries are included in "Rim 1" and distinguished from countries in "Rim 2" because diffusion there has been historically marked by more centralized decision processes; the remaining countries compose the "Periphery", where technology diffuses in the last place (see more details about the regions in Table 1).

The data shows that new technologies usually penetrate in Portugal with a delay of several years (sometimes decades) relative to the center. In the sample analyzed here, the longest delay was observed in the case of natural gas power plants (35 years), which was associated with the need to build a brand new infrastructure for gas transport and distribution. In contrast, the growth of the installed capacity of wind power and of refining was much faster, lagging less than a decade behind the diffusion in the Core (7 and 6 years, respectively).

Globally, the average delay in the adoption of energy technologies analyzed in the sample was around 15 years. This result is close to the lag normally observed in follower countries in "Rim 2", which are often associated with OECD countries that are not part of the "Core" (cf. Wilson, 2009). However, the estimate for the delay in adopting energy technologies must be approached with care. On the one hand, the results can only be interpreted in terms of the trend observed for the technologies analyzed in the sample, even if these represent important technological systems on the supply and end-use of energy. On the other hand, the estimated interval for the adoption of the technology can be affected by the level of aggregation of data. Methodological differences may exist and explain possible discrepancies in the estimates provided by several studies, but they did not appear to alter the main conclusion that the transfer of energy technologies to followers like Portugal has taken decades, rather than years (cf. Grubler, 2012).

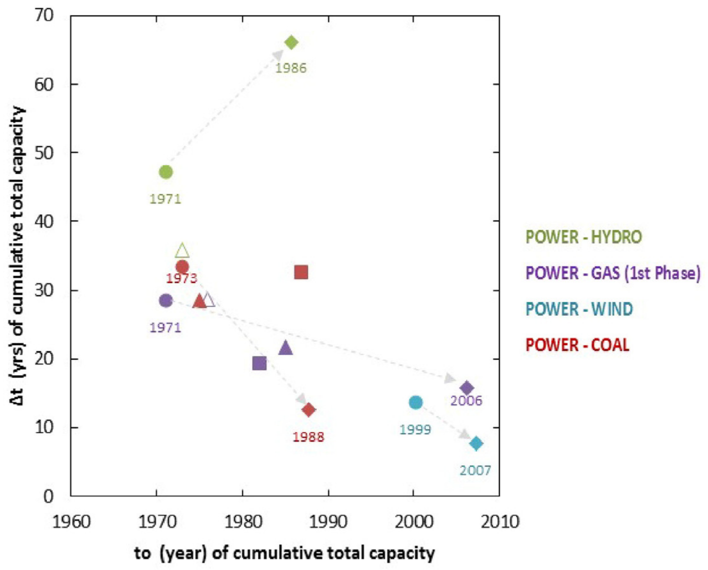
Despite the delay in the spatial diffusion of technologies, the data shows the speed of penetration increases when the technology reaches new markets. This acceleration effect is measured by the difference between the time taken for diffusion (Δt) in the Core and in other regions as shown in Fig. 3. The figure presents only the results for electricity generation technologies (hydro, natural gas, wind power), but a similar pattern was found for the other technologies in the sample as well.

As the technology leaves the "Core" and starts penetrating the follower countries, first, and the periphery, later, the time needed for diffusion becomes increasingly shorter. That is, the technology requires less time to reach saturation. This is clearly shown by the decreasing trend to the lower right corner of the chart (Fig. 3). In the Portuguese case, only hydroelectric power does not follow this pattern featuring an extraordinarily long period of growth. This can be explained by the idiosyncrasies of this technology and the constraints in terms of identification of suitable sites and obtainment of permissions.

In terms of the technologies for which there are data for all the regions, i.e. coal power plants and natural gas power plants, the diffusion was rather late in Portugal reaching the inflection point even after the Periphery. The time lag is larger in the case of natural gas power plants because of the inexistence of close natural gas resources nor of a network of pipelines for natural gas transport. Finally, the figure confirms once again the short delay with which wind power was adopted in Portugal in comparison with the Core.

4.3. Scaling effects on technology transfer: extension and duration of diffusion in Portugal

The analysis of the process of spatial diffusion enables a better understanding of the adoption behavior when the new technology spills over from the Core and penetrates into new markets. This can be namely investigated through the examination of technology and markets scaling patterns, i.e. the relationship between the duration (i.e., *Δt*)



Note: The light gray arrows link the inflection points (*t0*) of the diffusion in the Core and in Portugal, respectively.

Fig. 3. Spatial acceleration of diffusion when technology (power plants) reaches new markets — rates of diffusion (*Δt*) vs. inflection point (*to*). KEY: Core = circles, Rim1 = empty triangles, Rim2 = full triangles, Periphery = squares, Portugal = diamonds. Note: The light gray arrows link the inflection points (*t0*) of the diffusion in the Core and in Portugal, respectively.

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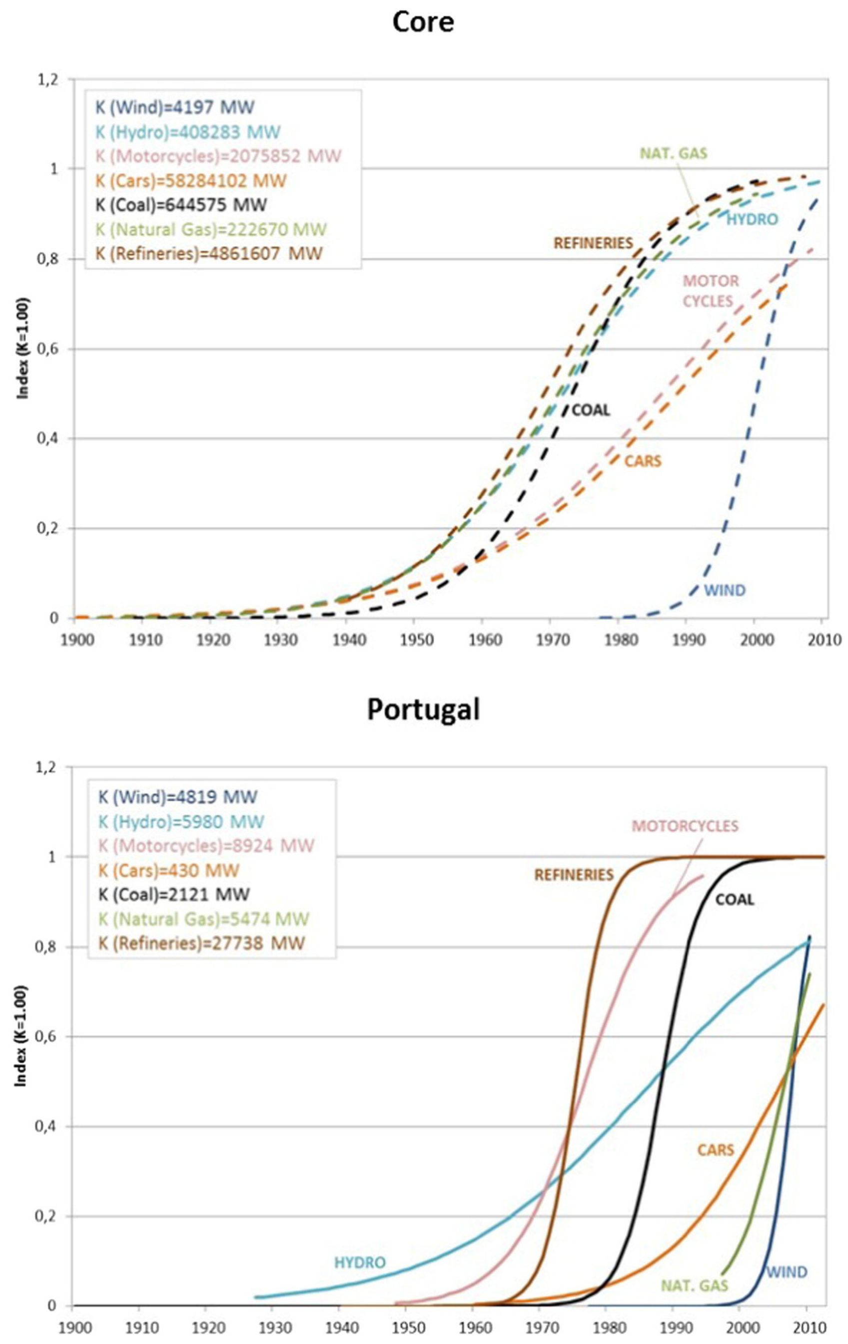

Fig. 4. Historical diffusion of energy technologies in the 20th century in the Core vs. Portugal — logistic fits to the evolution of cumulative total capacity, y-axis indexed to the saturation level (shown in the text box).

and the extent or saturation (i.e., *K*) of technological diffusion in different geographical levels, comparing Core countries and Portugal.

The relationship between the duration and the extent of technological diffusion has recently been demonstrated for a number of technologies. Empirical studies have shown that technologies that had a greater impact on the energy system required longer periods of diffusion (Wilson, 2012, 2009; Bento, 2013). This regularity can be explained by the technological, organizational and institutional requirements of technologies with greater diffusion potential (Markard et al., 2012; Bergek et al., 2008; Hekkert et al., 2007). Rosenberg and Trajtenberg (2004) illustrate these requirements well in the case of the formation of general purpose technologies such as steam engines. The relationship between duration and extent of diffusion was observed especially in transitions occurring in the Core, emphasizing the importance of market potential and economies of scale for the duration of technology diffusion in this region (Wilson, 2012). However, it is also relevant to investigate how these factors intervene in the context of follower countries like Portugal.

The scaling effect in the transfer of energy technologies from Core countries to Portugal is preliminary analyzed in Fig. 4, which presents the logistic curves fitted to the actual data on the growth of the technologies in the sample. Comparability of data is ensured by indexing the values of cumulative total capacity to the saturation level (*K*) previously estimated for each region.

The data reassert that the technologies arrive in Portugal with some delay (measured in decades) comparatively to the countries of the Core.

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However, the slope of the logistic curves is higher in Portugal, meaning that diffusion accelerates when innovations reach this country. Although technology diffusion is faster in the follower, the saturation level is attained more quickly (i.e. at lower levels) than in countries of the center. The only exception is wind energy, for which the saturation was estimated around 4800 MW in Portugal, which is slightly higher than in Denmark (almost 4200 MW). Thus, the evidence generally supports the hypothesis that technologies reach saturation faster in subsequent markets, which is usually lower than in the countries of the center.

The relationship between duration (Δt) and extent (K) of diffusion in the Core and Portugal respectively is compared in Fig. 5. The values K were normalized in order to make comparable the impact of technology diffusion in different moments of time and space — the saturation level is divided by the primary energy consumption (in EJ) of the respective region at the time *to* (cf. Wilson, 2009).

The analysis of the figure suggests the existence of a positive relationship (in the same direction) between the duration and extent of diffusion, especially in the Core. This means that technologies with greater potential for diffusion need typically longer to progress in the pioneer markets.

A more detailed comparison of diffusion in the Core and Portugal leads to two conclusions. On the one hand, the results confirm that, in general, diffusion is faster in Portugal, but reaches a lower saturation level. On the other hand, the relationship between duration and extension is clearer in the case of Core countries than in Portugal. The rate of diffusion has not been constrained by the scale/size of the market in the latter, as it was in the former. This is an important finding because it suggests that the rate of growth of new technologies may be less influenced by the scale of diffusion in the case of follower countries, making possible major technological transitions in a relatively shorter period of time. A preliminary analysis of the patterns in Rim (1 and 2) and Periphery, shown in Appendix (Fig. A.1), indicates that, in contrast with the case of Portugal, scaling has an effect in diffusion. However, the intensity of this effect (i.e. whether it is more, less or equally strong than in the Core) is still difficult to assess. The Portuguese case would then be an exception, exhibiting practically no scaling effect, as can be assessed by the flat trendline.

The fact that the pace of adoption in a follower country like Portugal is less constrained by the final extension of diffusion, when compared with the Core, may be explained by the differences occurring during the formative stage. The technological innovation systems perspective may contribute to explain this acceleration in the formation of new innovation systems in the subsequent countries. According to this approach the emergence and growth of innovation systems depends on the fulfillment of critical processes, such as knowledge creation or experimentation, that are required for the development of the technology in the market (Bergek et al., 2008; Hekkert et al., 2007). This process is made in an open environment in interaction with other countries, and thus, the follower may benefit from spillovers from the construction of the innovation system in the Core, providing that it has already developed some absorptive capacity (Criscuolo and Narula, 2008). As pointed out in Section 2.2, the follower can more rapidly develop the necessary knowledge to adopt and use the technology with only a fraction of the initial R&D costs spent in the Core. It can also benefit from the learning investments previously made by other countries to already start implementing a cheaper and more advanced version of the technology.

For example, the diffusion of wind energy in Portugal – which registered the lowest delay to the Core and the most rapid growth among the technologies surveyed in this study – starts already in the early 2000s, not long after the intense up-scaling and growth of the technology in Denmark that reduced costs of wind energy to more competitive levels (Neij and Andersen, 2013). Although a first move can open important opportunities for the pioneer countries, there are also "latecomer advantages" that contribute to facilitate the adoption of the new technology, namely by accelerating the processes of formation of a local innovation system.

4.4. Technological and institutional factors of diffusion

Measuring diffusion duration and delay to Core countries systematically permits a comparative analysis across technologies of the influence of technological and more contextual factors. Although the literature identifies determinants of duration of diffusion (relative advantage, pervasiveness, disruptiveness, complexity, infrastructural needs), it does not specify how long innovation systems take to form in follower countries, nor what may be the factors of spatial diffusion.

In contrast, these formative processes are more clearly understood in the innovation systems literature. They comprise the development of structural elements—actors, networks, institutions—and functional processes (functions of the innovation system) that affect the performance of the innovation systems (Bergek et al., 2008; Hekkert et al., 2007) and can be changed upon intervention on the elements of the structure (Wieczorek et al. (2015).

In what concerns technological factors, the sub-set of energy supply technologies (selected for greater comparability) were compared across the characteristics of the technology identified by the diffusion literature (Rogers, 2003; Grubler, 2012) (Table 3). Only disruptiveness and infrastructure appear to explain the duration of diffusion and delay of adoption in Portugal. Disruptiveness can be defined as the extent to which innovations open new markets, depend on novel service provision, new supporting institutions or user practices. Table 3 indicates a relatively more rapid diffusion in the case of less disruptive, substitute technologies, such as wind power, that come to fit into established systems (e.g. the electricity system). More disruptive technologies, as coal and hydro power, needed more time — which in the case of the former, corresponded to a very long formative phase — to develop the knowledge and institutional capacity required to grow.

Infrastructure needs concern the requirements in terms of the development of ancillary physical artifacts (electricity grids, pipelines, etc.) necessary for innovations to diffuse. Technologies with less stringent requirements, such as wind power, progressed more rapidly by using the system already in place. Their diffusion had a shorter delay to pioneer countries than that of coal and hydro power, which needed more time to mobilize resources and materialize the construction and extension of the early electricity networks. Similarly, natural gas power entered in Portugal with a long delay mainly because of the absence of an infrastructure for gas transport.

The analysis also addressed the other technological determinants of the duration of diffusions: pervasiveness, relative advantage and complexity. All else being equal, longer lengths and delays of diffusion

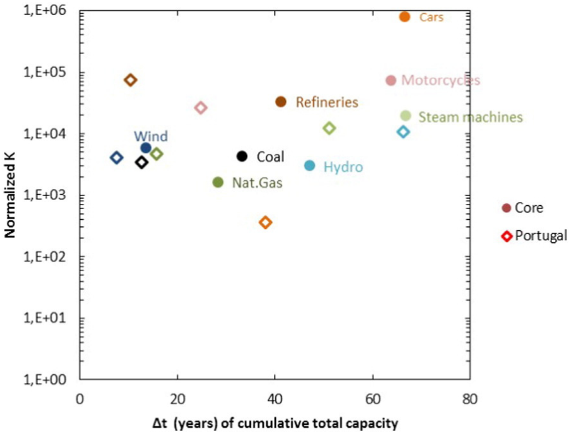

Fig. 5. The relationship between duration and extent of the historical diffusion of several energy technologies in the countries of the Core (circles) and in Portugal (empty diamonds). Normalized K (Cumulative Total Capacity) vs Δt, semi-log scale.

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Table 3
Synthesis of technological factors and structural requirements.

Technology	Technological factors					Structural requirements			Diffusion (years)*	Delay for the Core (years)
	Relative advantage (price/cost)	Technology pervasiveness (market size)	Technology disruptiveness (or substitute)	Technology Complexity	Infrastructure needs	Actors (value-chain)	Networks (diversity)	Institutions (laws, conducts..)		
Oil Refineries	++	−	.	−	.	+	+	.	*10*	*6*
Power – Coal	+	−	−	.	−	.	.	−	*13*	*15*
Power - Hydro	++	−	−	.	−	.	.	−	*66*	*15*
Power -Nat.Gas	+	−	++	+	−	+	+	−	*16*	*35*
Power - Wind	−	−	++	−	+	−	−	−	*8*	*7*

(++): Strong advantage; (+): advantage; (.): even or not applicable; (−) disadvantage; (−−) serious barrier.

* The number of years taken to pass from 10% to 90% of saturation. Fig. 1 above shows the growth of the cumulative installed capacity of the different energy technologies in a log-scale y-axis. Long penetration processes may not necessarily signify slow diffusion rates (i.e. higher number of years) as this type of graphs tends to smooth out jumps in the installed capacity. For example, coal power plants were introduced in Portugal long ago in the early XXth century but their installed capacity knew an enormous impulse after 1984. Hence, this technology shows a rapid diffusion rate (13 years) relatively to hydropower (66 years), whose diffusion started in the middle of the past century but developed in more incremental steps.

would be expected for innovations that are more pervasive, have higher (initial or operating, depending on each one dominates) costs and greater complexity. The former factor involves mobilization of more resources (financial, human, etc.) and legitimation for the formation of a market for higher capacities, while the latter two imply more costly opportunities for experimentation and learning — especially for technology complexity, which is approached in terms of the technology modularity and the need for up-scaling at unit level to become competitive. However, there is no clear relationship between these factors and the duration and delay of diffusion. Some technologies that had great cost advantage (e.g. hydro power) took longer to diffuse. Others that were very pervasive (e.g. refineries) or complex and expensive (e.g. wind power) were rapidly adopted.

These results suggest that other factors may also contribute to explain the delay of adoption and duration of diffusion of energy supply technologies in Portugal. Thus, the effect on diffusion duration and delay of contextual factors – more specifically, of the structural requisites for the development of an innovation system around the technology – were equally analyzed (Table 3). The analysis addressed the structural elements defined by the innovation systems literature: actors, networks and institutions. Actors are considered with regard to the organization of a value-chain, assuming that the presence of actors positioned along the chain could contribute to overcome barriers to system development more rapidly. Networks concern the capacity to attract, integrate and coordinate the required diversity of activities and competences (research, business, ancillary services, lobbying etc.). And, finally, institutions comprise the need of regulations, codes, standards, as well as supporting policies.

The combined analysis of technological factors and structural requirements improves the understanding of the diffusion and delay lengths. For example, technologies with relatively lower requirements for the development of an innovation system, such as refineries or natural gas power, tend to diffuse faster than others more dependent on institutions. This was namely the case of hydropower, where the strong institutional regulation played a significant role in its long diffusion. However, the need for a variety of networks (academic, research, industry, lobbying, etc.) was not an obstacle for the rapid development of wind power, since wind actors were able to build the required system elements.

This case points to the fact that these system requirements involve dynamic processes. In fact, the structural requisites for the emergence of an innovation system around a given technology raise both opportunities and challenges. They can only become a barrier if there is no ability, in the innovation system, to introduce structural changes capable of overcoming the obstacles that prevent the performance of the key innovative activities or functions (Wieczorek et al., 2015). This makes it necessary to study internal "enablers" such as the formation of supporting policies that accompanied the diffusion processes.

While the technological factors discussed above can influence the duration of diffusion, the delay to the Core and the length of the formative period (seen, for example, in coal power) may depend more on the enabling role of "internal processes" such as the general absorptive capacity and the existence of supporting policies. This coevolution of technological and institutional elements has been highlighted in socio-technical approaches (Jacobsson and Bergek, 2011) and is well illustrated in the recent successful case of the development of wind power (see Box 1 for a resume).

5. Discussion and conclusion

This paper analyzes the patterns and drivers of adoption of energy technologies in Portugal, including the process of spatial diffusion in a typical follower context. Energy technologies were found to be adopted with an average delay of one to two decades with regard to their diffusion in the pioneer countries. The rate of diffusion, however, accelerates when the technology reaches Portugal – even if the potential of diffusion is often lower than in the Core – confirming the regularities found in the historical energy transitions research (Grubler et al., 2012) and marketing literature (Peres et al., 2010).

The results also show that there are differences in terms of the scaling dynamics in the Core and in Portugal. That is, the relationship between duration and extent of technology diffusion, which tend to be highly correlated in the Core (Wilson, 2012), turned out to be much less intense in Portugal. This is an important finding and deserves further attention in future research, because it raises the possibility that the diffusion process of the next sustainable technologies can be relatively faster when they reach the follower countries, regardless of their impact on the energy system.

These patterns can be explained by the fact that next markets benefit from the experience gained during the previous development and deployment in the "Core" to adopt better and cheaper technologies. The results of this process become available to other countries at a fraction of their original cost, providing that there are enough internal conditions to absorb the knowledge and experience gained in the first markets. In particular, these internal conditions enable the performance of key innovative activities (i.e. functions), upholding the development of a local innovation system around the new technology, as explained by the technological innovation system approach (Bergek et al., 2008; Jacobsson and Bergek, 2011).

The contribution of this study to the diffusion theory further comprises the empirical assessment of the technological determinants of growth that have been identified in the literature (e.g. Rogers, 2003; Grubler, 2012). The pace at which energy technologies disseminate in Portugal has been influenced by the characteristics of the technologies, such as disruptiveness and infrastructural needs. Substitutive technologies like wind power tend to progress faster in mature electricity systems. Greater infrastructure needs slow or even delay technology

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Box 1
The emergence and growth of the wind power TIS in Portugal.[4]

The success of wind in Portugal confirms that the construction of an innovation system is a continuous process encompassing the phases of formation of the structure—including networks of agents (e.g. industry association APREN) and institutions (e.g. national energy policy "E4 program")—and development of the functions that enable the emergence and growth of the system. In fact, two functions at least were decisive for the success of wind energy in Portugal: early development of formal and practical knowledge, and the institutional alignment with the needs of the technology.

The development of science and technology activities since mid-1980s, involving investment in R&D and the participation in European-level research consortia, led to the creation of a local knowledge base (e.g. specialized human resources, know-how) that, later on, supported the extensive technology implementation. This was critical, since it enabled key actors (e.g. academics, energy companies, industry, government) to be exposed to and learn about the latest technology developments, which also contributed to influence the expectations about the technology potential and thus to legitimate its adoption.

The institutional changes, on the other hand, created a favorable legal and regulatory framework, including high investment subsidies and feed-in tariffs, which formed a market that attracted a large amount of national and foreign capital (Bento and Fontes, 2015).

Therefore, these early activities around wind energy technologies configure the "internal processes" that allowed the development of absorptive capacity as well as legitimacy. They contributed to support wind power's fast diffusion, which also benefited from the aforementioned favorable technology attributes, such as the substitutive nature of the technology and its relatively low infrastructural needs.

adoption, as observed in the case of hydroelectric and natural gas power plants. Other determinants such as technology pervasiveness, relative advantage and complexity, did not appear to have a clear effect in diffusion duration and adoption delays of energy technologies in Portugal.

Although this research provides partial empirical support to the aforementioned determinants of diffusion, the adoption lag and the length of the formative period cannot be fully understood without the consideration of more contextual aspects. These include "internal processes" that influence the absorptive capacity (R&D investment, human capital, etc.) and the existence of supporting policies.

Thus, technological and institutional factors together play a key role in spatial diffusion. Their complementary importance in diffusion has been illustrated in the case of the spectacular growth of wind power in Portugal. The installed capacity grew with a relatively short delay to the Core and evolved at a very fast pace. The rapid adoption can be partly explained by technological factors (e.g. substitutive technology and low infrastructural needs) but a more complete explanation requires an understanding of the changes in internal conditions. In particular, the introduction of science and technology policies in the late 1980s contributed to the development of local absorptive capacity and legitimacy, facilitating the institutional alignment that boosted diffusion later on. This case shows how the institutional changes promoted the fulfillment of key innovation activities (functions) and took advantage of the favorable attributes of the technology.

To the authors' knowledge, this is the first attempt to understand the joint effect of technological factors and more institutional requirements, permitting to gain some insights about adoption delay and rate of diffusion in receiving countries. However, further research is still needed to fully understand how the requisites for the emergence and growth of a technological innovation system (in terms of structure setting and development of system functions) influence the duration of diffusion. But this study already shows that the combination of the technological innovation systems with the more empirical diffusion of technologies literature offers a more comprehensive framework to address this question, opening exciting perspectives for future research. This would namely benefit from the analysis of more technologies and countries.

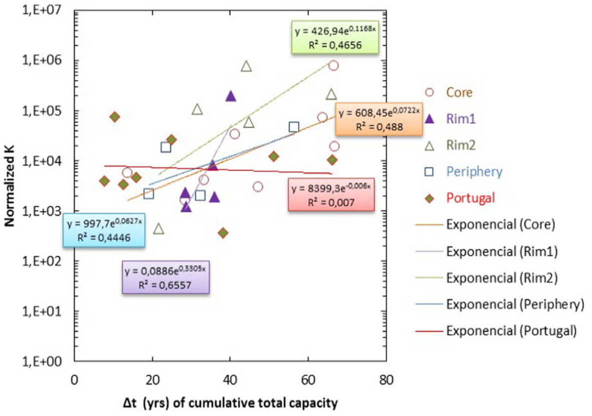
Finally, the recent success in the diffusion process of wind power in Portugal – as compared with much slower processes in the past – raises the question of whether there has been an overall improvement in the country's internal conditions that affect the capacity to rapidly absorb foreign sustainable technologies. More research is needed on this point, particularly regarding the role of "enablers" such as policy incentives and support schemes in promoting technology adoption – including an economic assessment of their application – as well as on the effect of local competencies enhancement in the persistent improvement of absorptive capacity.

Acknowledgments

We gratefully acknowledge the funding of this research by the FCT (Fundação para a Ciência e a Tecnologia) through the research grant Refª SFRH/BPD/91183/2012 and the research project Refª PTDC/CS-ECS/113568/2009. The authors would like to thank Charlie Wilson, Museu da Electricidade, REN, DGEG, ACAP and the participants of the XV Latin Ibero-American Conference on Management of Technology — ALTEC 2013, Oporto. Special thanks are due to the anonymous referees for their patience and helpful suggestions. The usual disclaimer applies.

Appendix A

Fig. A.1. The relationship between duration and extent of the diffusion of several energy technologies in all regions. Normalized K (Cumulative Total Capacity) vs Δt, semi-log scale. Data source (Rim1/Rim2/Periphery): Bento, 2013.



References

ACAP, 2013. Personal communication.
AIMA/ACAP, 1997. O comércio e a indústria automóvel em Portugal. Associação do Comércio Automóvel em Portugal - ACAP, Auto Informa, Lisboa.
AIMA/ACAP, 2002. O comércio e a indústria automóvel em Portugal. Associação do Comércio Automóvel em Portugal - ACAP, Auto Informa, Lisboa.
APA, 2013. Portuguese National Inventory Report on greenhouse gases, 1990–2010. Agência Portuguesa do Ambiente, Lisboa.
Bento, N., 2013. New evidence in technology scaling dynamics and the role of the formative phase. IIASA Interim Report. Laxenburg, International Institute for Applied Systems Analysis.

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[4] A more detailed analysis of the formation of the wind technological innovation system in Portugal, namely the formation of the structure and the performance of the main innovation activities (functions), is available in Bento and Fontes (2013, 2015).

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Bento, N; Fontes, M. Spatial diffusion and the formation of a technological innovation system in the receiving country: the case of wind energy in Portugal. Environmental Innovation and Societal Transitions, 2015. v. 15, p. 158-179.

Bento, N., Fontes, M., 2013. Mechanisms that accelerate the diffusion of renewable technologies in new markets: insights from the wind industry in Portugal. DINÂMIA'CET, Working Paper n.° 11/2013, Lisbon.

Bergek, A. et al. Analyzing the functional dynamics of technological innovation systems: a scheme of analysis. Res. Policy, 2008. v. 37, n. 3, p. 407–407.

Cappelli, R.; Czarnitzki, D.; Kraft, K. Sources of spillovers for imitation and innovation. Res. Policy, 2014. v. 43, n. 1, p. 115-120.

Clark, G.L.; Wrigley N. The spatial configuration of the firm and the management of sunk costs. Econ. Geogr., 1997. v. 73, p. 285–304.

Criscuolo, P.; Narula, R. A novel approach to national technological accumulation and absorptive capacity: aggregating Cohen and Levinthal. The European Journal of Development Research, 2008. v. 20, n. 1, p. 56-73.

Cohen, W.; Levinthal, D. Innovation and learning: the two faces of R&D. Econ. J., 1989. v. 99, p. 569–596.

Cohen, W.; Levinthal, D. Absorptive capacity: a new perspective on learning and innovation. Adm. Sci. Q., 1990. v. 35, p. 128–152.

Conceição, P., Heitor, M.V., 2005. Innovation for all? Learning from the Portuguese path to technical change and the dynamics of innovation. Praeger, Westport and London.

Debecker, A.; Modis, T. Determination of the uncertainties in S-curve logistic fits. Technol. Forecast. Soc. Chang., 1994. v. 46, p. 153–173.

DGEG. 2013. Estatística da energia. Available at: <www.dgeg.pt>.

ERSE. Analise à procura de gás natural 2007–2008. 2007. Available at: <http://www.erse.pt/pt/gasnatural/tarifasprecos/historico/tarifasreguladasdejulhode2007ajunhode2008/Documents/AnaliseconsumoGN20072008_Final.pdf>. Last access: 7 fev. 2013.

ERSE, 2013. Personal communication.

Fagerberg, J., Godinho, M.M., 2008. Innovation and catching-up. In: Fagerberg, J., Mowery, D.C., Nelson, E.R.R. (Eds.), The Oxford Handbook of Innovation, 19 ed. Oxford University Press, pp. 514–542 Chapter.

Fouquet, R. Past and prospective energy transitions: insights from history. Energy Policy, 2012. v. 50, p. 1–7.

Frankel, M., 1955. Obsolescence and technological change in a maturing economy. Am. Econ. Rev. 45 (3), 296–319.

Freeman, C., Perez, C., 1988. Structural crises of adjustment: business cycles and investment behaviours. Technical Change and Economic Theory. Pinter, London.

GALP. 2013. Refinação. Available at: <http://www.galpenergia.com/EN/agalpenergia/os-nossos-negocios/Refinacao-Distribuicao/ARL/Refinacao/Paginas/Home.aspx AND http://www.galpenergia.com/PT/investidor/ConhecerGalpEnergia/Os-nossos-negocios/Refinacao-Distribuicao/ARL/Refinacao/RefinariaMatosinhos/Paginas/DatasChave.aspx>. Last access: 11 Feb., 2013.

Geels, F., 2005. Processes and patterns in transitions and system innovations: refining the co-evolutionary multi-level perspective. Technol. Forecast. Soc. Chang. 72, 681–696.

Gerschenkron, A., 1962. Economic Backwardness in Historical Perspective. Harvard University Press, Cambridge, MA.

Godinho, M. M. Difusão internacional de tecnologia e perspectivas de convergência. Sociologia - Problemas e Praticas, 1995. v. 18, p. 9–21.

Godinho, M. M. Indicadores de C&T, inovação e conhecimento: onde estamos? Para onde vamos? Análise Social, 2007. v. XLII, n. 182, p. 239–274.

Godinho, M. M.; Caraça, J. M. Inovação tecnológica e difusão no contexto de economias de desenvolvimento intermedio. Análise Social, 1988. v. XXIV, n. (103–104), (4.°, 5.°), p. 929–962.

Grubler, A., 1998. Technology and Global Change. Cambridge University Press, Cambridge.

Grubler, A. Energy transitions research: insights and cautionary tales. Energy Policy, 2012. v. 50, p. 8–16.

Grubler, A., et al., 2012. Policies for the energy technology innovation system (ETIS). Global Energy Assessment — Toward a Sustainable Future. Cambridge University Press, Cambridge, and IIASA, Laxenburg, pp. 1665–1744 (Chapter 24).

Grubler, A.; Nakicenovic, N.; Victor, D. G. Dynamics of energy technologies and global change. Energy Policy, 1999. v. 27, n. 5, p. 247–280.

Guedes, M.V., 2001. 1936 — central termoeléctrica do freixo. Actos do 5° Encontro do Colegio de Engenharia Electrotecnica da Ordem dos Engenheiros.

Hekkert, M. et al. Functions of innovation systems: a new approach for analysing technological change. Technol. Forecast. Soc. Chang., 2007. v. 74, n. 4, p. 413–432.

INE, 1945. Estatísticas industriais 1945–1948. Instituto Nacional de Estatísticas, Lisboa.

INEGI-APREN. Parques eólicos em Portugal. 2011. Available at <http://e2p.inegi.up.pt/relatorios/Portugal_Parques_Eolicos_201112.pdf>. Last access: 3 jan. 2013.

IPCC, 2014. Climate change 2014: mitigation of Climate change. Working Group III Contribution to the Fifth Assessment Report (WGIII AR5), United Nations Intergovernmental Panel on Climate Change, Stockholm, 23–26 September 2013 Available at <http://mitigation2014.org>.

Jacobsson, S.; Bergek, A. Innovation system analyses and sustainability transitions: contributions and suggestions for research. Environmental Innovation and Societal Transitions, 2011. v. 1, n. 1, p. 41–57.

Jacobsson, S.; Johnson, A. The diffusion of renewable energy technology: an analytical framework and key issues for research. Energy Policy, 2000. v. 28, p. 625–640.

Jacobsson, S.; Lauber, V. The politics and policy of energy system transformation-explaining the German diffusion of renewable energy technology. Energy Policy, 2006. v. 34, n. 3, p. 256–276.

Jaffe, A. B. 2005 The importance of "spillovers" in the policy mission of the advanced technolgy program. Available at: <http://www.atp.nist.gov/eao/jtt/jaffe.htm>.

Keller, W., 2010. International trade, foreign direct investment, and technology spillovers. In: Hall, B., Rosenberg, N. (Eds.), Handbook of the Economics of Innovation. North-Holland, Elsevier, pp. 793–829 Chapter 19.

Lains, P. Catching up to the European core: Portuguese economic growth, 1910–1990. 2003. Explor. Econ. Hist., v.40, n.4, p. 369-386.

Lains, P., Silva, A., 2013. História económica de Portugal 1700–2000: o século XIX. ALFA Collections.

Lall, S., 2001. Competitiveness, Technology and Skills. Edward Elgar, Cheltenham.

Marchetti, C., Nakicenovic, N., 1979. The Dynamics of Energy Systems and the Logistic Substitution Model. Laxenburg, Austria, IIASA.

Markard, J.; Raven, R.; Truffer, B. Sustainability transitions: an emerging field of research and its prospects. Res. Policy, 2012. v. 41, n.6, p. 955-967.

Museu da Electricidade, 2013. Centrais eléctricas. Available at: <http://www.wikienergia.pt> Last access: 4 fev. 2013.

Narula, R. Understanding absorptive capacities in an "innovation systems" context: consequences for economic and employment growth. DRUID Working Papers 04–02, Available at: <http://www3.druid.dk/wp/20040002.pdf>, 2004.

Neij, L., Andersen, P.D., 2013. A comparative assessment of wind turbine innovation and diffusion policies. In: Grubler, A., Wilson, C. (Eds.), Energy Technology Innovation. Learning from Historical Successes and Failures. Cambridge University Press, Cambridge, UK, pp. 221–230.

Nelson, R.R. The changing institutional requirements for technological and economic catch up. International Journal of Technological Learning, Innovation and Development, 2007. v.1, n.1, p. 4-12.

OICA. 2013. Production statistics. Available at: <http://www.osica.net>. Last access: 7 jul. 2013.

Pedreira, J.M., 1990. Máquina a Vapor. In: Pereira, J.C. (Ed.), Dicionário Enciclopédico da História de Portugal. Lisboa, Alfa.

Peres, R.; Muller, E.; Mahajan, V. Innovation diffusion and new product growth models: a critical review and research directions. Int. J. Res. Mark., 2010. v.27, n.2, p. 91-106.

Perkins, R., Neumayer, E., 2005. The international diffusion of new technologies: A multitechnology analysis of latecomer advantage and global economic integration. Ann. Assoc. Am. Geogr. 95 (4), 789–808.

REN, 2013. Technical Data. Available at: http://www.centrodeinformacao.ren.pt/PT/InformacaoTecnica/DadosTecnicos/Forms/VistaPadrao.aspx (last access 6/2/2013).

Rogers, E.M., 2003. Diffusion of Innovations. 5th ed. Free Press, New York.

Rosenberg, N.; Trajtenberg, M. A. General-purpose technology at work: the Corliss steam engine in the late-nineteenth-century United States. J. Econ. Hist., 2004. v. 64, n. (1) March, p. 1–39.

Selada, C., Felizardo, J.R., Rollo, M.F., 2004. Da produção à concepção: meio século de história automóvel em Portugal. In: Heitor, M., Brito, J.M.B. (Eds.), Momentos de Inovação e Engenharia em Portugal no Século XX. Lisboa, Dom Quixote.

Serrão, J., 1971. Vapor, Máquina DE. *In*: », Joel Serrão (dir.), Dicionário de História de Portugal. Iniciativas Editoriais.

Spliid, J. "Stamdataregister for vindmøller," HTML-spreadsheet, Danish Energy Agency. 2013. Available at: <http://www.ens.dk/info/tal-kort/statistik-noegletal/oversigt-energisektoren/stamdataregister-vindmoller>. Last access: 23 abr. 2013.

Tann, J.; Berckin, M. J. The international diffusion of the Watt engine, 1775–1825. The Economic History Review, New Series, 1978. v. 3, n. 4, p. 541–564.

Teixeira, A.A.; Fortuna, N. Human capital, R&D, trade, and long-run productivity. Testing the technological absorption hypothesis for the Portuguese economy, 1960–2001. Res. Policy, 2010. v. 39, n. 3, p. 335-350.

United Nations, 2008. Industrial Commodity Statistics Database. United Nations Statistics Division (UNSD), New York.

United Nations. UN Industrial Commodity Statistics Database. 2013. Available at: <-website: data.un.org>. Last access: 11 jan. 2013.

Unruh, G. C. Understanding carbon lock-in. Energy Policy, 2000. v. 28, p. 817–830.

Wieczorek, A. J.; Hekkert, M.P.; Coenen, L.; Harmsen, R. Broadening the national focus in technological innovation system analysis: the case of offshore wind. Environmental Innovation and Societal Transitions, 2015. v.14, p. 128-148.

Wilson, C., 2009. Meta-analysis of unit and industry level scaling dynamics in energy technologies and climate change mitigation scenarios. International Institute for Applied Systems Analysis (IIASA), Laxenburg, Austria.

Wilson, C. Up-scaling, formative phases, and learning in the historical diffusion of energy technologies. Energy Policy, 2012. v. 50, p. 81–94.

Wilson, C.; Grubler, A. Lessons from the history of technology and global change for the emerging clean technology cluster. Nat. Res. Forum, 2011. v. 35, p. 165–184.

Woytinsky, W. L. Die welt in zahlen. Berlin: Rudolf Mosse-Buchverlag 1926. v. VI.

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Please cite this article as: Bento, N., Fontes, M., The capacity for adopting energy innovations in Portugal: Historical evidence and perspectives for the future, Technol. Forecast. Soc. Change (2015), http://dx.doi.org/10.1016/j.techfore.2015.09.003