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The Determinants of Invention in Electricity Generation Technologies

A PATENT DATA ANALYSIS

Elisa Lanzi, Ivan Haščič, Nick Johnstone

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**THE DETERMINANTS OF INVENTION IN ELECTRICITY GENERATION TECHNOLOGIES:
A PATENT DATA ANALYSIS**

By Elisa Lanzi, Ivan Haščič and Nick Johnstone, OECD Environment Directorate

Keywords: Patents, energy, climate change

JEL Classifications: Q54, Q55, Q4

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ABSTRACT

This paper analyses the determinants of invention in efficiency-enhancing electricity generation technologies that have the potential to facilitate climate change mitigation efforts, including fossil fuel-based technologies aimed at reducing carbon emissions, renewables and nuclear technologies. The evolution of inventive activity in these technologies is analysed by considering patent data for 11 OECD countries over the period 1978-2008. The analysis considers various drivers of inventive activity, including R&D expenditures and electricity consumption, but pay particular attention to the role of fossil fuel prices because they suggest the impact that price mechanisms such as emissions trading and carbon taxes are likely to have on invention in the electricity generation sector.

The results show that the effect of fossil fuel prices varies according to the different types of technologies. As fossil fuel prices increase, inventive activity in renewable energy technologies increases while the effect of on fossil fuel-based technologies is positive but with decreasing increments. The results show that there is no effect of fossil fuel prices on patenting activity in nuclear energy technologies. These results illustrate that there may be a price-induced switching between renewable and fossil fuel-based technologies. As fossil fuel prices rise, an efficiency effect encourages inventive activity in both fossil fuel-based and renewable technologies. As fossil fuel prices increase further, invention in fossil fuel-based technologies starts declining suggesting that a substitution effect drives away innovation from fossil fuel-based towards renewable energy technologies.

JEL Classification: Q54, Q55, Q4

Keywords: Patents, Innovation, Energy, Climate Change

RÉSUMÉ

Le présent document analyse les déterminants de l'innovation dans les technologies améliorant l'efficacité énergétique de la production d'électricité et qui facilitent les efforts nécessaires à l'atténuation des changements climatiques. Ces technologies regroupent notamment les technologies à base de combustibles fossiles visant à réduire les émissions de carbone, les énergies renouvelables et les technologies nucléaires. L'évolution de l'innovation dans ces technologies est étudiée à partir de données sur les brevets pour 11 pays de l'OCDE sur la période 1978-2008. L'analyse des divers facteurs ayant conduit à ces innovations comprend notamment : les dépenses de recherche et développement, la consommation d'électricité, mais surtout le rôle des prix des combustibles fossiles, car ceux-ci décrivent l'impact que les mécanismes de prix tels ceux concernant l'échange de droits d'émissions et la taxe carbone peuvent avoir sur l'innovation dans le secteur de la production d'électricité.

Les résultats montrent que l'effet des prix des combustibles fossiles varie selon le type de technologie. Quand les prix des combustibles fossiles augmentent, l'activité inventive dans les technologies à énergie renouvelable augmente tandis que l'activité inventive dans les technologies à base de combustibles fossiles augmente, mais avec une progression moins marquée à mesure que les prix augmentent. Les résultats montrent qu'il n'y a pas d'impact du prix des combustibles fossiles sur les brevets relatifs aux technologies nucléaires. Ces résultats illustrent qu'il peut y avoir un changement d'orientation de l'innovation induit par les prix, vers les technologies renouvelables ou les technologies basées sur les combustibles fossiles. Suite à une augmentation des prix des combustibles fossiles, un effet de recherche d'efficacité va encourager l'innovation à la fois dans les technologies à base de combustibles fossiles et dans les énergies renouvelables. Lorsque l'augmentation des prix des combustibles fossiles se poursuit, l'innovation dans les technologies à base de combustibles fossiles commence à diminuer, ce qui suggère que par un effet de substitution, l'innovation va s'éloigner des technologies basées sur les combustibles fossiles pour s'orienter vers les énergies renouvelables.

Classification JEL: Q54, Q55, Q4

Mots-clés: Brevets, Innovation, Énergie, Changements Climatiques

FOREWORD

This report is a contribution to the OECD Environment Directorate project on Environmental Policy and Technological Innovation (www.oecd.org/environment/innovation), and is the outcome of collaboration between the OECD and the Fondazione Eni Enrico Mattei (FEEM). It has been authored by Elisa Lanzi, Ivan Haščič and Nick Johnstone of the OECD Environment Directorate. A previous version of this report was presented to the OECD's Working Party on Climate, Investment and Development (WPCID) and the report has benefited from the comments received. The report has also benefited from valuable comments by colleagues at the OECD, including Marie-Christine Tremblay and Simon Upton.

This document does not necessarily represent the view of either the OECD or its member countries.

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THE DETERMINANTS OF INVENTION IN ELECTRICITY GENERATION TECHNOLOGIES: A PATENT DATA ANALYSIS

Elisa Lanzi, Ivan Haščič and Nick Johnstone

1. Introduction

With increasing pressure to reduce greenhouse gases emissions, much of the focus has been on the energy sector as one of the main source of emissions. Electricity production accounts for about a quarter of the overall anthropogenic CO₂ emissions, thus greatly contributing to the problem of climate change. In this context, the importance of the development and use of low and zero emissions electricity generation technologies is crucial. Without significantly greater penetration by such technologies, climate policy objectives will be difficult to achieve. These technologies include (i) technologies that aim to reduce emissions from electricity production derived from fossil fuel combustion, (ii) renewable energy technologies, and (iii) technologies associated with the production of electricity nuclear energy sources.

According to the International Energy Agency (IEA) *Electricity Information 2012* (IEA, 2012a) total world gross electricity production is heavily dependent on fossil fuels. In 2010 2.8% of gross electricity production in the OECD was produced with oil, 23.3% with gas and 34.3% with coal/peat. Nuclear energy accounted for 21.0%, hydro for 13.0%%, and solar/wind for 2.8%. For the world as whole, fossil fuels represented an even more significant share in 2010: 4.6% for oil, 22.2% for gas, and 40.4% for coal/peat. Solar/wind is 1.8%. Therefore, the invention and diffusion of efficiency-enhancing technologies is crucial, but it is also important that there is a switching from fossil fuels based to low-carbon technologies.

Inventive activity in this sector can be expected to respond to price incentives and particularly to an increase in fossil fuel prices, which can be considered as an indicator of the pressure on the electricity market also deriving from increasing attention to climate change. As fossil fuel prices rise there will be an efficiency effect, inducing innovation in all efficiency-enhancing technologies - both fossil fuel based and low-carbon – for electricity generation. However, there may also be a substitution effect driving away innovation from fossil fuel based towards low-carbon technologies.

This hypothesis is supported by recent works on directed technical change applied to the environmental sphere, such as Acemoglu et al. (2009) and Sue Wing (2006), which shows that substitution between intermediate inputs is the crucial parameter in the determination of innovation. If substitution between energy production sources is easy, then the substitution effect will prevail. In this case, fossil fuel energy will be replaced with low-carbon energy and innovation in fossil fuel technologies will decline. Innovation in low-carbon technologies is expected to increase as both the efficiency and the substitution effects will induce more innovation.

The literature on innovation and patents mostly focuses on patenting activity and environmental regulation in specific sectors. Lanjouw and Mody (1996) for example examined the relationship between patenting activity and stringency of environmental policy measured in terms of pollution abatement. They found that pollution abatement induces innovation by increasing the number of patents. Jaffe and Palmer (1997) use R&D expenditure and patents to study whether changes in regulatory stringency lead to innovation. They do not find evidence that patenting activity responds to environmental regulation. More recently, studies such as Popp (2006) focused on the effect that different policy instruments have on innovation. He finds that command-and-control policy instruments are less effective than market-based instruments. Most of these studies are country-specific or consider a limited number of countries. De Vries and Withagen (2005) instead use cross-country data to investigate the relationship between environmental

policy for limiting SO₂ emissions and patenting activity. They find some evidence that the stringency of environmental policies induces innovation.

Only a few papers have focused more specifically on the energy sector. Popp (2002) considers the effect of energy prices on innovation in efficiency-enhancing technologies and finds that energy prices are a determinant of innovation. A recent study by Johnstone et al. (2010) uses a panel of OECD economies with data on patents and R&D for different renewable technologies and on different types of environmental regulations to check for the presence of induced innovation. The authors find that different types of policies are effective for different types of renewable technologies.

This paper draws on the work by Johnstone et al. (2010) to study the dynamics of innovation between different technology types as induced by fossil fuel prices using a panel of patent data relative to 11 OECD economies over the period 1978-2008. The analysis uses public R&D expenditure, as it is an essential component of an innovation strategy to improve energy efficiency (Nemet and Kammen, 2007). R&D expenditure is expected to have a positive effect on inventions. Inventive activity also depends on the size of the sector and of the market it is serving. In a large and fast growing market there will be higher potential for inventive talent and stimulus to improve efficiency (see Popp, 2006). Electricity consumption is used to proxy for the growing size of markets and expects that it will have a positive sign. Finally, economies that have a high propensity to patent and a large production of innovative output in general are expected to produce more innovation in specific fields. To control for this effect, the total number of patents is also included as an explanatory variable.

The contribution of this paper is twofold. First, it illustrates that increasing fossil fuel prices drive innovation in efficiency-enhancing electricity generation technologies. Second, by analysing innovation in different technological fields, it shows that the effect of fossil fuel prices is not the same for all energy generation technologies. This provides insights on the substitutability of innovation efforts between energy types. An increase in fossil fuel prices is therefore likely to have a positive impact on the carbon efficiency of energy, as it both leads to an increase in efficiency-enhancing technologies, and to a switching from fossil fuel towards low-carbon technologies. Further, current investments in low-carbon technologies will also mean that fewer emissions will be produced in the future.

The paper is organized as follows. Section 2 describes the data used with a particular focus on patent data, which are analysed to understand the innovation dynamics. Section 3 illustrates the empirical analysis by specifying the model, the estimation method used, and the empirical results. Section 4 concludes.

2. Patent data in the electricity sector

Patents have emerged as one of the main indicators used for measuring innovation. They are a measure of the output of innovation, and as such reflect the innovative performance of firms and economies (Griliches, 1990). They are a useful indicator as they can be distinguished by the nature of the applicant and of the invention. This allows for the generation of patent counts by year, country, and technological field. Although not all inventions are patented there are few examples of economically significant inventions that have not been patented (Dernis et al., 2002). Patents are issued by national offices as a means to protect new technologies with property rights within that country. This excludes others from the production for a defined number of years, which varies upon the nature of the innovation and the rules of the national offices. In order to be patented, an innovation needs to be novel, non-obvious, and commercially viable (Dernis et al., 2002).

However, patents are an imperfect measure of innovation. First of all, it is difficult to identify the value of a patent and some patents may have a higher impact on the market than others. For this reason, patents are usually weighted to account for their difference in value, which in this case would consist in

appreciably lowering greenhouse gas emissions. The most common procedure to weight patents is to use citations (Popp, 2002).¹ As an alternative methodology, only patents that are protected in multiple countries (so-called “claimed priorities”)² are selected. Previous research has demonstrated that the number of offices for which protection of a given invention is sought is a good indicator of patent value (see Guellec and van Pottelsberghe, 2000; Harhoff et al., 2003).

The second shortcoming in the use of patents is that the propensity to patent, the patent regimes, and the innovative activity change across countries. In this paper, this problem is addressed in two ways: a) by including country fixed effects; and b) by controlling for the total number of claimed priorities in all technological fields.

The fact that patent data can be disaggregated by technology proves useful for the selection of the technological areas of interest. The International Patent Office (IPO) supplies patent classification codes developed by the World Intellectual Property Organization (WIPO), thanks to which patents are classified into different technological areas and at several hierarchical levels. The International Patent Classification (IPC) (WIPO, 2006) is application-based, thus facilitating the identification of specific technology classes, and particularly for the scope of the present work, of classes including efficiency-enhancing patents for electricity production. These refer to technologies for electricity generation targeted at decreasing GHG emissions by enhancing the efficiency of the energy generation process.

Relevant patent classes have been selected after a careful and extensive review of technological developments in the area of efficiency-enhancing technologies (Lanzi et al., 2011). Thanks to this review a set of technology-specific keywords has been identified. These were then used to determine the appropriate IPC codes related to each of the technologies of interest. The fossil fuel technologies are gas turbines, compressed ignition engines, cogeneration, combined cycles, superheaters, steam engines, boilers, burners and fluidized beds, and the related IPC classes are listed in Annex I. IPC technology classes for the renewable energy technologies have been taken from Johnstone et al. (2010). These include wind, solar, geothermal, ocean, biomass and waste. Finally, IPC classes have been selected for both nuclear fusion and fission.

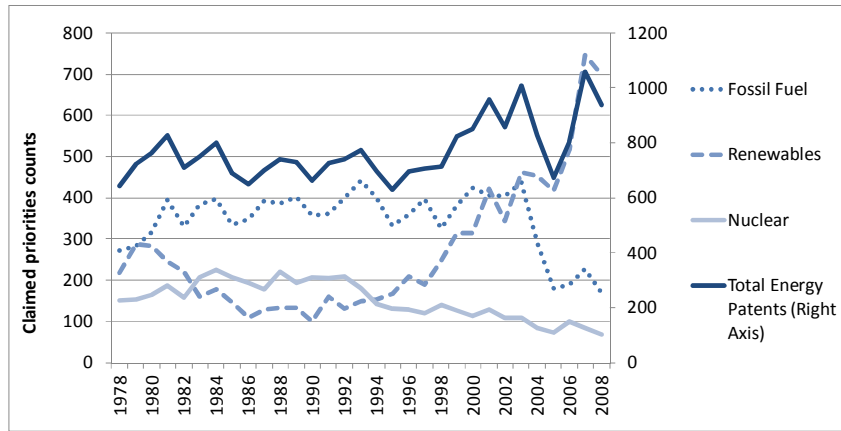
With the use of the selected IPC classifications, data have been extracted from the EPO/OECD Worldwide Patent Statistical Database (usually referred to as PATSTAT). The PATSTAT database is an extensive and comprehensive database that answers the needs of researchers and policy-makers to combine different data sets for patent-related information.

The patent selection process allowed us to create a database of patent data for the different types of technologies. Thus, it is possible to study innovation in this sector in aggregate as well as to analyse the development of the different technologies over time. Figure 1 illustrates the development for the world sum of claimed priority counts for efficiency-enhancing patents in aggregate and by technology type for the period 1978-2008. The total of efficiency-enhancing energy patents was rather stable until 1997, the year of ratification of the Kyoto Protocol, when it started to increase rapidly. The political attention given to the problem of climate change and greenhouse gases emissions may have contributed to stimulate the development of efficiency-enhancing technologies for electricity generation.

1 The number of times the patent has been cited in other patent applications. This is an indicator on the importance of the innovation in the technological field.

2 Patents that have only been registered in one patent office are referred to as singulars. Patents that have been registered in multiple offices are instead referred to as claimed priorities. A patent that is registered in an office but that had already been registered before is referred to as a duplicate.

Figure 1. Trends in Invention in Energy Technologies
(Count of Claimed Priorities)



Looking at the different types of technologies aimed at enhancing efficiency in energy production, it is possible to see that they behave in different ways. Whereas some technologies increase in recent years, other ones appear to be declining. Renewable energy patents had a peak in the late 1970s and early 1980s, and then were stable until late 1990s where they started growing more rapidly. Fossil fuel technologies, though stable over time in the past, have declined in the past decade. Finally, patents relative to nuclear energy are stable overtime though exhibiting a slow decline since the early 1990s.

Figure 2 illustrates the number of claimed priorities in a stacked area graph that helps identify the relative increase in the different types of patents over time. The graph illustrates that renewables have been increasing more than fossil fuels and nuclear. This is mostly due to the fact that it is a new technology so that more inventions are created. Looking at all technologies together, it is possible to see that the overall investments have been stable while the dynamics between the different energy technologies have changed. In particular, patenting activity has decreased in fossil fuel technologies relative to the other technologies.

Figure 2. Relative Importance of Invention in Different Energy Technologies
(Count of Claimed Priorities)

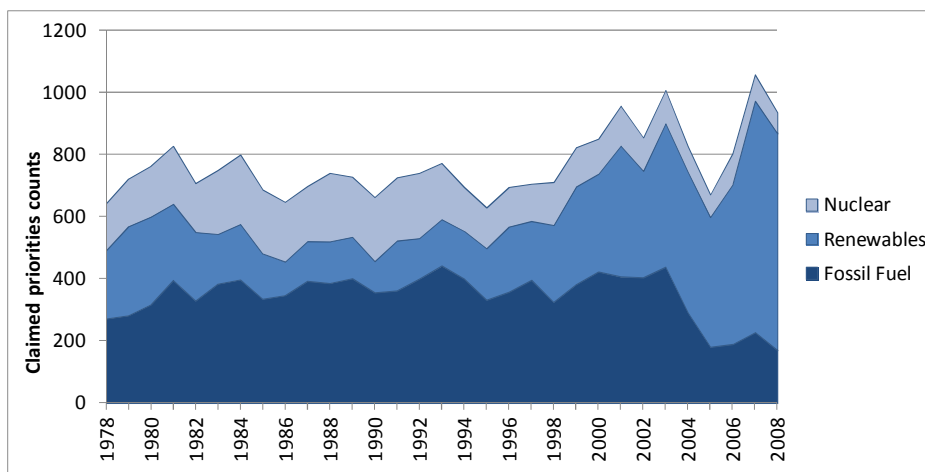
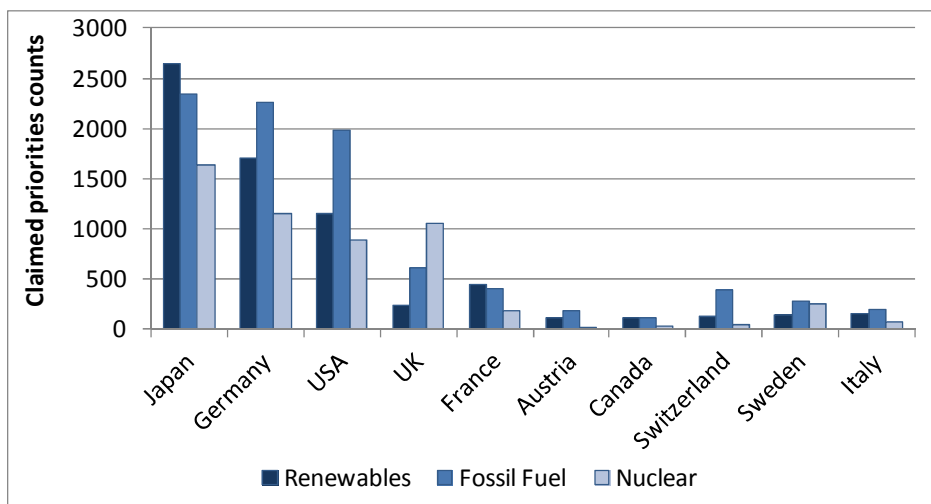


Figure 3 shows the aggregate count of patents over the time period 1978-2008 for the countries with highest number of patents in electricity generation. Main innovating countries are the same for the different types of technologies, although it is possible to see that there is a certain level of specialization. For

example, Germany and the USA have a large number of patents in fossil fuel technologies; while the UK has the highest number of patents in nuclear and Japan in renewables.

Figure 3. Main Innovating Economies in Different Energy Fields
(Count of Claimed Priorities)



These values do not control for the effect of relative size of the economies, nor their general ability and propensity to innovate. In order to normalise the relative amount of innovation in these technologies, Figure 4 illustrates the number of claimed priorities in electricity generation standardised with the total number of patents.

Figure 4. Percent of Energy Patents in Total Patents
(Count of Claimed Priorities)

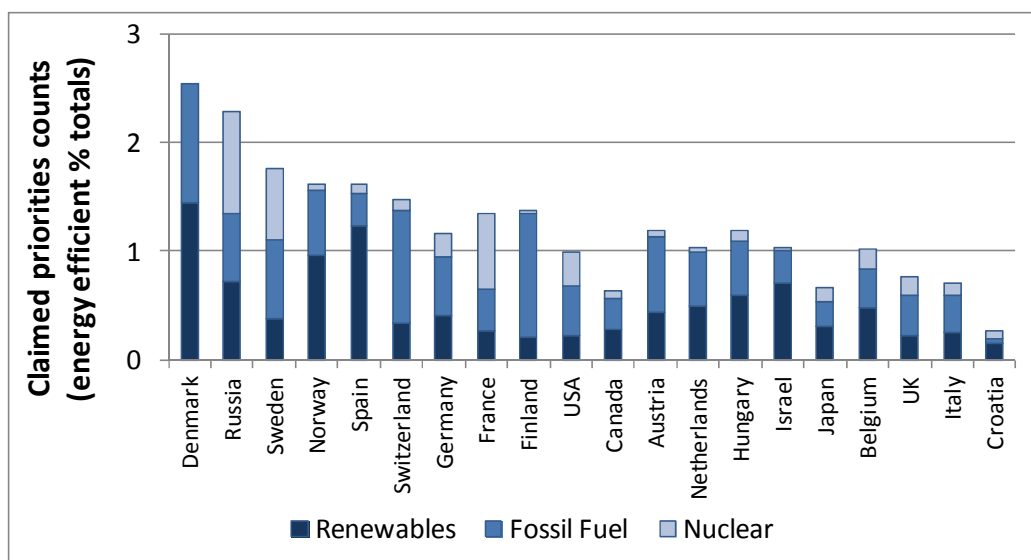


Figure 4 illustrates that the countries with the highest relative number of patents in electricity generation are Denmark, Russia, and Sweden. Some countries, like Russia, Germany, or the UK, have a homogenous number of patents across the different technology types. For other countries, there is a clear bias towards a certain type of technology, like renewables in Denmark and Spain, or fossil fuels in Switzerland and Finland. The differences between the standardized graph and the one in actual values

highlight the importance of taking into consideration the propensity to patent, and the country specific heterogeneities that derive from the different property right systems.

3. The determinants of invention in the energy sector

The first explanatory variable to study the determinants of patenting activity which is included in the model is the price of fossil fuels. Higher fossil fuel prices increase production costs of the firms. This encourages firms to invest in new technologies that lower the input of fossil fuels, and thus production costs. Thanks to this efficiency effect, fossil fuel prices produce an increase in innovation in efficiency-enhancing electricity generation technologies.

However, when looking at the single technologies there may also be a substitution effect. With fossil fuel prices increasing, there may be a switching towards low-carbon technologies. Thus, fossil fuel prices will have a positive effect on the disaggregated low-carbon technologies, while for fossil fuel technologies the effect will depend on the prevalence of the efficiency or substitution effect. Fossil fuel prices have been obtained for coal, oil and gas, using data from the IEA Energy Prices and Taxes Statistics (IEA, 2012b). Since they are highly correlated, an index of real prices for fuel oil used in industry (2010=100) has been used.³

Public R&D investments are also considered as an indicator of the public effort in support of technological development. R&D data are obtained from the IEA's Energy Technology R&D Statistics (IEA, 2010), which national public expenditures on energy R&D disaggregated by type of technology. Therefore, it is possible to create separate measures for the different technologies. It is generally expected that the sign on this variable is positive, as more investment in R&D should lead to a higher innovative activity. Having only public R&D data is a limitation. With full availability of data on both private and public R&D, it would have been possible to study innovation as a two step-estimation in which prices would influence the choice of firms in their R&D investments, and then R&D would have lead to innovation according to its effectiveness. However, the use of public R&D data only in a single equation is unlikely to result in problems of endogeneity.

To control for the electricity market size, which can influence the potential market for innovation, electricity consumption is included as an explanatory variable. Data on household and industry sector electricity consumption are obtained from the IEA's Energy Statistics and Balances Database (IEA, 2012c). To control for the different propensity to patent, the total count of claimed priorities are considered. Finally, fixed effects control for country specific heterogeneities.

Table 1 summarises the descriptive statistics for the explanatory variables included in the panel. For the patent data the mean of the variables are rather similar between all technology types, but the standard deviations differ consistently. There is a higher variation in patenting activity in fossil fuels than in renewable and nuclear. For R&D investment, the highest variation is in nuclear. As the aim of the empirical analysis is to compare the effect of the price index on the different types of technologies, the same panel has been used for all regressions. This facilitates the comparability of results.

³ More specifically, prices of oil and gas are historically highly correlated, thus only price of oil is included. The price of coal is not correlated to the other two fuel input prices, and it is rather stable over time. Further, the coal prices data are scarce in terms of number of countries covered and they consistently lower the number of observations in the sample. Thus, as coal price is never found significant in the regressions, and as its omissions does not significantly change the results, it is omitted from the regressions, leaving the price of oil to be the unique measure of fuel input prices.

Table 1. Descriptive Statistics of Explanatory Variables (1978-2008)

Variable	Unit of Measure	Obs.	Mean	Std.Dev.
Claimed Priorities – Fossil Fuels	Number of claimed priorities	123	48.82	39.96
Claimed Priorities – Renewables	Number of claimed priorities	123	26.07	21.36
Claimed Priorities – Nuclear	Number of claimed priorities	123	23.50	21.76
Claimed Priorities – Total	Number of claimed priorities (th.)	123	12.88	11.97
Oil price index	Price index for fuel oil (2010=100)	123	61.10	24.43
Consumption of electricity	Thousand TWh	123	969.99	1049.22
R&D – Fossil Fuels	Billion 2000 US\$ - Constant prices and PPP	123	0.03	0.04
R&D – Renewables	Billion 2000 US\$ - Constant prices and PPP	123	0.16	0.25
R&D – Nuclear	Billion 2000 US\$ - Constant prices and PPP	123	0.82	0.89

4. Model specification, estimation method and results

The model is a reduced form equation and is estimated for all energy technologies, as well as for the single technologies:

$$CP_{it} = \beta_0 + \beta_1 R\&D_{it} + \beta_2 P_{it} + \beta_3 P_{it}^2 + \beta_4 CONS_{it} + \beta_5 CPT_{it} + \alpha_i + \varepsilon_{it} \quad (1)$$

where $i = (1, \dots, 18)$ indexes the cross-sectional unit (country) and $t = (1978, \dots, 2008)$ indexes time. The dependent variable, patenting activity $CP_{i,t}$, is measured by the number of patent claimed priorities in the relevant technology areas. The explanatory variables include specific R&D expenditures ($RD_{i,t}$), fossil fuel prices ($P_{i,t}$) as well as the square of fossil fuel prices, growth rate of electricity consumption ($CONS_{i,t}$), and total patent counts ($CPT_{i,t}$). Fixed effects (α_i) are introduced in order to capture unobservable country-specific heterogeneity. All residual variation is captured by the error term ($\varepsilon_{i,t}$). In the estimation of fossil fuel technologies, the squared price index has also been included as for this technology in particular it is reasonable to expect that the effect of prices is non-linear.

The model applies the framework used in Johnstone et al. (2010) to explore the effect that fossil fuel prices have on efficiency-enhancing technologies for electricity generation for the single technology types and in aggregate. As fossil fuels are an input for one of the main technology types, they will not only influence innovation in this sector but also in the substitute ones.

Patent data are usually estimated with techniques appropriate for count data models, namely data for which the dependent variable is non-negative.⁴ The classical approach to count data estimation is to use the Poisson regression, assuming that the conditional distribution of the dependent variable follows a Poisson distribution, as in El Sayyad (1973) and Maddala (1983). However, the Poisson regression is based on the strong assumption of variance-mean equality, which has been rejected in numerous applications.

A relaxed version of this assumption is provided by the Poisson quasi-maximum likelihood estimator (QMLE), which allows the variance-mean ratio to be any positive constant σ^2 . When $\sigma^2 < 1$, the mean of the distribution is greater than the variance, thus there is underdispersion in the sample. When $\sigma^2 > 1$ instead, thus there is overdispersion. In the latter case, the distribution corresponds to a Negative Binomial I, which is a particular parameterization of the negative binomial distribution, as explained in Cameron and Trivedi (1986). Given that our sample has a high number of zero counts, it is likely to be overdispersed, and thus the negative binomial estimation is preferable to the Poisson.

4 For an overview of count data models see Cameron and Trivedi (1998) or Wooldridge (2002).

Whilst count data models were initially designed for cross-sectional data, extensions have been developed for panel data model, starting with the pioneering work by Hausman, Hall and Griliches (1973), who studied patent applications by firms in terms of R&D spending. This analysis follows their work in using a fixed effect negative binomial estimation technique. A further problem with the data is that it is not just heteroschedastic because of its count data nature, but also heteroschedastic across countries. In fact, because most innovation takes place in a limited number of countries, there is a further problem of heteroschedasticity. This is corrected for by applying a robust estimation.

The model is estimated using the same panel to facilitate the comparison of results (see Table 2). The oil price index has different effects across the technology types. Its effect is positive on renewables, non-significant on nuclear technologies, and positive but decreasing over time on fossil fuel technologies.⁵ The positive effect of fossil fuel prices on inventive activity shows that there is an efficiency effect: as fossil fuel prices increase and electricity production becomes more expensive, more innovation takes place in efficiency-enhancing technologies. The non-linear effect on fossil fuel technologies shows that whereas initially a price increase leads to more innovation in efficiency-enhancing fossil fuel technologies, as price becomes higher, less innovation takes place. This, combined with the positive effect on renewable, suggests that there is a substitution effect between renewable and fossil fuel technologies. Fossil fuel prices do not influence technologies regarding nuclear power plants. Innovation in this sector is more influenced by other variables, such as energy consumption.

Table 2. Estimation Results

	Fossil fuel	Renewables	Nuclear
Oil price index	0.0243 *** (-0.005)	0.0089*** (0.000)	-0.0039 (-0.110)
Oil price index, sq.	-0.0002*** (-0.001)		
R&D Fossil Fuels	1.1074 (-0.331)		
R&D Renewables		0.9723*** (0.000)	
R&D Nuclear			0.4403*** (0.000)
Electricity consumption	-0.0009*** (0.000)	0.0006*** (0.000)	-0.0007*** 0.000
Total patents	-.0204*** (-0.008)	.0180* (-0.025)	.0879** (0.000)
Fixed Effect	Yes	Yes	Yes
Observations	123	123	123
Log-likelihood	-472.75	-424.65	-403.29
Pseudo R2	0.2144	0.19	0.2136
(Prob.>chi2)	0	0	0

P-values are in parentheses. The dependent variable is claimed priorities in fossil-fuel energy-enhancing technologies.

Public R&D expenditures have a positive and significant effect on innovation in renewable and nuclear technologies, but no significant effect on patenting activity in fossil fuel technologies. The effect of electricity consumption is negative and significant for fossil fuel and nuclear technologies, and positive and significant for renewables. The estimated coefficient of the total number of patents is positive and statistically significant for renewable and nuclear, but negative for fossil fuels. This suggests that fossil fuel technologies are not the main focus of the countries with the highest propensity to patent.

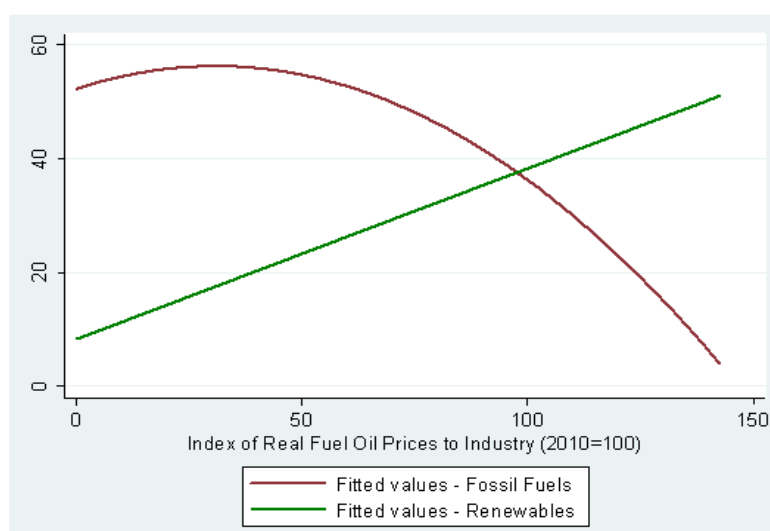
⁵ The squared term on the oil price was statistically insignificant for renewable and nuclear.

For all regressions, values of the likelihood ratio chi-squared test with three degrees of freedom are given. From these it is possible to see that all models are statistically significant. Estimates of the log of the over-dispersion parameter alpha are also obtained in order to check whether the negative binomial estimation is appropriate. The likelihood ratio chi-square tests support the use of negative binomial.⁶

The results of the empirical analysis illustrate that there may be a price-induced switching between low-carbon and fossil fuel based technologies. In particular, given the non-significant results of the effect of fossil fuel prices on patenting activity in nuclear technologies, the results suggest that there may be a switching between fossil fuel and renewable technologies. To illustrate the switching between these two technology types, a calculation of the predicted values for these technologies is used to then graphically compare the effect of the price index on innovative activity. Figure 5 shows that while the price index has a positive effect on renewables, the effect is only initially positive on fossil fuel technologies.

As fossil fuel prices rise there is an increase in both types of technologies. This reflects an efficiency effect, which induces innovation in both efficiency-enhancing technologies. However, after a certain level of the price index, invention in fossil fuel based technologies starts declining suggesting that a substitution effect drives away innovation from fossil fuel based towards renewable technologies. The point at which the curves intersect is in the region of oil prices experienced during the most recent oil price shock.

Figure 5. Oil Prices and Invention in Fossil Fuel and Renewable Energy



While this result is specific to an empirical estimation of the effect of fossil fuel prices on inventive activity, it indicates that policies that increase the relative price of fossil fuel energy with respect to renewable energy may lead to a switching in innovation. A relative increase of innovation in renewable generation technologies would in turn increase the availability of these technologies, facilitate their adoption and help achieve climate change mitigation objectives.

⁶ The test is used to verify whether the overdispersion parameter alpha is statistically significant from zero. If alpha equals zero, then there is no overdispersion. If the test is significant zero-truncated negative binomial is preferred to zero-truncated Poisson. In all estimated models the test is significant supporting the choice of estimating with negative binomial.

5. Concluding remarks

A panel of OECD economies for the period 1978-2008 is used to analyse innovation in efficiency-enhancing electricity generation technologies. Different technologies – namely fossil fuel-based, renewable and nuclear energy technologies – are considered separately in order to study the intra-sectoral dynamics. The empirical results indicate that fossil fuel prices, which in this analysis are used as an indicator of underlying climate policies, lead to an increase in invention in efficiency-enhancing electricity generation technologies. The results show that the effect is not uniform across the different technologies. As fossil fuel prices increase, invention in renewable energy technologies also increases. The effect of increasing fossil fuel prices on fossil fuel-based is positive. However, as fossil fuel prices increase, their positive impact on inventive activity in fossil fuel-based technologies decreases. The effect of fossil fuel prices on patenting activity in nuclear energy technologies is found to be non-significant. This result supports the hypothesis of a substitution effect between fossil fuel and renewable energy technologies.

This paper finds long-run internal dynamics, which could lead to a change in the technology mix for electricity production. From an initial analysis of the effect of fossil fuel prices on innovation it is found that increasing costs of fossil fuels is likely to induce such a change in the energy mix. Although the results of this analysis are based on a specific set of data, the results suggest that price mechanisms such as emissions trading, and carbon taxes are likely going to lead to a change in the direction of innovation towards low-carbon technologies.

This empirical analysis contributes to the literature by combining and comparing information on innovation in different types of technologies. Whereas this is usually done with applied climate-economy models, such as Integrated Assessment Models (IAMs), Computable General Equilibrium (CGE) Models or partial equilibrium energy models, the empirical literature analyzing the changes in the direction of innovation in the energy sector is not yet well developed. This paper underlines the need to continue to explore this topic further, including integrating the results of empirical analyses with more structural models of directed technical change.

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ANNEX 1: SELECTED PATENT DATA CLASSES FOR FOSSIL FUEL-BASED TECHNOLOGIES

Table 3. Patent Data Classes for Fossil Fuel-Based Technologies

COAL GASIFICATION	
C10J3	Production of combustible gases containing carbon monoxide from solid carbonaceous fuels
IMPROVED BURNERS	
[Classes listed below excluding combinations with B60, B68, F24, F27]	
F23C1	Combustion apparatus specially adapted for combustion of two or more kinds of fuel simultaneously or alternately, at least one kind of fuel being fluent
F23C5/24	Combustion apparatus characterized by the arrangement or mounting of burners; Disposition of burners to obtain a loop flame.
F23C6	Combustion apparatus characterized by the combination of two or more combustion chambers (using fluent fuel)
F23B10	Combustion apparatus characterized by the combination of two or more combustion chambers (using only solid fuel)
F23B30	Combustion apparatus with driven means for agitating the burning fuel; Combustion apparatus with driven means for advancing the burning fuel through the combustion chamber
F23B70	Combustion apparatus characterized by means for returning solid combustion residues to the combustion chamber
F23B80	Combustion apparatus characterized by means creating a distinct flow path for flue gases or for non-combusted gases given off by the fuel
F23D1	Burners for combustion of pulverulent fuel
F23D7	Burners in which drops of liquid fuel impinge on a surface
F23D17	Burners for combustion simultaneously or alternatively of gaseous or liquid or pulverulent fuel
FLUIDIZED BED COMBUSTION	
B01J8/20-22	Chemical or physical processes (and apparatus therefore) conducted in the presence of fluidised particles, with liquid as a fluidising medium
B01J8/24-30	Chemical or physical processes (and apparatus therefore) conducted in the presence of fluidised particles, according to "fluidised-bed" technique
F27B15	Fluidised-bed furnaces; Other furnaces using or treating finely-divided materials in dispersion
F23C10	Apparatus in which combustion takes place in a fluidised bed of fuel or other particles
IMPROVED BOILERS FOR STEAM GENERATION	
F22B31	Modifications of boiler construction, or of tube systems, dependent on installation of combustion apparatus; Arrangements or dispositions of combustion apparatus
F22B33/14-16	Steam generation plants, e.g. comprising steam boilers of different types in mutual association ; Combinations of low- and high-pressure boilers
IMPROVED STEAM ENGINES	
F01K3	Plants characterised by the use of steam or heat accumulators, or intermediate steam heaters, therein
F01K5	Plants characterised by use of means for storing steam in an alkali to increase steam pressure, e.g. of Honigmann or Koenemann type
F01K23	Plants characterised by more than one engine delivering power external to the plant, the engines being driven by different fluids
SUPERHEATERS	
F22G	Superheating of steam
IMPROVED GAS TURBINES	
F02C7/08-105	Gas turbine plants - Heating air supply before combustion, e.g. by exhaust gases
F02C7/12-143	Cooling of gas turbine plants

F02C7/30	Gas turbine plants - Preventing corrosion in gas-swept spaces
COMBINED CYCLES	
F01K23/02-10	Plants characterised by more than one engine delivering power external to the plant, the engines being driven by different fluids; the engine cycles being thermally coupled
F02C3/20-36	Gas turbine plants characterised by the use of combustion products as the working fuel
F02C6/10-12	Combinations of gas-turbine plants with other apparatus; Supplying working fluid to a user, e.g. a chemical process, which returns working fluid to a turbine of the plant
IMPROVED COMPRESSED-IGNITION ENGINES	
[Classes listed below excluding combinations with B60, B68, F24, F27]	
F02B1/12-14	Engines characterised by fuel-air mixture compression ignition
F02B3/06-10	Engines characterised by air compression and subsequent fuel addition; with compression ignition
F02B7	Engines characterised by the fuel-air charge being ignited by compression ignition of an additional fuel
F02B11	Engines characterised by both fuel-air mixture compression and air compression, or characterised by both positive ignition and compression ignition, e.g. in different cylinders
F02B13/02-04	Engines characterised by the introduction of liquid fuel into cylinders by use of auxiliary fluid; Compression ignition engines using air or gas for blowing fuel into compressed air in cylinder
F02B49	Methods of operating air-compressing compression-ignition engines involving introduction of small quantities of fuel in the form of a fine mist into the air in the engine's intake.
COGENERATION	
F01K17/06	Use of steam or condensate extracted or exhausted from steam engine plant; Returning energy of steam, in exchanged form, to process, e.g. use of exhaust steam for drying solid fuel of plant
F01K27	Plants for converting heat or fluid energy into mechanical energy
F02C6/18	Using the waste heat of gas-turbine plants outside the plants themselves, e.g. gas-turbine power heat plants
F02G5	Profiting from waste heat of combustion engines
F25B27/02	Machines, plant, or systems using waste heat, e.g. from internal-combustion engines