Journal of Environmental Economics and Management 67 (2014) 396–411

Contents lists available at ScienceDirect

Journal of Environmental Economics and Management

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

Environmental policies, competition and innovation in renewable energy

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ARTICLE INFO

Article history:
Received 12 February 2013
Available online 6 February 2014

Keywords:
Renewable energy technology
Environmental policies
Competition
Endogeneity
Pre-sample mean GMM

ABSTRACT

We investigate the effect of environmental policies on innovation under different levels of competition. Using information regarding renewable energy policies, competition and green patents for OECD countries since the late 1970s, we develop a pre-sample mean count-data econometric specification that accounts for the endogeneity of policies. We find that renewable energy policies are more effective in fostering green innovation in countries with liberalized energy markets. We also find that environmental policies are crucial only in the generation of high-quality green patents, whereas competition enhances the generation of low-quality green patents.

Introduction

This paper investigates the effectiveness of policies in support of renewable energy under different levels of competition. Our contribution is motivated by the fact that although both competition and environmental policies are key drivers of innovation (Newell, 2011), their interplay has never been explored. The literature stresses the importance of either policy interventions (Fischer and Newell, 2008; Acemoglu et al., 2012; Popp et al., 2009; Popp, 2002; Johnstone et al., 2010) or market liberalization (Jamasb and Pollitt, 2008; Sanyal and Ghosh, 2014) as determinants of innovation in the energy sector. Instead, we argue that it is the interplay between environmental policies and competition that matters.

Our contention is that environmental policies, essentially in the form of subsidies for renewable energy, are more efficient when conducted in competitive markets. The intuition is the following: because the production of energy is generally more costly when using green technologies, only public subsidies can spur demand for renewable energy and make market entry – a competition enhancer – attractive to new players. Without the entry of new players, environmental policies are less likely to favor radical innovation because large incumbents have little incentive to fully develop renewable technologies that would jeopardize their investments in large-scale energy production.

To our knowledge, this paper is the first to carry out a cross-country analysis that empirically assesses the complementarity between environmental policies and competition in energy production. To do so, we assemble a dataset that contains cross-country information on renewable energy policies (henceforth RE policies or REP), product market regulation (PMR) and various measures of renewable energy patents, which allows us to differentiate their effects depending on the quality of inventions. Based on Blundell et al. (2002), the econometric specification controls for unobserved country heterogeneity by means of the pre-sample mean using a Poisson model. In addition, we use a dynamic

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http://dx.doi.org/10.1016/j.jeem.2014.01.001
0095-0696

empirical setup that accounts explicitly for the fact that innovation activities are highly persistent. Finally, we choose the GMM estimator to account for the endogeneity of both renewable energy policies and product market regulation.

Our main findings are the following: first and foremost, we find that renewable energy policies are more effective in fostering green innovation in countries with liberalized energy markets. Second, the effect of renewable energy policies is sizeable for high quality innovation, where such policies are almost three times as effective in highly deregulated energy markets than in more regulated ones. Conversely, energy market liberalization has a positive and large effect on low-quality innovations rather than on radical ones. Third, the independent effect of REP disappears when accounting for policy endogeneity. Fourth, frontier innovation exhibits far less path dependency than generic innovation, implying that to remain at the technological frontier is a matter of sustained research efforts.

The remainder of the paper is organized as follows. The section "Factors affecting renewable energy innovations" discusses the theoretical underpinnings upon which our empirical strategy is based. The first part of the section "Empirical protocol" presents the methodology used to build our dataset and our main policy indicators, and the second part describes the econometric specification and discusses the endogeneity of the policy variables. The section "Empirical results" presents the baseline results, estimates the impact of the variables of interest on various measures of patent quality and quantifies the marginal effect of the policy variables. The final section concludes.

Factors affecting renewable energy innovations

In the past two decades, the realm of energy production and distribution has undergone profound structural changes in two directions. First, the liberalization of the energy markets in many countries has aimed to challenge the monopolistic power of large utilities. The main contention is that increasing market competition will induce reductions in energy prices, in turn leading to higher social welfare.[1] Second, global warming and increased environmental awareness have favored demand for alternative forms of energy, such as wind, geothermal and solar, in response to negative environmental externalities stemming from traditional energy sources. Because cleaner forms of energy production cannot compete with traditional ones in terms of cost, they receive public support by means, *inter alia*, of fiscal or investment incentives.

An important question then arises. In fostering market competition and addressing environmental externality, what is the effect of these broad policy reforms on a country's capacity to actually improve the efficiency of alternative solutions? And does the combination of the two reforms matter for innovation?

Below, we discuss the expected effect on innovation of these two variables and of their interaction.

Competition and innovation: The question of whether competition stimulates innovative activities is certainly not new. From a theoretical standpoint, the innovation regime theory (Winter, 1984) and the industry life cycle theory (Klepper, 1996) insist on the importance of small firms.[2] In these models, radical or product innovation is generated by new, generally smaller players, which contest the dominant position of incumbents. The latter generally focuses on process – not product – innovation, both to increase their cost competitiveness and to avoid product cannibalization. Renewable energy innovations fit well with this explanation because they are competence-destroying for the centralized paradigm of energy production (David and Wright, 2006; Lehtonen and Nye, 2009). In particular, while production of energy from renewable sources, such as wind, biomass, geothermal and solar, is mainly decentralized in small- and medium-sized units, the skills of incumbents are tied to large-scale plants using coal, nuclear materials or gas as primary energy inputs.

From the empirical standpoint, past contributions have previously assessed the effect of liberalization on innovation in the energy sector. Country-level studies, mostly limited to the US and the UK, found that R&D expenditures and patent activities declined after liberalization.[3]

In the case of renewable energy innovation more specifically, competition seems to support innovative activities, at least in the short run. Jamasb and Pollitt (2011) analyze UK patents in the energy sector, and observe that renewable patents have significantly increased in the post-liberalization period. Liberalization favors the entry of nonutility generators, such as farmers, small communities, municipalities and environmentally conscious households, who diversify their offer toward green energy (Delmas et al., 2007; Bird et al., 2006) and specialize in decentralized energy production (e.g., combined generation, local heating systems and renewable sources).[4] For the US, Sanyal and Ghosh (2014) show that the entry of non-utility generators increased the incentives of specialized suppliers of electric equipment to innovate. Additionally, there is a rich case-study evidence for Nordic and Central European countries showing the sustained entry of new firms producing

[1] However, empirical evidence shows that liberalization has not brought down consumer prices see, e.g., Fiorio and Florio (2013).

[2] Recent Schumpeterian models by Aghion et al. (2001, 2005) incorporate both the classical Schumpeterian effect, in which competition reduces innovative rents and therefore R&D investments, and an escaping competition effect. The latter effect holds that the threat of entry of new firms induces incumbents to increase R&D investments to preserve or enhance their market shares. The interplay of these two mechanisms generates an inverted-U shaped relationship between competition and innovation.

[3] See, e.g., for the US: Dooley (1998), Sanyal (2007), Nemet and Kammen (2007), Sanyal and Cohen (2009) and Sanyal and Ghosh (2014) and for the UK: Jamasb and Pollitt (2008). Similar negative effects of deregulation on energy R&D were found for electric utilities worldwide by Sterlacchini (2012) and Salies (2010).

[4] In Denmark, for instance, most wind turbines are owned by households, municipalities and small communities, whereas utility-owned wind capacity accounted for only 15% of the total installed wind capacity in 1990 (Hadjilambrinos, 2000). Similarly, in the US, the approval of the Public Utility Regulatory Policies Act mandates that public utilities purchase energy from small-scale power producers, essentially non-utility generators producing from renewable sources (Loiter and Norberg-Bohm, 1999).

clean energy or new electric equipment.[5] By way of example, the key role of small suppliers is documented for wind and solar energy by Jacobsson and Bergek (2004). In particular, the expansion of wind energy was carried out by German suppliers of machinery and electric equipment, especially through the entry of 14 new firms.

In sum, while seminal studies focus on the role of utilities as key innovative players, these works stress the role of new firms and upstream suppliers of electric equipment as the main innovators in the area of renewable energy. Greater competition in the energy market seems to have redirected the innovative effort of specialized suppliers toward green energy. Hence:

Proposition 1. *The expected effect of market competition on innovation is positive in new technological domains, such as renewable energy*.

Renewable energy policy and innovation: The interest in the relationship between renewable energy policy and innovation is admittedly more recent. In the practical sense, the chief objective of RE policies is to generate a certain volume of demand for clean energy (Popp et al., 2009). The positive demand shock is then expected to stimulate innovation due to higher expected returns from research investments. In essence, innovative activities in the domain of renewable energy are radically uncertain and highly complex. Innovating firms must conjecture about expected demand (e.g., consumer preferences, budget constraints), about complementary investments by upstream and downstream partners, and about investments by rival firms. Such uncertainty is likely to hamper innovative efforts, particularly when the final product is fully undifferentiated. As a result, any policy that reduces uncertainty and increases the size of the market for clean energy is likely to support innovation.

Externalities too hamper innovative efforts. Investments in renewable energy technologies are subject to well-known knowledge externalities, acting as a disincentive to invest in R&D. In a similar fashion, innovation in environmentally friendly energy sources cannot be valued in the final, perfectly homogenous output if the social cost of CO_2 emissions is not internalized. Finally, the inappropriability of learning through the production and the use of new technologies may reduce a country's research efforts in renewable energy. In this context, theory suggests that the more cost-effective intervention for restoring an optimal level of green investment consists of a diversified policy mix, with each policy targeting one of the above externalities (see e.g. Bovenberg and Smulders, 1995; Fischer and Newell, 2008; Acemoglu et al., 2012).

The only cross-country analysis specifically investigating the relationship between RE policies and innovation is that of Johnstone et al. (2010). These researchers show that REP have heterogeneous effects on different renewable energy technologies. In particular, guaranteed price schemes and investment incentives played a major role in the early phase of the technology life cycle, whereas for relatively more mature technologies, quantity-based instruments seem more suitable. We hypothesize the following.

Proposition 2. *The expected effect of renewable energy policies on innovation is positive*.

Expected joint effect of competition and REP on innovation: Less is known about the joint effect of competition and public policies on innovation. From the theoretical side, Aghion et al. (2012) address the issue of complementarity between market competition and industrial policies along the lines of recent Schumpeterian models on innovation and competition (see e.g. Aghion et al., 2001, 2005). Policies targeted at sectors with higher technological potential have a larger effect on firm innovative efforts, conditional on the absence of collusion between firms. For renewable energy, our conjecture is that the joint effect should be positive, pointing to the complementarity between liberalization and environmental policies. Yet there are additional reasons supporting the complementary hypothesis.

The key argument is heterogeneity in incentives to develop renewable energy sources. Electric utilities are hesitant to develop a set of technologies that may eventually cannibalize their core business. They are specialized in the centralized paradigm of energy production, and a decentralized energy production sector would jeopardize their *raison d' etre*.[6] Rather, electric utilities will invest in renewable energy and small scale generation mainly to diversify their energy portfolios, increase their stock of intangible assets and cope with unexpected demand changes.[7]

As a result, public policies will be more successful when new players developing radical technologies enter the market. New players need financial resources to support the upfront cost of a new investment project. In the presence of high uncertainty, it is unlikely that the private sector will provide the financial resources for these projects, so that potential entrants will be financially constrained. Public interventions, such as investment incentives and tax credits, can help alleviate these constraints and make entry more profitable. Feed-in tariffs, instead, will help reduce the uncertainty associated with the future option of selling green energy once the upfront costs have been paid.

Altogether, this suggests that RE policies will be successful, especially in high-quality innovation, when combined with lower entry barriers because reduced uncertainty will apply to a larger pool of potential entrants. Therefore,

[5] See, e.g., Jacobsson and Johnson (2000), Jacobsson and Bergek (2004), Nilsson et al. (2004), Lauber and Mez (2004), Hadjilambrinos (2000) and Makard and Truffer (2006).

[6] Stenzel and Frenzel (2008) report that two of the main reasons why German utilities did not invest in the emerging wind market were a lack of technological capabilities and the mismatch of small-scale and decentralized generation with their business model. A formal argument can be found in Spence (1976), Eaton and Lipsey (1979).

[7] For instance, large utilities may want to have quick-to-start facilities to comply with regulations rather than to develop renewable energy technologies.

Proposition 3. *The expected effect of renewable energy policies on innovation is stronger in competitive energy markets, especially for radical innovations.*

Empirical protocol

Data sources

Our database combines several sources, gathering patent data to measure innovation together with policy and regulatory variables found in various data sources. While the set of explanatory variables used in this paper is similar to the set used in the closely related paper of Johnstone et al. (2010), we use patent families rather than patents registered at the European patent office as our dependent variable. Moreover, we add the PMR index and build an aggregate policy index that may be instrumented. Appendix A provides more details on data sources and methods used to build the key variables for the econometric analysis.

Dependent variable: We measure innovation by means of patent statistics. We use the 2011 version of the European Patent Office Worldwide Patent Statistical Database PATSTAT (EPO, 2011), which provides codified information on the legal authorities issuing the patent document to the name of the inventor, the priority dates and the assignee being granted ownership of the invention. We assign patents to countries using the nationality of the patent assignee as provided by PATSTAT.[8]

The availability of the technological content of patents by means of the International Patent Classification (IPC) system allows us to distinguish an invention in renewable energy from other innovations. Following Johnstone et al. (2010), we use patents registered in the sub-fields of wind, marine, solar thermal, solar photovoltaic, biofuels, hydroelectric, fuels from waste, geothermal and tidal to construct a single indicator of innovative activity in the field of renewable energy. Table A1 in Appendix displays the list of IPC classes used to identify these subfields as belonging to the realm of renewable energy.

Because patents grant protection to inventions of substantially heterogeneous economic value (Pavitt, 1988), we account for quality of patents using patent family size and triadic patents. Patent family size refers to the number of patent offices to which an application for a patent has been filed (Dernis and Khan, 2004). Only patent applications of the most valuable inventions are filed in other jurisdictions. We therefore weight each patent by the number of offices to which it has been filed. We also screen out patents filed to only one office, thereby setting a quality threshold that eliminates low-value applications (Popp et al., 2011). A particular patent family is the so-called Triadic Patent Family (TPF), which includes patent applications filed in the patent offices of the three largest markets, i.e., the European, Japanese and US patent offices (EPO, JPO, USPTO). Our results are also extended to triadic patents, the use of which sets an even higher threshold on the expected patent quality.

Fig. 1 shows the flow of patent applications for our three innovation measures: patent count, patent families, and triadic patent count. Until the 1990s, both green and generic patents grew at a similar pace, except for a small boom in green innovation following the oil shocks of the 1970s, when trends began to diverge substantially and green innovations began to increase at a much faster rate than generic ones.

Renewable energy policy: The REP index is based on the exploitation of a comprehensive dataset made available by the International Energy Agency (IEA, 2004), which provides information on the year of adoption of selected RE policies (e.g., tax credit, investment incentives, feed-in-tariff, etc.) for most OECD countries (Johnstone et al., 2010, see also Table A2 in the data appendix for a detailed description of the policies used). To build a single policy index that varies over years and across countries, we create a series of dummy variables reflecting the adoption of the following eight policies: investment incentive schemes, tax measures, incentive tariffs, feed-in tariffs, voluntary programs, obligations, tradable certificates, and public investment in research and development in renewable energy.

Viewing the implementation of policies as *signals* to potential consumers and suppliers of renewable energy, the REP index is the sum of all implemented policies expressed as dummies. A more diversified policy mix will lead to a higher REP index. Similar examples of environmental policy indices based on a synthesis of diverse policies can be found in Dasgupta et al. (2001) and Esty and Porter (2005). Stacking all variables within a single index implies a loss of information because the effect of individual policies on renewable energy can no longer be detected, as is evident in the closely related paper of Johnstone et al. (2010). Yet an aggregate index allows us to address the rather unexplored issue of endogeneity in the effect of REP on innovation. There are also good theoretical arguments in favor of the use of an index that rewards a diversified policy portfolio rather than stringency for specific policies. In particular, a diversified portfolio allows a country both to better cope with uncertainty characterizing renewable energy investments and to target with each policy a different set of actors.[9]

Note that public R&D was the first policy measure implemented in the 1970s (Johnstone et al., 2010). Hence, including the R&D signal in the REP index is important in capturing initial commitment to renewable energy. However, in addition to considering public R&D as a signal, we also include public R&D expenditures in renewable energy per capita. Our motivation

[8] This assignee can be either a legal entity if it is a public or private organization, or an individual if the inventor is granted ownership of the patent. Hence, a patent filed in several legal authorities but for which the applicant belongs to one country only – say Germany – will be recorded as a German patent. Patents with several applicants from different countries will be assigned to each applicant's country.

[9] See Appendix A for a more thorough description and discussion of the construction of the REP index.

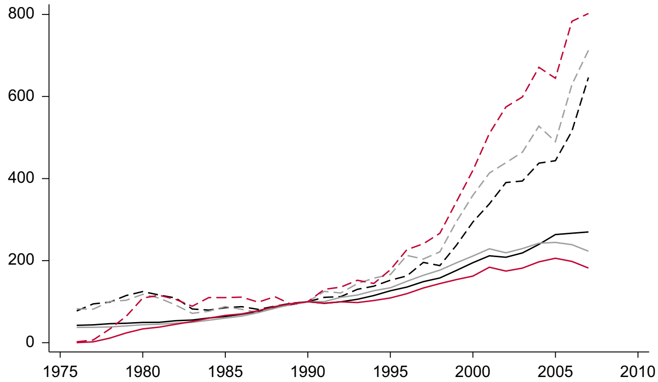

Fig. 1. Evolution of patent generation between 1976 and 2007 (1990 = 100, patent count in black, patent family in gray, triadic patent family in red. Dashed lines denote green patents). (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this article.)

is that this particular policy is targeted toward addressing the issue of knowledge externality as opposed to the other policies, which are mainly targeted at environmental externalities.

Competition: We characterize competition using product market regulation (PMR), the time-varying sector-specific index developed at the OECD. Deregulation of the energy market has generally implied the establishment of authority to regulate abuse of market power and access to the grid for independent producers, privatization and ownership fragmentation, permitting customers to freely choose their favorite suppliers, and the promotion of a progressive unbundling of distribution, generation and transmission activities. The PMR index for electricity and gas essentially ranges from 0 to 6, where high values denote lack of product market competition.[10]

Fig. 2 displays the evolution of green family patent production, the renewable energy policy index and product market regulation between 1976 and 2007 for a set of large and small countries. The tendency toward convergence in the PMR index and, to a lesser extent, in REP contrasts with the divergent pattern observed in the flow of patent applications. This descriptive evidence suggests that the timing of policy adoption and of liberalization matters in the establishment of technological advantages, as if the time of policy adoption yields a first mover advantage. By way of example, Anglo-Saxon and Scandinavian countries that outperform most countries in terms of green innovation liberalized their electricity sectors in the late 1980s and early 1990s, significantly before the bulk of other OECD countries (Glachant and Finon, 2003; IEA, 2004).

Control variables: We augment the econometric specification with a series a standard control variables that may affect green innovation beyond and above the presumably lead roles of REP and PMR (Johnstone et al., 2010). Following the literature on induced innovation (Popp, 2002; Newell et al., 1999), we should expect that an increase in the price of electricity would amplify the incentives for innovation in renewable energies.

We include electricity consumption by households and industry sectors to control for the dimension of the potential market for renewable energies. We also include a dummy variable set to unity for years after the Kyoto Protocol in 1997 to capture changes in expectation on both the context for future policy and the global market size for renewable energy. Note that the Kyoto dummy is positively correlated with the REP index. Hence, adding the Kyoto dummy is important for distinguishing the genuine effect of REP from the effect imposed by an external acceleration in policy support for renewables.

To account for the country's technological capabilities, we include the overall number of patent families generated by a particular country in a particular year, irrespective of their IPC class. Including the total number of patents in the controls – instead of the ratio of green over total patents as the dependent variable – generalizes the econometric strategy followed by Popp (2002) and Aghion et al. (2011) because we do not constrain the model to unit proportionality between green and generic patents. We also introduce a time trend to depurate our results from the influence of global time varying factors, such as macroeconomic cycles. Finally, we augment our model by including the lagged dependent variable, which is tantamount to controlling for persistency in inventive activities (Blundell et al., 1995).

Tables 1 and 2 provide summary statistics by country and for the overall panel. Observe the leadership of the Scandinavian countries (such as Norway and Denmark) in green patent intensity and the remarkable positions of Spain, Greece, Portugal, the Czech Republic and Poland. Germany is the only large and wealthy country with a green intensity above the cross-country average. Table 1 also provides the average patent production for all three measures of innovation:

[10] In fact, the PMR index combines three different sub-indices: entry barriers, vertical integration and public ownership. Each sub-index ranges from 0 to 6, where high values indicate lack of access to the grid from independent producers and consumers, full integration as opposed to unbundling and full public ownership as opposed to private ownership. Clearly, the PMR index represents a crude proxy for situations that are very difficult to capture with a quantitative measure. Assessing the extent of energy market liberalization is an exceedingly difficult task (Pollitt, 2012) and our results should hence be interpreted bearing these caveats in mind.

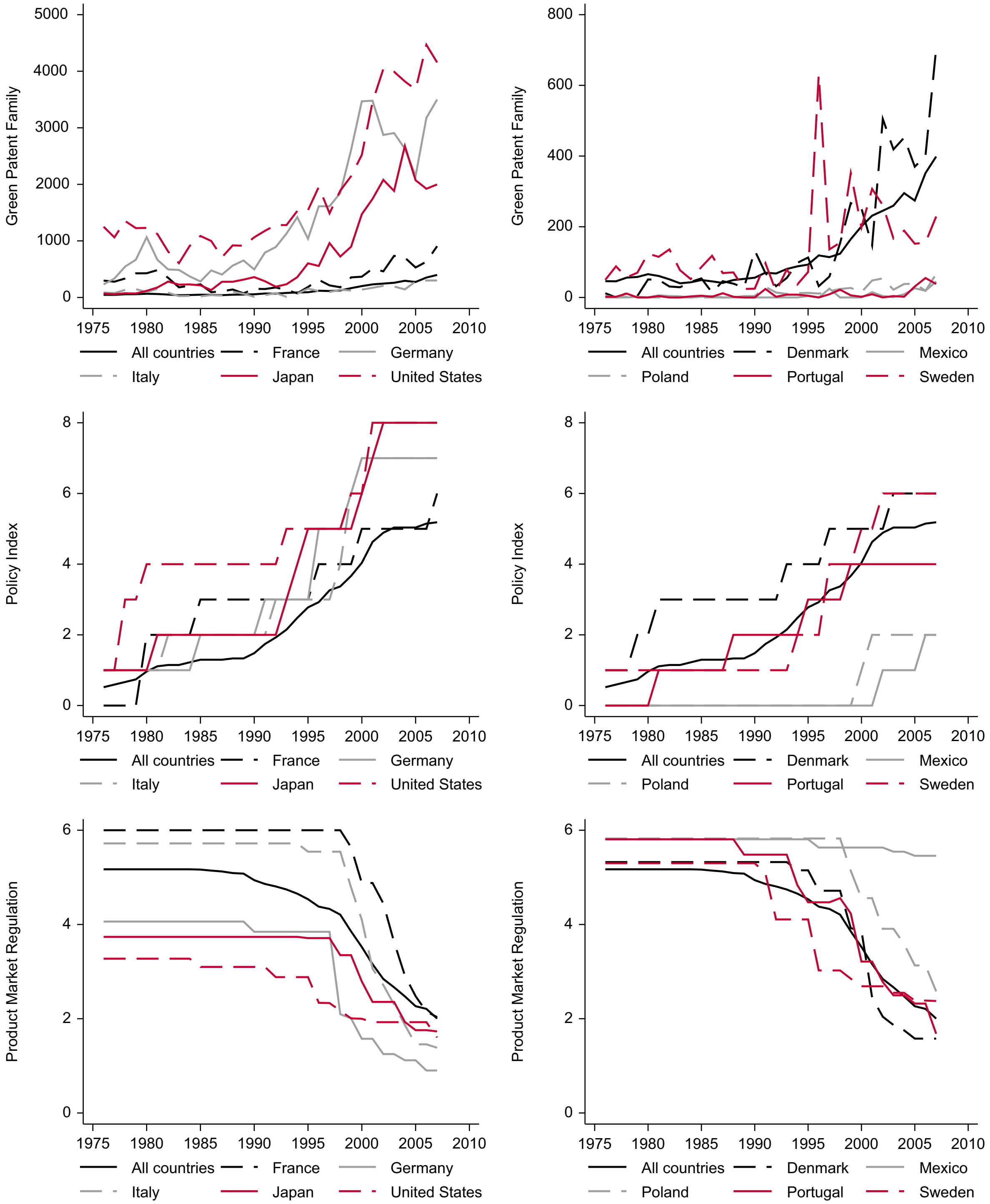

Fig. 2. Evolution of green family patent production, of the renewable energy policy index and of product market regulation between 1976 and 2007 in large countries (left panel) and small countries (right panel).

family weighted number of green patents (GPF), number of green patents (GPAT), and triadic filtered number of green patents (GTRI). Although their correlation ranges between .8 and .9, the latter drops to .5 when considering green innovation relative to the overall patent pool (variables GFI, GNI, GTI in Table 1). This suggests, first, that accounting for these various measures of performance matters and, second, that their determinants may differ significantly.

Table 1
Country characteristics in green patenting and policy indices – averages over the period 1976–2007.

Country	PF	GPF	PAT	GPAT	TRI	GTRI	GFI	GNI	GTI	REP	PMR	DG
All countries	19,083	224	21,143	110	1499	7.94	11.75	5.20	5.30	2.48	4.33	–
Australia	4429	86	4374	41	309	3.44	19.33	9.44	11.13	2.31	3.40	Low
Austria	5996	90	6449	49	358	1.78	15.00	7.65	4.97	2.97	4.42	Med
Belgium	5583	36	5661	19	469	1.19	6.41	3.33	2.53	3.00	3.79	Low
Canada	10,464	151	11,418	70	624	4.59	14.46	6.14	7.36	2.59	3.54	Low
Czech Republic	695	27	2,586	20	23	0.13	38.83	7.72	5.36	1.38	5.04	High
Denmark	4136	146	4393	75	221	2.69	35.34	17.14	12.17	3.72	4.40	High
Finland	5939	58	6916	27	277	1.59	9.82	3.94	5.76	3.06	3.97	Low
France	35,043	325	39,383	177	2,360	9.88	9.28	4.50	4.18	3.13	5.35	Low
Germany	87,129	1402	100,210	733	5,313	35.19	16.10	7.32	6.62	3.53	3.17	High
Greece	251	8	400	5	24	0.13	31.11	12.42	5.16	1.41	5.43	Low
Hungary	1158	17	1670	11	45	0.19	14.60	6.72	4.16	1.09	4.82	Low
Ireland	1281	17	1316	8	97	0.63	13.07	5.99	6.43	2.41	5.31	Low
Italy	14,119	114	19,686	59	675	2.97	8.09	2.99	4.40	3.41	4.81	Low
Japan	84,244	736	84,224	333	9655	53.00	8.73	3.95	5.49	3.81	3.31	Med
Luxembourg	799	11	804	6	62	0.38	13.19	7.11	6.02	1.88	4.88	Low
Mexico	364	5	547	3	23	0.09	14.93	6.00	4.07	0.25	5.72	Low
Netherlands	15,108	142	15,327	73	1659	5.59	9.42	4.74	3.37	3.03	4.62	High
New Zealand	666	9	670	4	45	0.28	13.42	5.93	6.32	1.63	3.84	Med
Norway	2230	65	2525	32	97	1.59	29.24	12.49	16.40	2.28	3.59	Low
Poland	476	15	2038	16	23	0.03	30.87	7.81	1.39	0.47	5.27	Med
Portugal	215	8	336	7	17	0.13	39.02	21.55	7.29	2.16	4.70	Med
Spain	3533	103	5639	65	164	1.66	29.12	11.45	10.10	2.56	3.40	Med
Sweden	14,015	137	14,012	63	810	3.44	9.80	4.52	4.24	2.56	4.16	High
Switzerland	17,195	138	17,405	68	1402	5.22	8.02	3.92	3.72	3.09	4.96	Low
Turkey	244	3	685	5	20	0.03	13.32	7.03	1.59	1.84	5.32	Low
United Kingdom	27,577	338	28,665	163	2109	12.91	12.26	5.68	6.12	2.53	3.03	Low
United States	172,358	1865	193,518	835	13,582	65.72	10.82	4.32	4.84	4.94	2.71	Low

Considered time span: 1976–2007; PF: family weighted overall number of patents; GPF: family weighted number of green patents; PAT: overall number of patents; GPAT: number of green patents; TRI: triadic filtered overall number of patents; GTRI: triadic filtered number of green patents; GFI: green intensity using patent family (PF/GPF, per thousand); GNI: green intensity using patent counts (PAT/GPAT, per thousand); GTI: green intensity using triadic patents (GTRY/TRY, per thousand); REP: renewable energy policy index; PMR: product market regulation aggregate index; DG: distributed generation before liberalization. Source: Our elaboration on information in Glachant and Finon (2003), IEA (2004) and country reports of the International Energy Agency.

Table 2
Descriptive statistics.

Variable	Mean	Median	St. dev.	Min.	Max.
Green patents (family weighted)	224.2	42	557.9	0	4,468
Green patents (triadic weighted)	7.942	1	23.24	0	193
Number of patents (family weighted)	19,083	3338	44,480	3	336,096
Number of patents (family weighted, log)	8.009	8.113	2.182	1.386	12.730
Pre-sample mean (green patents)	10.350	1.133	23.660	0.000	114.300
Electricity consumption (log)	11.030	10.990	1.332	7.920	14.660
Energy price index (log)	0.105	0.102	0.044	0.015	0.234
Public R&D in renewable Energy (log)	0.615	0.567	0.538	0.000	2.442
Kyoto (dummy)	0.344	0.000	0.475	0.000	1.000
REP index	2.483	2.000	2.062	0.000	8.000
Product market regulation	4.332	4.720	1.472	0.254	6.000

$N=843$. Time span: 1976–2007.

Econometric specification

The discreteness of the dependent variable advocates the use of count-data models. Let y_{it} be the number of family weighted patents assigned to country i, where $i=1,\ldots,N$, at time t, where $t=1,\ldots,T$. Dependent variable y_{it} has a Poisson distribution with parameter λ_{it}, which we condition on the host of factors $\mathbf{X_{it}}$ and the associated set of parameters $\boldsymbol{\beta}$ that are, in this case, the estimated effects of the set of factors affecting innovation in renewable energy: $E(y_{it}|\mathbf{X}_{it})=\exp\,(\mathbf{X_{it}}\beta)$.

The major feature of the Poisson model lies in the assumption of the equality of the mean and the variance of parameters, although often the empirical mean and variance reveals the presence of overdispersion. The choice of family as opposed to triadic patents to account for quality is motivated by the presence of the many zeros in the triadic patent count, rendering the overdispersion problem more severe than in the case of family patents. This choice allows us to use cluster-robust standard errors to account for mild cases of overdispersion, as stipulated by Cameron and Trivedi (2005).

Apart from the count-data nature of the dependent variable, the econometric specification must address three important matters in the estimation procedure. First, as in panel data settings, persistent – but unobserved – differences across countries are likely to explain the rise of renewable energy sources in given countries. Natural endowments such as wind, sun and hydropower are obvious candidates. Preference for sustainable development – a country-specific characteristic – may also explain given trajectories. More generally, unobserved time-invariant country characteristics may affect our results.

We account for unobserved heterogeneity using Blundell et al.'s (2002) pre-sample mean (PSM) estimator. We prefer the PSM estimator to the traditional fixed effect count-data estimator developed by Hausman et al. (1984) and the quasi-differenced estimator proposed by Chamberlain (1992) and Wooldridge (1997) because the latter two estimators lack consistency.[11] In the Blundell et al.'s (2002) estimator, information on the dependent variable prior to the initial year of investigation (1976) can be used to capture unobserved heterogeneity. The PSM estimator is shown to be consistent when the number of pre-sample periods is large (as is the case with patent data) and to have better finite sample properties than the quasi-differenced GMM estimator (Blundell et al., 2002).

The inclusion of the pre-sample mean value of the dependent variable is done as follows:

$$y_{it} = \exp\,(\mathbf{X_i}\boldsymbol{\beta} + \gamma\,\ln\,\overline{y}_{ip}) + \varepsilon_{it} \tag{1}$$

where $\overline{y}_{ip} = (1/TP)\sum_{r=0}^{TP-1} y_{i,0-r}$ represents the pre-sample mean, which grasps persistent differences across panels of the database (countries). TP is the number of pre-sample observations.

Although past studies have tested the effect of policy on innovation using patent data,[12] only a few studies have incorporated some form of path dependency into their empirical specification. The seminal paper of Popp (2002) shows that it is important to include the past knowledge stock to obtain unbiased estimates of the policy inducement effect. Verdolini and Galeotti (2011) amend this result showing that foreign knowledge has also a significant impact on green innovation. Aghion et al. (2011) consider the ratio between green and brown knowledge stock to test how the direction of technical change is affected by environmental and innovation policies. Differently from these works, the inclusion of a linear feedback allows us to disentangle the short- and long-run effects of our variables of interest (Blundell et al., 2002). More precisely

$$y_{it} = \rho y_{it-1} + \exp\,(\mathbf{X_i}\boldsymbol{\beta} + \gamma\,\ln\,\overline{y}_{ip}) + \varepsilon_{it} \tag{2}$$

The purpose of imposing a linear feedback, as opposed to an exponential feedback, is that it eliminates the possibility of an explosive series. Thus, imposing a linear feedback model is akin to imposing a lower bound to the expected patent count set to ρy_{it-1} because $\exp(\mathbf{X_i}\boldsymbol{\beta} + \gamma\,\ln\,\overline{y}_{ip})$ is always positive. Note that the inclusion of the lagged dependent variable allows us to account for lags between the set of covariates and the dependent variable without imposing a lag structure.

The last econometric issue concerns the possible endogeneity of REP policies, which we will discuss in the next section. We will therefore estimate Model 2 using the generalized method of moments. Relying on a GMM estimator allows for the use of instruments as follows:

$$\frac{1}{N}\sum_{i=1}^{N}\sum_{t=1}^{T} \mathbf{Z_{it}}\Big(y_{it} - \rho y_{it-1} - \exp\Big(\mathbf{X_{it}}\boldsymbol{\beta} + \gamma\,\ln\,\overline{y}_{ip}\Big)\Big) = 0 \tag{3}$$

where we define exclusion restrictions in the case of endogeneity of the regressors as $\mathbf{Z_{it}} = (\mathbf{1}, \tilde{\mathbf{X}}_{\mathbf{it}}, \mathbf{y_{ip}}, \mathbf{P}_{\mathbf{it}-\tau}, \mathbf{IV}_{\mathbf{it}-\tau})$, $\tilde{\mathbf{X}}_{\mathbf{it}}$ is the adapted set of variables, which are considered exogenous, $\mathbf{P}_{\mathbf{it}-\tau}$ are our various measures of policy indices (REP and PMR), and $\mathbf{IV}$ are instruments that serve as additional moment restrictions to account for the endogeneity of the policy variables.

Endogeneity

Endogeneity is a pervasive issue in the estimation of the effects of the REP and PMR indices because both reverse causality and omitted variables can induce a bias in the estimated coefficients. Further complicating the estimation of their joint effect is a mutual reinforcement effect between them, which amplifies the sources of reverse causality, as discussed by Downing and White (1986). Historic successful innovations in clean energy reinforce the lobbying power of innovating firms toward policy makers. In turn, current policies may have a positive influence on future innovation.[13] Without accounting for endogeneity, reverse causality is likely to bias upwardly the estimated effects of REP and PMR.

Our strategy is to use both within-sample and out-of-sample instruments. First, our time-series cross-country database fits perfectly with the use of lags in the policy variables. We therefore use two-year lags as instruments for future levels in the policy variables (REP index, PMR index, their interaction and a one-year lag for green R&D per capita). Reverse causality may also be an issue with energy prices. Although our model stipulates that energy prices induce innovation, innovation in renewable energy also translates into higher electricity costs for consumers because of an REP cost pass-through. We therefore choose to instrument energy prices with their own past levels.

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[11] This lack of consistency is due to the endogeneity of some regressors for the former estimator and due to persistent series for the latter.

[12] See, e.g., Lanjouw and Mody (1996), Brunnermeier and Cohen (2003), Popp (2002, 2006), Johnstone et al. (2010) and Verdolini and Galeotti (2011).

[13] Note that the positive feedback mechanism may become negative because existing lobbies in the energy sector and large utility generators are likely to exacerbate failures in given policies and/or green innovation output by postulating a reduction in the support for renewable energy (Jacobsson and Johnson, 2000; Nilsson et al., 2004; Lauber and Mez, 2004; Nicolli and Vona, 2012).

Second, we include a series of out-of-sample instruments, which serve as predictors of policy implementation. The close interplay between competition and RE policies points to the existence of a latent factor affecting both the liberalization process and the adoption of REP, including green R&D per capita. Moreover, because of the strong persistence of our two policy indicators, the timing of reforms is of paramount importance in establishing comparative advantages in renewable energy technologies. Accordingly, we chose an instrument that jointly influences the two policy indicators and, in particular, their time of adoption: TENSYS, a variable accounting for the time length for which a country has had consolidated, and durable democratic institutions. This information is provided by the 2010 version of the World Bank Database on Political Institutions (for details see, Beck et al., 2001). In fact, a growing literature shows that democratic countries tend to approve stricter environmental policies and foster product market liberalizations.[14] With respect to younger democracies, our conjecture is that durable democracies ensure a longer time horizon for decision making and should be more responsive to citizens' preferences as a result of environmental activists and NGOs exerting a positive influence on environmental policies (Fredriksson et al., 2005; List and Sturm, 2006).

We also consider the share of decentralized energy production before the liberalization process (DG henceforth). It acts as a proxy for the initial know-how in decentralized energy production that fits well with several renewable energies. In the late 1980s, energy generation was essentially centralized when liberalization started. However, Nordic and Central European countries were previously committed to dispersed ownership structures (Glachant and Finon, 2003) with a significant share of energy produced in local heating systems (e.g., Sweden) as by-products of farm and industry activities (e.g., in Germany), or in some remote areas that were difficult to reach (e.g., in Denmark).[15] Lacking detailed information on distributed generation in the 1970s, we build our DG variable using the taxonomy on energy system contained in Glachant and Finon (2003) and from our reading of the various publications of the International Energy Agency.[16] In particular, we use three dummy variables quantifying the degree of commitment of countries to decentralized energy production (high, medium and low share). We expect a positive effect of the initial share of distributed generation on both the REP and the PMR indexes. Appendix B displays the results of the usual tests for the validity of the external instruments that are largely passed by both the DG dummies and TENSYS.

Empirical results

Main results

Table 3 displays the results of regressions in which we introduce the main variables of interest independently (Models 1 and 2) and then add the interaction term (Models 3 and 4). Models 1 and 3 assume exogeneity of the policy variables. We instead focus on Models 2 and 4, which account for the endogeneity of the REP index and aggregate PMR.

In Model 2, the linear feedback and the family weighted number of patents capture a significant share of the variance of the dependent variable. The country-specific initial conditions (*Pre-sample mean*), computed over the period 1960–1975, are both positive and significant. In turn, the energy price index has the expected sign and is near significance (p-value = .147). Neither Public R&D in renewable energy nor the Kyoto dummy exhibit statistical significance, implying that neither has an effect on innovation activities in renewable energy. Finally, the time trend is negative, suggesting the presence of a technological frontier that becomes more difficult to move forward as the knowledge stock increases.[17]

Turning to the variables of interest, we observe that *PMR*, the index for product market competition, has a negative and significant effect on the generation of green patents implying that invention in renewable energy occurs in more competitive markets.[18] Past literature has produced results that are both consistent and at odds with our findings. On the one hand, Jamasb and Pollitt (2008) (resp., Sanyal and Ghosh, 2014) find that liberalization in the energy market in the UK (resp., in the US) has had a negative effect on utility (resp. overall) energy patents. On the other hand, for the manufacturing sectors, Blundell et al. (1995) (resp., Griffith et al., 2010) estimate a positive effect on generic innovation in the UK (resp., for a group of EU countries), particularly in sectors characterized by low initial levels of competition. These discrepancies may reveal systematic differences in the way liberalization has been implemented in these countries and may reflect differences in measurements and econometric specifications.

The striking result of Model 2 is that the effect of RE policies on innovation is virtually nil.[19] Observe, however, that in Model 1, not accounting for endogeneity, REP is positive and significant. Hence, if implementation of RE policies is positively

[14] See, e.g., Congleton (1992), Murdoch and Sandler (1997), Fredriksson et al. (2005), Neumayer (2002), Pitlik (2007), Pitliks and Wirth (2003) and Chang and Berdief (2011).

[15] Note that the initial share of distributed generation also captures the political strength of players, which are potentially more interested in switching to renewable energy, such as municipalities and local communities.

[16] http://www.iea.org/

[17] This latter result is consistent with the idea that invention becomes more difficult as time goes on. For example, renewable energies are characterized by decreasing returns associated with the limited number of appropriate geographical locations (Fischer and Newell, 2008).

[18] The inclusion of PMR squared does not provide evidence in favor of a non-linear effect of PMR. If we split the PMR into its three components (vertical integration, public ownership and entry barriers), the aggregate effect seems largely driven by barriers to entry and, to a lesser extent, by the percentage of public ownership in energy utilities. Results are available upon request.

[19] Because the out-of-sample instruments are not directly derived from a fully fledged theoretical model, their theoretical validity may be questioned. To test the robustness of our choice, we use a different main instrument: per capita income. Its use is motivated by the robust evidence that ambitious

Table 3
Determinants of family weighted number of green patents, exogenous and endogenous regressors.

Variable	Model 1	Model 2	Model 3	Model 4
Linear ρ	0.740***	0.800***	0.675***	0.691***
	[0.070]	[0.053]	[0.075]	[0.081]
Overall families (log)	0.793***	0.908***	0.792***	0.889***
	[0.121]	[0.127]	[0.114]	[0.118]
Time trend	−0.029***	−0.006	−0.027	−0.019
	[0.007]	[0.018]	[0.024]	[0.013]
Pre-sample mean (log)	0.004*	0.004**	0.004**	0.004**
	[0.002]	[0.002]	[0.002]	[0.002]
Electricity consumption (log)	−0.117	−0.177	−0.102	−0.195
	[0.118]	[0.133]	[0.096]	[0.124]
Energy price index (log)	2.849	2.474	2.701	1.349
	[1.964]	[2.359]	[1.767]	[2.193]
Public R&D in renew. (log)	−0.001	0.200	0.054	0.136
	[0.128]	[0.131]	[0.131]	[0.121]
Kyoto	0.130	0.052	0.153	0.108
	[0.157]	[0.163]	[0.198]	[0.114]
REP index	0.090**	−0.010	0.143***	0.131***
	[0.037]	[0.073]	[0.054]	[0.046]
Aggregate PMR	−0.234***	−0.224***	−0.135*	−0.117
	[0.047]	[0.047]	[0.078]	[0.075]
REP index × PMR			−0.024**	−0.027*
			[0.012]	[0.014]
Constant	55.024***	8.586	51.004	35.417
	[14.421]	[36.200]	[47.148]	[26.711]
Observations	843	816	843	816
Moments	11	16	12	18
Hansen's J	0	8.941	0	8.988
Hansen's d.f.	0	5	0	6
Hansen critical probability		0.111		0.174

Pre-sample mean Poisson model with linear feedback. GMM estimator. Pre-sample mean information computed for the first 15 years available. Estimation time span: 1976–2007. Standard errors are cluster-robust by countries.
List of endogenous regressors for Models 2 and 4: Energy price index; public R&D in renewable energy; policy index; aggregate PMR; policy index × PMR.
List of instruments: energy price index lagged one year; R&D in renewable energy lagged one year; policy index, aggregate PMR, policy index × PMR lagged one and two years; dummies for DG before liberalization (medium and high) and democracy longevity (Tensys).

* Statistical significant at 10%.

** Statistical significant at 5%.

*** Statistical significant at 1%.

correlated with past innovations, its effect must be upwardly biased when not properly accounting for endogeneity. Once the latter is accounted for, the independent effect of REP vanishes. We interpret this as evidence of the presence of a reverse causality: past successes in innovation in clean energy legitimize the implementation of RE policies. This result is consistent with the recent papers of Popp et al. (2011) and Comin and Rode (2013).[20] In turn, the effect of R&D per capita is greatly underestimated without properly accounting for endogeneity, although this effect remains statistically insignificant.

The lack of effect of REP is in fact at odds with prior art (Johnstone et al., 2010). However, part of the puzzle is alleviated in the key specification (Model 4), in which we include an interaction term between PMR and the Policy Index. Recall that Proposition 3 stipulates that RE policies are more effective in competitive energy markets. The results exhibit a negative and significant sign of the interaction term, which is consistent with the proposition. The finding reveals that renewable energy policies are more effective in more competitive markets, validating the policy complementarity hypothesis.

Analyzing the sign of the marginal effect of RE policies provides additional insights. Because of the interaction term, the sign of the marginal effect is entirely defined by $\partial z/\partial REP = \beta_{REP} + \beta_{REP \times PMR} \times PMR$.[21] Fig. 3 displays $\partial z/\partial REP$ and shows that when PMR is low and market competition is high, the effect of RE policies on innovation is positive. Instead beyond a given level of product market regulation, the contribution of REP becomes negative. This finding is consistent with the case-study evidence presented in the section "Factors affecting renewable energy innovations". In particular, it suggests that incumbents and entrants have different incentives to innovate. Low entry barriers reveal this difference only in the presence of active RE policies, which increases the potential market for renewable energy and makes entry profitable.

(*footnote continued*)
environmental policies tend to be adopted in more developed countries (Dasgupta et al., 2001; Esty and Porter, 2005; Nicolli and Vona, 2012). The results are fully robust to this extension.

[20] The former paper finds a positive effect of technology on the demand for renewable energy capacity, and the latter finds a positive effect of installed Photovoltaic modules on the share of green party votes for German districts.

[21] Computing $\partial y/\partial REP$ yields $\partial z/\partial REP \times \exp(z)$, where $z = \mathbf{X_i}\boldsymbol{\beta} + \gamma \ln \overline{y}_{ip}$.

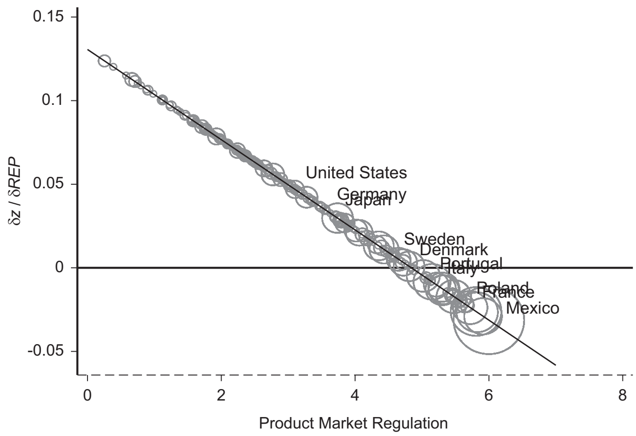

Fig. 3. Estimated linear effect of renewable energy policies, conditional on product market regulation (circles are proportional to the number of observations).

Fig. 3 also positions the average PMR value over the period. US performance seems most appropriate, scoring highest in the $\partial z/\partial REP$ and achieving the lowest score in PMR. However, in France and Mexico, public support for renewable energy may be made less efficient by the lack of competition in the energy markets. It should be noted that apart from Mexico, all countries increased product market competition enough to enjoy a positive contribution of RE policies to innovation.

In a similar vein, observe that the effect of PMR becomes insignificant in Model 4. Yet one should not conclude on the absence of correlation between PMR and green innovation. Rather, the significance of the effect of PMR on innovation is now conditional on the portfolio of policies in renewable energy. As depicted by the interaction term $REP \times PMR$, countries with at least one policy instrument in renewable energy will enjoy a significant effect of market competition on green innovation. But in the complete absence of RE policies, market competition will neither support nor deter innovation in renewable energy. In our dataset, only 18% of observations comply to this condition, most of them occurring in the early years of the period under investigation.

Quality of inventions

This section aims to address the quality of invention by using two additional ways of computing patent production. First, we use simple patent counts in renewable energy without accounting for patent quality, that is, without weighing patents by the number of offices to which each patent is filed. Second, we use triadic patents. Whereas patent families control for the number of foreign offices, they do not control for the quality of patent offices, namely market size.[22] Therefore, an even more stringent proxy for high-quality inventions is obtained counting only patents jointly registered at the Japanese, US and European patent offices. The only drawback associated with using triadic patents is time-truncation because the European Patent Office was first established in 1978. We overcome this problem by using the pre-sample mean information on green patent families.[23] Using Model (4) as our baseline specification, Table 4 shows the results for green patent count (Model 5) and for the number of triadic patents (Model 6).

First and foremost, the complementarity hypothesis seems to hold for high-quality patents. To produce frontier innovations in the realm of renewable energy, countries with more ambitious environmental policies perform better if their energy market has been liberalized (Model 6). Although the PMR has the expected sign, its individual effect is not significant. This result suggests that it is the commitment of public authorities to cleaner energy production – not market deregulation – that is a first-order condition for yielding high-quality innovation. Deregulation thus remains a second-order condition that renders REP more effective in frontier research. Denmark and Germany are examples of countries that adopted ambitious policies first and then fully liberalized the energy market.

The pattern for green patent count, not controlling for patent quality, is remarkably different (Model 5). We observe no significant effect on patent count from the REP index. Instead, product market regulation displays larger effects for low-quality patents. We interpret this result as stemming from the strategic behavior of large utilities: knowledge appropriation by incumbents impedes innovation by potential rivals, thereby deterring entry (Smiley, 1988).

[22] Imagine an invention being granted by, for example, 10 legal authorities, none of which cover a large market. How would that compare with an invention being granted in the three largest markets worldwide, which are the US, the European and the Japanese markets?

[23] Between 1978 and 1985, both triadic green patents and green patent families are highly correlated, with a Pearson correlation coefficient reaching .97. It is worth noting again that we do not use triadic as our favorite measure of innovation because green triadic patents contain more zero values than green families. The problem with zero-inflated count variables is that the issue of overdispersion may not be successfully resolved using cluster-robust standard errors, as we do with the pre-sample mean GMM estimator (Cameron and Trivedi, 2005). However, the results are robust to the use of a negative binomial model.

Table 4
Determinants of inventions of different quality: green families (Model 4); green patents (Model 5); triadic green patents (Model 6).

Variable	Model 4	Model 5	Model 6
Linear ρ	0.691***	0.845***	0.503***
	[0.081]	[0.056]	[0.102]
Overall number of patents (log)	0.889***	0.817***	*0.760****
Overall number of triadic patents (log)	[0.118]	[0.099]	[*0.050*]
Time trend	−0.019	−0.045***	−0.024*
	[0.013]	[0.014]	[0.014]
Pre-sample mean (log)	0.004**	0.008	−0.003***
	[0.002]	[0.005]	[0.001]
Electricity consumption (log)	−0.195	−0.163	0.124***
	[0.124]	[0.107]	[0.047]
Energy price index (log)	1.349	3.011	−0.910
	[2.193]	[2.235]	[1.268]
Public R&D in renew. (log)	0.136	−0.171	0.151
	[0.121]	[0.207]	[0.126]
Kyoto	0.108	0.693***	0.149
	[0.114]	[0.147]	[0.142]
REP index	0.131***	0.008	0.272***
	[0.046]	[0.047]	[0.044]
Aggregate PMR	−0.117	−0.283***	−0.032
	[0.075]	[0.081]	[0.060]
REP index × PMR	−0.027*	−0.006	−0.035***
	[0.014]	[0.022]	[0.012]
Constant	35.417	86.679***	40.975
	[26.711]	[28.736]	[28.039]
Observations	816	816	816
Moments	18	18	18
Hansen's J	8.988	9.03	4.311
Hansen d.f.	6	6	6
Hansen critical probability	0.174	0.172	0.635

Pre-sample mean Poisson model with linear feedback and endogenous regressors. Standard errors are cluster-robust by countries.
List of endogenous regressors: energy price index; public R&D in renewable energy; policy index; aggregate PMR; policy index × PMR.
List of instruments: energy price index lagged one year; R&D in renewable energy lagged one year; policy index, aggregate PMR, policy index × PMR lagged one and two years; dummies for DG before liberalization (medium and high); democracy longevity (Tensys).

* Statistical significant at 90%.

** Statistical significant at 95%.

*** Statistical significant at 99%.

In the same vein, the Kyoto Protocol has had a remarkably positive effect on low-quality green innovations. The ratification of Kyoto increases the expected size of the global market for clean energy, pushing all countries to redirect innovative efforts toward renewable technologies. However, Kyotos lack of significance in terms of high-quality inventions may reveal the presence of a resource misallocation problem. Countries located far from the frontier put too much effort on research in which they lack expertise.

In sum, our empirical results corroborate the three propositions in the section "Factors affecting renewable energy innovations". First, we estimate a positive effect of competition on innovation (Proposition 1). The effect is decreasing with patent quality, being significantly different from zero only for low-quality patents. Second, the independent effect of renewable energy policies is significant for high-quality patents (Proposition 2). Third, the joint effect of competition and renewable energy policies is positive and statistically significant, but only for patents of higher quality (Proposition 3).

Marginal effects

This section examines the actual magnitude of the effect of policy variables on inventive activities in renewable energy. Using estimates from Models 4 to 6, we compute the country-year short-run marginal effects of policy j as the discrete change in the expected output resulting from an inter-quartile change in policy j, holding all variables at their observed value.[24]

Table 5 shows for each policy variable the short-term variations in the expected number of patents in absolute terms (1st row), relative to the mean (2nd row) and median (3rd row).[25] Our discussion focuses primarily on the marginal effects derived from significant parameter estimates.

[24] See Appendix C for a detailed presentation of the computation of marginal effects.

[25] For triadic patents, we choose to express this relative to the mean, the median of triadic patents being 1.

Table 5
Average marginal effects of policies on various forms of innovation in renewable energy.

Variable	Patent family (Model 4)	Patent number (Model 5)	Triadic patents (Model 6)
Unconditional mean	224.2	109.9	7.94
Unconditional median	42	25	1
Long run multiplier	3.2	6.5	2.0
Aggregate PMR	*30.54*	11.10	*1.39*
	13.62	10.09	17.53
	72.71	44.38	139.20
REP index	10.19	*−0.49*	1.24
	4.55	−0.44	15.61
	24.26	−1.95	123.90
REP index × PMR (both vary)	26.04	*10.36*	1.46
	11.61	9.43	18.37
	61.99	41.43	145.90
PMR varies, REP index at the median	21.31	*11.05*	0.50
	9.51	10.05	6.26
	50.74	44.18	49.70
PMR varies, REP index at the 25th per	17.73	*11.01*	0.29
	7.91	10.02	3.66
	42.22	44.05	29.05
PMR varies, REP index at the 75th per	28.77	*11.10*	1.06
	12.83	10.10	13.36
	68.50	44.39	106.1
REP index varies, PMR at the median	0.47	*−3.86*	0.65
	0.21	−3.51	8.21
	1.11	−15.44	65.17
REP index varies, PMR at the 25th per	8.31	*−0.65*	1.17
	3.70	−0.60	14.71
	19.77	−2.62	116.80
REP index varies, PMR at the 75th per	−2.73	*−0.74*	0.40
	−1.22	−0.67	5.01
	−6.51	−2.96	39.76

Italics denote marginal effects derived from non-significant parameters at the 10% level.
Each cell displays the change in the expected number of patents in absolute terms, relative to the mean and median.
All marginal effects have been computed based on the discrete changes in the expected number of patents resulting from a change in policy j, holding all variables at their observed value ($\mathbf{X}_{-\mathbf{j,it}}$), and fixing the variable of interest x_j at the 1st and 3rd quartiles. For variable aggregate PMR, the change is computed from the 3rd to the 1st quartile.

In the case of patent families, the expected increase is mostly accounted for by the REP Index and the interaction term with PMR. Taking all variables at their observed value, an increase from the first to the third quartile of the REP Index yields an increase in patent families by 10, representing almost a 4.5% (resp. 24%) increase with respect to the mean (resp. median). PMR also has a sizeable marginal effect. An increase in product market competition will be associated with an increase in patent families by 30, that is, patent applications to 30 intellectual authorities other than the original country of application.[26]

Note that the effectiveness of RE policies vanishes for green patent production. In contrast, the effectiveness of such policy changes becomes remarkably high for triadic patents. An increase by two quartiles of the policy index yields 1.2 more triadic patents, which represents nearly 15.5% of the mean of triadic patents and a doubling of the median (+123%). Market deregulation has a larger effect on generic green patents than on triadic ones. The effect on frontier innovation (triadic patent count) is substantial (+17% in triadic patents relative to the mean), but its lack of significance (p-value = 0.59) implies a large cross-country heterogeneity in this policy tool.

The above results show that the policy tools in support of innovation may be different, depending on whether we focus on frontier research activities or R&D outcome irrespective of quality. Yet the complementary hypothesis implies that the effect of a given policy tool depends on the level of the other policy of interest. The last rows of Table 5 display the marginal effects of a policy change from the first to the third quartile, holding the complementarity policy at the first, the second or the third quartile. We find that the size of the interacted effect is large for high-quality triadic patents and, to a lesser extent, for medium quality patent families. In the case of triadic patents, REP is three times more efficient under deregulated markets, with a marginal effect ranging from 5% in highly regulated markets to 15% in more competitive markets. For green families, the marginal effect is almost twenty times larger in liberalized energy markets compared to mildly regulated markets. In this case, however, the effect is quite sizeable only when the expected increase in the number of inventions is expressed as a fraction of the median family size. Finally, similar gains in efficiency are found for PMR as marginal effects increase nonlinearly depending on the level of the REP index.

[26] With critical probability value of .119 in Model 4, PMR is near significance.

Finally, it is important to note that the value of the linear feedback for generic patents exceeds .8, implying a high level of persistence in patent generation. Such persistence also renders the long-run multiplier remarkably high, inflating all marginal effects by a factor of 6. In turn, past successes in high-quality triadic patents do not guarantee high-quality production in the future. The decrease in persistence ($\rho = .503$) entails a corresponding decrease in the long-run multiplier, inflating short-term marginal effects only by a factor of 2. Therefore, as countries draw near the technological frontier, the long-term effectiveness of policies will gradually decrease consistently with the rising costs of path-breaking invention.

Conclusions

Innovation in renewable energy is now widely regarded as the key to sustaining and improving the quality of life for current and future generations. In addition to standard differences in overall technological levels and life standards, environmental policies alone appear important but not sufficient for explaining cross-country differences in innovation. Our empirical analysis shows that the extent to which these policies are effective largely depends on complementary regulatory features. In particular, the combination of environmental policies and market deregulation is the most effective method of inducing innovation in renewable energy, particularly near the technological frontier. This finding corroborates the complementarity hypothesis that environmental policies are more effective in competitive markets.

The reader may think that our results depict spurious correlations rather than causalities, due to the fact that we do not account for the country's natural endowment for renewable energy. Imagine for example that liberalization in the energy markets occurs in countries well endowed in renewable energy potential. It could then be argued that the observed effect of PMR reveals the incentive effect of natural endowment on green innovation, not the causal effect running from liberalization to innovation. Yet we believe that our results are immune to this caveat insofar as the pre-sample mean correctly captures the RE potential, a country characteristic which for the most part is time-invariant. We are therefore inclined to interpret our results as depicting causalities. However, we do acknowledge that further research is required to test their robustness when including direct proxies for such natural endowments in renewable energy.

Our research agenda must address three important issues. First, the overall effect of liberalization and policy on innovation conceals heterogeneous firm responses. A better understanding of their response function would unravel the channels by which policy changes translate into overall country performance. Second, our dynamic specification can be enriched to test the hypothesis of directed technical change by Acemoglu et al. (2012). In a context where global warming questions the ability of policy makers to intervene on given technological trajectories, whether energy market deregulation and public policy adoption can convert conventional patent production into green innovation is of the utmost importance. Finally, the EUs integration of energy markets may have had unintended consequences on green innovation insofar as integration may select out small players, reinforcing the power of incumbents. EU incumbents are more likely to lobby for policies that are less conducive to innovation, i.e., RECs rather than feed-in tariffs (Jacobsson et al., 2009). These concerns could be rigorously tested using firm-level data for EU countries within the appropriate time frame.

Acknowledgments

We are especially thankful to David Popp, The Editor of the Journal, and two anonymous referees for their support and insightful comments. We also thank Alessandro Sapio and Elena Verdolini for their suggestions, and Philippe Aghion, Ufuk Akcigit, Christopher Baum, Valentina Bosetti, Diego Comin, Davide Consoli, Enrica De Cian, Pedro Linares, Vincenzo Lombardo, Alberto Marzucchi, Andrea Mina, Pietro Peretto, Francesco Saraceno, David Soskice, Massimo Tavoni and Jeroen van den Bergh. We are also indebted to Giuseppe Nicoletti for providing us with data on product market regulation by sector. One of the author wishes to thank Fondazione Enrico Mattei for hosting him during the writing of this paper. The usual disclaimer applies.

Appendix A. Supplementary material

Supplementary data associated with this article can be found in the online version at http://dx.doi.org/10.1016/j.jeem.2014.01.001.

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