Routledge
Taylor & Francis Group

Journal of Economic Policy Reform

ISSN: 1748-7870 (Print) 1748-7889 (Online) Journal homepage: https://www.tandfonline.com/loi/gpre20

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To cite this article: Alessandro Sterlacchini (2020) Trends and determinants of energy innovations: patents, environmental policies and oil prices, Journal of Economic Policy Reform, 23:1, 49-66, DOI: 10.1080/17487870.2019.1565410

To link to this article: https://doi.org/10.1080/17487870.2019.1565410

JOURNAL OF ECONOMIC POLICY REFORM
2020, VOL. 23, NO. 1, 49–66
https://doi.org/10.1080/17487870.2019.1565410

ARTICLE

Trends and determinants of energy innovations: patents, environmental policies and oil prices

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ABSTRACT
This paper examines the relationship between energy innovations, environmental policies and oil prices. With a panel of 19 OECD countries over the period 1990–2013, we test how the stringency of environmental policies has affected the intensity of energy patents, while controlling for the effect of oil prices and other country-level variables. We found that the overall level of policy stringency has exerted a more significant impact than individual country measures. Moreover, the recent reduction of energy patenting is discussed, especially in the light of the staggering drop of oil prices.

ARTICLE HISTORY
Received 30 December 2017
Accepted 10 December 2018

KEYWORDS
Energy innovations; patents; environmental policies; oil prices

JEL CLASSIFICATION
Q42; Q55; Q58; O34

Policy Highlights

- The stringency of environmental policies is a key determinant of energy innovations.
- The international level of policies' stringency is more effective than that recorded at national level.
- In light of the recent reduction of energy patents, coupled with that of oil prices, stringent environmental policies should be reinforced.
- To foster further innovations in the energy field, environmental and innovation policies should be more focused on long-term R&D.

1. Introduction

For various reasons, energy is one of the most important sectors of general interest. The need for a universal provision of energy to households and businesses (possibly at fair prices), coupled with the need for energy safety and security, place this sector among those most regulated and considered as strategic for protecting national interests. In this respect, another reinforcing argument is due to the strong linkage between energy production and consumption and environmental protection. Due to the harmful consequences of climate-change, to exploit clean sources of energy has become crucial, even for addressing the issues of energy safety and security.

This paper provides evidence on the relationship between innovation in energy technologies, stringency of environmental policies and changes in oil prices. We use international

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Supplemental data for this article can be accessed here.

patent applications as proxies of valuable energy innovations. The share of energy patents has remarkably increased during the period 1990–2013 and such a positive trend appears to be closely associated with both a synthetic index for the stringency of environmental policies and the oil prices index.

With a panel analysis for 19 OECD countries we attempt to identify the causal relationships between the above variables by controlling for the impact exerted by other country-specific determinants of energy innovations. We find that the aggregate international index of environmental policies' stringency (averaged across the OECD countries) has an effect on energy patents more significant than the effect of individual policy measures at the country level. Moreover, when such an aggregate policy index is used, the impact of oil prices decreases or loses significance. Some policy considerations are added in discussing the recent reduction of energy patenting, coupled with the staggering drop of oil prices.

Our paper relates to a large body of empirical literature aimed at testing the *weak version* of the so called "Porter Hypothesis", according to which stringent and well-designed environmental regulations may induce innovations (Ambec et al. 2013). In particular, we refer to a number of studies that use patents to measure environment-friendly and/or energy-efficient innovations and, by means of panel data across countries, estimate how their number is affected by environmental policies (along with other factors). Relevant examples of such empirical studies are Popp (2002, 2010), Johnstone, Hascic, and Popp (2010), Cheon and Urpelainen (2012), Nesta, Vona, and Nicolli (2014), Calel and Dechezleprêtre (2016). However, while most of the previous studies focus upon specific environmental or energy technologies (and policies), our analysis is concerned with a broad set of energy innovations (and a composite index of environmental policies). Recent works that adopt a similar approach are Dasgupta, De Cian, and Verdolini (2016) and Fabrizi, Guarini, and Meliciani (2018). Finally, our main finding (i.e. the limited role of country-level environmental policies) is consistent with the results of Peters et al. (2012), Dechezleprêtre and Glachant (2014), and Costantini, Crespi, and Palma (2017): these authors find that environmental policies adopted by foreign countries influence domestic innovations not only significantly but sometimes to a larger extent than domestic policies. Accordingly, the presence of cross-country innovation spillovers reinforce the need for coordinating stringent environmental policies on a global scale (as happened with the Kyoto Protocol and, more recently, with the Paris Agreement).

The paper is organized as follows. Section 2 discusses the use of patent data to approximate energy innovations and presents some descriptive evidence at the aggregate level. Section 3 illustrates the role of environmental policies and oil prices as determinants of energy patents; in particular, the properties and trends of a synthetic index for the stringency of environmental policies are discussed and presented. Section 4 provides panel estimates for the impact of environmental policies and oil prices on energy patents by controlling for the role played by other relevant determinants. In the light of the recent reduction of energy patents, Section 5 introduces some reflections and policy considerations. Concluding remarks are contained in the final section.

2. Energy patents: classification, data sources and descriptive analysis

In this paper, like in a wide number of empirical studies mainly focused upon renewable or clean energy sources (see the previous section), energy innovations are proxied by patent applications. Another proxy could be the amount of energy R&D expenditures. Public R&D

spending on energy technology is available for most of the OECD countries also at a disaggregate level (e.g. by different energy sources). However, for private R&D spending it is impossible to get equally comprehensive information (Hascic and Migotto 2015). In fact, data on business R&D in the energy (or power) field are usually confined to the expenditures recorded in the "Electricity water and gas distribution industry" (i.e. the downstream sector for energy production). Such a definition is clearly too narrow because energy innovations may arise from different sectors: a key role is played by the power companies' suppliers of materials, equipment, electronic devices, and measurement instruments; however, also other industries for which energy is a crucial input can provide important innovative contributions.[1]

As opposed to R&D, energy patents explicitly refer to clean and energy saving innovations irrespective of the industry in which they are introduced and, therefore, provide direct and comprehensive measures of the inventive activities concerned with energy. So, along with being relevant outcomes of the innovative process and widely available, the most important advantage of patent data is that they can be disaggregated into specific technological fields, including those concerned with energy and environmental innovations (see below).

Obviously, along with these advantages, data on patent applications are affected by some important drawbacks (Hall and Helmers 2010). First, many patent applications are not granted and, even then, they do not always translate into actual innovations. Moreover, the propensity to patent varies remarkably both between and within industries, according to firms' strategies, size and capability to enforce patent rights (Schettino and Sterlacchini 2009). Most importantly, patent counts do not distinguish between inventions having different technological importance and economic value. To address the last drawback, scholars have used different indicators of patent quality[2]: among the most widely used there are forward citations (i.e. those received by patent applications after their publication) and patent families (i.e. the number of countries for which protection is sought for the same invention). Because for inventive firms seeking patent protection in many different countries is costly and time consuming, it can be assumed that the extent of patent families is able to capture the most valuable inventions. Accordingly, in this paper we shall use data on patent applications filed in different countries or to international patent offices or organizations with a view to provide an extensive protection for the same inventions.

Data on patent applications related to energy are taken from the OECD Patent Database (OECD 2015) in which patents related to different environmental-related technologies are identified by means of search strategies based on the International Patent Classification (IPC).[3] Among these "green" patents, we focus on those referring to "Climate change mitigation technologies related to energy generation, transmission or distribution". Table A1 in the online appendix details the numerous and comprehensive technological groups and subgroups corresponding to the definition of "energy patents" adopted in this paper. They range from wind and solar energy generation to non-fossil fuels, nuclear technologies, energy storage and batteries, smart grids and systems for improving the efficiency of electricity generation, transmission and distribution.

For international patenting in the energy field we consider three data sources, all available in the OECD patent data base:

- patent applications to the European Patent Office (which are filed when the applicants intend to patent the same invention in several countries adhering to the European Patent Convention[4]);
- patent applications submitted to the World Intellectual Property Organization (WIPO) – under the Patent Co-operation Treaty (PCT) – and designating the EPO as the subsequent patent office[5];
- patent applications belonging to Triadic Patent Families, i.e. filed together, to protect the same invention, at the EPO, the United States Patent and Trademark Office (USPTO) and the Japanese Patent Office (JPO).

Data for energy patent applications have been extracted from the OECD database in May 2017: we considered patent applications by priority date, i.e. that closest to the time span in which the inventive activities have been carried out.

Figure 1 illustrates the trend of world patent applications related to energy over the period 1985–2013 coming from the three sources of international patenting mentioned above. Note that the figure does not report patent numbers but rather the shares of energy patents on total patent applications, so as to account for the increasing propensity to patent worldwide during the period.

From 1985 to 1997, the shares of energy patents were almost constant over time and varied from 0.5% of PCT applications to 1.5% of Triadic patents. Starting from 1997, there was a first increase up to a share ranging from 2 to 2.5% in 2005. Then, a further and remarkable surge occurred during the following years and the percentage of energy patents reached its peak in 2010: from 4.7% of EPO applications to 5.4% of Triadic patents. These percentages are remarkable in light of the performance of other relevant technological areas: for instance, in 2010 the share of biotechnology patents on total PCT applications was 6%, i.e. only 1 per cent above that recorded by energy patents (see Figure 4 in Section 5). Only in the latest years (2011–2013), there is a decrease of patent applications related to energy (this issue will be discussed in Section 5).

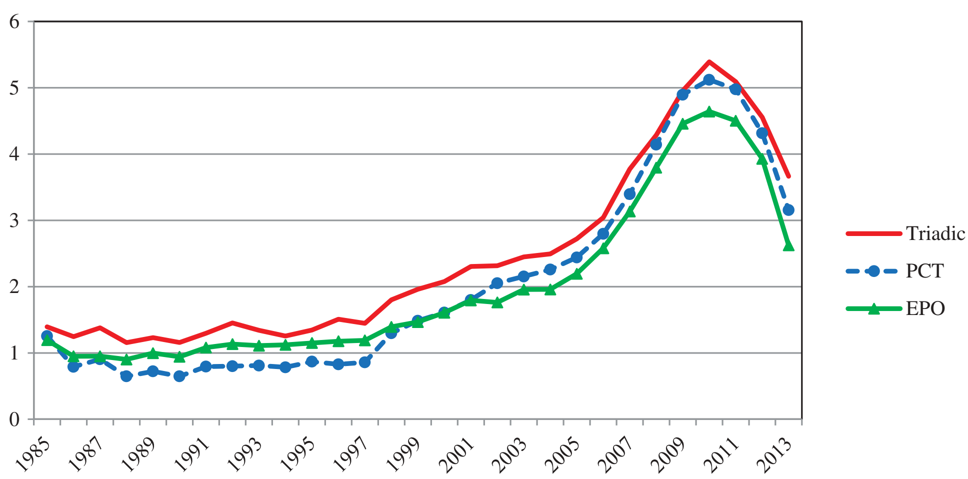

Figure 1. Share of energy on total world patent applications by priority date.
Source: own computations from the OECD patent database.

Table 1. Top countries in terms of energy patents: PCT patent applications.

	1990–1998		1999–2007		2008–2013	
	World share	Share on total country patents	World share	Share on total country patents	World share	Share on total country patents
Japan	11.39	1.40	24.97	3.78	28.06	5.90
US	33.06	0.69	29.40	1.91	22.57	3.57
Germany	19.15	1.29	12.55	2.40	11.62	5.15
Korea	0.60	0.92	2.90	2.17	6.74	5.25
France	3.86	0.74	3.76	2.02	4.11	4.17
UK	4.97	0.67	3.67	2.11	2.75	4.59
World total	100.00	0.90	100.00	2.32	100.00	4.40
Top 6 countries	73.03	0.87	77.25	2.40	75.85	4.68

Source: own computations from the OECD patent database.

The above trends are common to the three patent datasets, although higher shares emerge when the most selective category of Triadic patents is considered: in fact, looking at the absolute numbers in 2010, there are around 2,800 Triadic patent applications in the energy field, versus 6,170 applications to the EPO and 8,800 following the PCT route. In the rest of the paper we shall make use of both the most wide (PCT) and narrow (Triadic) classification of energy inventions in terms of patent families.

Looking at the behaviour of different countries, Table 1 shows the performance of the top 6 countries in terms of share of world energy patents, averaged over three sub-periods from 1990 to 2013: countries are ranked according to the latest figure concerned for the years 2008–2013.

During the 1990s, the leading role was played by the US which, in terms of world share, remarkably outperformed both Germany and Japan. However, the latter countries had a much higher intensity of energy patents over total PCT applications.[6] In the subsequent periods, and especially in the latest one, Japan was able to take the lead, while both the US and Germany recorded declining shares (though Germany only between the first two sub-periods). Note that in the last time span the US experienced the lowest intensity of energy patents of all the 6 countries. The most relevant change over time is the performance of South Korea: its contribution to world energy patents was very low during the 1990s, while it remarkably increased in the subsequent periods, up to the latest in which Korea achieved the fourth position in the ranking. On the contrary, the UK was losing ground while France experienced a small increase. Looking at the more recent sub-period, all the examined countries but the US achieved a remarkable intensity of energy patents, above 5% in Japan, Germany and Korea and 4% in France and the UK.

Most of the above considerations hold when Triadic patent applications are considered (see Table 2). The top 6 countries in terms of energy patents are the same; the US decline and low intensity of energy patents in 2008–2013 are confirmed; the same applies to the Korean surge in the more recent sub-period. In the meantime, some important differences are worth to be stressed. Japan has always been the world leader, experiencing only a small decline between the 1990s and the early 2000s. All the European countries were able to maintain their shares of world energy patents throughout the whole period. Finally, the top 6 countries have greater cumulative shares when Triadic applications are taken into account.

Taken together, these findings suggest that when a more selective identification of patentable inventions is applied, energy patents are more concentrated in the countries

Table 2. Top countries in terms of energy patents: Triadic patent applications.

	1990–1998		1999–2007		2008–2013	
	World share	Share on total country patents	World share	Share on total country patents	World share	Share on total country patents
Japan	37.09	1.98	35.67	3.20	36.66	5.19
US	29.37	1.09	23.70	2.16	20.05	3.56
Germany	11.14	1.27	10.17	2.48	10.53	5.36
Korea	0.21	0.43	2.69	2.39	7.50	7.43
France	5.34	1.48	4.30	2.46	5.72	5.46
UK	2.97	1.30	2.80	2.65	2.82	4.88
World total	100.00	1.42	100.00	2.58	100.00	4.75
Top 6 countries	86.11	1.41	79.33	2.63	83.29	4.82

Source: own computations from the OECD patent database.

characterized by a higher level of technology development and, possibly, a greater capability to introduce valuable inventions, also in the field of energy.

3. The role of environmental policies and oil prices

Many energy technologies, and especially those concerned with energy generation, can be classified as environmental-related technologies. Environmental innovations are adversely affected by the so-called "dual externality" problem (Rennings 2000; Jaffe, Newell, and Stavins 2005): a positive externality (due to the public-good nature of new knowledge) which however reduces the incentive to perform innovative activities, and a negative one which stimulates environmentally harmful behaviours. Environmental externalities combined with knowledge market failures push private companies to underinvest in technologies that reduce emissions. As a consequence, to jointly address both problems, a mix of complementary policies is needed (Popp 2010; Hall and Helmers 2010).

Innovation policies (e.g. R&D subsidies or tax incentives) are of horizontal nature, being generally applied across several technologies. Conversely, when coupled with environmental policies regulating externalities (e.g. carbon taxes or emission limits), innovation policies may focus on specific technological directions such as alternative and clean methods of energy generation and new systems of energy storage (see Table A1 in the online appendix). The advantage of implementing complementary policies, is stressed, among others, in Popp (2006): by examining the welfare gains arising from a carbon tax and an R&D subsidy he finds that their combination generates the largest welfare gain.

Table 3, first column, reports a taxonomy of policies (taken from De Serres, Murtin, and Nicoletti 2010) aimed at reducing environmental damages and, hence, providing further incentives to the introduction and diffusion of environmental innovations. These policies are grouped into the two broad categories of market-based measures (e.g. carbon tax and cap-and-trade) and non-market instruments (e.g. command-and-control regulation based on emission limits). It is generally argued that the former should provide greater incentives to innovation, though this may not be always the case (Rennings 2000; Popp 2010).

Johnstone, Hascic, and Kalamova (2010) emphasize the importance of looking at the characteristics of different instruments and, then, the impact they exert on innovation. Among the most important policy features, they stress those of stringency, predictability and flexibility. A policy is called "stringent" in as much as it provides greater

Table 3. Taxonomy of environmental policy instruments.

	Name	Examples in the OECD EPS database(*)
Market-based instruments	Taxes and charges directly applied to the pollution source	*Tax on emission of NO_x*
	Taxes and charges applied on input or output of a production process	Diesel tax
	Trading scheme	*Emissions Trading Scheme for CO_2, Renewable Energy Certificates*
	Subsidies for environmental-friendly activities	*Feed-In Tariffs*
	Deposit-refund system	Deposit Refund Scheme for beverages
Non-market instruments	Command-and-control regulation	*Emission Limit Value for NO_x for large size coal-fired plants*
	Technology-support policies	*Government R&D expenditures (% GDP, Renewable energy)*
	Voluntary approaches	Not covered

Source: De Serres, Murtin, and Nicoletti (2010). (*) Source: Botta and Koźluk (2014). Items in italics refer to policies affecting the energy sector considered in the OECD EPS database.

incentives to avoid the costs imposed by the same policy. According to the so-called "induced innovation hypothesis", changes in the relative costs of production factors will push firms to introduce new production methods. Predictability is another crucial feature because discontinuous and changing policies push companies to under-invest in innovative activities that yield returns in the medium- or long-term only. Finally, more flexible (or bottom-up) policies are preferable because they make it possible for firms to choose the technological means in order to meet environmental targets.

By focusing on the stringency feature of environmental policies, the OECD has recently elaborated a composite index of Environmental Policy Stringency (EPS) (Botta and Koźluk 2014), were stringency is defined as a higher implicit or explicit cost of polluting or having an environmental harmful behaviour. Their analysis encompasses different types of environmental policies (both market- and non-market-based): the second column of Table 3 illustrates some examples of the instruments that have been taken into account.

The composite index is measured on a 0–6 scale (ranging from less to more stringent environmental policies) and is available for several OECD countries from 1990 to 2012. A specific EPS index was computed for the energy sector, which mainly (though not exclusively) focuses on policies applied to electricity generation. It should be stressed that, for the energy sector, the environmental regulations "are consistently framed across countries in order to differentiate technologies according to the fuel used to generate electricity and the size of the plants" (Botta and Koźluk 2014, 15) Table 3 shows, in italics, the environmental policies that are specifically related to the energy sector: market- and non-market based policies take an equal weight in the composite EPS index for energy (equal weights are also attached to the items of each main group).

Figure 2 reports the performance of different OECD countries (and their average) in 2012 and 1990–1995. Comparing the two periods, the cross-country variation has decreased although, even in 2012, there are remarkable differences in terms of EPS: the score for Denmark is 4, while that for Greece, Ireland and Portugal is below 2.

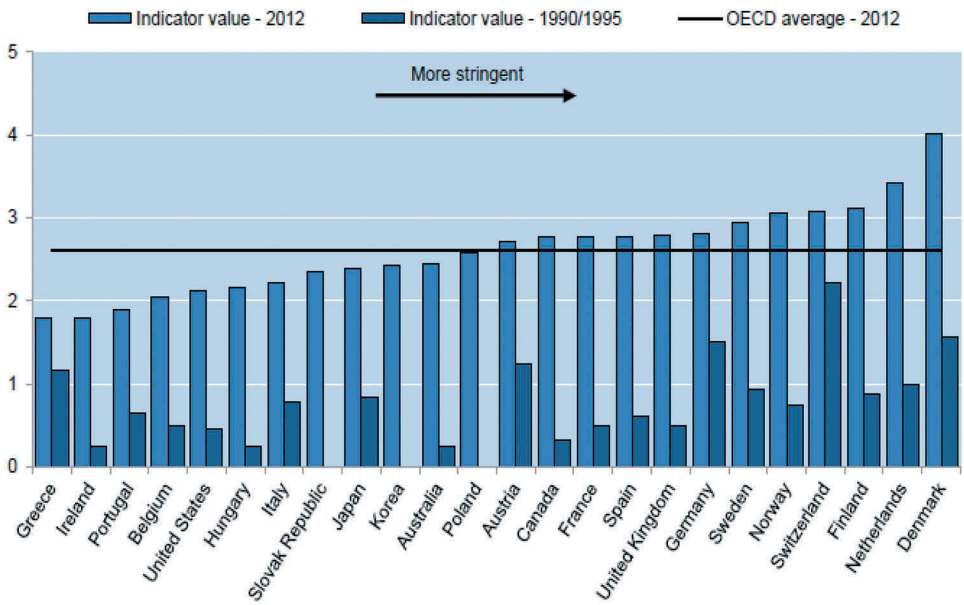

Figure 2. Environmental policy stringency: energy sector.
Source: Botta and Koźluk (2014).

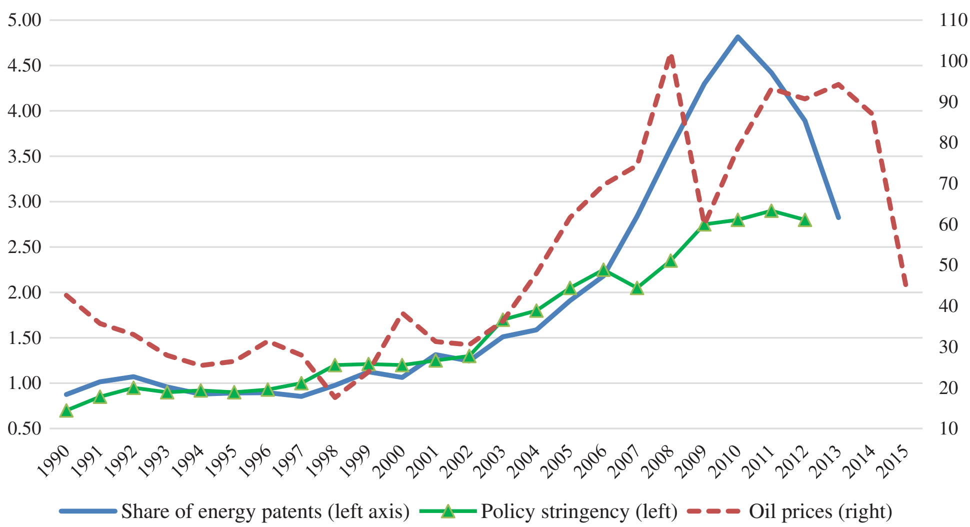

Figure 3. Share of energy patents on Triadic applications and environmental policy stringency in OECD countries (left axis) and oil prices (right axis).

Along with these differences, the figure shows that the EPS in the energy sector has recorded a remarkable increase over time for all countries.

This finding is confirmed by Figure 3, which shows the increasing trend of the EPS, averaged among OECD countries, over the period 1990–2012 (line with triangles): the index went from about 1 in the 1990s to 2 in 2005–2007 and, then, approached the value of 3 in 2010–2012. The same figure also reports the share of energy patents on total Triadic applications from OECD countries (period 1990–2013; continuous line) and the oil prices expressed at constant prices (period 1990–2015; dotted line).

Empirical studies that, such as the present one, are based on country panel data sets (cf. Section 1), have shown that environmental policies played a crucial role in increasing the propensity to patent in environment-friendly technologies, including those related to energy. As already stressed in the previous section, the first rise of energy patents occurred after 1997 (cf. Figure 3) as a reaction to the Kyoto Protocol, which was signed in that year. Similarly, the subsequent rise in the second half of the 2000s could be due the international diffusion of more stringent environmental and climate policies.

The inclusion in Figure 3 of the trend of international oil prices (measured as the annual crude oil prices, in US dollars, adjusted for inflation) clearly suggests that they represent another important determinant of energy patenting. Building on the above mentioned "induced innovation hypothesis", Popp (2002) showed that in the US, over the period 1970–1994, energy prices positively affected the share of energy-efficient innovations measured by granted patents. However, looking at patents in renewable energy for a panel of high-income countries observed from 1978 to 2003, Johnstone, Hascic, and Popp (2010) show that electricity prices did not have a significant effect.

It should be pointed out that, when considering more recent years, the use of electricity prices is not advisable. In fact, renewable sources have been accounting for an increasing share of total electricity generation so that the price of electricity cannot be considered exogenous with respect to the propensity to patent inventions in renewable energy. Accordingly, the demand of energy innovations can be assumed to grow in response to exogenous and country-invariant increases of international oil prices. In this regard Cheon and Urpelainen (2012) consider patents on renewable energy for 23 countries over the years 1989–2007 and find a positive impact of oil prices when interacted with the countries' shares of electricity generation coming from renewable sources.

These contrasting findings could be partly due to the different time-spans under consideration. In fact, as Figure 3 illustrates, while from 1990 to 2001 oil prices were almost constant, starting from 2002 they remarkably increased up to a peak in 2008, followed by a staggering reduction in 2009 (in coincidence with the international economic downturn) and, then, a recovery in the years 2010–12. The figure also shows the dramatic drop of oil prices in 2014 and, especially, 2015 (these latest figures and their possible adverse effect on energy innovations will be discussed in Section 5).

When comparing the share of energy patenting to the evolution of oil prices, it appears that the recent increase of the former has followed the staggering increase of the latter between 2002 and 2008. Over the same years a parallel, though less evident, increase has characterized the index of EPS. As a consequence, it is not clear whether the increase of energy patents is the result of environmental policies, oil prices, both of them, or other omitted factors (Calel and Dechezleprêtre 2016).

4. Impact of environmental policies and oil prices on energy patents: a panel analysis

Due the common aggregate trends in energy patents, Environmental Policy Stringency and oil prices, it is difficult to estimate and identify causal relationships. However, we attempted to do so by using panel data for 19 OECD countries for which there is a complete set of data for energy patenting (both Triadic and PCT patent applications; cf. Section 2) and the EPS indices related to energy over a sufficiently long period of time. The countries are: Australia, Austria, Belgium, Canada, Denmark, Finland, France, Germany, Ireland, Italy, Japan, Korea, Netherlands, Norway, Spain, Sweden, Switzerland, UK and US.

The equation to be estimated is the following:

$$\begin{aligned} ENERGYP_{i,t} = \ & \alpha_0 + \ \alpha_1 lnEPS_{i,t-1} + \alpha_2 lnOILP_{t-1} + \alpha_3 lnENCONS_{i,t} + \alpha_4 lnRENEW_{i,t-1} \\ & - \alpha_5 lnPMR_{i,t-1} + \alpha_6 dKYOTO + u_i + \varepsilon_{i,t} \end{aligned} \tag{1}$$

where $i = 1, \ldots, 19$ and $t = 1991, \ldots, 2013$ are the country and time index respectively. *ENERGYP* denotes the number of Triadic or PCT patent applications classified in the energy field. As per the discussion developed in Section 2, Triadic applications are assumed to capture more valuable patented inventions. *EPS* is the index of environmental policy stringency at country level. However, in an alternative specification, we will use the aggregate OECD index of EPS which, by definition, is varying over time only. The same applies to the variable *OILP* which stands for crude oil prices (in US dollars, adjusted for inflation and averaged between WTI and Brent). Since international oil prices (like the averaged OECD index of EPS) do not vary across countries, year fixed effects are not included in the regression.

Although our focus is on the role of EPS and oil prices, in order to limit the omitted variable bias additional country-specific regressors are included. First, as the incentives to patent in the energy field are likely to be affected by the trend of energy demand, we include *ENCONS* which denotes the total energy consumption at country level expressed in ktoe (thousands tons of oil equivalent) and taken from IEA. Secondly, we add the variable *RENEW* which is the country share of electricity generation coming from renewable sources (also taken from IEA): thus, as in Cheon and Urpelainen (2012), we conjecture that an intensive use of renewables should stimulate the introduction of environment-friendly innovations in the energy sector. Then, we insert the variable *PMR* which stands for the OECD indicator of Product Market Regulation in the electricity sector: such an index varies from 0 to 6 according to the level of regulatory restrictiveness (or lack of competition). So, like Nesta, Vona, and Nicolli (2014), we assume that a domestic electricity market more open to competition is conducive to more energy patents: it should be noticed that, in this case, the parameter of *PMR* (contrary to that of *EPS*) should get a negative sign. Finally, as done in other econometric analyses on "green" patents (Johnstone, Hascic, and Popp 2010; Cheon and Urpelainen 2012; Nesta, Vona, and Nicolli 2014), we include *dKYOTO*, i.e. a dummy for the years 1998–2013, after the Kyoto Protocol was signed. The underlying hypothesis is that this event, and the subsequent implementation of environmental policies in ratifying countries, provided a strong incentive to energy innovators.

All the continuous explanatory variables are in natural logs. Apart from *ENCONS* (which plays also the role of scale variable), all other regressors are lagged by one year. The assumption is that changes in energy policies, regulation and oil prices, as well as in the use of renewable sources[7] induce inventive efforts which subsequently materialize in patented inventions. In principle, a greater lag could occur but we have not tested it in order to have sufficient degrees of freedom in our regressions.

The Poisson and the negative binomial models are the appropriate approaches to regress count data variables as it is with patent applications. In our case, because both Triadic and PCT energy patents are over-dispersed[8] we opt for a negative binomial model. However, because the conditional binomial model for panel data does not control for all time-invariant covariates, as a robustness check, we also estimate equation (1) by means of a Poisson fixed-effects model with robust standard errors clustered among countries (as in Costantini, Crespi, and Palma 2017).

In Table 4 the results of negative binomial regressions are distinguished between the model in which the EPS index refers to each single country and that including the EPS averaged among OECD countries. In the first case, for both Triadic and PCT patent applications, all the explanatory variables but EPS are statistically significant and get the expected signs: negative for the PMR index and positive in all the other cases. Instead, the EPS at the country level turns out to be barely significant only when the dependent variable is the number of Triadic patent applications in the energy field. Note that, when the regressors are in logs, the estimated parameters of the binomial model (as well as those of Poisson model) can be interpreted as elasticities. Thus, the regression results indicate that oil prices exert a sizeable impact on energy patents only when PCT applications are considered.

In the second set of regressions (Model 2), the EPS variable is averaged among OECD countries: like for oil prices, it is assumed that, in terms of energy innovation, each country reacts to the overall changes in the stringency of energy-related

Table 4. Negative binomial estimates with country fixed effects. Dependent variables: Triadic and PCT patent applications in the energy field.

	Model 1 (with country Environmental Policy Stringency)		Model 2 (with OECD Environmental Policy Stringency)	
	Triadic	PCT	Triadic	PCT
Constant	−2.671*** (0.983)	−2.550*** (0.866)	−2.140** (1.001)	−1.497* (0.869)
Country EPS	0.127* (0.064)	0.082 (0.059)		
OECD EPS			0.359** (0.154)	1.149*** (0.128)
Oil prices	0.170** (0.073)	0.728*** (0.065)	0.071 (0.099)	0.188** (0.082)
Energy consumption	0.396*** (0.079)	0.157** (0.070)	0.395*** (0.079)	0.205*** (0.069)
Share of renewables	0.230*** (0.056)	0.242*** (0.054)	0.228*** (0.056)	0.160*** (0.053)
PMR electricity sector	−0.533*** (0.104)	−0.556*** (0.099)	−0.469*** (0.106)	−0.368*** (0.095)
Kyoto dummy (1998–2013)	0.462*** (0.092)	1.195*** (0.101)	0.395*** (0.103)	0.845*** (0.104)

Observations: 437 (19 OECD countries over the years 1991–2013. Standard errors in brackets. Significance: * = $p < 0.10$; * = $p < 0.05$; *** = $p < 0.01$.

environmental policies rather than on those implemented at national level. In this case, the estimated effect of EPS on energy innovation is always positive and statistically significant and turns out to be particularly strong when PCT applications are taken into account. Instead, compared to previous results, the impact of oil prices is lower or, when the dependent variable is the number of Triadic applications, not significant. For all the other explanatory variables the findings are in line with the previous ones.

With respect to the role played by the EPS, oil prices and the Kyoto dummy, similar results arise from the estimation of a Poisson model (see Table A2 in the online appendix). As far as the other country-level variables are concerned, there are instead some differences. The share of renewable sources in electricity generation is never significant while the trend in energy demand in barely significant only in Model 2 when Triadic applications are considered. On the other hand, the negative and strong impact exerted by the level of electricity market regulation is confirmed, especially in Model 1.[9]

4.1. Discussion

Our results, in line with the findings of previous studies, confirm that environmental policies have played a key role in fostering environment-related or "green" innovations, as proxied by international patent applications. However, while previous empirical analyses with country data stressed the significant impact of national policies, our study shows that these lose significance when controlling for other determinants and, especially, the increasing global attention to environmental goals as captured by the Kyoto dummy variable. The aggregate index of environmental policies' stringency at the OECD level is more effective than the country-level one. Moreover, when the aggregate measure of policy stringency is used, the impact of oil prices on energy patents, though positive, becomes less significant.

The limited effect of national environmental policies on energy innovations could be due to the way in which the latter have been approximated, i.e. by means of international patent applications. In such a case, the reference market for innovators is international rather than domestic and this explains why the propensity to patent in the energy field has been particularly affected by the increasing adoption of stringent environmental policies at the global rather than the national level.

This finding is in line with that by Peters et al. (2012), Dechezleprêtre and Glachant (2014), and Costantini, Crespi, and Palma (2017) who, by using different approaches and focusing upon different technologies, have stressed the important role of the environmental policies adopted by foreign countries in inducing domestic firms to introduce "eco-innovations" (as measured through international patent applications). Foreign demand-pull policies (as proxied by photovoltaic capacity, demand for wind power or energy taxation) appear to stimulate more innovation than domestic policies. In such cases, national governments could be encouraged, for instance, to reduce the incentives for the deployment of renewable energy technologies if foreign companies were likely to take advantage from them more than domestic companies would do. However, if every country adopted a similar free-riding behaviour there would be an insufficient provision of environment-friendly policies on a global scale. To avoid that, multilateral agreements on policies aimed at addressing environmental problems (such as the Kyoto Protocol and, more recently, the Paris Agreement) are necessary.

It must be stressed that, contrary to most previous studies (cf. Section 1), our analysis is concerned with a broad set of energy innovations (and a composite index of environmental policies) rather than specific environmental or energy technologies and policies. Hence, and aside from other differences regarding the time periods and the countries taken into account, it is difficult to find strictly comparable studies in order to check for the consistency of our findings.

A distinctive feature of the present study (with the exceptions of Dasgupta, De Cian, and Verdolini 2016; Fabrizi, Guarini, and Meliciani 2018) is that of using a composite indicator of different environmental policies rather than only those related to renewable energy. Obviously, this is done at the price of neglecting the possible differentiated effects of specific policies. Such an issue has been stressed, in particular, by Johnstone, Hascic, and Popp (2010). With a panel of countries, these authors examine the determinants of patent applications to the EPO in various renewable energy technologies (wind, solar, geothermal, etc.) and find that some specific instruments of environmental policy (feed-in tariffs, renewable energy certificates, etc.) affect the renewable sources of energy to a different extent. However, it is interesting to notice than, when Johnston et al. include a dummy for the Kyoto Protocol among the explanatory variables, most of the policy instruments become statistically insignificant. The message arising from these findings is consistent with our main conclusion: our empirical analysis does not suggest that, to foster energy innovations, national environmental policies are useless but, rather, that they are by far less effective than those implemented on a global scale.

5. The recent drop of energy patents: relevance and policy considerations

This section is devoted to some preliminary reflections about the reduction in energy patent applications recorded in the latest years for which data are available. As shown in Figure 1, after the 2010 peak, the share of energy patent applications (no matter which source of international patenting is used) has declined in the subsequent years, and especially in 2013. Such a drop seems particularly worrying in the light of the recent trend of international oil prices: they were almost constant over 2012–2013, they slightly decreased in 2014 and, then, recorded a dramatic fall in 2015: as Figure 3 illustrates, the deflated oil prices index has returned to the level of 2003–2004. In the empirical analysis described in the previous section, we found that oil prices have positively affected energy patents, although their impact was less significant than that exerted by the OECD level of environmental policies' stringency. Thus, it remains to be seen whether the recent and staggering drop of oil prices has determined a further, and perhaps more pronounced, reduction of energy patents.

Although the lack of patent data for the years 2014 and 2015 makes it impossible to perform a proper empirical test for the above hypothesis, some scholars, as well as practitioners and commentators, have raised concerns about the possible decline of environment-related patents (Kollewe 2015; Dechezleprêtre 2016; Condliffe 2017; Cornwall 2017; Saha and Munro 2017).

These concerns seem justified for different reasons. First of all, by widening the price gap between low carbon and conventional energy, the dramatic fall of oil prices in 2015 could further reduce the incentives to innovate in the field of energy. Another discouraging factor could be the oversupply of some innovative energy devices (such as that of solar panels due to the Chinese mass production) which has lowered the profit margins of companies operating in these markets. In addition, some countries, such as Spain, Germany and the UK, have reduced the subsidies for renewable energy sources (Kollewe 2015).[10] Finally and more recently, President Trump withdrew the US from the Paris Agreement on climate change (drafted in 2015 and signed in 2016) and, most importantly, the House of Representatives approved his budget for 2018, which includes remarkable cuts to the federal funding for clean energy (a 31% reduction in funds to the Environmental Protection Agency).

All the above arguments and events must be taken seriously into account. However, they can be counter-balanced by less pessimistic considerations. For instance, the US withdrawal from the Paris Agreement has not been followed by other major countries in the global scenario, including China and India, along with the most developed economies. Thus, if the promised abatement of global greenhouse gas emissions is effectively achieved, it is unlikely that public resources aimed at environmental protection will be reduced. Moreover, it should be stressed that in the energy field the stock of knowledge (in terms of patents) is still substantial and there is still ample room for an effective deployment of energy innovations. The decreasing flows of energy patents could be due to a temporary reduction of profit incentives to invest in some specific fields (such as solar energy) as well as a partial exhaustion of technological opportunities.[11]

In this regard, it is interesting to compare, over a long time period, the shares of energy patents with those of another relevant technology field such as that of biotechnology. Figure 4 shows that, in terms of PCT applications, biotechnology patents experienced a dramatic increase during the 1980s and early 1990s, followed by a constant trend and, then, a sharp decline during the 2000s. Thus, a reduction in

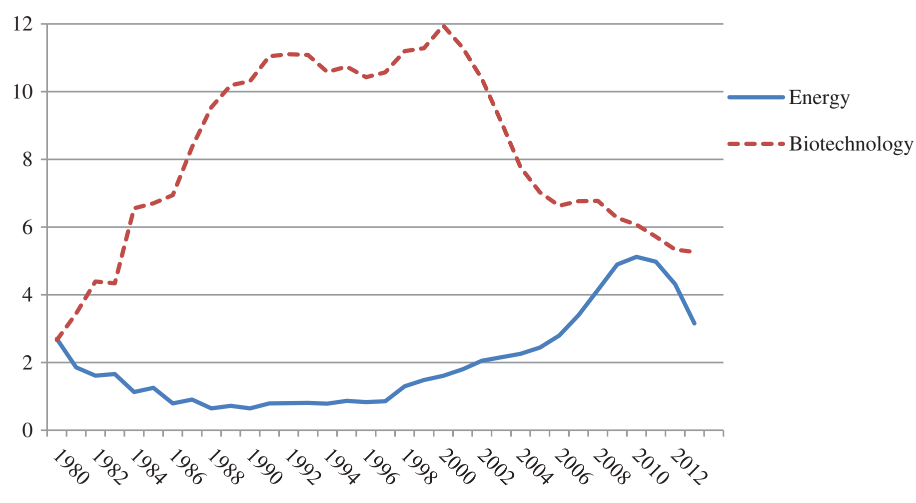

Figure 4. World shares of PCT applications in biotechnology and energy.

patent flows can be a common feature for different technological areas and cannot be taken, by itself, as a sign of decline.

Obviously, technological opportunities (and long-term profitability) are likely to remain large only in the presence of a stable level of investment in basic (or long-term) research related to clean energy technologies. The declining R&D efforts by electric utilities in the early 2000s (Sterlacchini 2012) have been counter-balanced only in part by public R&D programmes and incentives to private companies investing in clean energy sources. As stressed by Dechezleprêtre (2016), the good news is that, during the Paris talks, twenty developed and developing countries have promised to double their clean energy R&D investment over five years. The emphasis on research activities is important because some instruments of environmental policy (such as renewable energy targets and emission trading schemes) tend to favour incremental innovations in technologies that are closest to the market (Dechezleprêtre, Martin, and Bassi 2016). These policy instruments have been mostly used in the EU to foster the deployment of clean energy technologies. Albeit important, such a goal should not be pursued at the expense of the other crucial goal of increasing basic, long-term R&D in the field of energy.

6. Concluding remarks

In this paper, in line with previous studies focusing on environmental technologies, energy innovations are proxied by international patent applications with a view to selecting the most valuable inventions. In this regard, we use data for Triadic patent applications as proxies for high quality inventions, but we also control our results for less selective PCT applications. Data on energy patents are defined as those related to "Climate change mitigation technologies related to energy generation, transmission or distribution".

The increasing aggregate trend of energy patents over the period 1990–2013 appears to be closely associated with both a synthetic index for the stringency of environmental policies (recently released by the OECD) and the oil prices index. With a panel analysis for 19 OECD countries we have attempted to identify the causal relationships among the above variables, by controlling for other country-level determinants of energy innovations. We find that the stringency of environmental policies has exerted a more significant impact on energy patents than that of oil prices. However, this emerges when the aggregate index of policy stringency (averaged among OCED countries) is applied. Instead, the stringency of the environmental policies implemented at the national level has a less significant effect. These findings are consistent with the way in which energy innovations have been approximated, since inventive firms seeking patent protection in many countries want to market their innovations in several foreign markets rather than in their domestic market only. Thus, it is the global adoption of stringent environmental policies that mainly stimulates international patenting in the energy field. Obviously, this does not mean that national policies are useless. On the contrary, like in the "tragedy of the commons", if each country would refrain from giving priority to environmental policies the global level of stringency will be null.

The above empirical analysis was complemented by a few reflections on the recent decrease of energy patents, especially in the light of the huge drop of oil prices in 2015. Although worrisome, we argue that the latest evidence cannot be taken as a sign of exhaustion of technological opportunities. Anyhow, stringent environmental policies should be maintained and possibly reinforced at the global level; in this regard, the Paris Agreement on climate change goes in the right direction. Moreover, in order to foster further and important innovations in the energy field, environmental (and innovation) policies should be more focused on long-term R&D.

Notes

1. A possible way to partially circumvent these limitations is to impute the R&D expenses of suppliers to the energy sector depending on the extent to which the output of the former sectors is used by the latter as intermediate input. Using input-output tables, Dasgupta, De Cian, and Verdolini (2016) perform such a computation for OECD countries with a view to capturing the indirect or "embedded" level of energy R&D. However, still neglected remains the energy-related R&D performed by downstream industries (i.e. the customers of power companies).
2. Multiple measures of patent quality are reviewed and applied in Lanjouw and Schankerman (2004), van Zeebroeck (2011) and Schettino, Sterlacchini, and Venturini (2013).
3. The IPC system classifies inventions into more than 70,000 technological groups and subgroups (Hascic and Migotto 2015).
4. The EPO centralized procedure is convenient for applicants if they wish to subsequently extend patent protection in at least four countries.
5. By using the PCT route, applicants can seek subsequent protection for an invention in 148 countries. Thus, being more expensive than those filed at national level, PCT applications should cover inventions of higher value.
6. As also noted by Dasgupta, De Cian, and Verdolini (2016), in terms of shares of "green" patents, some small countries such as Finland, Austria and, especially, Denmark record very good performances.
7. The inclusion of *RENEW* with a lag is debatable. However, the results (available from the author upon request) do not significantly change when the same variable is inserted without lags.
8. Triadic patent applications vary from 0 to a maximum of 1,140 (mean: 64.8; standard deviation: 144.9), while PCT patent applications from 0 to 2,882 (mean: 159.6; standard deviation: 379.2) .
9. We have performed further robustness checks by using as dependent variables the shares of energy patents on total Triadic and PCT applications. Panel regressions with country fixed effects and, especially, dynamic panel estimates in first differences confirm that the EPS index at country level is never statistically significant, while the EPS at the OECD level has always a positive and significant effect on energy patents. These results are available from the author upon request.
10. The Environmental Policy Stringency index used in our empirical analysis does not account for these recent changes, although a slight reduction of the OECD EPS was recorded in 2012 (cf. Figure 3).
11. Talking about a "partial" exhaustion seems appropriate if one considers that some energy technologies (such as more efficient electrical grids and devices for storing intermittent solar and wind power) are still in the early stages.

Acknowledgements

With the usual disclaimers, I wish to thank Riccardo Lucchetti, Claudia Pigini and two anonymous referees for their comments and suggestions.

Disclosure statement

No potential conflict of interest was reported by the author.

References

Ambec, S., M. A. Cohen, S. Elgie, and P. Lanoie. 2013. "The Porter Hypothesis at 20: Can Environmental Regulation Enhance Innovation and Competitiveness?" *Review of Environmental Economics and Policy* 7: 2–22. doi:10.1093/reep/res016.

Botta, E., and T. Koźluk. 2014. "Measuring Environmental Policy Stringency in OECD Countries: A Composite Index Approach". OECD Economics Department Working Papers 1177. Paris: OECD Publishing.

Calel, R., and A. Dechezleprêtre. 2016. "Environmental Policy and Directed Technological Change: Evidence from the European Carbon Market." *Review of Economics and Statistics* 98 (1): 173–191. doi:10.1162/REST_a_00470.

Cheon, A., and J. Urpelainen. 2012. "Oil Prices and Energy Technology Innovation. An Empirical Analysis." *Global Environmental Change* 22: 407–417. doi:10.1016/j.gloenvcha.2011.12.001.

Condliffe, J. 2017. "Clean Technology Innovation Is in Decline". *MIT Technology Review*. April 26.

Cornwall, W. 2017. "Clean Energy Patent Slump in U.S. Stirs Concern". *Science*, April 26.

Costantini, V., F. Crespi, and A. Palma. 2017. "Characterising the Policy Mix and Its Impact on Eco-Innovation: A Patent Analysis of Energy-Efficient Technologies." *Research Policy* 46: 799–819. doi:10.1016/j.respol.2017.02.004.

Dasgupta, S., E. De Cian, and E. Verdolini. 2016. "The Political Economy of Energy Innovation". WIDER Working Paper 2016/17. United Nations University UNU-WIDER.

De Serres, A., F. Murtin, and G. Nicoletti. 2010. "A Framework for Assessing Green Growth Policies". OECD Economics Department Working Papers, No. 1448. Paris; OECD Publishing.

Dechezleprêtre, A. 2016. "How to Reverse the Dangerous Decline in Low-Carbon Innovation". *The Conversation*, October 24.

Dechezleprêtre, A., and M. Glachant. 2014. "Does Foreign Environmental Policy Influence Domestic Innovation? Evidence from the Wind Industry." *Environmental and Resource Economics* 58: 391–413. doi:10.1007/s10640-013-9705-4.

Dechezleprêtre, A., R. Martin, and S. Bassi. 2016. "Climate Change Policy, Innovation and Growth".Global Green Growth Institute and Grantham Research Institute on Climate Change and the Environment – London School of Economics. Policy brief, January.

Fabrizi, A., G. Guarini, and V. Meliciani. 2018. "Green Patents, Regulatory Policies and Research Network Policies." *Research Policy* 47: 1018–1031. doi:10.1016/j.respol.2018.03.005.

Hall, B., and C. Helmers. 2010. "The Role of Patent Protection in (Clean/Green) Technology Transfer". Centre for the Study of African Economies WPS/2010-23.

Hascic, I., and M. Migotto. 2015. "Measuring Environmental Innovation Using Patent Data". OECD Environment Working Papers No. 89. Paris: OECD Publishing.

Jaffe, A., R. Newell, and R. Stavins. 2005. "A Tale of Two Market Failures: Technology and Environmental Policy." *Ecological Economics* 54: 164–174. doi:10.1016/j.ecolecon.2004.12.027.

Johnstone, N., I. Hascic, and D. Popp. 2010. "Renewable Energy Policies and Technological Innovation: Evidence Based on Patent Counts." *Environmental and Resource Economics* 45 (1): 133–155. doi:10.1007/s10640-009-9309-1.

Johnstone, N., I. Hascic, and M. Kalamova. 2010. "Environmental Policy Characteristics and Technological Innovation." *Economia Politica* 27 (2): 275–299.

Kollewe, J. 2015. "Global Hopes for Renewable Energy Fading, Patents Data Show". *The Guardian*, May 4.

Lanjouw, J., and M. Schankerman. 2004. "The Quality of Ideas: Measuring Innovation with Multiple Indicators." *Economic Journal* 114 (495): 441–465. doi:10.1111/j.1468-0297.2004.00216.x.

Nesta, L., F. Vona, and F. Nicolli. 2014. "Environmental Policies, Competition and Innovation in Renewable Energy." *Journal of Environmental Economics and Management* 67: 396–411. doi:10.1016/j.jeem.2014.01.001.

OECD. 2015. "Patents by Main Technology and by International Patent Classification (ICP)". OECD Patent Statistics (database).

Peters, M., M. Schneider, T. Griesshaber, and V. H. Hoffmann. 2012. "The Impact of Technology-Push and Demand-Pull Policies on Technical Change – Does the Locus of Policies Matter?" *Research Policy* 41: 1296–1308. doi:10.1016/j.respol.2012.02.004.

Popp, D. 2002. "Induced Innovation and Energy Prices." *American Economic Review* 92 (1): 160–180. doi:10.1257/000282802760015658.

Popp, D. 2006. "R&D Subsidies and Climate Policy: Is There a 'Free Lunch'?" *Climate Change* 77 (3–4): 311–341. doi:10.1007/s10584-006-9056-z.

Popp, D. 2010. "Innovation and Climate Policy". NBER Working Paper No. 15673.

Rennings, K. 2000. "Redefining Innovation - Eco-Innovation Research and the Contribution from Ecological Economics." *Ecological Economics* 32: 319–332. doi:10.1016/S0921-8009(99)00112-3.

Saha, D., and M. Munro. 2017. "Patenting Invention. Clean Energy Innovation Trends and Priorities for the Trump Administration and Congress". Brookings Metropolitan Policy Program, April.

Schettino, F., and A. Sterlacchini. 2009. "Reaping the Benefits of Patenting Activities: Does the Size of Patentees Matter?" *Industry and Innovation* 16 (6): 613–633. doi:10.1080/13662710903371140.

Schettino, F., A. Sterlacchini, and F. Venturini. 2013. "Inventive Productivity and Patent Quality: Evidence from Italian Inventors." *Journal of Policy Modeling* 35 (6): 1043–1056. doi:10.1016/j.jpolmod.2013.02.008.

Sterlacchini, A. 2012. "Energy R&D in Private and State-Owned Utilities: An Analysis of the Major World Electric Companies." *Energy Policy* 41: 494–506. doi:10.1016/j.enpol.2011.11.010.

van Zeebroeck, N. 2011. "The Puzzle of Patent Value Indicators." *Economics of Innovation and New Technology* 20: 33–62. doi:10.1080/10438590903038256.