Energy Economics xxx (2016) xxx–xxx

Contents lists available at ScienceDirect

Energy Economics

journal homepage: www.elsevier.com/locate/eneeco

Heterogeneous policies, heterogeneous technologies: The case of renewable energy☆

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ARTICLE INFO

Article history:
Received 27 July 2014
Received in revised form 6 March 2016
Accepted 12 March 2016
Available online xxxx

JEL classification:
Q55
Q58
Q42
Q48
O34

Keywords:
Renewable energy technology
Environmental innovation
Heterogeneous policy effect
Feed-in tariff
Renewable energy certificates
Entry barrier

ABSTRACT

This paper investigates empirically the effect of market regulation and renewable energy policies on innovation activity in different renewable energy technologies. For the EU countries and the years 1980 to 2007, we built a unique dataset containing information on patent production in eight different technologies, proxies of market regulation and technology-specific renewable energy policies. Our main finding is that, compared to privatisation and unbundling, reducing entry barriers is a more significant driver of renewable energy innovation, but that its effect varies across technologies and is stronger in technologies characterised by potential entry of small, independent power producers. In addition, the inducement effect of renewable energy policies is heterogeneous and more pronounced for wind, which is the only technology that is mature and has high technological potential. Finally, ratification of the Kyoto protocol, which determined a more stable and less uncertain policy framework, amplifies the inducement effect of both energy policy and market liberalisation.

1. Introduction

Innovation commonly is regarded as the best way to sustain current standards of living while overcoming severe environmental concerns. This is especially relevant in the case of energy, where increasing resource scarcity calls for the rapid development of alternative energy sources, notably Renewable Energy (RE). Although RE cannot currently compete with fossil fuels in terms of production costs, impressive technological progress is paving the way to promising new sources such as biomass and solar energy, among others. Countries have also developed areas of specialisation in specific types of RE sources. For example, Denmark has established a strong technological advantage in wind technologies, whereas Sweden and Germany have specialised in bioenergy, Germany and Spain in solar, and Norway and Austria in hydropower.

In addressing the issue of how technological advantages have emerged for RE, the economic literature emphasises the key role of public policies in fostering environmental innovation. Moving from these premises, assessing the effects of targeted environmental policies and/or energy prices on environmental innovations has been the main goal of most empirical research (Jaffe et al., 2003). The seminal contribution of Johnstone et al. (2010) (henceforth JHP) emphasises how guaranteed price schemes and investment incentives appear to play a major role in the early phases of technological development, whereas for relatively more mature technologies, i.e. wind, obligations and quantity-based instruments appear to be more effective policy tools. More recently, Nesta et al. (2014) found a significant effect of energy market liberalisation on innovation in RE technologies (RETs). This result implies that, given the characteristics of the energy market, in which the core competences of the incumbent are generally tied to fossil fuel plants whereas the production of RE is mainly decentralised in small-sized units, the entry of non-utility generators made possible by market liberalisation has increased the incentives to innovate for specialised suppliers of electric equipment, such as wind turbines or solar cells.

However, much less attention has been paid to the heterogeneous effects that equal policy or equal market stimulus exerts on different RETs. A first step in this direction is the study by Lee and Lee (2013), who proposed a taxonomy of RETs according to a set of indicators

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☆ The authors want to thank seminars participants at the ZEW energy conference, the 20th EAERE conference, the IEB Symposium on R&D and Energy and at the WCERE 5th World Congress of Environmental and Resource Economists for useful comments and suggestions. FV gratefully acknowledges the funding received from the European Union's Seventh Framework Programme for research, technological development and demonstration under grant agreement no 320278 (RASTANEWS).

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http://dx.doi.org/10.1016/j.eneco.2016.03.007

Please cite this article as: Nicolli, F., Vona, F., Heterogeneous policies, heterogeneous technologies: The case of renewable energy, Energy Econ. (2016), http://dx.doi.org/10.1016/j.eneco.2016.03.007

derived from the innovation literature, and use it to study the similarities and differences across technologies.[1] This taxonomy identifies six types of innovation patterns depending on market structure and degree of technological maturity and potential. For instance, Lee and Lee show that, with the exception of solar Photovoltaic (PV) and geothermal energy, the market structure of innovators in RETs tends to be level (innovators are close competitors, with similar shares of patents granted), which means, among other things, that late entrants can still gain technological leadership of the market (Lee and Lee, 2013). This result suggests that the aggregate effect of deregulation found in Nesta et al. (2014) could be heterogeneous across technologies. They show also that RETs differ in terms of their technological potential, measured here as growth in number of patents, which can influence the magnitude of the inducement effect exerted by policy on different technologies and, consequently, its overall profitability.

This paper extends the previous research in three directions. First, building on the results of Lee and Lee (2013), we exploit their taxonomy to study how the market and policy effects identified in the literature differ across the eight different RETs. This analysis is important, first, because it disentangles the heterogeneous factors underlying aggregate innovation dynamics in RE and, second, because it helps in designing customised policy interventions for each specific technologies. In particular, we expect a different degree of technological maturity and technological potential to influence the inducement effect of renewable energy policies (REPs). We expect also that the increase in competition due to deregulation is expected to have a positive effect on the innovation performance of ‘level’ manufacturing industries[2] where firms tend to innovate to escape competition and a negative effect on ‘un-level’ industries where stronger competition reduces the post-innovation rents of laggard firms and decreases innovation (Aghion et al., 2005; Sanyal and Ghosh, 2013). Moreover, we expect the effect of lower entry barriers to be stronger in those renewable technologies that, by nature, are more suited to small-scale generation and, consequently, are characterised by the entry of small independent power producers following liberalisation, such as in the cases of wind and solar energy (Jacobsson and Bergek, 2004; Lehtonen and Nye, 2009).

Second, our analysis extends JHP by testing the role of market liberalisation and employing a dynamic specification which accounts for the accumulated stock of knowledge. At the same time, we extend Nesta et al. (2014) analysis by allowing for differences in the effects of REPs across technologies and considering the effects of disaggregated policy instruments (Renewable Energy Certificates (RECs), feed-in tariffs, public Research and Development (R&D) expenditure and single index summarising remaining REPs — see Section 3.2 for more details). We also split the single Product Market Regulation (PMR) index used by Nesta et al. (2014) into its three sub-components, namely, ownership, entry barriers and vertical integration, and we test them separately. Energy market liberalisation is a long and complex process, involving myriad aspects that can exert opposite effects on the development of RE (e.g. Pollitt, 2012). These effects can be captured best using these three sub-indexes rather than a single indicator. In particular, we expect that the increased competition derived from lowering entry barriers and granting to independent power producers free access to the grid, thus, favouring the development of decentralised energy production, should act as a positive incentive for innovation especially in wind and solar thermal energy. In contrast, privatisation and unbundling should favour the emergence of large players and, thus, could have an ambiguous effect on innovation in RETs since large players usually are tied to large-scale plants using coal, nuclear or gas as the primary energy input.

Third, endogeneity is an unresolved issue. Nesta et al. (2014) show empirically that historical successful innovation in clean energy increases the power of green lobbies towards policy makers. Since here we consider different REPs rather than a single REP index, finding good instruments for each endogenous policy is difficult. We hence rely on a different strategy and indirectly address the issue of policy endogeneity using the ratification of the Kyoto protocol as an exogenous shock for national-level policies in a difference-in-difference setting. To ensure that Kyoto effect has been incorporated into the national policy framework, we consider only countries that are members of the European Union, where ratification is enforced by all states. Although this strategy cannot provide a definitive quantification of the policy effect, it allows us to assess whether the results are qualitatively robust.

To address the issues discussed above, we constructed a cross-country dataset covering eight RE technologies (geothermal, hydroelectric, marine, wind, solar thermal, solar PV, biofuel and waste) and 19 European countries covering the period 1980–2007. The paper is organised as follows: Section 2 defines the main determinants of RE innovations; Section 3 describes the data used in the analysis; Section 4 presents the empirical strategy; and Section 5 discusses the main results. Section 6 concludes the paper.

2. Heterogeneous determinants of renewable energy innovations

Establishing comparative advantage in a given RE technology depends on a host of factors. Sub-section 2.1 is concerned with the effect of environmental policy, Sub-section 2.2 describes the role of market structure and liberalisation and Sub-section 2.3 exploits Lee and Lee's (2013) taxonomy to discuss the rationale behind the expected heterogeneous effect of policy and market factors on RE innovation.

2.1. Environmental policies and innovation

Early theoretical studies on the impact of environmental policies on firms' competitiveness emphasise the static trade-off between firm competitiveness and compliance with environmental regulation (for a review, see Jaffe and Stavins, 1995). This idea was criticised in the seminal study by Porter and van der Linde (1995), which considering the dynamic effect of regulation on the incentive to innovate, predicts a different effect of environmental regulation on firm competitiveness. In particular, the so-called Porter hypothesis, in its ‘weak’ version (as defined by Jaffe and Palmer, 1997), argues that environmental regulation fosters innovation, while no expectations can be formulated *ex-ante* on the effect of regulation on firm competitiveness.[3]

The implications of these studies are of particular interest in the context of a growing, but still limited sector such as renewables, where, in the absence of a public intervention, production costs are generally higher compared to fossil fuel energy sources. In this case, the inducement effect of environmental policy is expected to act through several channels. First, both quota systems and demand subsidies, which increase the market for RE, are expected to stimulate innovation thanks to the higher expected return from R&D investments (Popp et al., 2009). Second, since innovative activities in RE sectors are characterised by a high degree of uncertainty in all phases of product life cycle, any policies able to reduce this uncertainty can be expected to spur innovation. More specifically, in the early phase of technological development, manufacturer producers may under-invest in emerging RETs if they are uncertain about outcomes and the economic relevance of their R&D activity. Technology-specific policy support, such as R&D subsidies, can reduce this source of uncertainty and sustain the development of a broader spectrum of RETs. In the mature phase, when the new green technologies are exposed to competition with established incumbent

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[1] This taxonomy has been created by applying a cluster analysis to energy-technology patents filed at the USPTO over the years 1991–2010.

[2] In line with Aghion et al. (2005), by level we mean an industry in which innovators are close competitors which hold similar market share.

[3] This effect operates through several channels. First, regulation reduces uncertainty in environmental pollution activities; second, it signals to firms potential technological improvements and potential resources inefficiencies; third, it induces cost-saving innovation in order to minimise compliance costs. The Porter hypothesis has been the focus of several studies; a good review is Ambec et al. (2013).

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technologies, energy producers may under-invest in renewables if they are uncertain about their future costs, technical development or their overall profitability. In this case, quota systems can be a good tool to defend and support further market development of renewables (on this point see Midttun and Gautesen, 2007).

Finally, in line with the theory, the development of green technologies is subject to two types of market failure: environmental externalities and knowledge externalities due to the low appropriability of innovation. In this context, environmental policies alone, although necessary to internalise the social costs of Greenhouse Gases (GHG) and other pollutants, are not sufficient. Consequently, an optimal policy portfolio should include at least one instrument for each of the abovementioned market failures, such as a tradable permit scheme and R&D subsidies (Jaffe et al., 2005; Fischer and Newell, 2008; Acemoglu et al., 2012). The effect of REPs on innovation is the precise aim of the abovementioned work of JHP and Nesta et al. (2014), to which we refer for further reference.

2.2. Market structure, liberalisation and renewable energy innovation

The relationship between innovation and competition has been thoroughly analysed in the vast economic literature on endogenous growth (e.g., Boone, 2000, 2001; Aghion and Howitt, 1998). The argument proposed by first-generation models, which claims imperfect competition to enhance the appropriability of R&D investments, has been challenged by a new strand of literature offering a more problematic view of this relationship. Aghion et al. (2001, 2005) develop models showing that an escaping competition effect counterbalances the standard appropriability (or Schumpeterian) effect. In line with this logic, increased competition can reduce the firm's pre-innovation rents more than its post-innovation rents, thereby increasing the profit from innovation activities and R&D expenditure aimed at escaping competition (Aghion et al., 2005). In their view, whether the traditional Schumpeterian effect or the escaping competition effect prevails depends mainly on the industry structure of the innovators. Incumbents are induced to invest more in R&D if the competitive pressure from new entrants is higher and if they are operating in a level industry (where firms are neck-to-neck competitors — Aghion et al., 2005), while the increased pressure from new entrants discourages R&D investments in unlevel markets where laggard incumbents have competences that are too distant from those needed to imitate the leading-edge technologies.

Sanyal and Ghosh (2013) investigate how the deregulation of the US electricity market affected the patenting propensity of upstream equipment manufacturers (i.e. General Electric), which are acknowledge to be the key innovation actors in the electricity sector. They find a negative effect and, also, their rich dataset allows them to distinguish between a positive appropriation effect and a pure Schumpeterian effect. The former occurs because stronger competition in wholesale market increases the bargaining power of upstream specialised suppliers and, thus, their innovative efforts. The appropriation effect tends to be stronger the more non-utility generator actors enter the wholesale market. These new actors (i.e. farmers, firms, small communities, municipalities, households, environmental activists) are generally specialised in decentralised energy production such as combined generation, local heating systems and renewable sources. Hence, the entry of non-utility generators and the associated appropriation effect are expected to be significantly stronger for RETs with respect to general electricity due to the high lock-in of incumbents to fossil fuel technologies, and the orientation of entrants in the energy market towards RE, generally produced by medium- and small-sized firms (David and Wright, 2003; Lehtonen and Nye, 2009).

Among the three components of the PMR index used by Nesta et al. (2014), in particular, we expect that lowering entry barriers will trigger an increase in RE innovation. This prediction is supported by anecdotal evidence for wind and solar technologies suggesting that the entry of new actors contributed to the creation and diffusion of new knowledge (Jacobsson and Bergek, 2004). In contrast, there is no consensus about the expected effect of unbundling, i.e. the separation of ownership between energy generation and other segments of the industry. On the one hand, unbundling, which increases the competition in energy markets, should spur innovation. On the other hand, the financial resources made available by the sale of vertically integrated assets might provide financial resources for mergers, acquisitions and horizontal integration, which can become a barrier to the diffusion of decentralised energy production and the entry of new players (Pollitt, 2008), thus, inhibiting RE innovation. Finally, privatisation may not necessarily result in the development of RETs for several reasons. First, private companies might be less willing to internalise the pollution externalities stemming from traditional energy sources through the development of RE. Second, private companies tend to be engaged in short-term research rather than in the fundamental research needed to develop RETs.[4] As a result, we expect a market characterised by low entry barriers and a certain degree of public ownership to be a more fertile context for the development of renewable energy technologies. On the role of vertical unbundling we have, on the contrary, no a priori expectations.

2.3. Heterogeneous effects

To better understand the evolution of renewable energy technologies, we believe it is important to take a step forward and study how the two mechanisms highlighted above vary across different RETs. We draw on the taxonomy proposed by Lee and Lee (2013) and use the indicators employed in their analysis to propose a set of implications that are testable in a rigorous econometric setup.

First, we expect the effect of lowering entry barriers to depend on the degree of concentration of innovation among firms, which in the work by Lee and Lee (2013) is measured using an index called 'developer intensity'. Technically, this indicator is computed as the ratio of patents granted by the top five most active patenting firms, to all the patents in that technology. Thus, it can be regarded as a proxy for the structure of the upstream electric equipment manufacturer industry. A low level of the index means innovation activities are spread among firms and there are no technology leaders; a high level of the index means the industry is not levelled and has a few leaders and several followers. Consequently, we expect an escaping competition effect to prevail in the first 'levelled' case, and a Schumpeterian effect to prevail in the second case. According to Lee and Lee's (2013) taxonomy, technologies such as solar thermal, waste and wind are characterised by low developer intensity, geothermal and PV technology show high developer intensity, and the remaining technologies are between these two. Also, we expect the magnitude of the appropriation effect described in the previous section to differ across technologies and to be stronger in RETs where renewable energy production is decentralised in small- or medium-sized units. This applies to wind and solar energy, which, in the 1980s, showed a high degree of distributed generation.[5] In these cases, lowering entry barriers is more likely to induce the entry of independent power producers, which would increase the rents of upstream electricity equipment manufacturers. In contrast, we expect the appropriation effect to be weaker or absent for technologies such as hydro energy, which, being generally implemented by large utilities with large sized plants, are less likely to experience the entry of small-scale producers after liberalisation. This brings us to the first testable hypothesis:

Hypothesis 1. *The effect of lowering entry barriers on innovation activities is expected to be positive for wind, solar thermal and waste technologies, which are characterised by both lower developer intensity and the entry of many independent producers.*

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[4] Jamasb and Pollitt (2008) is generally sceptical about the incentives of private companies to engage in R&D projects with long-term payback.

[5] Jacobsson and Johnson (2000), Jacobsson and Bergek (2004) and Nilsson et al. (2004) provide anecdotal evidence of the sustained entry of new small producers of wind turbines in Sweden, the Netherlands, Denmark and Germany in the 1970s and 1980s, before the liberalisation process began. Q12

Note that the effect of lowering entry barriers on solar PV is mainly an empirical issue. On the one hand, it should be negative or absent in the presence of few well-established leaders. On the other hand, it should be positive if PV generation is highly decentralised.

The second issue is related to the heterogeneous effect of REPs and was investigated in the seminal paper of JHP. Standard economic theory leads to the conclusion that economic instruments generally are more efficient than regulatory mechanisms at promoting technical change (Jaffe et al., 2003). Technical change allows firms to reduce the costs of complying with emissions taxes or other economic instruments, while regulation does not provide any incentive to reduce emissions via technological change beyond the standards imposed. Also, different instruments produce a different effect in terms of how the surplus is distributed. For instance, feed-in tariffs, which increase the energy producer surplus, stimulate demand for upstream innovation. Conversely, quantity-based systems do not directly generate a surplus for producers, which, consequently, are not encouraged to demand more innovations from upstream equipment manufacturers (Menanteau et al., 2003). These results have been contested in some recent contributions. Fischer et al. (2003) find a clear-cut and unique ranking of policy instruments is infeasible because the inducement effect of different policies depends on several industry-specific factors such as innovation cost, innovator's ability to appropriate other firms' innovations and the number of firms in the market. Bauman et al. (2008) show that under certain circumstances, command and control policies may induce more innovation than market-based instruments. However, applied work, such as JHP, stresses that in the case of RE, it is not just the distinction between price and quota systems that matters but also the degree of the technological maturity of the different RETs.[6] Quantity-based policies, e.g. RE certificates, tend to promote more mature and cost-effective technologies, such as wind, geothermal and solar technologies, which guarantee lower short-run compliance costs. Since firms are likely to choose technologies that are close to the market or technologies in which they already have a competitive advantage, the incentive for long-run research in less cost-competitive and emerging technologies (such as solar PV or ocean energy) will be fairly low. On the other hand, technology-specific policies, such as public R&D, and technology-specific price systems, e.g. feed-in tariffs, which allow differentiation and the specific pricing of individual technologies, might be able to support emerging technologies such as solar PV. Consequently, the second hypothesis is:

Hypothesis 2. *The effect of broad policies is stronger for mature technologies, while emerging technologies are more responsive to technology-specific instruments.*

The magnitude of these effects can depend on the intrinsic characteristics of different RETs and, in particular, on their technical potential, intended here as achievable energy generation given system performance, environmental, land-use and physical constraints. It is reasonable to assume that energy operators will tend to react more promptly to policy and market stimuli directed at sustaining the development of more promising technologies, in terms of both their natural availability and expected technological growth. This is especially true for more mature technologies that have advanced beyond the initial experimentation and learning phases and are more consolidated in the market. For instance, some recent contributions on the optimal energy mix (Zubi, 2011) show that a policy portfolio based on a high share of wind and solar energy (especially PV) seems to be a valid choice in order to meet European carbon emissions standards at an acceptable cost. This result depends on their specific resource availability[7] and the rapid technological growth they experienced in the early stage of development. On the same point, Lee and Lee (2013) highlights that wind, solar, marine and biofuel have been characterised in the past by a rapid surge in patenting and, for this reason, they classify them as high technological potential RETs.[8] From our reading of these contributions, we expect the magnitude of the policy inducement effect or the increasing size of the energy market more generally, to be stronger for technologies with high technological potential — and particularly wind and solar. However, to our knowledge, a precise index of technological potential is currently unavailable, making it difficult to imagine a formal test of this hypothesis. As a consequence, we take this into consideration as additional descriptive evidence of the heterogeneous effect of different factors on RET developments.

3. Data, measurement issues and descriptive evidence

The set of variables to be included in the empirical analysis concerns a potentially large host of factors, ranging from innovation measurement to policy type, in addition to the more traditional macroeconomic characteristics. Table 5 at the end of this section summarises the variables used and presents the basic descriptive statistics.

3.1. Innovative activity indicator

We use patent counts to proxy for innovation performance. This choice is consistent with prior studies on RE innovations such as Popp et al. (2011), JHP and Nesta et al. (2014). We refer to patents filed at the European Patent Office (EPO) in the eight sub-fields: wind, marine, solar thermal, solar PV, biofuels, hydroelectric, fuels from waste, geothermal and marine.[9] We aggregate these patents to form a pooled panel which varies across technologies, time and countries. The choice of adopting patents filed at the EPO is particularly attractive for studying innovative activity in European countries: first, it avoids home country bias issues[10] (Dernis and Kahn, 2004); second, we expect patents filed at the EPO generally to be of high quality and to have homogeneous economic value,[11] and third, it eliminates potential bias due to different legal and institutional contexts.[12]

Figs. 1 and 2 present patent count trends for the eight RETs from 1980 to 2007. All technologies experienced a visible surge in patenting after ratification of the Kyoto protocol in 1997, marked by a line on the graphs. This rise was particularly evident in technologies with high potential such as solar, wind and biofuel, which is coherent with our third research hypothesis. Prior to 1997, patenting activity in biofuels, wind, marine and geothermal energy appeared relatively flat

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[6] Note here that building a precise ranking of the degree of maturity of different RETs is not straightforward, especially because the broad technological classification employed in this paper may include several sub-categories at different levels of development (e.g. offshore wind energy is less mature than onshore, and in relation to biomass, ethanol production from sugar and starch is more mature than liquid biofuel production from algae — on this see Edenhofer et al., 2011). Generally, by technological maturity we refer to the position of the considered RET in the product life cycle. An immature technology is generally one at an early stage of development, characterised by a high level of R&D-based experimentation, with huge potential for learning and improvement. These technologies often do not have a wide commercial deployment, are harder to integrate with existing energy systems and are not cost effective compared to fossil fuel alternatives. However, cost maturity does not necessarily imply cost competitiveness.

[7] Zubi (2011) refers to European countries only.

[8] In particular, the authors refer here to a specific index of technological potential, defined in Holger (2003), which is measured as the average patent growth rate of a technology. They believe this measure can be used to proxy for innovation potential.

[9] These eight sub-fields have been chosen accordingly to the OECD classification of environmental related technologies (ENVTECH), which is based on IPC classes. Patent have been assigned to country by "Applicant" in the year of first priority. If a patent included applicants located in different countries we split the count accordingly.

[10] This effect is due to the fact that inventors almost always file first for protection in their home country, resulting in the majority of patents filed at national offices coming from domestic inventors.

[11] Inventors seeking protection abroad, which is more costly than patenting solely in their home country, generally expect higher returns from their inventions.

[12] E.g., up to 1988, the Japanese patent system required a single patent application for each separate claim (Ordover, 1991), which resulted in a higher number of patent applications from a single invention with respect to the European and US systems.

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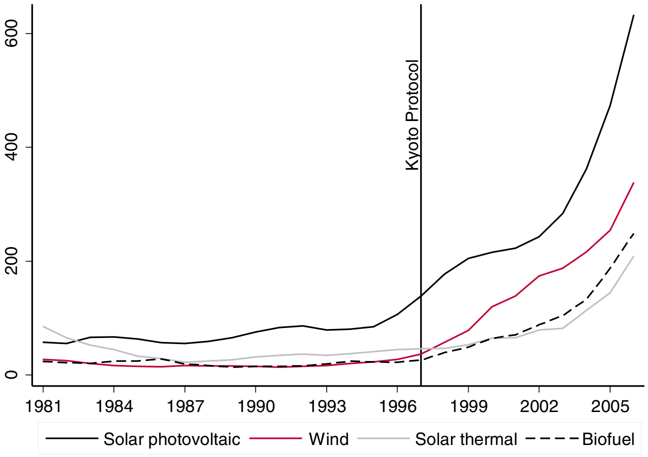

Fig. 1. Patent trends for solar PV, wind, solar thermal and biofuel. Years 1980–2007.

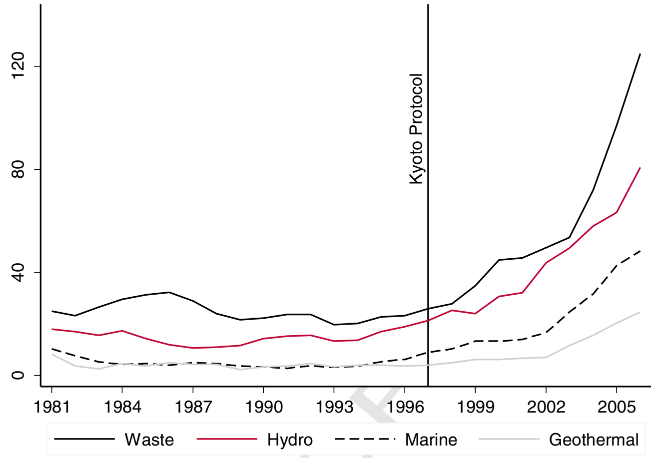

Fig. 2. Patent trends for waste, hydro, marine and geothermal. Years 1980–2007.

but slightly steeper for the other technologies, especially solar PV and waste. The predominance of wind, solar PV and solar thermal technologies, which account for 24%, 25% and 18% of total patenting respectively, is confirmed also in Table 1. Biofuel is ranked 4th with a share of 12%. As expected, the main innovators in Europe are Germany, France, the UK, Denmark and the Netherlands, which generally show similar technological specialisation with respect to the European average (see Tables 1 and 2).[13] Nevertheless, there are some remarkable differences, including the lower share of wind patents in France with respect to the average, lower share of solar patents in Denmark, and the relevant role of patenting in fuel from waste technologies in eastern European countries, Finland and Denmark.

3.2. Environmental policy

Concerning environmental policy data, we refer here to the database on public policies for RE compiled by the International Energy Agency (IEA) and used by JHP. This database and the related IEA (2004) publication contain detailed fact sheets at country level, which make it possible to construct adoption dummies reflecting the chronology of policy implementation, for most OECD countries. One limitation of this dataset is that it provides information on year of adoption, but does not specify the degree of intensity of the policy adopted. We hence integrate this information with other available data on policies measured on a continuous scale. This seems to be possible for the following three instruments: public renewable R&D expenditures (R&D), feed-in tariff schemes (FEED-IN) and RECs. Information on the first instrument is available from the IEA-OECD dataset, while data on feed-in tariffs was collected from several sources including two reports compiled by the IEA (2004) and Cerveny and Resch (1998), and two websites on RE regulations.[14] Finally, our measure of the stringency of RECs is the variable constructed by JHP, which reflects the share of electricity that must be generated by renewables or covered by RECs.

In this work, we consider the following policy instruments:

1) *government R&D expenditure* on each specific RET;
2) *incentive (feed-in) tariffs*, i.e. prices above the market tariffs for a certain number of years guaranteed by government. Tariffs vary across technologies;
3) *investment incentives*, i.e. capital grants and all other measures aimed at reducing the capital costs of adopting RETs, generally provided from state budgets;
4) *tax measures* used to either encourage production or discourage consumption (e.g. tax credits or property tax exemptions);
5) *voluntary programmes* adopted at country level by different stakeholders, i.e. government, public utilities and energy suppliers, which agree to buy energy generated from renewable sources;
6) *obligations* which place a requirement on suppliers to provide a share of their energy supply from renewables;
7) *renewable energy certificates*, which are tradable certificates generally used to track or document compliance with the quota system.

Our analysis includes continuous variables for policies for which information is available (RECs, feed-in tariffs and public R&D support).[15] For all other policies, as in JHP, we set the variable "OTHER POL" equal to 1 if any of them is present in a given country in a given year. Finally, we construct a dummy variable equal to 1 after the signing of the Kyoto protocol in 1997 and zero before (KYOTO), which captures country expectations about both the future policy context for climate change mitigation and the size of the market for renewables (Popp et al., 2011).

Policy support for RE follows a similar path of development in all European countries. The first wave of policies began in the late 1970s and early 1980s and most likely was a response to the two oil crises. The main instruments developed at that time were public R&D and investment incentives (included in our OTHER POL variable) (see Table 3). In the 1990s, a second wave of policies emerged, composed mainly of feed-in tariffs and tax measures, while the following decade was characterised by the development of quota systems and RECs, which were reinforced by EU Directive 2001/77/EC.[16] It should be noted that the stringency of policy support has increased (see Table 3), while the ranking across technologies has remained unchanged. Table 4 shows that for feed-in tariffs, the two solar technologies and wind have received the strongest support, while public subsidies for R&D have always been higher for biofuels and solar technologies.

3.3. Market liberalisation

To measure market competition, we use the OECD index for Product Market Regulation (PMR AGGREGATE), which combines information on barriers to entrepreneurship and administrative regulation (e.g., licences and permits, administrative burdens and legal barriers), state control (e.g., price control and ownership), and barriers to trade and foreign

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[13] The shaded areas in Tables 1 and 2 represent the three main specialisations in each country in terms of share of patents.

[14] http://www.ren21.net/ and http://www.res-legal.de.

[15] It must be noted that due to data constraints, the data on both feed-in tariffs and R&D do not vary between solar PV and solar thermal. In both cases, the available data generally refer to solar energy.

[16] This directive established the first shared framework for the promotion of electricity from renewable sources at the European level and encouraged the development of RECs.

Table 1
Total count of patent by country and share of each technology on total Renewable Energy patenting. Solar PV, wind, solar thermal and biofuel. Shaded area represent the three main country specialisation (in terms of share of patents).

Country	Total patent	Solar photovoltaic		Wind		Solar thermal		Biofuel	
		Count	Share of total patent	Count	Share of total patent	Count	Share of total patent	Count	Share of total patent
Germany	2985	**912**	**0.31**	**745**	**0.25**	**602**	**0.20**	205	0.07
France	767	**244**	**0.32**	89	0.12	**147**	**0.19**	**103**	**0.13**
United Kingdom	655	**140**	**0.21**	**112**	**0.17**	73	0.11	**101**	**0.15**
Denmark	503	6	0.01	**299**	**0.59**	26	0.05	**112**	**0.22**
Netherlands	459	**157**	**0.34**	68	0.15	**69**	**0.15**	**69**	**0.15**
Italy	383	**88**	**0.23**	**59**	**0.15**	**90**	**0.24**	56	0.15
Spain	307	**43**	**0.14**	**135**	**0.44**	**73**	**0.24**	16	0.05
Austria	266	**42**	**0.16**	25	0.09	**64**	**0.24**	26	0.10
Sweden	245	23	0.09	**70**	**0.29**	**42**	**0.17**	**34**	**0.14**
Belgium	197	**63**	**0.32**	**38**	**0.19**	22	0.11	**36**	**0.18**
Finland	134	20	0.15	**21**	**0.16**	10	0.07	**41**	**0.31**
Ireland	68	6	0.09	5	0.07	9	0.13	**10**	**0.14**
Greece	48	**9**	**0.18**	**11**	**0.23**	**9**	**0.18**	8	0.17
Luxembourg	40	6	0.14	**7**	**0.18**	**14**	**0.34**	3	0.08
Portugal	37	3	0.08	**7**	**0.19**	**8**	**0.22**	**7**	**0.19**
Hungary	32	2	0.06	3	0.09	**12**	**0.37**	3	0.08
Czech Republic	20	0	0.00	1	0.05	2	0.10	**8**	**0.40**
Poland	17	0	0.00	1	0.06	**3**	**0.18**	**4**	**0.24**
Slovak Republic	12	0	0.00	1	0.09	**3**	**0.26**	1	0.09
Total	7172	1762	0.25	1695	0.24	1276	0.18	839	0.12

Table 2
Total count of patent by country and share of each technology on total Renewable Energy patenting. Waste, hydro, marine and geothermal. Shaded area represent the three main country specialisation (in terms of share of patents).

Country	Total Patent	Waste		Hydro		Marine		Geothermal	
		Count	Share of total patent	Count	Share of total patent	Count	Share of total patent	Count	Share of total patent
Germany	2985	303	0.10	135	0.05	19	0.01	65	0.02
France	767	94	0.12	70	0.09	16	0.02	6	0.01
United Kingdom	655	62	0.09	94	0.14	70	0.11	6	0.01
Denmark	503	**33**	**0.07**	12	0.02	16	0.03	0	0.00
Netherlands	459	55	0.12	25	0.05	8	0.02	10	0.02
Italy	383	36	0.09	29	0.08	17	0.04	9	0.02
Spain	307	9	0.03	12	0.04	18	0.06	2	0.01
Austria	266	37	0.14	**58**	**0.22**	3	0.01	11	0.04
Sweden	245	21	0.09	25	0.10	20	0.08	10	0.04
Belgium	197	20	0.10	13	0.07	1	0.01	5	0.03
Finland	134	**26**	**0.19**	7	0.05	7	0.05	2	0.01
Ireland	68	8	0.12	**17**	**0.25**	**13**	**0.19**	0	0.00
Greece	48	3	0.06	5	0.10	4	0.08	0	0.00
Luxembourg	40	**8**	**0.19**	3	0.08	0	0.00	0	0.00
Portugal	37	4	0.11	6	0.16	2	0.05	0	0.00
Hungary	32	**4**	**0.12**	2	0.06	2	0.06	**5**	**0.15**
Czech Republic	20	**6**	**0.28**	**3**	**0.12**	0	0.00	1	0.05
Poland	17	**6**	**0.35**	0	0.00	0	0.00	**3**	**0.18**
Slovak Republic	12	**3**	**0.26**	**3**	**0.22**	1	0.09	0	0.00
Total	7172	735	0.10	516	0.07	215	0.03	135	0.02

Please cite this article as: Nicolli, F., Vona, F., Heterogeneous policies, heterogeneous technologies: The case of renewable energy, Energy Econ. (2016), http://dx.doi.org/10.1016/j.eneco.2016.03.007

Table 3
Average value (across technologies) of different REPs by Country in the three decades (In Log). Shaded areas highlight positive values.

Country	FEED-IN			RECs			R&D			OTHER POL		
	80–89	90–91	00–07	80–89	90–91	00–07	80–89	90–91	00–07	80–89	90–91	00–07
Austria	0.00	**0.02**	**0.13**	0.00	0.00	**1.92**	**0.58**	**0.63**	**0.87**	0.00	**0.80**	**1.00**
Belgium	0.00	**0.03**	**0.10**	0.00	0.00	**1.01**	**0.85**	**0.31**	**0.80**	0.00	**0.80**	**1.00**
Czech Republic	0.00	0.00	**0.10**	0.00	0.00	0.00	0.00	0.00	**0.13**	0.00	**0.90**	**1.00**
Denmark	0.00	**0.02**	**0.01**	0.00	0.00	**1.90**	**0.42**	**1.00**	**1.06**	**1.00**	**1.00**	**1.00**
Finland	0.00	0.00	0.00	0.00	0.00	0.00	0.00	**0.45**	**0.64**	0.00	**1.00**	**1.00**
France	0.00	**0.00**	**0.03**	0.00	0.00	0.00	**0.53**	**0.71**	**1.61**	**1.00**	**1.00**	**1.00**
Germany	0.00	**0.05**	**0.09**	0.00	0.00	0.00	**1.86**	**1.95**	**2.13**	**0.50**	**1.00**	**1.00**
Greece	0.00	**0.04**	**0.05**	0.00	0.00	0.00	0.00	**0.32**	**0.61**	0.00	0.00	0.00
Hungary	0.00	0.00	**0.08**	0.00	0.00	0.00	0.00	**0.02**	**0.37**	0.00	**0.40**	**1.00**
Ireland	0.00	0.00	**0.01**	0.00	0.00	0.00	**0.00**	**0.08**	**0.30**	**0.60**	**1.00**	**1.00**
Italy	0.00	**0.04**	**0.01**	0.00	**0.11**	**1.14**	**1.64**	**1.44**	**1.34**	**0.80**	**1.00**	**1.00**
Luxembourg	0.00	**0.04**	**0.05**	0.00	0.00	0.00	0.00	**0.03**	**0.13**	0.00	**0.60**	**1.00**
Netherlands	0.00	0.00	**0.03**	0.00	**0.43**	**1.44**	**1.32**	**1.49**	**1.67**	0.00	**1.00**	**1.00**
Poland	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Portugal	**0.01**	**0.07**	**0.18**	0.00	0.00	0.00	**0.58**	**0.31**	**0.18**	0.00	**0.50**	**1.00**
Slovak Republic	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	**0.00**	0.00	0.00	0.00
Spain	0.00	**0.06**	**0.14**	0.00	0.00	0.00	**1.56**	**1.25**	**1.41**	0.00	0.00	**1.00**
Sweden	0.00	**0.00**	**0.01**	0.00	0.00	**1.76**	**1.46**	**0.84**	**1.21**	0.00	**0.60**	**1.00**
United Kingdom	0.00	0.00	0.00	0.00	0.00	**0.84**	**1.51**	**1.10**	**1.35**	0.00	0.00	**1.00**

Note: Values equal to zero mean that the given policy has not been enforced in the respective Country in the considered time period.

direct investment (e.g., tariffs and ownership barriers). In the present paper, the main sectors of interest are electricity (ISIC 4010) and, to a lesser extent, gas (ISIC 4020). The PMR indexes for electricity and gas essentially combine three sub-indexes ranging from 0 to 6 (maximum anticompetitive regulation). The first is ownership (PMR PUB OWN), which takes five values: private (0), mostly private (1.5), mixed (3), mostly public (4.5) and public (6). The second is an index for entry barriers (PMR ENTRY), which combines information on third-party access to the grid (regulated (0), negotiated (3), no access (6)) and minimum consumer size to freely choose suppliers (from 'no threshold' (0) to 'no choice' (6)). The third component is vertical integration (PMR VERT INT), ranging from unbundling (0) to full integration (6).

Fig. 3 depicts PMR patterns for selected countries and shows the widespread reduction of market regulation, especially in the 1990s. Entry barriers almost disappeared in all countries at the end of the period analysed, but vertical unbundling is still not completed in the EU countries. Privatisation is not a smooth process and shows important cross-country differences. Fig. 3 highlights that in the 1970s, Germany and Spain had a certain degree of privatisation, while in France and Denmark, for instance, state ownership is still widespread (Pollitt, 2012).

Table 4
Average value (across countries) of different REPs by technology in the three decades (In Log).

Country	Feed-in			R&D		
	80–89	90–91	00–07	80–89	90–91	00–07
Biofuel	0.01	0.02	0.05	0.97	1.12	1.51
Geothermal	0.01	0.02	0.03	0.63	0.29	0.37
Hydro	0.01	0.02	0.03	0.01	0.10	0.18
Marine	0.01	0.01	0.02	0.17	0.10	0.20
Solar photovoltaic (PV) energy	0.01	0.03	0.11	1.23	1.23	1.49
Solar thermal energy	0.01	0.03	0.11	1.23	1.23	1.49
Waste	0.01	0.01	0.03	0.00	0.00	0.40
Wind	0.01	0.03	0.05	0.94	0.95	1.01

Note: Only technologies specific policies are considered.

3.4. Other variables

Popp (2002) emphasises the importance of accounting for the dynamics of knowledge stock in policy inducement studies. This result is reinforced by Aghion et al. (2012), who show that past knowledge, creating a lock-in effect, influences the choice between clean and dirty technologies and partially inhibits policy inducement. To account for this effect, we include in our specification a patent stock that varies across countries, technologies and time (K STOCK).[17] We also test the robustness of our results to the use of a standard measure of knowledge stock varying over time, but not across countries (K STOCK GLOBAL). This second measure captures the evolution of the global capacity to innovate rather than the local country capacity.[18] In addition to the core variables, we add a consolidated set of controls, which include per capita income levels (GDP_pc) and electricity consumption (ELECT CONS). The first is a proxy for the willingness to pay for a clean environment (Diekmann and Franzen, 1999),[19] the second captures a simple market size effect (JHP). We expect both variables to have a positive effect on innovation. We control also for electricity prices (ELECT PRICE), which, in line with the literature on induced innovation (Popp, 2002; Newell et al., 1999), we expect will be positively correlated with innovation incentives.[20] Finally, we introduce a dummy reflecting EU enlargement history, which takes a value equal to 1 from the year when the country joined the EU (ENLARG), and controls for structural heterogeneity and the different policy settings of new entrant countries.

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[17] Similarly to previous work on patent data (Popp et al., 2011; Lovely and Popp, 2011), we measure the knowledge capital of country *i* at time *t* for each technology *k* based on the following equation: $K\ Stock_{i,k,t} = \sum_{s=0}^{\infty} e^{-\beta 1(s)}(1 - e^{-\beta 2(s+1)})PAT_{i,k,t-s}$. We set the rate of knowledge obsolescence to 0.1 ($\beta 1 = 0.1$) and the rate of knowledge diffusion to 0.25 ($\beta 2 = 0.25$). As a result, we obtain a knowledge stock that varies by country, year and technology.

[18] This second variable is constructed according to the following equation $K\ Stock_{k,t} = \sum_{s=0}^{\infty} e^{-\beta 1(s)}(1 - e^{-\beta 2(s+1)})PAT_{k,t-s}$ and is identical to the one used in Popp et al. (2011).

[19] Recent micro-level empirical evidence suggests that the willingness to pay higher prices for green energy would seem to be positively related to per capita income and education (Roe et al., 2001; Wiser, 2007).

[20] Following JHP, we argue that because RE represents only a small portion of total electricity generation, the price of electricity can be considered exogenous.

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Table 5
Descriptive statistics.

Acronim	Description	Obs	Mean	St. Dev.	Min	Max
Patent at the EPO						
SOLAR_PV	Solar photovoltaic	532	3.2	11.4	0	153
SOLAR_TH	Solar thermal	532	2.2	6.2	0	77
WIND	Wind	532	3.1	10.9	0	131
HYDRO	Hydroelectric	532	0.9	2.2	0	27
GEOTHERMAL	Geothermal	532	0.2	1.1	0	15
MARINE	Marine and Ocean	532	0.3	1.1	0	14
BIOFUEL	Biofuel	532	1.5	3.5	0	35
WASTE	Fuel from waste	532	1.3	3.3	0	39
ELEC PRICE	Average of Households and industrial energy end use price, USD ppp/unit. (Log).	520	0.09	0.03	0.03	0.18
ELEC CONS	Average of Households and industrial electricity consumption, GWh per capita. (Log)	532	1.5	0.4	0.77	2.6
GDP	Gross Domestic Product per capita. USD 2006 prices and PPP. (Log).	515	3.1	0.3	2.1	4.4
PMR AGGREGATE	Product Market Regulation, average electricity and gas Sector.	520	4.3	1.6	0	6
PMR ENTRY	Product Market Regulation, average electricity and gas Sector. Sub-index: Entry Barrier	520	4.1	2.1	0	6
PMR VERT INT	Product Market Regulation, average electricity and gas Sector. Sub-index: Vertical Integration	532	4.4	1.7	0	6
PMR PUB OWN	Product Market Regulation, average electricity and gas Sector. Sub-index: Public Ownership	532	4.3	1.6	0	6
Technology-specific public R&D expenditure. USD 2006 prices and PPP. (Log).						
R&D	SOLAR_PV	532	1.3	1.4	0	5.1
R&D	SOLAR_TH	532	1.3	1.4	0	5
R&D	WIND	532	0.9	1.1	0	4.1
R&D	HYDRO	532	0.1	0.2	0	2.4
R&D	GEOTHERMAL	532	0.4	0.7	0	3.6
R&D	MARINE	532	0.1	0.4	0	3.1
R&D	BIOFUEL	532	1.1	1.1	0	4.2
R&D	WASTE	532	0.1	0.4	0	4.1
Technology-specific feed-in tariff. USD 2006 prices and PPP. (Log).						
FEED-IN	SOLAR_PV	532	0.04	0.09	0	0.47
FEED-IN	SOLAR_TH	532	0.04	0.09	0	0.47
FEED-IN	WIND	532	0.02	0.04	0	0.15
FEED-IN	HYDRO	532	0.01	0.03	0	0.11
FEED-IN	GEOTHERMAL	532	0.01	0.03	0	0.17
FEED-IN	MARINE	532	0.01	0.04	0	0.44
FEED-IN	BIOFUEL	532	0.02	0.03	0	0.14
FEED-IN	WASTE	532	0.01	0.02	0	0.11
KYOTO	Kyoto Protocol dummy	532	0.39	0.48	0	1
RECs	Share of electricity covered by a tradable permit. (Log)	532	0.16	0.54	0	3.04
OTHER POL	Adoption dummy for other REPs	532	0.53	0.49	0	1
Lagged knowledge stock						
K STOCK	SOLAR_PV	532	8.7	26.32	0	295.1
K STOCK	SOLAR_TH	532	8.2	18.8	0	164.7
K STOCK	WIND	532	7.5	22.7	0	91
K STOCK	HYDRO	532	3.1	5.1	0	38.4
K STOCK	GEO	532	0.7	1.6	0	17.8
K STOCK	MARINE	532	1.1	2.1	0	24.8
K STOCK	BIOFUEL	532	4.4	7.4	0	63.5
K STOCK	WASTE	532	4.9	9.9	0	91
K STOCK GLOBAL	SOLAR_PV	532	164.01	136.1	18.5	571.9
K STOCK GLOBAL	SOLAR_TH	532	156.31	60.9	42.6	348.5
K STOCK GLOBAL	WIND	532	142.5	142.1	13.6	579.8
K STOCK GLOBAL	HYDRO	532	58.7	33.2	9.9	154.2
K STOCK GLOBAL	GEO	532	14.3	6.5	5.1	38.2
K STOCK GLOBAL	MARINE	532	21.2	15.1	3.8	68.5
K STOCK GLOBAL	BIOFUEL	532	83.1	56.8	7.5	257.5
K STOCK GLOBAL	WASTE	532	93.7	44.3	9.7	205.3
ENLARG	Dummy for new entrant in the EU	532	0.2	0.4	0	1

4. Empirical strategy

Our econometric analysis includes 19 EU countries[21] over the years 1980–2007. The choice of referring to EU countries guarantees a highly homogeneous political and institutional framework, reducing the possibility of bias from unobservable institutional and political variables on estimated effects. Our main analysis is based on specification 1 below, which is applied to the eight different technologies. We take the logarithmic transformations of all the variables in the analysis to mitigate for potential outliers and provide coefficients that are easier to interpret. In contrast to JHP,[22] we disaggregate patents into more subfields to better capture the specificity of each technology.

The benchmark specification for each technology k is:

$$\begin{aligned}\mathrm{EPO\_PAT}_{it} = f(&\beta_1 \mathrm{K\ STOCK}_{it\text{-}1} + \beta_2 \mathrm{PMR\ ENTRY}_{it} + \beta_3 \mathrm{PMR\ VERT\ INT}_{it} \\ &+ \beta_4 \mathrm{PMR\ PUB\ OWN}_{it} + \beta_5 \mathrm{Log\ R\&D}_{it} + \beta_6\ \mathrm{Log\ FEED\text{-}IN}_{it} \\ &+ \beta_7 \mathrm{KYOTO}_{it} + \beta_8 \mathrm{Log\ RECs}_{it} + \beta_9 \mathrm{OTHER\ POL}_{it} \\ &+ \beta_{10}\ \mathrm{LogELECT\ PRICE}_{it} + \beta_{11}\ \mathrm{Log\ ELECT\ CONS}_{it} \\ &+ \beta_{12} \mathrm{Log\ GDP\_pc}_{it} + \beta_{13} \mathrm{ENLARG}_{it} + \beta_i + \beta_t),\end{aligned} \tag{1}$$

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[21] Finland, Greece, Italy, Luxembourg, Sweden, the UK, Austria, the Czech Rep., France, Hungary, the Netherlands, Portugal, Belgium, Denmark, Germany, Ireland, Spain, Poland, and the Slovak Republic.

[22] JHP considers only 5 technologies, pooling together biomass and waste and the two solar technologies.

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Table 6
Technological sub-sample.

	Wind	Solar_th	Solar_PV	Marine	Hydro	Biofuel	Geothermal	Waste
K STOCK	0.0039***	0.0092**	−0.0036**	−0.1115***	−0.0024	−0.0184*	−0.1005	0.0195***
	(0.0013)	(0.0040)	(0.0018)	(0.0390)	(0.0181)	(0.0103)	(0.0921)	(0.0059)
PMR ENTRY	−0.2405***	−0.1413*	−0.0960	−0.0855	0.0959	−0.0751	−0.3270	0.0129
	(0.0705)	(0.0726)	(0.0606)	(0.1373)	(0.1014)	(0.0766)	(0.2425)	(0.0854)
PMR VERT INT	0.1082	−0.0934	0.1298*	0.1643	−0.1652	−0.0263	0.3428	−0.0810
	(0.0694)	(0.0869)	(0.0775)	(0.1534)	(0.1213)	(0.0760)	(0.2694)	(0.0956)
PMR PUB OWN	0.0600	0.0207	−0.0503	−0.2086	−0.0140	0.0063	0.1229	−0.0564
	(0.0707)	(0.0646)	(0.0602)	(0.1373)	(0.0898)	(0.0751)	(0.2144)	(0.0814)
R&D	0.3198***	0.0054	0.0968	0.4111**	0.3600	0.1666**	0.1111	−0.0554
	(0.0742)	(0.0766)	(0.0708)	(0.1980)	(0.2741)	(0.0768)	(0.2600)	(0.1050)
FEED-IN	−5.0025**	−0.8592	1.5440***	−10.3654*	2.9548	−0.0210	−0.2011	2.8425
	(2.0575)	(0.5869)	(0.5780)	(5.6795)	(2.6000)	(2.1857)	(4.2731)	(3.6925)
KYOTO	1.0542**	0.1342	1.9649***	1.5505*	0.7505	1.7038***	2.4133	0.5473
	(0.4965)	(0.4779)	(0.4749)	(0.9070)	(0.6580)	(0.5929)	(1.7388)	(0.5429)
RECs	0.1100*	0.1938**	−0.0886	−0.2727**	−0.1796	−0.0589	−0.1430	0.0080
	(0.0662)	(0.0847)	(0.0845)	(0.1366)	(0.1121)	(0.0774)	(0.2827)	(0.1012)
OTHER POL	0.1791	0.2623	0.4142**	1.0488***	0.1956	0.4505**	0.1990	0.1827
	(0.2116)	(0.1843)	(0.1863)	(0.3991)	(0.2514)	(0.2053)	(0.6746)	(0.1910)
ELEC PRICE	−3.7448	9.1864**	14.3594***	3.5062	4.4071	15.4684***	9.1358	3.7185
	(4.4063)	(4.2926)	(3.8492)	(9.4867)	(6.2890)	(4.7205)	(13.0994)	(4.8740)
ELEC CONS	0.1998	2.0008***	2.0909**	3.1956*	−0.7365	1.1801	2.8881	1.6076*
	(0.6487)	(0.6719)	(0.8967)	(1.8755)	(1.4082)	(1.0308)	(2.4253)	(0.8605)
GDP_pc	1.7942	1.5128*	−1.2488	0.8518	3.5998***	0.2730	−0.9729	2.0857**
	(1.1472)	(0.8581)	(1.0836)	(1.6638)	(1.3068)	(1.0664)	(4.0254)	(0.9636)
ENLARG	−0.4683*	−0.4486*	0.2711	−0.6014	0.2461	−0.3641	−0.4113	0.2570
	(0.2585)	(0.2421)	(0.3834)	(0.5255)	(0.3619)	(0.2662)	(0.6531)	(0.2626)
Country FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
N	495	495	448	429	475	495	346	495

Table 6 bis. Technological sub-sample. Estimations for PMR AGGREGATE and GLOBAL K STOCK only.

	Wind	Solar_th	Solar_PV	Marine	Hydro	Biofuel	Geothermal	Waste
PMR	−0.2528***	−0.2391***	−0.0163	−0.0650	−0.0945	−0.1060	0.1262	−0.1313*
AGGREGATE	(0.0730)	(0.0727)	(0.0589)	(0.1006)	(0.0849)	(0.0763)	(0.1815)	(0.0793)
GLOBAL	0.0026	0.0067*	0.0033**	0.0458***	0.0132	0.0066	0.0713	0.0135
K STOCK	(0.0019)	(0.0036)	(0.0015)	(0.0141)	(0.0135)	(0.0048)	(0.0668)	(0.0090)
Country FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
N	495	495	448	429	475	495	346	495

Negative binomial estimations. Standard error in parenthesis. All regressions include year and country effects.

* Indicate significance at 10% level.

** Indicate significance at 5% level.

*** Indicate significance at 1% level.

where EPO_PAT_{it} is the number of patent applications filed at the EPO by country i at time t in the eight RETs analysed. Fixed effects are calculated on the country unit i. Time-fixed effects are included in all the specifications to control for common time shocks. As Popp et al. (2011) highlight, time trends or year-fixed effects rule out the possibility that the knowledge stock (K STOCK), which, by construction, grows through time, picks up only other tendencies for investment to increase over time. Following Aghion et al. (2012), we lag knowledge stock by one year to account for possible contemporaneous feedback and delayed effects. Overall, this specification enriches previous work by JHP, by accounting for the dynamics of past innovation stock and reflecting the degree of market liberalisation through the inclusion of the PMR variables.

The range of controls added to the main specifications, along with country-fixed effects, should eliminate several time-varying sources of unobservable heterogeneity that might bias the estimation of the effect of PMR and REPs on innovation. However, reverse causality and measurement error could induce a bias in the estimated coefficient. First, there is a mutual reinforcement effect, initially recognised by Downing and White (1986), which might generate reverse causality: if innovation in environmental technologies follows the implementation of effective policy support and liberalisation of the energy market, progress in the generation of RE will, in its turn, reinforce the lobbying power of innovating firms and the associations of RE producers, calling for more policy support and greater liberalisation. In addition, a negative feedback effect could emerge since policy-induced technological change can influence the dynamics of policy support via various channels. For instance, in the German case, the unexpectedly high rate of development of solar PV energy driven by a decrease in the marginal cost of production led policy makers to underestimate the social costs of the feed-in tariff scheme and to adapt the design of the policy accordingly (Hoppmann et al., 2014). Second, the specific design of REPs is heterogeneous across countries and our variable, which mainly considers stringency, cannot fully account for these characteristics. Hence, omitted variables bias might plague the estimated relationship between policy and innovation. Third, some renewable energy policies are measured with substantial error, which can generate a bias in the regression estimates (Wooldridge, 2003). For most policies, especially those in place since the 1970s and the 1980s (summarised in the variable OTHER POL), lack of detailed information allows only for policy dummies, which, at best, can be considered only rough proxies and subject to measurement error.

However, since the focus of this work is the heterogeneous effect of different REPs, an Instrumental Variables (IV) strategy is not feasible,

Please cite this article as: Nicolli, F., Vona, F., Heterogeneous policies, heterogeneous technologies: The case of renewable energy, Energy Econ. (2016), http://dx.doi.org/10.1016/j.eneco.2016.03.007

Table 7
Full sample & Kyoto interactions.

	(1)	(2)	(3)	(4)	(5)	(6)
K STOCK	0.0035***	0.0035***	0.0026***	0.0035***	0.0027***	0.0057***
	(0.0008)	(0.0008)	(0.0008)	(0.0008)	(0.0009)	(0.0009)
PMR ENTRY	−0.0918***	−0.0997***	−0.1054***	−0.0880***	−0.0762**	−0.1197***
	(0.0312)	(0.0325)	(0.0312)	(0.0318)	(0.0317)	(0.0277)
PMR VERT INT	0.0022	0.0046	0.0016	−0.0020	−0.0131	−0.0645**
	(0.0346)	(0.0346)	(0.0346)	(0.0353)	(0.0351)	(0.0311)
PMR PUB OWN	0.0010	0.0084	0.0222	−0.0045	0.0165	0.0898***
	(0.0264)	(0.0278)	(0.0269)	(0.0279)	(0.0268)	(0.0276)
R&D	0.0708**	0.0715**	0.0859***	0.0689**	0.0781***	0.1753***
	(0.0290)	(0.0290)	(0.0293)	(0.0292)	(0.0291)	(0.0300)
FEED-IN	−0.1801	−0.1871	−0.4205	−0.1738	−0.2093	−0.0253
	(0.3176)	(0.3174)	(0.3182)	(0.3169)	(0.3134)	(0.3348)
KYOTO	1.0449***	1.0062***	0.8128***	0.9804***	0.8040***	0.5475***
	(0.2082)	(0.2131)	(0.2147)	(0.2340)	(0.2225)	(0.1814)
RECs	−0.0001	0.0048	0.0195	−0.0003	−0.0011	0.0381
	(0.0342)	(0.0345)	(0.0350)	(0.0342)	(0.0343)	(0.0348)
OTHER POL	0.2950***	0.3076***	0.3162***	0.3101***	0.2679***	0.0127
	(0.0825)	(0.0839)	(0.0825)	(0.0864)	(0.0827)	(0.0840)
ELEC PRICE	6.0912***	6.6982***	6.3398***	5.8701***	5.3447***	11.0561***
	(1.9456)	(2.0659)	(1.9399)	(1.9766)	(1.9602)	(1.6896)
ELEC CONS	1.4987***	1.4780***	1.5725***	1.4858***	1.7606***	0.6485**
	(0.3247)	(0.3262)	(0.3369)	(0.3251)	(0.3414)	(0.2673)
GDP_pc	1.1276***	1.1794***	1.2294***	1.1728***	1.1746***	0.7048**
	(0.3921)	(0.3973)	(0.3900)	(0.3984)	(0.3797)	(0.3171)
ENLARG	−0.2053**	−0.2340**	−0.1596	−0.1950*	−0.1061	−0.3595***
	(0.1046)	(0.1098)	(0.1066)	(0.1059)	(0.1104)	(0.1019)
KYOTO∗RECs		−0.8530				
		(0.9976)				
KYOTO∗FEEDIN			10.1263***			
			(2.3669)			
KYOTO∗OT POL				0.0797		
				(0.1346)		
KYOTO∗R&D					0.2567***	
					(0.0878)	
KYOTO∗PMR ENTRY						−0.0604*
						(0.0334)
Country∗tech FE	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
N	3678	3678	3678	3678	3678	3678

Negative binomial estimations. Standard error in parenthesis. All regressions include year and country effects.
* Indicate significance at 10% level.
** Indicate significance at 5% level.
*** Indicate significance at 1% level.

given the high number of potentially endogenous regressors. Therefore, we test the robustness of our results to endogeneity indirectly using Kyoto ratification as a quasi-natural experiment or exogenous policy shock. The shortcut for giving a causal interpretation of the Kyoto shock is that each individual country in Europe had some degree of influence on the ratification decision; obviously, this is only partially true, as large countries have more influence over common EU decisions than smaller ones. Thus, we consider this additional exercise as a robustness check rather than an ideal specification. Technically, we augmented the pooled specification by including the interaction between

Table 8
Average marginal effect.

	Wind	Solar_th	Solar_PV	Marine	Hydro	Biofuel	Geothermal	Waste
Mean	3.13	2.24	3.21	0.389	0.928	1.53	0.238	1.34
PMR ENTRY	0.32	0.26	*0.13*	*0.95*	*−0.44*	*0.21*	*6.05*	*−0.04*
PMR VERT INT	*−0.12*	*0.14*	−0.13	*−1.29*	*0.61*	*0.06*	*−5.06*	*0.21*
PMR PUB OWN	*−0.05*	*−0.02*	*0.05*	*1.77*	*0.04*	*−0.01*	*−1.70*	*0.11*
R&D	0.18	*0.01*	*0.08*	0.19	*0.14*	0.24	*0.55*	*−0.02*
FEED-IN	−0.11	*−0.02*	0.03	*−0.24*	*0.02*	*0.01*	*−0.01*	*0.01*
KYOTO	0.15	*0.24*	0.18	2.16	*0.29*	1.10	*−0.10*	*0.01*
RECs	0.05	0.12	*−0.04*	−1.01	*−0.28*	*−0.06*	*−0.86*	*0.01*
OTHER POL	*0.06*	*0.12*	0.13	2.70	*0.21*	0.29	*0.84*	*0.14*
ELEC PRICE	*−0.04*	0.15	0.14	0.29	*0.17*	0.36	*1.26*	*0.10*
ELEC CONS	*0.03*	0.38	0.28	*3.15*	*−0.30*	*0.33*	*4.28*	0.52

Italics denote marginal effects derived from non-significant parameters at the 10% level. Each cell displays the change in the expected number of patents relative to the mean. All effects have been calculated based on the discrete changes in the expected number of patents in absolute terms resulting from a change in Xi from the 1st to 3rd quartiles of the distribution, holding all other variables at their observed values. For the three PMR variables, the change is computed from the 3rd to the 1st quartile. For RECs we calculated the marginal effect in the shorter period 1990–2005 given the high rate of zero in the first decade analysed.

Please cite this article as: Nicolli, F., Vona, F., Heterogeneous policies, heterogeneous technologies: The case of renewable energy, Energy Econ. (2016), http://dx.doi.org/10.1016/j.eneco.2016.03.007

Table 9
Lagged policy — PMR ENTRY.

PMR ENTRY	Nr. lags	Effect	Cumulative effect	Av marginal effect	Av marginal effect (Cumulative)	AIC baseline specification	AIC with maximum lags
Wind	4	−0.2405***	−0.1905**	0.32	0.26	1198.41	1147.95
Solar Thermal	4	−0.1413*	−0.1083*	0.26	0.21	1175.13	1119.09
Solar PV	4	−0.096	−0.0637	0.13	0.09	1064.96	1030.56
Marine	4	−0.0855	−0.0351	0.95	0.39	520.916	498.5621
Hydro	4	0.0959	0.1921*	−0.44	−0.89	906.403	871.03
Biofuel	4	−0.0751	−0.0969	0.21	0.27	1101.09	1074.87
Geothermal	4	−0.327	−0.5561**	6.05	1.06	363.036	304.11
Waste	4	0.0129	−0.1619*	−0.04	0.52	1026.83	986.99

Table 10
Lagged policy — R&D.

R&D	Nr. lags	Effect	Cumulative effect	Av marginal effect	Av marginal effect (Cumulative)	AIC baseline specification	AIC with maximum lags
Wind	5	0.3198***	0.6371***	0.18	0.37	1198.41	1100.61
Solar Thermal	5	0.0054	0.1331	*0.01*	0.14	1175.13	1071.06
Solar PV	5	0.0968	0.0081	*0.08*	0.01	1064.96	1004.31
Marine	5	0.4111**	0.7256*	0.19	0.34	520.916	479.74
Hydro	5	0.3600	0.3849	*0.14*	0.03	906.403	860.95
Biofuel	5	0.1666**	0.1501	0.24	0.21	1101.09	1044.52
Geothermal	5	0.1111	0.3297***	*0.55*	1.4	363.036	307.63
Waste	5	−0.0554	0.7575	*−0.02*	0.00	1026.83	967.67

the Kyoto dummy and the pre-Kyoto mean (1990–1996) of the potential endogenous regressors (END_POL(it)), i.e., RECs, FEED-IN, OTHER POL, R&D, and PMR. Specification 2 thus becomes:

$$\begin{aligned}\mathrm{EPO\_PAT}_{ijt} = f(&\beta_1 \mathrm{K\ STOCK}_{ijt\text{-}1} + \beta_2\ \mathrm{PMR\ ENTRY}_{it} + \beta_3 \mathrm{PMR\ VERT\ INT}_{it} \\ &+ \beta_4 \mathrm{PMR\ PUB\ OWN}_{it} + \beta_5\ \mathrm{Log\ R\&D}_{ijt} + \beta_6\ \mathrm{Log\ FEED\text{-}IN}_{ijt} \\ &+ \beta_7 \mathrm{KYOTO}_{it} + \beta_8 \mathrm{Log\ RECs}_{it} + \beta_9 \mathrm{OTHER\ POL}_{it} \\ &+ \beta_{10}\ \mathrm{LogELECT\ PRICE}_{it} + \beta_{11}\ \mathrm{Log\ ELECT\ CONS}_{it} \\ &+ \beta_{12} \mathrm{Log\ GDP\_pc}_{it} + \beta_{13} \mathrm{ENLARG}_{it} \\ &+ \beta_{14} \mathrm{KYOTO} * \mathrm{Log\ END\_POL}_{ijt} \beta_i + \beta_t),\end{aligned} \tag{2}$$

where all technologies j are pooled in a single panel in which fixed effects are calculated on the country unit i and the technology unit j. The term β_{14} is the coefficient of the interaction effect between Kyoto and the 1990–1996 values of the selected possible endogenous regressors.

As an alternative way to address endogeneity concerns, we tested whether the coefficients estimated in Eq. (1) remain statistically significant if we use future rather than current policies as explanatory variables.[23] This exercise gives an idea of the existence of an estimation bias due to reverse causality, but is not necessarily conclusive about the direction of the bias. For example, a significant effect of future policies might be the result simply of the high persistence in policy choices rather than a sign of reverse causality. Therefore, these results should be taken with caution and as mostly hinting at the potential presence of a bias.

5. Results

Table 6 displays the regression results obtained using specification 1 for eight different RETs. For each technology, we present the results for the PMR index split into its three subcomponents. Given the count nature of the dependent variable, we employed a negative binomial model to estimate the regression coefficients, as in JHP. The differences in the total number of observations across specifications are due to countries with zero outcomes for the dependent variable being dropped. This applies particularly to marginal technologies such as marine and geothermal. Finally, it should be noted that, given the dynamic specification employed here, the results should be interpret as a short-term effect.

Overall, policy support, stock of past knowledge, level of entry barriers and electricity prices would appear to be the main drivers of patenting in RETs, compared to energy market size and consumer preferences for green goods, proxied here by ELEC CONS and GDP_pc, respectively. The effect of the PMR AGGREGATE indicator (in Table 6 bis),[24] despite always showing the expected negative coefficient, is statistically significant only for wind, solar thermal and waste energy technologies. Interestingly, the low level of significance of deregulation in overall RE innovation found in Nesta et al. (2014) hides significant heterogeneity across RETs, as these results highlight.[25] Table 6 provides a better understanding of the heterogeneous effects of different liberalisation reforms by showing that, among the three subcomponents of PMR, only PMR ENTRY drives the aggregate result, as it is statistically significant for wind and solar thermal. For the other technologies, the coefficient of PMR ENTRY has the expected negative coefficient with the exception of hydro and waste, and it is nearly significant for geothermal and solar PV technologies. These results are consistent with the idea that liberalisation, favouring the entry of non-utility and independent power producers which, generally, are oriented towards green energy, increases the incentives of electric equipment manufacturers to innovate. Consistent with Hypothesis 1, this result is driven by wind and solar thermal technologies, which are characterised by a low level of concentration in innovative activities across innovators, and by the entry of several independent power producers following liberalisation.

In relation to the other components of market regulation, PMR PUB OWN has the expected positive sign for five of the eight technologies, but the respective coefficients are never statistically significant, suggesting a low impact of the type of ownership on RE innovation. Similarly, the contrasting effects on innovation exerted by unbundling, described in Section 2.2, are reflected in the insignificance of the coefficient of PMR VERT INT in most specifications (except SOLAR_PV where unbundling

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[23] We thank an anonymous referee for this suggestion.

[24] For brevity, we present only the coefficient of PMR AGGREGATE in Table 6 bis. Other covariate coefficients remain substantially unchanged using the PMR AGGREGATE in the analysis rather than its three sub-components.

[25] We refer in particular to the results in Nesta et al. (2014) where the analysis is restricted to high-quality patents only (as in our case).

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Table 11
Lagged policy — FEED-IN.

FEED-IN	Nr. lags	Effect	Cumulative effect	Av marginal effect	Av marginal effect (Cumulative)	AIC baseline specification	AIC with maximum lags
Wind	4	−5.0025**	−3.7647*	−0.11	−0.08	1198.41	1152.97
Solar Thermal	4	−0.8592	−0.0282	*−0.02*	−0.01	1175.13	1117.98
Solar PV	4	1.5440***	2.7412***	0.03	0.06	1064.96	1027.19
Marine	4	−10.3654*	−5.2046	*−0.24*	0.00	520.916	502.6041
Hydro	4	2.9548	1.9711	*0.02*	0.00	906.403	502.6041
Biofuel	4	−0.021	5.5035**	*0.01*	0.22	1101.09	1058.887
Geothermal	4	−0.2011	−9.9897	*−0.01*	0.00	363.036	344.52
Waste	4	2.8425	6.9329	*0.01*	0.00	1026.83	988.05

Table 12
Lagged policy — RECs.

RECs	Nr. lags	Effect	Cumulative effect	Av marginal effect	Av marginal effect (Cumulative)	AIC baseline specification	AIC with maximum lags
Wind	4	0.1100*	0.0963	0.05	0.04	1198.41	1156.12
Solar Thermal	4	0.1938**	0.3355**	0.12	0.12	1175.13	1122.35
Solar PV	4	−0.0886	−0.3431**	*−0.04*	−0.15	1064.96	1028.19
Marine	4	−0.2727**	0.0381	−1.01	0.14	520.916	499.06
Hydro	4	−0.1796	−0.4031*	*−0.28*	−0.62	906.403	877.29
Biofuel	4	−0.0589	−0.2867**	*−0.06*	−0.27	1101.09	1062.56
Geothermal	4	−0.143	−0.0319	*−0.86*	−0.19	363.036	347.71
Waste	4	0.008	−0.2003	*0.01*	−0.21	1026.83	982.31

has a negative effect on innovation, but is significant at the 10% level only).

Moving to the policy variables, in line with Hypothesis 2, technology-specific policies, such as FEED-IN and R&D, appear to play a major role in the early phases of technological developments, such as in the case of solar PV and marine energy, while for relatively more mature technologies, e.g. wind and solar thermal, quota systems are a more effective policy tool. In particular, R&D is a significant determinant of innovation for several RETs including wind, marine, biofuel and geothermal. This confirms the results in JHP, which remain robust even in our dynamic specification which accounts for the stock of past knowledge. The only real difference is the insignificance of the coefficient of R&D for the two solar technologies analysed in our study. Empirically, this difference is due in part to our choice to split solar energy into two categories and in part to the fact that our analysis does not include the US and Japan. The results in JHP might be driven in part by these two countries being positive outliers in the distribution of R&D. The insignificant effect of R&D on solar PV is counterbalanced by a positive effect of FEED-IN, the policy instrument designed to promote decentralised energy production directly.[26] Note that, as in JHP, FEED-IN does not have a significant effect on other technologies when controlling for other policies. In contrast, RECs have a significant effect on patenting in wind energy, which being close to competitive with fossil fuels, is able to capitalise on a quota system in order to strengthen its role in the market. Similarly, tradable certificates show a significant and positive effect on the less competitive technology solar thermal, a result which probably is driven by the overall potential of this technology across European countries. The small significance of tradable certificates in all other cases reinforces the idea that when policy allows the firm to choose how to meet renewables targets, it will tend to select the least costly option. Future policy expectations, proxied by the KYOTO protocol dummy, exert a significant and positive effect for wind, solar PV, marine and biofuel technologies; OTHER POL, controlling for all those policy instruments for which continuous information is not available, shows the expected positive and significant effect for solar PV, marine and biofuels. It is interesting that, in line with the discussion in Section 2.3, this last set of policy instruments exerts a positive effect only on technologies with high potential such as solar energy and wind power.

Before discussing the economic relevance of the results for our variables of interest, we comment briefly on the effects of the two basic controls — electricity prices and knowledge stock. Similarly to the results in JHP, ELEC PRICE has a positive effect on the two solar technologies and biofuel.[27] Less straightforward is the result for K STOCK, which is positive and statistically significant only for wind, solar thermal and waste energy. The stronger persistence of past innovation in the case of more mature RE sources is the simplest explanation of this anomaly. Specifically, innovation in emerging RETs is more likely to be driven by serendipity than innovation in well-established technologies. Another explanation might be that the impact of knowledge stock is conditional on the presence of time effects (dummies), which tend to absorb past levels of technological development. As a robustness check, Table 6-bis present the results of an additional set of estimations that include global knowledge stock, which does not vary across countries and represents the global frontier for each specific RET in any given year. The coefficients of global knowledge stock are always positive and often significant, which is in line with our previous expectations.

To have a proper quantifications of different effects, Table 8 presents the short-term marginal effects, computed as the change in the expected number of patents relative to the mean resulting from an inter-quartile change in a certain variable, holding all variables at their observed value (as in Nesta et al., 2014). The caveat here is that, due to reverse causality, the effects should be interpreted as the upper bound. PMR ENTRY exerts a sizeable effect on both wind and solar thermal energy, being associated with an increase in patents filed at the EPO of respectively 32% and 26%. The size of the effect is in line with Nesta et al. (2014). Moving to the policy variables, the quantification confirms our expectations about heterogeneous effects, showing a stronger effect of policy and market factors on technologies with high potential

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[26] The negative coefficient of FEED-IN for wind is an unexpected result but is in line with JHP. Like them, we believe it is an empirical issue due to the potential presence of endogeneity and collinearity with other policy variables. When we run specification 2 for wind patents only, to mitigate the potential endogeneity, the results change and the marginal effect of FEED-IN becomes positive.

[27] Concerning the two proxies for demand, energy market size, proxied by ELEC CONS, is significant only for the two solar energy technologies, while GDP_pc (reflecting consumer preferences for clean energy not captured by REPs) shows the expected positive sign for 4 of the 8 technologies. The effect of ENLARG is significant and negative for wind and solar thermal, suggesting a generally lower level of patenting in new EU member countries.

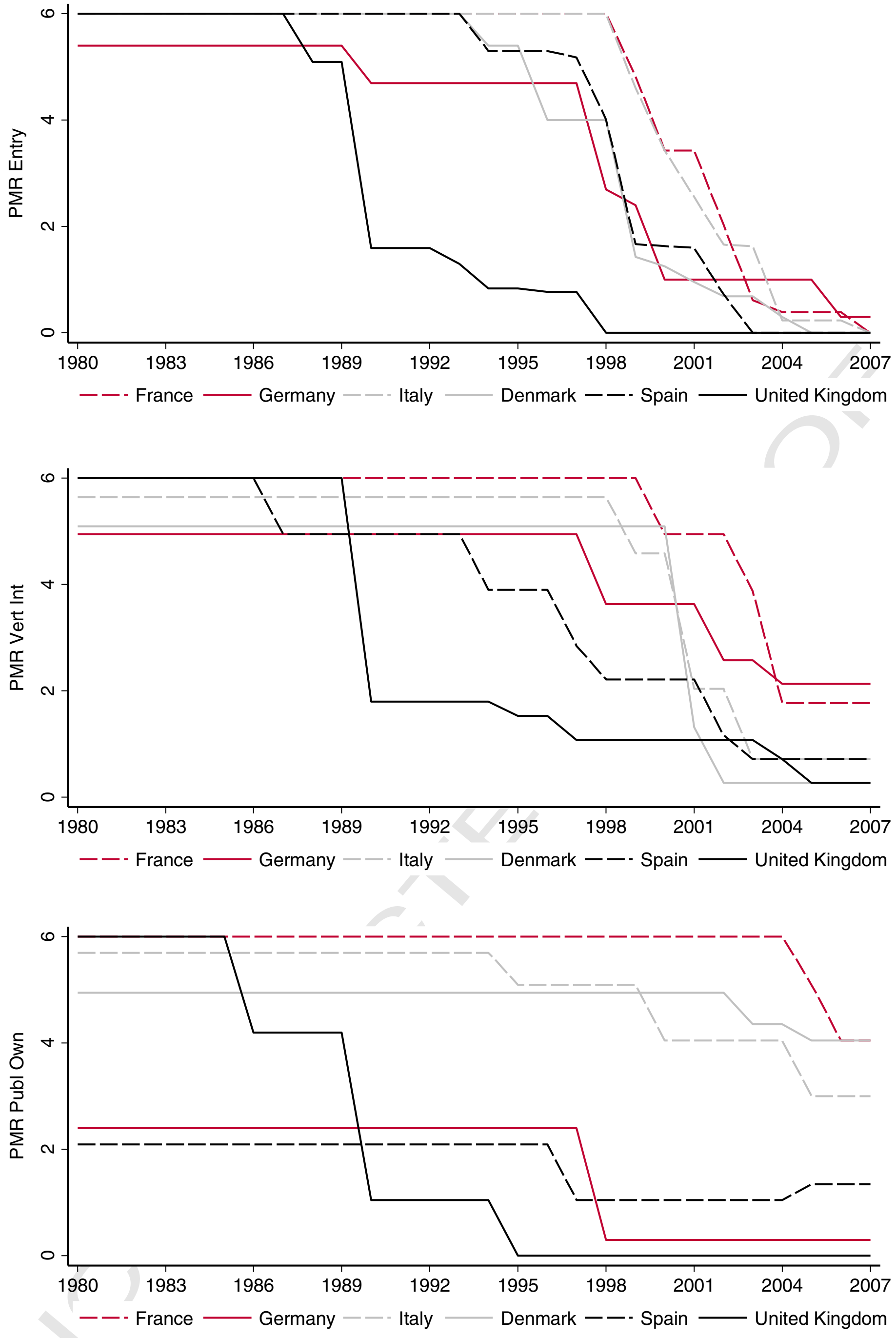

Fig. 3. Trend in PMR in Selected Countries (respectively: Entry, Vertical Integration and Public Ownership). Years 1974–2007.

(especially wind and solar and, to a lesser extent, marine). The effects of KYOTO and OTHER POL are particularly striking in the case of marine energy (resp. 216% and 270%), and biofuel (resp. 110% and 29%). However, the effect of R&D is stronger for wind and biofuel energy. Note that the policy variables are never significant for hydro and waste, two technologies not accounted for directly in JHP. In the case of hydropower, this result is due most likely to its being a mature and consolidated technology with few opportunities for technological improvement (Popp et al., 2011) and close to full capacity in several EU countries (IEA, 2010). For waste energy, this result is not surprising for several reasons. Firstly, as shown in Nicolli (2012), waste energy is strictly related to waste policies, which are not accounted directly in this work. Secondly, it is probably still too early to judge its response to policy stimulus, as it is a new and emerging technology with low technological potential (Lee and Lee, 2013) representing only a small portion of the renewable electricity portfolio. Finally, also market stimulus given by an increase in the ELEC PRICE have a stronger effect on solar thermal, PV and marine energy (resp. 15%, 14%, and 29%); ELEC CONS is a significant exception and has a large effect on waste energy (52%), and a relatively strong effect also on the two solar technologies (resp. 38% and 28%).

For simplicity, in our main specification of Eq. (1) we use only the contemporaneous policy effect, under the assumption that past policies are captured by the knowledge stock. However, recent research by Popp (2015) would question this assumption by showing that the time lags in the effect of certain policies, especially R&D, can be substantial even when conditioning for past knowledge stock. Also, a misspecification of the lag structure can lead to incorrect quantification of the effects of interest since policy can have a cumulative effect over time. In a complex

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system, such as the energy sector, where renewable energy policies often target downstream distributors, which consequently indirectly demand more upstream 'green innovation', it is reasonable to assume that the effect of the policy stimulus on patenting could take several years to be realised. Similarly, a FEED-IN tariff scheme can take several years before it is internalised by manufacturers' cost functions. Tables 9–12 present the results for the cumulative effect of the main variables analysed in this work, i.e. PMR ENTRY, R&D, FEED-IN and RECs. As in Popp (2015), in order to define the optimal lag structure we choose the specification that minimises the AIC statistic across a range of models and, in the case of conflicts, we prefer the lag length at which the cumulative effect of the lagged policies levels out, which suggest that all appropriate lags have been considered. The results mainly confirm the previous findings with some small but interesting differences, showing that accounting for past effects can uncover some dynamic linkages that otherwise are underestimated. The differences are in the coefficients of PMR ENTRY and R&D for geothermal technology, which now are statistically significant and have the expected sign. Similarly, the cumulative effect of PMR ENTRY is also statistically significant for waste while FEED-IN becomes significant for biofuel. Finally, if we compare the contemporaneous and cumulative average marginal effects quantifications we see that, as expected, the latter are generally higher. Specifically, the marginal effect of R&D on wind energy doubles if we consider the dynamic of past R&D; the results are similar for FEED-IN in relation to solar PV technologies.

As discussed in the empirical strategy section, the quantification of our effects of interest is not accurate due to endogeneity problems. In particular, reverse causality is likely to upward bias our estimations. Table 7 presents the results of the Kyoto quasi-experiment to check whether qualitatively the results do not change when we try to mitigate these concerns. Table 7 column 1 presents the benchmark results for a pooled specification with country- and technology-specific fixed effects in which the coefficients represent an average effect and are not allowed to vary across technologies. These averaged results confirm the previous evidence. The controls and the K STOCK are associated with the expected coefficients, while, among the three components of PMR, only entry barriers constitute a statistically significant driver of innovation. It should be noted that the aggregate results are driven mainly by wind and solar technologies, which represent approximately 70% of total patenting in RE. The effect of FEED-IN is never significant in the pooled specification (Table 7 column 1) while KYOTO and R&D have the expected positive coefficients. RECs are not statistically significant, a result that reflects their heterogeneous effect across technologies (see Table 6). The more homogeneous results for PMR ENTRY, R&D, KYOTO and OTHER POL are reflected here by statistically significant coefficients, which are in line with our expectations. Table 7 columns 2–6 present the robustness checks where Kyoto protocol is interacted with the 1990–1996 levels of the five policy variables. The regression results mainly confirm the previous findings, while the interaction is significant for FEED-IN, R&D and PMR ENTRY. An exogenous policy shock such as the ratification of the Kyoto protocol, on aggregate, amplifies the inducement effect of FEED-IN and R&D subsidies. In particular FEED-IN, which were never significant except in the case of solar PV and wind, becomes significant after Kyoto, most likely due to the less uncertain policy environment induced by the ratification of the international protocol. Table 7, column 6, also shows the amplifying effect of energy market liberalisation after KYOTO, corroborating Nesta et al. (2014) result that the effect of REPs is stronger in more competitive markets. However, the insignificant effect of RECs, which are strongly supported by the Kyoto protocol, is somewhat surprising. This result is probably due by the heterogeneous effect that quota systems exert on different technologies, as shown in Table 6.[28]

Table A1 in the Appendix presents the results for the alternative approach to endogeneity, i.e. the inclusion of forward policies. More specifically, it presents only the statistically significant forward policy coefficients. The coefficients of future policy become insignificant for FEED-IN tariff and, to a lesser extent, for OTHER POL and RECs. However, for wind, future RECs appears to have a much stronger effect than current ones. This may reflect the fact that large utilities lobbied actively in favour of the Emissions Trading Scheme, which allows RECs to be traded, and, thus, to anticipate future policies by seeking to protect their intellectual property rights in the most promising technology, i.e. wind. Finally, the effect of future R&D on current innovation remains statistically significant with a lead of five years. This may be due to the complex lag structure of R&D effects, which were explored briefly in this paper and are analysed in depth in Popp (2015).

6. Conclusions

This paper contributes to the growing literature on environmental innovation in several ways. First, we test the qualitative implications in Lee and Lee (2013) and use them to disentangle the aggregate evidence from previous studies of the determinants of RE innovation, accounting for the intrinsic characteristics of eight different renewable technologies and for dynamics in the innovation equation. As a result, we find that the aggregate effect of market liberalisation found in the previous literature is driven by technologies with a lower developer intensity (i.e., with less concentrated patenting activity across firms) and more subjected to the entry of independent power producers, such as wind and solar thermal energy. Similarly, the effect of REPs is heterogeneous across technologies and depends on their degree of maturity. In line with previous work (JHP), mature technologies are more responsive to quota systems, which ensure lower compliance costs for producers, while emerging technologies benefit mostly from demand subsidies and public support for R&D. Contrary to our expectations, FEED-IN is statistically significant and is associated with a positive coefficient only in the case of solar PV, but the aggregate effect turns strongly significant after ratification of the Kyoto protocol when the policy framework becomes more stable and less uncertain. We tried to reconcile previous contradictory empirical evidence. For example, JHP finds a significant effect for several policies while Nesta et al. (2014) find an insignificant effect of their aggregate REP indicators when controlling for potential endogeneity and the dynamics of past knowledge. However, it is difficult to compare these studies given their completely different empirical settings. In the present work we fill this gap, showing as even partially accounting for endogeneity thanks to the KYOTO interactions and including a K STOCK, REPs still have a relevant inducement effect. This result goes some way towards reconciling the previous evidence and stresses the importance of accounting for the intrinsic heterogeneity of both policy support and RET.

Second, the analysis in this paper shows that the magnitude of these effects depends also on the overall potential of different RETs and, consequently, is stronger for wind, solar and, although to a lesser extent, marine energy. This suggests that additional specific policy support for these technologies might be beneficial for countries with appropriate natural conditions.

Third, we further develop the idea proposed in Nesta et al. (2014) by providing a careful evaluation of the impact of energy market liberalisation on RET. In particular, we have shown that lowering entry barriers has a significant positive impact on renewable energy technologies, while degree of vertical integration and type of ownership are not influential. We found also that KYOTO amplifies this effect, confirming the complementarity hypothesis put forward in Nesta et al. (2014), that environmental policies are more effective in competitive markets. In the future, a major concern will be the recent trend towards market integration in EU countries, which has resulted in a few large players, e.g. EDF, ENI, E-ON, and Vattenfall, dominating the market. This process

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[28] A potential issue with this approach is that since Kyoto ratification is itself a policy choice, this exercise could be biased if large countries have a bigger say in guiding EU policy formation. In some additional regressions, available upon request, we excluded Germany from the sample and the results remained qualitatively unchanged.

Please cite this article as: Nicolli, F., Vona, F., Heterogeneous policies, heterogeneous technologies: The case of renewable energy, Energy Econ. (2016), http://dx.doi.org/10.1016/j.eneco.2016.03.007

could undermine the entry of new innovative players and the development of the Distributed Generation paradigm.

Q13

Uncited reference

Popp, 2010

Appendix A. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.eneco.2016.03.007.

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Please cite this article as: Nicolli, F., Vona, F., Heterogeneous policies, heterogeneous technologies: The case of renewable energy, Energy Econ. (2016), http://dx.doi.org/10.1016/j.eneco.2016.03.007