NOTA DI LAVORO
71.2016

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Mitigation, Innovation and Transformation Pathways
Series Editor: Massimo Tavoni

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Summary

A major concern regarding innovation in clean technologies in the EU is that the fragmentation of its innovation system may hinder knowledge flows and, consequently, spillovers across member countries. A low intensity of knowledge flows across EU states can negatively impact their technological base, suppressing opportunities for further innovations and hindering the movement towards the technological frontier. This paper evaluates the fragmentation of the EU innovation system in the field of renewable energy sources (RES) by examining the intensity and direction of knowledge spillovers over the years 1985-2010. We modify the original double exponential knowledge diffusion model to provide information on the degree of integration of EU countries' innovation efforts and to assess how citation patterns changed over time. We show that EU RES inventors have increasingly built "on the shoulders of the other EU giants", intensifying their citations to other member countries and decreasing those to domestic inventors. Furthermore, the EU strengthened its position as source of RES knowledge for the US. Finally, we show that this pattern is peculiar to RES, with other traditional (i.e. fossil-based) energy technologies behaving in a completely different way.

Keywords: Knowledge Spillovers, Renewable Energy Technologies, Fossil Energy Technologies, EU Innovation

JEL Classification: Q55, Q58, Q42, O31, O33

Chiara Conti, Francesca Sanna-Randaccio, Roberta Sestini gratefully acknowledge funding provided by MIUR (Italian Ministry for Education, University and Research) under the research programme "Climate Change in the Mediterranean Region: Evolutionary Scenarios, Economic Impacts, Mitigation Policies and Technological Innovation" (PRIN project 2010--2011). Elena Verdolini gratefully acknowledges funding from the EU FP7 research and innovation programme under grant agreement no. 388329 (ADVANCE) and from the EU Horizon 2020 research and innovation programme under grant agreements no.642147 (CD-LINKS) and no. 730403 (INNOPATHS). Earlier versions of this paper were presented at the Paris Environmental and Energy Economics Seminar and at the GRI Conference on Innovation and Growth. The authors would like to thank Laura Diaz Anadón, David Popp, and Francesco Vona as well as all the participants to seminars and conferences for insightful comments.

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Transition Towards a Green Economy in Europe: Innovation and Knowledge Integration in the Renewable Energy Sector

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Abstract
A major concern regarding innovation in clean technologies in the EU is that the fragmentation of its innovation system may hinder knowledge flows and, consequently, spillovers across member countries. A low intensity of knowledge flows across EU states can negatively impact their technological base, suppressing opportunities for further innovations and hindering the movement towards the technological frontier. This paper evaluates the fragmentation of the EU innovation system in the field of renewable energy sources (RES) by examining the intensity and direction of knowledge spillovers over the years 1985-2010. We modify the original double exponential knowledge diffusion model to provide information on the degree of integration of EU countries' innovation efforts and to assess how citation patterns changed over time. We show that EU RES inventors have increasingly built "on the shoulders of the other EU giants", intensifying their citations to other member countries and decreasing those to domestic inventors. Furthermore, the EU strengthened its position as source of RES knowledge for the US. Finally, we show that this pattern is peculiar to RES, with other traditional (i.e. fossil-based) energy technologies behaving differently.

Keywords: Knowledge spillovers; renewable energy technologies; fossil energy technologies; EU innovation

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1. Introduction

One of the top priorities of the European Union is the creation of a resilient Energy Union with a forward-looking climate policy, capable of delivering long-term climate and energy targets and objectives. This transition is characterized by huge challenges, but also represents an unprecedented opportunity for member countries. Member states will benefit from reduced environmental and health pressure, lower dependence on fossil fuel imports, more diversified energy supply and the creation of jobs, skills and innovation in progressive sectors with significant growth potential. A strong renewable energy base in Europe has indeed long-lasting implications for Europe's competitiveness and export potential (EEA, 2012). This is even more the case in the present context, as clean[1] energies are expected to play a pivotal role in the implementation of the 2015 Paris Climate Change Agreement (IEA, 2015a) at the global level.

Clean energy technologies have been steadily rising towards the top of EU and member states agendas for the compelling economic and environmental reasons cited above and relevant efforts have been deployed in this field both in terms of innovation technologies and legislative and regulatory frameworks. Indeed, the EU Lisbon strategy was centered on the promotion of green, sustainable growth and these concepts are even more prominent in the Europe2020 strategy. Following the implementation of the Kyoto Protocol, EU countries tightened their environmental regulation, launched in 2005 the EU Emission Trading System to curb carbon emissions, and supported the development and deployment of renewable energy sources (RES) through several channels, including feed-in tariffs, quotas, green certificates, and R&D investment and subsidies. Major efforts to promote innovation in this key sector were undertaken at the EU and at the member state level via the implementation of legislative and regulatory frameworks, such as the Directives enacting the 1997 White Paper on renewable sources,[2] and through financial support. Public R&D funding for renewables increased from EUR 338 million in 2005 to EUR 874 million in 2013 (in 2010 prices), and EU member countries have been particularly active in implementing stringent climate policy. As a result, the EU became a frontrunner in the deployment of clean technologies. Between 2005 and 2012, the EU exhibited the highest new investments in RES in the world every single year and was only surpassed by China in 2013. Over this period, the compound annual growth rate of renewable energy consumption of EU was 7%. The benefits of such strong commitment include: an increase in the innovation rate of RES technologies for EU countries; the highest rise in the share of renewable energy in gross inland energy consumption (GIEC) worldwide between 2005 and 2013; an associated decrease in carbon intensity; and a high per capita employment in the area of renewable energy in 2014 (EEA, 2016).[3] Yet, much remains to be done to further support the energy transition, especially in the development of frontier carbon-free technologies (IEA, 2015b). Indeed, notwithstanding a significant effort, in 2013, fossil fuels still accounted for more than 80 percent of the EU's GIEC (EEA, 2016).

A major concern in this respect is that the fragmentation of the EU innovation system may hinder knowledge flows and, consequently, spillovers across member countries for RES technologies (European Commission, 2010; Fisher et al., 2009; LeSage et al., 2007). A low integration of the innovation system characterizes the EU in general, but is particularly troublesome for RES insofar as these technologies are instrumental in promoting and supporting green growth. Technological capabilities and the ability to absorb and exploit foreign-generated knowledge are complementary to each other (Cassiman and Veugelers, 2006). A low intensity of knowledge flows across EU states can negatively impact their technological base, suppressing opportunities for further innovations and hindering the movement towards the technological frontier. Hence, fragmentation delays (or, in the worst scenario, impedes) the achievement of the ambitious EU climate targets (EC, 2007; EC, 2015).

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[1] Here and in what follows,we use the terms renewable, clean, carbon-free interchangeably.

[2] Energy for the Future: Renewable Sources of Energy COM(97) 599 final. These measures were enacted in Directive 2001/77/EC establishing indicative targets and Directive 2009/28/EC setting mandatory targets. See also IEA (2015c) for a list of policies both at the national and the EU level.

[3] Of the three countries with highest per capita employment in renewable energies, two were from Europe: Germany, with 0.9 % of its labour force working in jobs related to renewable energies; and France, with 0.58 % of the workforce being employed in the area of renewable energy.

This paper evaluates the fragmentation of the EU innovation system in the field of renewable energy sources by examining the intensity and direction of knowledge spillovers over the years 1985-2010. This question has yet to receive the attention it deserves. Some recent studies have evaluated the EU RES innovation performance, both in terms of quantity and quality, but did not address this particular issue (Corsatea, 2014; Borghesi et al., 2015; Cantner et al., 2016; Nicolli and Vona, 2016; Noailly and Shestalova, 2016). Understanding how technology flows among EU countries and between the EU and other top innovators is a question of paramount importance because it can (i) help to assess the effectiveness of past actions and policy support to promote RES development, (ii) shed light on the relative performance of EU countries vis-à-vis other top innovators in this field and (iii) provide a first look into the future potential of this strategic sector for EU member countries.

Our analysis begins with the observation that EU15 countries experienced a significant increase in innovation in RES technologies since the turn of the century, with renewable energy patents jumping from 125 in 1985 to 2059 in 2010. Such increase was much more pronounced than that of the US and Japan, the other two frontier innovators (see Figure 1). We then ask a critical question: was this increase in the quantity of EU renewable energy innovation accompanied by a tightening of the EU RES innovation system? Is the EU better positioned to exploit knowledge spillovers now than it was two decades ago? Or is fragmentation still a key aspect that hinders the development of RES in the EU?

We tackle these questions by analysing the intensity and direction of intangible knowledge flows. Our focus is on the three main innovating regions of the world: the US, Japan and the EU15, which together account for roughly 87 percent of innovation in this field.[4] In line with a rich literature on similar subjects, we follow the paper trail left by within-country and cross-country patent citations, using citation frequencies to explore the patterns of knowledge flows within the EU and between the EU and other top innovators. We modify the original double exponential knowledge diffusion model of Caballero and Jaffe (1993) and Jaffe and Trajtenberg (1999) to provide information on the degree of integration of EU countries' innovation efforts and to assess how citation patterns changed over time.

We show that indeed EU RES inventors have increasingly built "on the shoulders of the other EU giants", intensifying their citations to other member countries and decreasing those to domestic inventors. Furthermore, the EU strengthened its position as source of RES knowledge for the US. Finally, we show that this pattern is peculiar to RES, with other traditional (i.e. fossil-based) energy technologies behaving in a completely different way. We thus confirm that the EU has improved the quality of its RES innovation and reduced the fragmentation of the innovation space in this specific field. As we discuss in the concluding Section of the paper, a likely explanation, which deserves further study, lies in the strong support of the EU to climate mitigation and renewable energy technology development vis-à-vis the laxer effort put forward by the US and Japan in this respect.

This paper provides two main novelties. Firstly, we use citation intensity within and between EU15 countries to empirically assess the extent to which the EU renewable energy innovation system is fragmented. As argued above, this is an important challenge for the sustainable development and climate targets of European countries (EC, 2007; Ruester et al., 2014; EC, 2015), but no empirical study has yet addressed this issue. Secondly, we compare RES with other energy technologies. Most of the literature on RES innovation does not explore whether patterns emerging for RES also apply to other types of energy technologies, such as for instance traditional-fossil based energy generation (see e.g. Johnstone et al., 2010; Nesta et al. 2014; Nicolli and Vona, 2016). Only a few contributions study both RES and other types of

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[4] EU15 RES patents represent 99 percent of EU27 RES patents over our sample period.

energy generation (Dechezleprêtre et al. 2013, Dechezleprêtre et al. 2014; Bosetti and Verdolini, 2013; Verdolini et al. 2016), but they address research questions different from the one we focus on.[5]

The rest of the paper is organized as follows. Section 2 presents our proxy for knowledge spillovers and provides a brief literature review on the topic. Section 3 describes our sample and provides descriptive evidence of the recent surge in renewable energy innovation in the EU and of changes in the patterns of knowledge flows. Section 4 describes in detail the empirical model we use to corroborate such evidence. Section 5 presents main results and Section 6 focuses on robustness checks. Finally, Section 7 concludes with a discussion of the possible reasons for such a change, as well as policy implications.

2. Measuring knowledge flows

Knowledge flows may occur through different channels. They may be embodied into goods or people, or rather they can be disembodied. Indeed, most of the literature on knowledge flows has focused on the latter. External accessible disembodied knowledge has been found to have a significant positive effect on TFP (Lee, 2006) and on local innovation production (Mancusi, 2008) and there is evidence that such effect might be even stronger than that of embodied knowledge (Drivas et al., 2016).

Our analysis focuses on disembodied knowledge transfer and we use patent citations as indicators of knowledge flows in RES technologies. This approach has a long tradition in the literature and itself relies on the use of patent data to assess the innovative effort of firms, sectors and countries. Patents are indeed the only available indirect evidence of innovative activity offering a detailed breakdown by technology for a large number of countries and for long time series. Furthermore, patent documents include references to previous patents, which are usually referred to as citations and provide information on the sources of knowledge that were relevant for the conception of the new invention. Although citations are widely employed in the literature, it should be mentioned that there are alternative indicators of disembodied knowledge flows. For instance, knowledge transfer can be traced also by considering the size and structure of co-inventor networks (e.g. Cantner et al., 2016) or university-industry research collaborations (e.g. Balconi et al., 2004).

Relying on patent and citation data to proxy for innovation and knowledge flows, respectively, has some shortcomings, but also significant advantages.[6] In particular, Jaffe et al. (1993) argue that patent citations can be interpreted as "bits" of previous knowledge that were important for developing the new knowledge contained in the citing patent. Although citations can at best capture flows of codifiable (vs. tacit) knowledge, they still provide insights on how knowledge may diffuse within and across geographical regions and technological fields (see e.g. Mancusi, 2008), and how the resulting patterns may change over time. This has been confirmed using data from the US Patent Office (USPTO) in Jaffe et al. (1998), but also (and importantly for our analysis) using data from the European Patent Office (EPO) in Duguet and MacGarvie (2005) and Bacchiocchi and Montobbio (2010).

An important part of the now large stream of literature relying on patent citations as indicators of knowledge flows builds upon the double exponential knowledge diffusion model proposed by Caballero

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[5] Dechezleprêtre et al. (2013) study the determinants of innovation in renewable and fossil-based generation technologies. Dechezleprêtre et al. (2014) compare the relative intensity of knowledge spillovers from clean and dirty technologies, to explore whether clean technologies warrant higher public subsidies than dirty ones. Bosetti and Verdolini (2013) use patent data to investigate the role of IPR protection and environmental policies on clean and dirty technology diffusion. Verdolini et al. (2016) focuses on the diffusion of clean and dirty power generation using data on installed capacity.

[6] See Griliches (1990) and Jaffe et al. (1993) for an extensive discussion on this.

and Jaffe (1993) and further developed by Jaffe and Trajtenberg (1996 and 1999). This model allows addressing truncation bias, a key feature of patent citations, which originates from the lower likelihood of citation of recent cohorts of patents with respect to older ones. We postpone the discussion of the features of the model to Section 4 and instead focus here on the most important findings of empirical studies that have employed citations to study the technological, geographical and institutional dimensions of the spread of newly created knowledge.

Early econometric studies on patent citations as indicators of knowledge flows were largely motivated by the growth and convergence effects of the rate and distance at which knowledge diffuses outwards from the geographical location in which it is created. As such, most of these studies focused on the role of geographical distance and contrasted local (national) with international knowledge diffusion, analyzing those factors contributing or hindering knowledge flows across geographical boundaries. The key findings in these studies can be summarized as follows: (i) the intensity of knowledge flows declines with geographical distance (Bottazzi and Peri 2003; Peri, 2005); (ii) national borders, language and institutional distance all represent an obstacle to knowledge diffusion (Maurseth and Verspagen, 2002; Li, 2014); (iii) by contrast, technological proximity facilitates cross-country knowledge flows (Jaffe and Trajtenberg, 1999; Hu and Jaffe, 2003; Hu, 2009).

Most of the studies cited above have used citations to estimate international knowledge flows between pairs of countries. However, the interest has gradually shifted from the intensity to the direction of cross-country knowledge diffusion. For example, Hu and Jaffe (2003) examine North-South patterns of knowledge diffusion from the U.S. and Japan, on the one side, to Korea and Taiwan, on the other side. Even more interesting for us, Hu (2009) estimates the citation intensity between East Asian countries, Japan and the US. His findings of a tight net of cross-country flows within East Asia are interpreted as a measure of integration of the innovation systems within that area and thus support the hypothesis of an increasing regionalization of knowledge diffusion within East Asia. We follow this approach and look for evidence on the degree of integration of national knowledge bases across the EU, while still accounting for knowledge flows between the EU and technological leaders (Japan and the US). Indeed, there is strong evidence that knowledge flows and, consequently, spillovers across member countries are hindered by the fragmentation of the EU innovation system (Fisher et al., 2009, LeSage et al., 2007), which has often been associated with the lack of a strong innovation policy at the EU supranational level. This is important because technological capabilities and the ability to absorb and exploit foreign-generated knowledge are complementary to each other, hence an increase in the intensity of knowledge flows across EU states can broaden and deepen their technological base, leading to opportunities for further innovations and possibly to a movement towards the technological frontier.

The idea above has been at the heart of the EU Lisbon strategy to promote growth and, in particular, green, sustainable growth, which has become an even more prominent objective under the more recent Europe2020 strategy. It is then interesting to see if there has indeed been an improvement in the degree of interconnectedness of the EU innovation system in the set of technologies aimed at reducing the carbon intensity of energy.

There are a few studies using citations for the analysis of knowledge flows in environmentally friendly technologies. Among these, Verdolini and Galeotti (2011) confirm that higher geographical and technological distances are associated with a lower probability of knowledge flows and provide evidence that spillovers between countries have a significant positive impact on further innovation in this field. Popp (2006) extends the original double exponential model to test the existence of knowledge spillovers for NO_X and SO_2 technologies among US, Japan and Germany and identify possible changes over time in both the intensity and direction of citation patterns. However, none of these studies deals with the fragmentation of the EU renewable energy innovation system and its changes over time.

To fill this gap in the literature, we estimate the probability of citation within and between EU15 countries, US and Japan in the clean energy sector as a measure of the intensity of knowledge flows across countries. Similarly to Hu (2009), we design the model so that we can interpret the results for the EU as providing information on the degree of integration of EU countries' innovation efforts. Also, following Popp (2006), we modify the original double exponential model to assess how citation patterns changed over time. This provides insights for what concerns changes in the intensity and direction of knowledge flows in frontier countries, and consequently informs on their innovation performance.

3. Data and descriptive evidence

For the purpose of our analysis, we collect data on patent applications by top inventors in RES technologies, which include hydro, solar, wind, biomass, geothermal, ocean, and waste. These are defined based on an extensive literature using IPC codes listed in Appendix A1. We consider applications to the European Patent Office (EPO) by inventors residing in the EU15, US and Japan from the PATSTAT-CRIOS database.[7]

To track citation patterns, we attach to each patent all the citations made to previous EPO patents (the so-called *backward* citations) in renewable energy technologies and assigned to inventors living in one of the three areas under investigation. Self-citations (i.e. citations to previous patents held by the same applicant firm) are excluded from the dataset in order to capture only true knowledge flows.[8]

The time coverage of our dataset is 1985 to 2010. Overall, our dataset on EPO patents applications consists of 23,162 RES patents and 43,090 citations to RES patents (Table 1). Over the whole sample period, EU15 accounted for 62 percent of applications, with the US and Japan accounting for roughly 20 and 18 percent, respectively. US inventors seem to be those relying more on previous knowledge: average backward citation per patent is 2.56, which is roughly 50 percent (65 percent) more than EU15 (Japanese) patents. Moreover, US patents emerge as those more cited on average.

The particularly high number of EU15 patents relative to US and Japanese patents in our sample is due to two main reasons. First, given that we are using EPO patent data, our statistics partly hide the significant home bias effect of European countries at the EPO.[9] This problem, which is bound to affect the descriptive statistics shown in this Section, will be fully addressed and controlled for in our empirical estimation. Second, around 50 percent of EU15 innovation in RES over the whole sample period is accounted for by Germany, which has historically been a top innovator.

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[7] CRIOS is a research center at Bocconi University where a large database on European patents has been created and is constantly maintained. This database, known as PATSTAT-CRIOS, contains information on patents applied for at the European Patent Office (EPO), from 1977 to 2012. Within this data base one may find: 1) patent data, such as the patent's publication number, its priority/application date, and main/secondary technological class, i.e. the IPC (International Patent Classification) code; 2) applicant (most often a firm or an institution) name and address, 3) inventor name and address, and, for each patent document, 4) all citations made to all prior EPO patents cited by the document itself.

[8] As discussed by Jaffe, Henderson and Trajtenberg (1993), self-citations cannot be regarded as evidence of spillovers.

[9] A similar pattern also emerges in Johnstone et al. (2010) where Germany, followed by US and Japan, exhibits the highest number of patents and a surge in patenting activity after 1997 (see Figure 2, p. 141). This is admittedly due to some extent to the presence of home bias when using EPO applications. The same effect is highlighted in OECD (2012) pp.23-24.

Table 1 Descriptive Statistics.

RENEWABLE ENERGY TECHNOLOGIES						
Country	*Patents*	*Percent*	*Backward citations*	*Avg Citation/Patent*	*Citations received*	*Received Citation/Patent*
EU15	14,263	0.62	24,478	1.72	23,082	1.62
JP	4,169	0.18	6,482	1.55	8,098	1.94
US	4,730	0.2	12,130	2.56	11,910	2.56
Total	23,162	1	43,090	1.86	43,090	1.86

Within EPO, RES innovation by the US, Japan and EU15 has been increasing over time, but such rise was particularly pronounced for the EU15 in the first decade of the century (Figure 1). That is a few years after the adoption of the Kyoto Protocol[10] and the release of the European Commission 1997 White Paper on renewable sources, and a period where EU commitment to RES development became even stronger. In 2001 the EU RES commitment put forward in the White Paper was further strengthened with the EU Directive 2001/77/EC, which, by stimulating demand, called for significant investment in electricity production from renewable energy sources. The Directive specifically pointed to the RES potential to increase energy security, promote technological development and innovation and provide opportunities for employment and regional development (see also Section 7).[11] Indeed, EU15 patent applications in the sample went from around 53% in 1985 to around 67% in 2010. In absolute terms, EU15 innovation at the end of our sample period is roughly four times that of the US and that of Japan.

As explained in Section 2, there is strong evidence that innovative activity in any given country benefits from spillovers from past domestic innovation and from other inventor countries. Given the innovation patterns displayed in Figure 1, it is thus legitimate to ask whether indeed the higher RES innovation rates in the EU have been accompanied by a change in the rate and direction of knowledge flows. So a crucial question that arises is whether the increase in EU RES innovation effort was occurring together with a strengthening of the EU as a source of knowledge both for domestic and foreign innovators.

To assess this, we explore patterns of citations across regions in our sample, which informs on whether innovation in the EU is of higher quality, and not only of larger quantity, than that of other innovating countries. Note that when focusing on the EU15, we look at aggregate citation flows, but also consider separately *national* citations (citing and cited patent belonging to the same country) and *international* citations (citing and cited patent belonging to distinct EU15 countries). This allows us to shed light on whether EU countries source knowledge from themselves or from other EU members. Arguably, these two patterns of knowledge flows have very different implications for the fragmentation of the EU innovation system.

Table 2 shows the percentage distribution of backward citations (i.e. the raw citation shares) for the different regions in our sample in the first half (left-side) and in the second half (right-side) of the sample period. Raw citation shares offer a preliminary view of whether the direction of RES knowledge flows changed. They are calculated as follows: the numerator is the count of citations received by patents of region *j* filed between the years 1987 and 1990 (2000 and 2003 for the second part of the sample) from

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[10] The Kyoto Protocol was adopted in 1997 and entered into force on the 16 February 2005.

[11] The Directive sets national targets for renewable energy production from individual member states. Although a directive implies that the EU does not strictly enforce the targets, the European Commission monitored the progress of the member states and could, if necessary, propose mandatory targets for those who missed their goals.

patents filed by inventors in region *i* between 1987 and 1997 (between 2000 and 2010 for the second period),[12] where *i,j=EU15, US, JP*. The denominator is the total number of citations made by region *i* over the same period (1987-1997 for the first period, 2000-2010 for the second period). We compare such indicators for the first and the second part of our sample period.

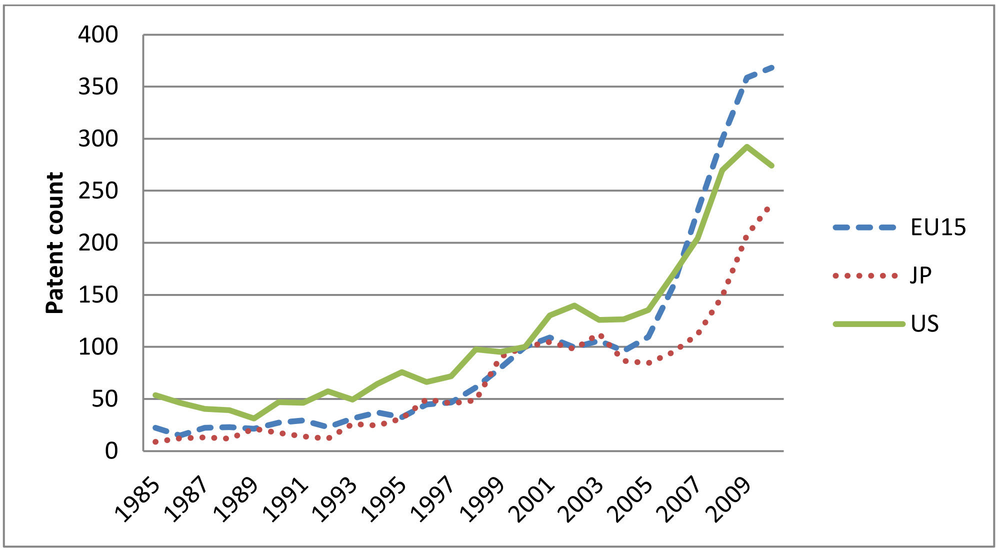

Fig. 1. Index of RES technologies patenting, EU15, US and Japan, 2000=100.

Three distinct patterns emerge. First, over the two periods the percentage of citations between different EU15 countries increased considerably. Second, the percentage of US national citations decreased, while the percentage of citations from the US to EU15 countries increased. Third, Japan seems to rely more on its own knowledge during the second period, but the share of citations to EU15 patents did not decrease significantly.

All in all, the descriptive evidence presented in this Section points to an improvement in the innovative performance of the EU15 in RES since the turn of the century, particularly with respect to the US. Such improvement at the EU level may be indicative of a reduction in the fragmentation of the EU RES innovation system, as testified by a more prominent role of EU countries as source of knowledge for other EU member states. By contrast, Japan's innovation levels in absolute terms are about two thirds of those of the EU, and the country appears more self-centered and less interconnected with either the EU or the US.

Though informative, conclusions drawn from raw citation shares can be misleading because the shares suffer from theoretical and actual biases. First, the shares are determined by both the citation frequency (i.e. the probability of a patent from the citing country citing a patent from the cited country) and the overall level of patenting. Second, citations are always subject to truncation bias. Third, the number of patents granted have been rising significantly in the last decades (see Figure 1), and so have the number of citations per patent. As Brahmbahatt and Hu (2009) conclude, raw citation shares inform on the gross flow of knowledge between two countries, but say little about the intensity of knowledge relationships. Thus, citation frequencies need to be properly modeled taking into account these effects in order to use them to

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[12] Note that any given patent is cited only by subsequent patents. The choice of lag is dictated by the fact that our dataset ends in 2010. Since the citation function generally peaks after 3/4 years, considering a minimum citation lag of 7 years to a maximum of 10 years would capture most citations.

draw inference on knowledge flows. In the next Section we detail our empirical strategy, which is designed to specifically address these issues and control for these confounding factors.

Table 2 Percentage distribution of citations, 1987-1997 and 2000-2010.

RENEWABLE TECHNOLOGIES											
Period of reference		**1987-1997**				*Period of reference*		**2000-2010**			
Cited country		EU15		JP	US	***Cited country***		EU15		JP	US
		Nat	*Int*					*Nat*	*Int*		
Citing country	EU15	0.33	0.25	0.10	0.32	***Citing country***	EU15	0.32	0.44	0.10	0.14
	JP	0.27		0.29	0.44		JP	0.26		0.61	0.13
	US	0.34		0.12	0.54		US	0.41		0.17	0.42

Note: the percentages in the table refer to the share of citations from the citing country directed towards the cited countries (row sums are equal to 1). In the left side, citations taken into account to calculate the percentages are those from patents with priority date between 1987 and 1997 to patents with priority date between 1987 and 1990. In the right side, citations taken into account to calculate the percentages are those from patents with priority date between 2000 and 2010 to patents with priority date between 2000 and 2003.

4. Empirical Framework

As discussed in the previous sections, our aim is to assess if, since the turn of the century, there has been higher interconnectedness in the RES EU innovation system and an overall better positioning of the EU with respect to the technological frontier. We do that by studying changes in the intensity of RES knowledge flows across the countries of interest through a double exponential knowledge diffusion model, proposed by Caballero and Jaffe (1993) and Jaffe and Trajtenberg (1999).

The model describes the random process underlying the generation of citations and allows estimating parameters of the diffusion process while controlling for variations over time in the propensity to cite. More precisely, the knowledge diffusion process is modelled as a combination of two exponential processes, one for the diffusion of knowledge and the other one for its obsolescence. The general formulation of the model is:

$$p_{iTjt} = \alpha(i, T, j, t) \exp[-\beta_1(T - t)] \, (1 - \exp[-\beta_2(T - t)]) \qquad (1)$$

where p_{iTjt} is the citation frequency, i.e. the likelihood that a patent from country *i* first applied in year T cites a patent from country *j* first applied in year t. The parameters β_1 and β_2 represent the rate of obsolescence and diffusion, respectively, and both exponential processes depend on the citation lag $(T - t)$. In this framework, the α represents shift parameters that depend on the attributes of both citing and cited patents: a higher α means a higher probability of citation at all lags. We allow this proportionality factor to vary with the following attributes: citing year, cited year and all possible combinations of citing and cited country.

The dependent variable p_{iTjt} is the expected frequency of citations and is calculated as the following ratio:

$$p_{iTjt} = \frac{C_{iTjt}}{(N_{iT})(N_{jt})}$$

where C_{iTjt} is the count of citations by country i's patents with priority date T to country j's patents with priority date t, and (N_{iT}) and (N_{jt}) are respectively the number of potentially citing patents from *i* at time *T* and potentially cited patents from *j* at time *t*. Citation frequencies are interpreted as an estimate of the probability that a randomly drawn patent in the citing group will cite a randomly drawn patent in the cited group.

We focus on citations within and between the EU15, the US and Japan and modify the above general model to take into account changes in citation patterns over the sample period by allowing our shift parameters to change as of year 2000. We choose 2000 as the cut-off point between the two periods in view of the acceleration in EU renewable energy patenting found in Section 3. As already noted such acceleration took place a few years after 1997, the year in which the Kyoto Protocol was adopted and the Commission White Paper "Energy for the Future: Renewable Sources of Energy" was released, indicating an increased commitment of the EU to decarbonize its energy sector.[13] We thus estimate the following equation:

$$p_{iTjt} = \alpha_T \alpha_t \alpha_{ij} \left[1 + \phi_{ij} * D_{2000}\right] \exp[-\beta_1 (T - t)] \left(1 - \exp[-\beta_2 (T - t)]\right) + \varepsilon_{iTjt} \qquad (2)$$

where D_{2000} is a dummy variable that takes the value of 1 when the citing patent's priority date is 2000 or later.[14]

Our parameters of interest are α_{ij} and ϕ_{ij}. The fixed effect α_{ij} indicates the *relative* likelihood that the average patent from country i cites a patent from country *j*, while ϕ_{ij} captures the additional likelihood of citation between a pair of countries for citing patents with priority date since 2000. If country *i* is taking advantage of technologies developed in country *j* by improving upon these innovations we should observe higher citation rates from *i* to *j* and interpret it as greater flow of knowledge from country *j* to country *i* in the second period. Positive estimates of ϕ_{ij} can thus be interpreted as a signal of quality of the innovations developed in the source country and therefore as a relative improvement of country *j* with respect to the technological frontier.

One of the novelties of our approach is to use the model to also study if there has been higher integration in the EU15 RES innovation system since year 2000. Indeed, we can distinguish citations where EU15 is both the source and the destination into national citations (i.e. the source and the destination within the EU15 are the same country) vs. international citations (i.e. the source and the destination within the EU15 are two different countries). Our original $\alpha_{EU15,EU15}$ is now split into two parameters: $\alpha_{EU15,nat}$ captures the intensity of citations of each EU15 country to itself, while $\alpha_{EU15,internat}$ captures the average citation intensity between any EU15 member and all other EU15 members. Similarly, we estimate $\phi_{EU15,nat}$ and $\phi_{EU15,internat}$, which capture the shift in national and cross-country citations within the EU15, respectively. Hence, if since 2000 there has been higher integration of the knowledge bases of EU15 member states we expect to find a positive $\phi_{EU15,internat}$ and a negative $\phi_{EU15,nat}$.

As customary in this type of models, the citing year fixed effects (α_T) and the cited year fixed effects (α_t) are grouped into 2-year and 5-year intervals, respectively (see Jaffe and Trajtenberg, 1999; Popp, 2006; Bacchiocchi and Montobbio, 2010). We estimate equation (2) by non-linear least squares. Since the model is heteroskedastic (the dependent variable is an empirical frequency), we weight the observation by the reciprocal of the estimated variance $\sqrt{(N_{iT})(N_{jt})}$ (Jaffe and Trajtenberg, 1999; Popp, 2006; Bacchiocchi and Montobbio, 2010).

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[13] We test the robustness of our results to changes in the choice of the cut-off (see Section 6).

[14] The dummy is introduced interactively as in one of Popp (2006) robustness exercises.

In this type of models, the null hypothesis of no fixed effect at the country level corresponds to parameter values of unity rather than zero for α_{ij} as well as for α_T and α_t (but not for β_1, β_2 and ϕ_{ij}). For each fixed effect, a group is omitted from estimation, i.e. its multiplicative parameter is constrained to unity. Thus the parameter values are interpreted as relative to the base group. The base group for country pairs fixed effects (α_{ij}) is $US - citing - US$;[15] if, for example, $\alpha_{EU15,US} = 0.8$, this means that a patent belonging to EU15 group is 20% less likely to cite a US patent than is a US patent.

5. Results

Table 3 presents results for the estimation of Equation (2) on our sample of RES patents. We report the parameters of interest α_{ij} and ϕ_{ij}, as well as estimates of β_1 and β_2 for comparison with the existing literature.[16] In all specifications, estimates for β_1 are in line with previous works, while those for β_2 are larger than those obtained in previous studies using USPTO data, but consistent with the results of Pillu and Koleda (2011), who use EPO data. Henceforth we focus our attention on α_{ij} and ϕ_{ij}. Recall from the previous Section that each α_{ij} is interpreted as the relative probability of citation between country *i* and country *j*, as compared to the probability that a US inventor cites a US inventor ($\alpha_{US,US} = 1$), while ϕ_{ij} indicates if the probability of citation between any couple of countries has changed starting from 2000.

Columns (1) and (2) of Table 3 present estimates of the likelihood of citation between any couple of countries over the full sample period (i.e. assuming $\phi_{ij} = 0$). Column (1) does not distinguish between national and international citations within the EU, while column (2) estimates separate effects for national ($\alpha_{EU15\,nat}$) vs. international ($\alpha_{EU15internat}$) citations within the EU. Comparing these coefficients provides insights on the geographical localization of EU RES innovation over the whole period and thus allows to characterize the degree of fragmentation of the EU15 RES innovation space.

Four main results emerge from these two regressions. First, knowledge flows within the EU15 are weaker than in the US and Japan, and knowledge flows within a EU15 member country are higher than between members. Specifically, inventors from any of the EU15 countries are 38 percent as likely to cite another inventor from a EU15 country as compared to a US inventor citing another domestic patent ($\alpha_{EU15,EU15} = 0.38$ in column 1). The corresponding likelihood for domestic citations of a Japanese inventor is 81 percent ($\alpha_{JP,JP} = 0.81$). Further, focusing on the results reported in column 2, any EU15 member is almost twice as likely to cite itself as opposed to citing any other EU member or the US. Indeed, $\alpha_{EU15\,nat} = 0.58$, while $\alpha_{EU15internat} = 0.3$ and $\alpha_{EU15,US} = 0.28$. EU15 inventors are basically as likely to benefit from spillovers from the US as they are to benefit from spillovers from other EU countries. Thus, EU15 members are each building upon their own knowledge, but not as much as the US or Japan are doing.

Second, the likelihood of a EU15 patent to be a source of knowledge for a foreign inventor is lower than that of a US or Japanese patent. This suggests that EU has to further strengthen its position as international innovation hub.

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[15] The base group for citing year fixed effects (α_T) is 1985-1986 and for cited year fixed effects (α_t) is 1985-1989.

[16] Complete regression results are available upon request.

Table 3 Regression Results: RES.

	(1)	(2)	(3)	(4)	(5)	(6)
Citing/cited country pairs (αi,j) [(a)]						
US citing US	1	1	1	1	1	1
	NA	NA	NA	NA	NA	NA
EU15 citing EU15	0.384***					
	(0.013)					
EU15 citing EU15 (national)		0.582***	0.655***	0.661***	0.647***	0.671***
		(0.022)	(0.044)	(0.045)	(0.043)	(0.047)
EU15 citing EU15 (international)		0.299***	0.246***	0.249***	0.243***	0.252***
		(0.011)	(0.019)	(0.019)	(0.018)	(0.019)
EU15 citing US	0.279***	0.280***	0.314***	0.317***	0.281***	0.322***
	(0.013)	(0.013)	(0.025)	(0.025)	(0.013)	(0.026)
EU15 citing JP	0.170***	0.170***	0.213***	0.215***	0.171***	0.219***
	(0.008)	(0.008)	(0.022)	(0.022)	(0.008)	(0.023)
US citing EU15	0.315***	0.314***	0.264***	0.314***	0.261***	0.270***
	(0.013)	(0.013)	(0.020)	(0.013)	(0.020)	(0.021)
US citing JP	0.470***	0.469***	0.468***	0.468***	0.469***	0.421***
	(0.027)	(0.027)	(0.027)	(0.027)	(0.027)	(0.057)
JP citing EU15	0.140***	0.140***	0.170***	0.139***	0.169***	0.175***
	(0.007)	(0.007)	(0.015)	(0.007)	(0.015)	(0.016)
JP citing US	0.262***	0.264***	0.264***	0.263***	0.264***	0.367***
	(0.014)	(0.014)	(0.014)	(0.014)	(0.014)	(0.038)
JP citing JP	0.814***	0.817***	0.816***	0.813***	0.819***	0.962***
	(0.038)	(0.038)	(0.039)	(0.039)	(0.039)	(0.079)
Citing pattern differences after 2000 (ϕ_{ij}) [(b)]						
US citing US			0	0	0	0
			NA	NA	NA	NA
EU15 citing EU15 (national)			-0.133**	-0.145**	-0.118*	-0.164**
			(0.065)	(0.063)	(0.065)	(0.065)
EU15 citing EU15 (international)			0.251**	0.233**	0.272***	0.208**
			(0.101)	(0.098)	(0.101)	(0.010)
EU15 citing US			-0.135*	-0.147*		-0.166**
			(0.078)	(0.077)		(0.078)
EU15 citing JP			-0.233***	-0.244***		-0.261***
			(0.086)	(0.084)		(0.085)
US citing EU15			0.245**		0.267**	0.202*
			(0.104)		(0.104)	(0.103)
JP citing EU15			-0.220***		-0.207***	-0.246***
			(0.079)		(0.079)	(0.078)
JP citing JP						-0.185**
						(0.077)
JP citing US						-0.370***
						(0.072)
US citing JP						0.132
						(0.168)
Decay (β_1) [(b)]	0.263***	0.264***	0.263***	0.263***	0.263***	0.262***
	(0.010)	(0.009)	(0.009)	(0.009)	(0.009)	(0.009)
Diffusion (β_2) [(b)]	0.001***	0.001***	0.001***	0.001***	0.001***	0.001***
	(0.0001)	(0.0001)	(0.0001)	(0.0001)	(0.0001)	(0.0001)
N° of obs.	3,159	3,510	3,510	3510	3,510	3,510

Notes: [a)] *H_0 is parameter = 1;* [(b)] *H_0 is parameter = 0. ***Significant at 1% level; **Significant at 5% level; *Significant at 10% level.*

Third, the US rely more on domestic spillovers as compared to the other countries in the sample, but also build more on the shoulders of the foreign giants. In particular, the US seem to benefit relatively more from knowledge produced in Japan than in the EU. The likelihood of a US patent citing a Japanese one is 47 percent, while that of citing a EU patent is 31 percent.

Fourth, the Japanese RES innovation space emerges as extremely self-referenced. The likelihood of a Japanese patent citing previous domestic innovation is almost as high as that of the US. In addition, we find a very low likelihood of Japanese patents citing previous patents by either US or EU15 inventors.

Overall, this preliminary evidence shows that the RES innovation system is geographically localized and rather fragmented, especially for what regards the EU15. The high values of the bilateral coefficients α_{ij} when *i*=*j*=US or *i*=*j*=JP are in line with previous findings (see e.g. Jaffe and Trajtenberg, 1999; Bacchiocchi and Montobbio, 2010). This, combined with the low probability that Japanese inventors cite knowledge from other countries, indicates a pattern of geographical localization of knowledge, which appears to be particularly strong for Japan as a recipient of knowledge flows.

To further explore these patterns and their development over time, columns 3 through 6 provide estimates of the citation likelihood before and after year 2000 while considering separately citations from EU15 countries to domestic and other EU patents. Specifically, column 3 estimates all ϕ coefficients where the EU is either the citing or the cited country, column 4 considers only the EU as citing country, and column 5 considers the EU only as cited country. Finally, column 6 reports estimated ϕ coefficients for all couples of citing and cited countries. The different models are presented to show the robustness of results to changes in the specification. Since all results are strongly consistent, we only comment column 6 and highlight differences with other models only where relevant.

First, our regression results confirm that EU15 inventors rely more on domestic innovation than on spillovers from other EU15 countries. However, since 2000 this pattern changed. Indeed, the likelihood of domestic citation in the first part of the sample is 67 percent ($\alpha_{EU15\ nat}$), and drops to 56 percent in the last part of the sample ($\alpha_{EU15\ nat} * (1 + \phi_{EU15nat})$). This was accompanied by an increase in the likelihood of citing other EU15 inventors, which climbed from 25 percent ($\alpha_{EU15\ internat}$) to 30 percent ($\alpha_{EU15\ internat} * (1 + \phi_{EU15internat})$). In growth terms, the percentage decrease in the probability of domestic citation was more than compensated by the increase in the probability of citation to other EU15 countries ($\phi_{EU15,nat} = -0.16$, $\phi_{EU15,internat} = 0.21$).

Second, spillovers to EU15 from the US and Japan further decreased since 2000. Specifically, the probability of a EU15 inventor citing a US patent dropped from 32 percent to less than 27 percent, and the probability of citing a Japanese patent from 22 percent to a mere 16 percent.

Third, the likelihood that EU15 inventors are a source of knowledge for US inventors went from 27 percent before 2000 to 32 percent since 2000, increasing by 20 percent.

Finally, while the likelihood of US inventors citing Japanese patents remained unchanged, there was a general decrease in the Japanese inventors' propensity to cite since 2000 and such decrease was 50% larger for JP-US citations as compared to JP-EU citations. Also, and differently from what suggested by the descriptive evidence in Section 3, our empirical results do not indicate an increased reliance by Japanese inventors on the domestic innovation system, but rather the opposite (the coefficient $\phi_{JP,JP}$ is found negative and significant). Note that a likely explanation for the results we present on Japan lies in the changes intervened around 2000 in the East Asian innovation geography, which witnessed an increased regionalization of knowledge flows, as shown by Hu (2009). On the one hand, China and Korea are strengthening their position as innovators also in renewable energy technologies (WIPO, 2009; OECD

Patent Statistics). On the other hand, there is strong evidence that China and Korea tend to patent less at EPO, as compared to USPTO or national patent offices (Helm et al., 2014; WIPO, 2009). Hence, our analysis, which relies on citations to EPO patents, may provide only partial results for East Asian countries. Indeed, for instance, any increase in the propensity to cite China and Korea by Japan cannot be fully captured by our data.[17] Overall, these patterns contribute to explaining our result which suggests a reduction in the probability of Japan citing EPO patents.

The patterns of RES knowledge flows and localization discussed so far give rise to four important insights. First, the EU RES innovation space is becoming more integrated, with international citations between EU countries becoming more important, and national citations less relevant. Second, the EU has increased its role as source of knowledge for the US. Third, Japan seems to have moved further away from both the US and the EU. Fourth, notwithstanding the progress, the RES innovation base at the EU level is still considerably more fragmented with respect to the US and Japanese systems. For what concerns the results on the EU15 innovation space, two important questions emerge. First, it is possible that they are driven by Germany, which, as explained in Section 3, accounts for 50 percent of the RES innovation in the EU15. Any aggregate trends such as the ones discussed so far could indeed be the result of Germany being a technological leader and thus a relevant source and an intensive user of foreign knowledge. Second, these trends in the fragmentation of the EU innovation space may not be specific to RES, but can rather be common to other energy technologies. We address these questions in the next Section.

6. Robustness

As a first robustness exercise, we single out Germany by estimating our main model with α parameters for Germany separate from the rest of the EU14. This set up allows focusing on any difference between national and international citations within the EU15 while isolating any specific “Germany effect”. Results are presented in Table 4. Columns 1 through 6 are as in Table 3, and again we focus on discussing the results of column 6, pointing out only major differences with other models where relevant.

We find that, over the period 1985-1999, an inventor from any EU14 country was about 2.5 times more likely to cite a national patent compared to US inventors. The corresponding likelihood of domestic citation for Germany is 45 percent. This stark difference between Germany and other EU14 countries is an indication that inventors in most national RES innovation systems in Europe predominantly build on local knowledge. Since EU14 countries were less innovative than the US, Germany or Japan over this period,[18] the high coefficient associated with national citations for EU14 countries indicates that overall Europe was far away from the technological frontier. Furthermore, in the first part of the sample period, EU14 countries sourced relatively little from abroad, especially from other EU14 countries. Indeed, the probability that any EU14 inventor cites an innovation from another EU14 country or from Germany is lower than that of citing a US inventor (28 and 23 percent as opposed to 47 percent). This, taken together with the high coefficient for national citations within the EU14 noted above, is a strong indication that the EU14 innovation system was highly fragmented.

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[17] Our data show a rise in Japanese citations to China and Korea in the second period, but the number of registered patents for these countries is too small to allow for an empirical investigation.

[18] Recall that Germany accounts for roughly 50 percent of EU15 innovation, as mentioned in Section 3.

Table 4 Regression results: RES with EU14 versus Germany.

	(1)	(2)	(3)	(4)	(5)	(6)
Citing/cited country pairs ($\alpha_{i,j}$) (a)						
US citing US	1	1	1	1	1	1
	NA	NA	NA	NA	NA	NA
EU14 citing EU14	0.550***					
	(0.022)					
EU14 citing EU14 (national)		2.020***	2.449***	2.479***	2.411***	2.505***
		(0.097)	(0.207)	(0.209)	(0.203)	(0.214)
EU14 citing EU14 (international)		0.344***	0.273***	0.277***	0.269***	0.280***
		(0.015)	(0.028)	(0.029)	(0.028)	(0.029)
EU14 citing DE	0.268***	0.270***	0.221***	0.224***	0.218***	0.226***
	(0.012)	(0.012)	(0.027)	(0.028)	(0.027)	(0.028)
EU14 citing US	0.339***	0.343***	0.462***	0.467***	0.342***	0.472***
	(0.018)	(0.018)	(0.044)	(0.045)	(0.018)	(0.046)
EU14 citing JP	0.162***	0.163***	0.189***	0.192***	0.163***	0.194***
	(0.009)	(0.009)	(0.027)	(0.027)	(0.009)	(0.028)
DE citing DE	0.432***	0.435***	0.435***	0.441***	0.429***	0.446***
	(0.017)	(0.017)	(0.032)	(0.033)	(0.032)	(0.034)
DE citing EU14	0.304***	0.306***	0.247***	0.250***	0.244***	0.253***
	(0.014)	(0.014)	(0.024)	(0.025)	(0.024)	(0.025)
DE citing US	0.224***	0.224***	0.193***	0.195***	0.224***	0.198***
	(0.011)	(0.011)	(0.017)	(0.018)	(0.011)	(0.018)
DE citing JP	0.179***	0.180***	0.231***	0.233***	0.179***	0.236***
	(0.009)	(0.009)	(0.027)	(0.027)	(0.009)	(0.028)
US citing EU14	0.380***	0.381***	0.307***	0.381***	0.302***	0.315***
	(0.018)	(0.018)	(0.031)	(0.018)	(0.031)	(0.032)
US citing DE	0.259***	0.259***	0.220***	0.258***	0.217***	0.225***
	(0.012)	(0.012)	(0.022)	(0.012)	(0.022)	(0.023)
US citing JP	0.470***	0.468***	0.466***	0.465***	0.468***	0.411***
	(0.027)	(0.027)	(0.027)	(0.027)	(0.027)	(0.057)
JP citing EU14	0.130***	0.130***	0.133***	0.129***	0.131***	0.136***
	(0.008)	(0.008)	(0.017)	(0.008)	(0.017)	(0.018)
JP citing DE	0.149***	0.150***	0.199***	0.149***	0.196***	0.204***
	(0.009)	(0.009)	(0.024)	(0.009)	(0.024)	(0.025)
JP citing US	0.263***	0.265***	0.264***	0.263***	0.265***	0.364***
	(0.014)	(0.014)	(0.014)	(0.014)	(0.014)	(0.036)
JP citing JP	0.816***	0.821***	0.816***	0.813***	0.820***	0.957***
	(0.039)	(0.039)	(0.039)	(0.039)	(0.039)	(0.080)
Citing pattern differences after 2000 (ϕ_{ij}) (b)						
US citing US			0	0	0	0
			NA	NA	NA	NA
EU14 citing EU14 (national)			-0.222***	-0.237***	-0.204***	-0.248***
			(0.074)	(0.072)	(0.075)	(0.073)
EU14 citing EU14 (international)			0.287**	0.264*	0.318**	0.246*
			(0.142)	(0.138)	(0.145)	(0.140)
EU14 citing DE			0.247	0.224	0.276*	0.205

			(0.162)	(0.158)	(0.165)	(0.158)
EU14 citing US			-0.324***	-0.335***		-0.346***
			(0.074)	(0.072)		(0.073)
EU14 citing JP			-0.166	-0.181		-0.194
			(0.126)	(0.124)		(0.123)
DE citing DE			-0.008	-0.026	0.016	-0.042
			(0.081)	(0.078)	(0.082)	(0.081)
DE citing EU14			0.281**	0.259*	0.309**	0.239*
			(0.138)	(0.134)	(0.139)	(0.136)
DE citing US			0.201*	0.181		0.159
			(0.122)	(0.119)		(0.120)
DE citing JP			-0.265***	-0.278***		-0.290***
			(0.092)	(0.090)		(0.090)
US citing EU14			0.312**		0.343**	0.270*
			(0.146)		(0.148)	(0.144)
US citing DE			0.221		0.251*	0.180
			(0.136)		(0.138)	(0.134)
JP citing EU14			-0.032		-0.011	-0.062
			(0.142)		(0.145)	(0.139)
JP citing DE			-0.307***		-0.292***	-0.330***
			(0.093)		(0.095)	(0.091)
JP citing JP						-0.180**
						(0.079)
JP citing US						-0.363***
						(0.072)
US citing JP						0.159
						(0.174)
Decay (β_1) [(b)]	0.263***	0.270***	0.270***	0.270***	0.270***	0.269***
	(0.009)	(0.010)	(0.010)	(0.010)	(0.010)	(0.010)
Diffusion (β_2) [(b)]	0.001***	0.000***	0.000***	0.000***	0.000***	0.000***
	(0.0001)	(0.0001)	(0.0001)	(0.0001)	(0.0001)	(0.0001)
N° of obs.	5616	5967	5967	5967	5967	5967

Notes: [a)] *H_0 is parameter = 1;* [(b)] *H_0 is parameter = 0. ***Significant at 1% level; **Significant at 5% level; *Significant at 10% level*

Since 2000, EU14 countries display trends similar to the one highlighted in the EU15 aggregate regressions. On the one hand, they show a significant reduction in the probability of domestic citation as well as citation to US inventions, the latter being larger than the former. On the other hand, the probability of cross-country/within EU14 citation increases, as does the probability that a German inventor cites a EU14 patents, and the magnitude of these effects are comparable. Furthermore, note that the US appears to be more likely to cite both EU14 countries and Germany, but that the increase is more robust and larger for the former than for the latter (the latter being statistically significant only in column 5).

Interestingly, we find that the negative coefficient associated with Japanese inventors citing the EU15 from year 2000 is fully explained by the lower propensity of Japanese patents to cite German patents. Even more so, the results suggest a weakening of the link between the German and Japanese innovation systems in RES.

We now move to testing whether the results presented for RES are peculiar to this strategic technological field. We do that by estimating all specifications on citations couples in other non-RES energy technologies. Specifically, we consider the highly efficient fossil energy technologies studied in Lanzi et al. (2011). Fossil-based technologies allow producing energy by burning oil, coal or gas in stationary plants.[19] These technologies represent the back-bone of the world energy system: the share of fossil fuel in the global energy mix amounted to 81% in 2013 (IEA, 2015a). The use of fossil fuels as main sources of energy is indeed the main reason behind rising carbon emissions worldwide. In an effort to reduce both energy dependency from fossil-exporting countries (and in particular gas and oil exporters) and anthropogenic emissions, countries have promoted two complementary strategies. On the one hand, governments promoted the development and deployment of RES, as previously mentioned. On the other hand, they pushed to increase the efficiency of fossil-based technologies, which also results in lower carbon intensity.

While RES represent a long-term and carbon-free strategy but entail drastic changes in the way in which energy is currently produced, highly efficient fossil technologies are a cheap medium-term option to address climate and energy security concerns. They significantly reduce emissions per unit of energy in the short-to-medium term and, contrary to the case of RES, they do not imply a significant shift in the energy system.[20] Given their short-to-medium-term potential, many countries provided significant support to the development of energy efficient fossil technologies. This, for instance, was particularly true in the US, partly due to the strength of the fossil fuels lobby.

Hence, in our specific case these technologies represent an interesting comparison to highlight if the developments we described in the previous section are peculiar to RES or more general. As in Lanzi et al. (2011), the efficient fossil technologies we consider here include all the technologies which have significantly improved the efficiency of fossil fuel burning for energy production, namely Integrated Gasification Combined Cycle, Improved Burners, Combined Heat and Power, and such. For a thorough description of these technologies, please refer to Lanzi et al. (2011). The list of IPC codes used to select patents for fossil-based technologies is provided in Appendix A2.

Results of the estimation of all models on efficient fossil technologies are presented in Table 5.

Similarly to what we found in RES, also in fossil energy technologies knowledge flows within the EU appear weaker than knowledge flows within the US and Japan (columns 1 and 2). This result is even more pronounced here than in RES with respect to Japan, which displays a probability of citing domestic fossil patents that is at least 50 percent above the same probability in the US, indicating that Japan relies even more on domestic knowledge than in the case of RES.[21] By contrast, international spillovers to the EU are higher than in the case of RES, and comparable to those of other top inventors for fossil-based technologies. Specifically, overall EU15 countries are as likely to cite a US patent as a Japanese inventor, and roughly as likely to cite a Japanese patent as a US inventor.

Focusing on changes in knowledge spillovers patterns since 2000 (column 6), note that national knowledge flows in fossil technologies within EU15 members became less likely, and the decrease is roughly comparable to that discussed in the case of RES. However, differently from RES, this is accompanied by a 14

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[19] Note therefore that transport technologies are excluded from this sample.

[20] In particular, grid integration of RES is complicated by their variability and by the fact that production is dispersed rather than centralized. Building a carbon-free energy system based on RES thus requires significant investment in upgrading the electricity grid, as well as in complementary technologies that can compensate for the variability of RES. For a thorough discussion of this issues, please see Carrara and Marangoni (2016) and Verdolini et al. (2016).

[21] Note however, that in the case of fossil technologies, international spillovers to and from Japan are higher than in the RES case, with the US being the foreign inventor from which Japan sources more knowledge. Specifically, a Japanese inventor is almost twice as likely to cite a US (or EU15) fossil invention than a US (or EU15) RES patent (columns 1 and 2).

Table 5 Regression Results: Efficient Fossil-based Technologies.

	(1)	(2)	(3)	(4)	(5)	(6)
Citing/cited country pairs ($\alpha i,j$)$^{(a)}$						
US citing US	1	1	1	1	1	1
	NA	NA	NA	NA	NA	NA
EU15 citing EU15	0.370***					
	(0.016)					
EU15 citing EU15 (national)		0.654***	0.715***	0.707***	0.720***	0.731***
		(0.031)	(0.047)	(0.046)	(0.047)	(0.050)
EU15 citing EU15 (international)		0.263***	0.278***	0.274***	0.279***	0.284***
		(0.013)	(0.018)	(0.018)	(0.018)	(0.019)
EU15 citing US	0.350***	0.350***	0.334***	0.330***	0.348***	0.342***
	(0.019)	(0.020)	(0.025)	(0.025)	(0.019)	(0.027)
EU15 citing JP	0.323***	0.324***	0.291***	0.288***	0.322***	0.297***
	(0.023)	(0.023)	(0.029)	(0.029)	(0.023)	(0.030)
US citing EU15	0.311***	0.311***	0.345***	0.310***	0.348***	0.353***
	(0.018)	(0.018)	(0.028)	(0.018)	(0.027)	(0.029)
US citing JP	0.377***	0.376***	0.376***	0.376***	0.375***	0.330***
	(0.027)	(0.027)	(0.027)	(0.027)	(0.027)	(0.037)
JP citing EU15	0.217***	0.217***	0.242***	0.217***	0.243***	0.248***
	(0.016)	(0.016)	(0.022)	(0.016)	(0.022)	(0.023)
JP citing US	0.359***	0.358***	0.358***	0.358***	0.358***	0.390***
	(0.033)	(0.033)	(0.033)	(0.033)	(0.033)	(0.049)
JP citing JP	1.507***	1.513***	1.509***	1.512***	1.507***	1.625***
	(0.096)	(0.097)	(0.097)	(0.097)	(0.096)	(0.133)
Citing pattern differences after 2000 (ϕ_{ij})$^{(b)}$						
US citing US			0	0	0	0
			NA	NA	NA	NA
EU15 citing EU15 (national)			-0.155**	-0.133*	-0.168**	-0.196***
			(0.070)	(0.070)	(0.066)	(0.072)
EU15 citing EU15 (international)			-0.100	-0.076	-0.115	-0.144*
			(0.078)	(0.078)	(0.074)	(0.080)
EU15 citing US			0.081	0.109		0.029
			(0.109)	(0.110)		(0.110)
EU15 citing JP			0.173	0.201		0.117
			(0.154)	(0.156)		(0.152)
US citing EU15			-0.212***		-0.224***	-0.248***
			(0.082)		(0.078)	(0.082)
JP citing EU15			-0.242**		-0.253**	-0.283**
			(0.114)		(0.110)	(0.110)
JP citing JP						-0.142
						(0.110)
JP citing US						-0.185
						(0.143)
US citing JP						0.226
						(0.177)
Decay (β_1)$^{(b)}$	0.278***	0.283***	0.283***	0.283***	0.283***	0.281***
	(0.016)	(0.016)	(0.016)	(0.016)	(0.016)	(0.016)
Diffusion (β_2)$^{(b)}$	0.001***	0.001***	0.001***	0.001***	0.001***	0.001***
	(0.0001)	(0.0001)	(0.0001)	(0.0001)	(0.0001)	(0.0001)
N° of obs.	3,159	3,510	3,510	3,510	3,510	3,510

Notes: $^{a)}$ *H_0 is parameter = 1;* $^{(b)}$ *H_0 is parameter = 0. ***Significant at 1% level; **Significant at 5% level; *Significant at 10% level* percent decrease in cross-country/within EU15 citation intensity for fossil technologies. Furthermore, since 2000 the likelihood that a US or a Japanese inventor cites a EU15 patent decreased by 25 and 28 percent, respectively. All these results show striking differences with respect to RES and point, if anything, to a weakening of the EU positioning with respect to the technological frontier in fossil energy technologies and show no sign of higher interconnectedness between the national knowledge bases of member states.

As a final robustness check, we also tested the sensitivity of the results to the choice of the cut-off point, finding that all our key results hold by changing the date to 1997, i.e. the year of the Kyoto Protocol and the Commission White Paper on renewable sources. Furthermore, our results hold when considering the EU27 countries as opposed to EU15 countries. All these results are available upon request.

7. Discussion and Conclusions

Clean energy production is among the top priorities of the EU, and significant public funding has been spent to support renewable energy development and deployment through direct or indirect support of R&D activities in this field. This paper uses patent citation patterns to shed some light on the degree of integration of the EU15 innovation system in the strategic field of renewable technologies and, more generally, on the degree of knowledge spillovers between top innovators (the US, Japan and the EU15). We provide two key insights.

First, the results emerging from our analysis point to some key weaknesses of the EU15 RES innovation system, which we show to be geographically localized and highly fragmented. Indeed, EU15 inventors rely more on domestic innovation than on spillovers from other EU15 countries. Yet, they are able to build on their domestic knowledge far less than the US or Japan. Finally, knowledge spillovers from EU15 countries are lower as compared to knowledge spillovers from other top inventors.

Second, we show that since 2000 the EU RES innovation space has become more integrated, with citations between EU15 countries growing in importance, while national citations turning less relevant. The EU15 has also increased its role as source of knowledge for the US while being less likely to source knowledge from this top inventor.

Quite importantly, we show that these results are not driven by Germany, but rather by other EU15 countries. Indeed, we find that the fragmentation of EU15 RES innovation system is even more pronounced when considering Germany as a separate country, as the remaining EU14 countries rely predominantly on domestic knowledge. This, combined with the lower patenting rates of EU14 countries as compared to other inventors in our sample, is an indication that overall the quality of EU14 RES innovation is significantly below that of the top RES innovators. However, it is worth noting that EU14 countries are the ones experiencing the most pronounced change in knowledge spillovers after 2000. Indeed, in the second part of our sample period, higher citations to EU14 countries indicate that they became more important as a source of knowledge for themselves as well as for the US, while relying less on knowledge spillovers from the US.

Taken all together, these results indicate that, since 2000, the patterns of knowledge flows in RES technologies have changed, the integration of the EU15 RES innovation system has increased and the EU14 has moved closer to the innovation frontier. These developments are peculiar to the strategic field of RES and do not apply to all power generation technologies. Indeed, we have shown that the patterns of knowledge flows in fossil-based technologies, while still confirming the overall high level of fragmentation in the EU innovation system, do not suggest that this fragmentation is diminishing over time.

While our empirical analysis cannot provide strong causal evidence explaining why RES are experiencing a strengthening of EU knowledge flows and an improvement of the EU15 position with respect to the technological frontier, a likely explanation for these developments can be found in the significant effort that the EU has put towards the development of a sustainable energy system. Over the past decade, Europe has strongly committed to reducing greenhouse gas emissions, and to doing so by promoting the development and deployment of RES. Indeed, the EU is keen to foster the strategic sector of low-carbon technologies as a means to achieve its sustainable growth goals.

In this respect, the EU15, the US and Japan differ significantly in their approach to climate mitigation and in their focus on sustainable development. On the one hand, the US took a very mild stand towards curbing CO2 emissions, relying mostly on soft measures (such as R&D investments and voluntary programs) and focusing in particular on improving the energy efficiency of fossil-based technologies (Carlarne, 2010; Brewer, 2014). Japan displayed a similar pattern, with the scaling up of energy efficiency becoming one of its top policy priorities (Takase and Suzuki, 2011; Moe, 2012). On the other hand, the EU has strongly committed to climate mitigation and decarbonization, as well as to strengthening the EU innovation capabilities and reducing the fragmentation of the EU innovation system. Starting from the late 1990s, among other things, the EU committed to the Kyoto protocol and embarked on the effort to curb emissions by implementing the EU-ETS. Furthermore, EU countries strongly supported renewable energy technologies, introducing mainly demand-pull measures with the 1997 White Paper and following Directives. Renewable technologies are newer, significantly more costly and uncertain than other fossil-based generation technologies, and will require drastic changes in the energy system. To this end, the EU implemented a number of support measures, ranging from feed-in-tariffs, R&D investments and support, green and white certificates, all of which favored a reduction of the price wedge between fossil-based and renewable technologies.

Therefore, our analysis provides suggestive evidence that the commitment of the EU to renewable energy development and deployment supported and promoted stronger integration of the innovation space. As such, climate mitigation comes as an opportunity to strengthen the EU position in the strategic field of RES, eventually resulting in sustainable growth. A caveat to this is that our results also suggest that the process of EU technological integration, although progressing, is advancing at a moderate pace and that innovative activities in RES at the EU level are still poorly integrated if compared to the US or Japan. This indicates that we are still away from the creation of a well-integrated EU innovative system in RES. Given the importance attributed to the integration of the EU innovation system as a means to become a leader innovation hub, a policy prescription emerging from our analysis is that efforts to sustain and increase this process should be pursued. Of course, while we testify an increasing integration of the renewable technology innovation system in the EU15, our evidence is only suggestive of the role that environmental policy and climate mitigation commitment have played in this respect and surely, if any role was indeed played, we cannot say if such developments were achieved in the most cost-effective manner. Further research is indeed necessary to provide evidence in both these respects.

Acknowledgements

Earlier versions of this paper were presented at the Paris Environmental and Energy Economics Seminar and at the GRI Conference on Innovation and Growth. The authors would like to thank Laura Diaz Anadón, David Popp, and Francesco Vona as well as all the participants to seminars and conferences for insightful comments.

Funding: This work was supported by MIUR (Italian Ministry for Education, University and Research) under the research programme “Climate Change in the Mediterranean Region: Evolutionary Scenarios, Economic Impacts, Mitigation Policies and Technological Innovation” (PRIN project 2010-2011) and by the EU FP7 research and innovation programme under grant agreement no. 388329 (ADVANCE) and the EU Horizon 2020 research and innovation programme under grant agreements no.642147 (CD-LINKS) and no. 730403 (INNOPATHS).

Appendix A

A.1. RES technologies - IPC codes

Wind	
B60L8/00	Electric propulsion with power supply from force of nature, e.g. wind
B63H13/00	Effecting propulsion by wind motors driving water-engaging propulsive elements
F03D1/00-06	Wind motors with rotation axis substantially in wind direction
F03D11/00-04	Details, components parts, or accessories not provided for in, or of interest apart from, the other groups of this subclass
F03D3/00-06	Wind motors with rotation axis substantially at right angle to wind direction
F03D5/00-06	Other wind motors
F03D7/00-06	Controlling wind motors
F03D9/00-02	Adaptation of wind motors for special use
Solar	
B60K16/00	Arrangements in connection with power supply of propulsion units in vehicles from force of nature, e.g. sun
B64G1/44	Cosmonautic vehicles - Arrangements or adaptations of power supply systems using radiation, e.g. deployable solar arrays
E04D13/18	Aspects of roofing for the collection of energy – i.e. Solar panels
F03G6/00-08	Devices for producing mechanical power from solar energy
F24J2/00-54	Use of solar heat, e.g. solar heat collectors
F25B27/00	Machine plant or systems using particular sources of energy – sun
F26B3/28	Drying solid materials or objects by processes involving the application of heat by radiation - e.g. sun
H01G9/20	Light-sensitive device
H01L25/00-04	Assemblies consisting of a plurality of individual semiconductor or other solid state devices
H01L31/04-078	Semiconductor devices sensitive to infra-red radiation, light - adapted as conversion devices
H02N6/00	Generators in which light radiation is directly converted into electrical energy

Waste

C10B53/02	Destructive distillation of cellulose-containing materials
C10J3/86	Prod. of combustible gases – combined with waste heat boilers
C10L5/46-48	Solid fuels based on materials of non-material origin – refuse or waste
F02G5/00-04	Hot gas or combustion – Profiting from waste heat of exhaust gases
F12K25/14	Plants or engines characterized by use of industrial or other waste gases
F23G5/46	Incineration of waste – recuperation of heat
F23G7/10	Incinerators or other apparatus consuming waste – field organic waste
F25B27/02	Machine plant or systems using particular sources of energy – waste
H01M8/06	Manufacture of fuel cells – combined with treatment of residues

Geothermal

F03G4/00-06	Devices for producing mechanical power from geothermal energy
F03G7/04	Mechanical-power-producing mechanism -- using pressure differences or thermal differences occurring in nature
F24J3/00-08	Other production or use of heat, not derived from combustion - using natural or geothermal heat
H02N10/00	Electric motors using thermal effects

Hydro

B62D5/06	Power-assisted or power-driven steering -- using pressurized fluid for most or all the force required for steering a vehicle
B62D5/093	Power-assisted or power-driven steering -- Characterized by means for actuating valve - Telemotor driven by steering wheel movement
E02B3/00	Engineering work in connection with control or use of streams, rivers, coasts, or other marine sites; sealings or joints for engineering work in general
E02B3/02	Stream regulation, e.g. breaking up subaqueous rock, clearing the beds of waterways, directing the water flow
E02B9/00-06	Water-power plants
F01D1/00	Non-positive-displacement machines or engines, e.g. stream turbines
F02C6/14	Gas-turbine plants having means for storing energy, e.g. for meeting peak loads
F03B13/08	Machines or engines aggregates in dams or the like; Conduits therefor
F03B13/10	Submerged units incorporating electric generators or motors
F03B17/06	Other machines or engines using liquid flow, e.g. of swinging-flap type
F03B3/00	Machines or engines of reaction type (i.e. hydraulic turbines)
F03B3/04	Machines or engines of reaction type with substantially axial flow throughout rotors, e.g. propeller turbine
H02K7/18	Structural association of electric generators with mechanical driving motors, e.g. with turbines

Ocean

E02B9/08	Tide or wave power plants
F03B13/12-26	Submerged units incorporating electric generators or motors characterized by using wave or tide energy
F03B7/00	Water wheels
F03G7/05	Mechanical-power producing mechanism -- ocean thermal energy conversion

Biomass

B01J41/16	Anion exchange - use of materials, cellulose or wood
C10L1/14	Liquid carbonaceous fuels; Gaseous fuels; Solid fuels
C10L5/40-44	Solid fuels essentially based on materials of non-mineral origin - animal or vegetables substances
F02B43/08	Engines operating on gaseous fuels from solid fuel - e.g. wood

A.2. Efficient fossil-based technologies - IPC codes

Coal gasification

C10J3	Production of combustible gases containing carbon monoxide from solid carbonaceous fuels

Improved burners [all these classes not in combination with B60, B68, F24, F27]

F23C1	Combustion apparatus specially adapted for combustion of two or more kinds of fuel simultaneously or alternately, at least one kind of fuel being fluent
F23C5/24	Combustion apparatus characterized by the arrangement or mounting of burners; disposition of burners to obtain a loop flame.
F23C6	Combustion apparatus characterized by the combination of two or more combustion chambers (using fluent fuel)
F23B10	Combustion apparatus characterized by the combination of two or more combustion chambers (using only fluent fuel)
F23B30	Combustion apparatus with driven means for agitating the burning fuel; combustion apparatus with driven means for advancing the burning fuel through the combustion chamber
F23B70	Combustion apparatus characterized by means for returning solid combustion residues to the combustion chamber
F23B80	Combustion apparatus characterized by means creating a distinct flow path for flue gases or for non-combusted gases given off by the fuel
F23D1	Burners for combustion of pulverulent fuel
F23D7	Burners in which drops of liquid fuel impinge on a surface
F23D17	Burners for combustion simultaneously or alternatively of gaseous or liquid or pulverulent fuel

Fluidized bed combustion

B01J8/20-22	Chemical or physical processes in general, conducted in the presence of fluids and solid particles; apparatus for such processes; with liquid as a fluidizing medium
B01J8/24-30	Chemical or physical processes in general, conducted in the presence of fluids and solid particles; apparatus for such processes; according to “fluidized-bed” technique
F27B15	Fluidized-bed furnaces; Other furnaces using or treating finely-divided materials in dispersion
F23C10	Apparatus in which combustion takes place in a fluidized bed of fuel or other particles

Improved boilers for steam generation

F22B31	Modifications of boiler construction, or of tube systems, dependent on installation of combustion apparatus; arrangements or dispositions of combustion apparatus
F22B33/14-16	Steam generation plants, e.g. comprising steam boilers of different types in mutual association; combinations of low- and high-pressure boilers

Improved steam engines

F01K3	Plants characterized by the use of steam or heat accumulators, or intermediate steam heaters, therein
F01K5	Plants characterized by use of means for storing steam in an alkali to increase steam pressure, e.g. of Honigmann or Koenemann type
F01K23	Plants characterized by more than one engine delivering power external to the plant, the engines being driven by different fluids

Superheaters

F22G	Steam superheating characterized by heating method

Improved gas turbines

F02C7/08-105	Features, component parts, details or accessories; heating air supply before combustion, e.g. by exhaust gases
F02C7/12-143	Features, component parts, details or accessories; cooling of plants
F02C7/30	Features, component parts, details or accessories; preventing corrosion in gas-swept spaces

Combined cycles

F01K23/02-10	Plants characterized by more than one engine delivering power external to the plant, the engines being driven by different fluids; the engine cycles being thermally coupled
F02C3/20-36	Gas turbine plants characterized by the use of combustion products as the working fluid; using special fuel, oxidant or dilution fluid to generate combustion products
F02C6/10-12	Plural gas-turbine plants; combinations of gas-turbine plants with other apparatus; supplying working fluid to a user , e.g. a chemical process, which returns working fluid to a turbine of the plant

Improved compressed-ignition engines [all these classes not in combination with B60, B68, F24, F27]

F02B1/12-14	Engines characterized by fuel-air mixture compression; with compression ignition
F02B3/06-10	Engines characterized by air compression and subsequent fuel addition; with compression ignition
F02B7	Engines characterized by the fuel-air charge being ignited by compression ignition of an additional fuel
F02B11	Engines characterized by both fuel-air mixture compression and air compression, or characterized by both positive ignition and compression ignition, e.g. in different cylinders
F02B13/02-04	Engines characterized by the introduction of liquid fuel into cylinders by use of auxiliary fluid; compression ignition engines using air or gas for blowing fuel into compressed air in cylinder
F02B49	Methods of operating air-compressing compression-ignition engines involving introduction of small quantities of fuel in the form of a fine mist into the air in the engine's intake

Cogeneration

F01K17/06	Use of steam or condensate extracted or exhausted from steam engine plant; returning energy of steam, in exchanged form, to process, e.g. use of exhaust steam for drying solid fuel of plant
F01K27	Plants for converting heat or fluid energy into mechanical energy
F02C6/18	Plural gas-turbine plants; combinations of gas-turbine plants with other apparatus; using the waste heat of gas-turbine plants outside the plants themselves, e.g. gas-turbine power heat plants
F02G5	Profiting from waste heat of combustion engines
F25B27/02	Machines, plant, or systems using waste heat, e.g. from internal-combustion engines

References

Bacchiocchi, E., Montobbio, F., 2010. International knowledge diffusion and home-bias effect: do USPTO and EPO patent citations tell the same story? The Scandinavian Journal of Economics 112, 441-470.

Balconi, M., Breschi, S., Lissoni, F., 2004. Networks of inventors and the role of academia: an exploration of Italian patent data. Research Policy 33, 127-145.

Borghesi, S., Crespi, F., D'Amato, A., Mazzanti, M., Silvestri, F., 2015. Carbon abatement, sector heterogeneity and policy responses: evidence on induced eco innovations in the EU. Environmental Science & Policy 54, 377-388.

Bosetti, V., Verdolini, E., 2013. Clean and dirty international technology diffusion. Working Paper 2013.43 Fondazione Eni Enrico Mattei, Milan.

Bottazzi, L., Peri, G., 2003. Innovation and spillovers in regions: evidence from European patent data. European Economic Review 47, 687-710.

Brahmbahatt, M., Hu, A.G.Z., 2009. Ideas and innovation in East Asia. World Bank Research Observer 25(2), 177-20.

Brewer, T.L., 2014. The United States in a Warming World. The Political Economy of Government, Business, and Public Responses to Climate Change. Cambridge University Press, New York.

Caballero, R.J., Jaffe, A.B., 1993. How high are the giants' shoulders: An empirical assessment of knowledge spillovers and creative destruction in a model of economic growth. NBER Macroeconomics Annual 1993, vol.8.

Carlarne, C. P., 2010. Climate Change Law and Policy. EU and US Approaches. Oxford University Press, New York.

Cantner, U., Graf, H., Herrmann, J., Kalthaus, M., 2016. Inventor networks in renewable energies: the influence of the policy mix in Germany. Research Policy. 45, 1165-1184.

Carrara, S., Marangoni, G., 2016. Including system integration of variable renewable energies in a constant elasticity of substitution framework: the case of the WITCH model. Energy Economics. Forthcoming.

Cassiman, B., Veugelers, R., 2006. In search of complementarity in innovation strategy: internal R&D and external knowledge acquisition. Management Science 52, 68-82.

Corsatea, T.D., 2014. Technological capabilities for innovation activities across Europe: evidence from wind, solar and bioenergy technologies. Renewable and Sustainable Energy Reviews 37, 469-479.

Dechezleprêtre, A., Glachant, M., Ménière, Y., 2013. What drives the international transfer of climate change mitigation technologies? Empirical evidence from patent data. Environmental and Resource Economics 54, 161-178.

Dechezleprêtre, A., Martin, R., Mohnen, M., 2014. Knowledge spillovers from clean and dirty technologies. CEP Discussion Paper No. 1300, Centre for Economic Performance, LSE, London.

Drivas, K., Economidou, C., Karkalakos, S., Tsionas, E.G., 2016. Mobility of knowledge and local innovation activity. European Economic Review 85, 39-61.

Duguet, E., MacGarvie, M., 2005. How well do patent citations measure flows of technology? Evidence from French Innovation Survey. Economics of Innovation and New Technology 14, 375-393.

EEA (European Environmental Agency), 2012. Greenhouse gas emission trends and projections in Europe 2012 – Tracking progress towards Kyoto and 2020 targets. EEA Report 6/2012, Copenhagen.

EEA (European Environmental Agency), 2016. Renewable energy in Europe 2016 – Recent growth and knock-on effects. EEA Report 4/2016, Copenhagen.

European Commission, 1997. Energy for the future: Renewable sources of energy. White Paper for a community strategy and action plan. COM(97) 599 final.

European Commission, 2007. A European Strategic Energy Technology Plan (SET-PLAN). COM(2007) 723 final.

European Commission, 2010. Europe 2020 Flagship Initiative Innovation Union . COM(2010) 1161.

European Commission, 2015. Towards an Integrated Strategic Energy Technology (SET) Plan: Accelerating the European energy system transformation. COM(2015) 6317 final.

Fischer, M.M., Scherngell, T., Jansenberger, E., 2009. Geographic localization of knowledge spillovers: evidence from high-tech patent citations in Europe. The Annals of Regional Science 43, 839-858.

Griliches, Z., 1990. Patent statistics as economic indicators: a survey. Journal of Economic Literature 28, 1661-1707.

Helm, S., Tannock, Q., Iliev, I., 2014. Renewable energy technology: Evaluation and policy implications – Evidence from patent literature. Global Challenges Report. WIPO, Genève.

Hu, A-G.Z., 2009. The regionalization of knowledge flows in East Asia: evidence from patent citations data. World Development 37, 1465-1477.

Hu, A.G.Z., Jaffe, A.B., 2003, Patent citations and international knowledge flow: the cases of Korea and Taiwan. International Journal of Industrial Organization 21, 849-880.

IEA (International Energy Agency), 2015a. World Energy Outlook 2015. OECD/IEA, Paris.

IEA (International Energy Agency), 2015b. Energy and Climate Change: World Energy Outlook Special Report. OECD/IEA, Paris.

IEA (International Energy Agency), 2015c. World Economic Outlook – Policy Databases, http:/www.worldenergyoutlook.org/weomodel/policydatabases.

Jaffe, A.B., Fogarty, M.S., Banks, B.A., 1998. Evidence from patents and patent citations on the impact of NASA and other federal labs on commercial innovation. Journal of Industrial Economics 46, 183-205.

Jaffe, A.B, Trajtenberg, M., Henderson, R., 1993. Geographic localization of knowledge spillovers as evidenced by patent citations. Quarterly Journal of Economics 108, 577-598.

Jaffe, A.B., Trajtenberg, M., 1996. Flows of knowledge from universities and federal laboratories: modeling the flow of patent citations over time and across institutional and geographic boundaries. NBER Working Paper n. 5712, National Bureau of Economic Research, Cambridge MA.

Jaffe, A.B., Trajtenberg, M., 1999. International knowledge flows: evidence from patent citations. Economics of Innovation and New Technologies 8, 105-136.

Jaffe, A.B., Trajtenberg, M., Fogarty, M.S., 2000. Knowledge spillovers and patent citations: evidence from a survey of inventors. American Economic Review 90, 215-218.

Johnstone,N., Hascic, I., Popp, D., 2010. Renewable energy policies and technological innovation: evidence based on patent count. Environmental and Resource Economics 45, 133-155.

Lanzi, E., Verdolini, E., Haščič, I., 2011. Efficiency-improving fossil fuel technologies for electricity generation: data selection and trends. Energy Policy 39, 7000-7014.

Lee, G., 2006. The Effectiveness of International Knowledge Spillover Channels. European Economic Review 50, 2075-2088.

LeSage, J.P., Fischer, M.M., Scherngell, T., 2007. Knowledge spillovers across Europe: evidence from a Poisson spatial interaction model with spatial effects. Papers in Regional Science 86, 393-421.

Li, Y.A., 2014. Borders and distance in knowledge spillovers: dying over time or dying with age? Evidence from patent citations. European Economic Review 71, 152-172.

Mancusi, M.L., 2008. International spillovers and absorptive capacity: a cross-country cross-sector analysis based on patents and citations. Journal of International Economics 76, 155-165.

Maurseth, P.B., Verspagen, B., 2002. Knowledge spillovers in Europe: a patent citations analysis. The Scandinavian Journal of Economics 104, 531-545.

Moe, E., 2012. Vested interests, energy efficiency and renewables in Japan. Energy Policy 40, 260-273.

Nesta, L., Vona, F., Nicolli, F., 2014. Environmental policy, competition and innovation in renewable energy. Journal of Environmental Economics and Management 67, 396-411.

Nicolli, F., Vona, F., 2016. Heterogeneous policies, heterogeneous technologies: the case of renewable energy. Energy Economics 56, 190-204.

Noailly, J., Shestalova, V., 2016. Knowledge spillovers from renewable energy technologies: lessons from patent citations. Environmental Innovation and Societal Transitions. Forthcoming.

OECD, 2012. Energy and climate policy. Bending the technological trajectory. OECD Studies in Environmental Innovation, Paris.

OECD Patent Statistics, http://www.oecd-ilibrary.org/science-and-technology/data/oecd-patent-statistics_patent-data-en.

Peri, G., 2005. Determinants of knowledge flows and their effect on innovation. Review of economics and Statistics 87, 308-322.

Pillu, H., Koléda, G., 2011. Determinants of innovation in efficient and renewable energy technologies. Economie & prévision 197-198, 105-128.

Popp D., 2006. International innovation and diffusion of air pollution technologies: the effects of NOx and SO2 regulation in the US, Japan and Germany. Journal of Environmental Economics and Management 51, 46-71.

Ruester, S., Schwenen, S., Finger, M., Glachant, J.M., 2014. A post-2020 EU energy technology policy: revisiting the strategic energy technology plan. Energy Policy 66, 209-217.

Takase, K., Suzuki, T., 2011. The Japanese energy sector: current situation, and future paths. Energy Policy 39, 6731-6744.

Verdolini, E., Galeotti, M., 2011. At home and abroad: an empirical analysis of innovation and diffusion in energy technologies. Journal of Environmental Economics and Management 61, 119-134.

Verdolini, E., Vona, F., Popp, D., 2016. Bridging the gap: do fast reacting fossil technologies facilitate renewable energy diffusion? NBER Working Paper n. 22454, National Bureau of Economic Research, Cambridge MA.

WIPO (World Intellectual Property Organization), 2009. Patent-based Technology Analysis Report - Alternative Energy Technologies, WIPO, Genève.

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