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**Environmental Regulations,
Market Structure and
Technological Progress in
Renewable Energy
Technology – A Panel Data
Study on Wind Turbines**

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Keywords: Environmental Policy, Renewable Energy, Market Structure, Wind Turbines, Innovation, Patents, Technological Change

JEL Classification: Q55, Q58, O34, O38

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Environmental Regulations, Market Structure and Technological Progress in Renewable Energy Technology — A Panel Data Study on Wind Turbines

Dirk Rübhelke* and Pia Weiss†‡

Abstract

We study the impact of environmental regulations on the patent activities for wind turbines between 1980 and 2008. We explicitly control for energy market liberalisation and take a potential interaction between liberalisation and policy instruments into account. We find a strong and highly significant effect of environmental tax revenues, which we regard as a proxy for the extent to which energy prices changed in favour of renewable energies, as well as foreign demand for wind turbines on innovation activities. In addition, we find that price-based policy instruments are more effective in fostering innovations in the wind turbine technology when energy markets are fully open to competition. In contrast, non-price-based policy instruments such as grants or low interest rate loans are largely independent from whether or not energy markets are liberalised.

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1 Introduction

The oil price shocks in the 1970s made it painfully clear how much the development and the welfare of countries depend on a steady and affordable energy supply. Therefore, it is not surprising that governments, especially in industrialised countries, initiated research programs that looked for alternative energy sources in order to improve the security of energy supply. The increasing concerns about climate change and global warming renewed and reinforced the interest in non-fossil energy sources as they promise to lastingly reduce greenhouse gases. According to Popp et al. (2010), the efforts to reduce carbon emissions have primarily driven investments into renewable energy sources.

Due to the global public good/bad characteristics of global warming (see e.g. Nordhaus, 2001, p. 1284), any effective intervention has to be supra-national. With a multitude of diverging interests, it is exceedingly difficult to reach an efficient global climate protection regime. The conclusion of the Kyoto Protocol in 1997 is therefore a remarkable step in the pursuit of

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efficient international climate protection. In the wake of the Kyoto Protocol, all participating industrialised countries had to adapt their laws. As a consequence, new research programs were established and a number of new policy instruments were introduced. Hahn and Kammen (1992, p. 466) stress: “In the long run, the effect of public policies on technological change may be among the most important determinants of success in environmental protection”.

Especially with respect to the management of long-term threats like climate change, the continued development and deployment of technologies, which cannot quite yet compete in the market, is pressing (see Arrow et al., 2009). According to Barrett (2009, p. 73): “[s]tabilizing atmospheric concentrations will require fundamental and comprehensive changes in technology.” Thus, identifying policy approaches and instruments, which support the development of new and improved technologies, is a crucial task in any solution for the global warming problem.

There are only a few early empirical studies which try to establish a link between environmental regulations as a whole and innovative activities. According to Porter (1991), adequate environmental regulations can exert the necessary outside pressure in the innovation process that is necessary to overcome obstacles such as organisational inertia (see also Porter and van der Linde, 1995, p. 100). Yet, Jaffe and Palmer (1997) criticise that Porter (1991) offers merely anecdotal evidence for his view on the importance of environmental regulation for technological change in eco-friendly technologies. As Nordhaus (2002, p. 182) points out, “[s]tudies of environmental and climate-change policy [...] have generally sidestepped the thorny issue of induced innovation, which refers to the impact of economic activity and policy on research, development, and the diffusion of new technologies.” Popp (2002, p. 160) also stresses that there is “little empirical evidence about the policy-induced development of environmentally friendly technology”. Jaffe and Palmer (1997) are among the first who provide the missing evidence that environmental regulation as a whole has a positive effect on innovative activities. Only recently however, researchers have paid attention to the question about the impact of individual policy instruments on innovation (see e.g. Klaassen et al., 2005; Johnstone et al., 2010).¹ Our study continues to ask how effective environmental policy instruments are in stimulating innovation. Unlike other studies, we explicitly take the influence of market liberalisation on the effects of such instruments into account.

In our understanding, any assessment of environmental regulations has to be made against the background of the liberalisation of energy markets in the recent decades for two reasons. Firstly, energy market liberalisation might induce significant changes in the energy use patterns, e.g. opening the energy markets to competition in the UK in the 1990s led to a partial substitution of ‘dirty’ coal by ‘cleaner’ natural gas as an input for electricity generation. Secondly, opening the energy market to a more market-oriented supply gave also rise to (the necessity of) new regulation approaches, e.g. the establishment of so-called feed-in tariffs or voluntary agreements. As van Rooijen and van Wees (2006, p. 62) state concerning the case of the Netherlands, the “liberalisation of the electricity sector [...] forced changes in the fiscal system as it was feared that reallocation of tax revenues to cover the cost of green energy would disturb the market.”

Our analysis of the effects of environmental regulations in the energy sector on innovation activities focuses on the wind energy sector in a selection of European countries, Japan and the US. Although wind potentials differ among (and within) countries, the availability of wind energy is relatively independent of geographical characteristics as compared to other non-carbon energy sources. An example to the point includes Norway which has an undeniable natural advantage for hydroelectricity or the countries in southern Europe which enjoy more hours of sunshine relative to countries in northern Europe. In contrast, wind power is much more readily

¹ Other studies that furthered the understanding of the relationship between environmental regulations and innovation are e.g. Popp (2006) or Pizer and Popp (2008).

available in all countries.² A second reason for studying wind energy is that it is the most advanced technology among the ‘new’ renewable energy technologies. Both facts together lead to the conjecture that firms and researchers in most European countries, Japan and the US have an incentive to contribute to the technological progress of wind turbines.

In detail, our analysis is organised as follows. In Section 2 we form the hypotheses about the factors influencing innovation in the wind turbine sector; and we briefly discuss the employed model. In Section 3, we describe the dependent and independent variables we use in our estimation. Section 4 presents the estimation results. Section 5 discusses these results in a broader context and draws some conclusions.

2 Hypotheses and model

2.1 Hypotheses

Usually, a specific investment opportunity is chosen because it yields higher expected profits relative to the expected profits of available alternatives. This is true for research and development (R&D) as well as the subsequent dissemination and adoption of the new technology if R&D was successful. Given that the path from the idea for an invention to the market introduction of a new technology is long and highly uncertain, a large number of factors affect the profitability of investments. This provides policy makers with an equally large number of potential policy instruments to stimulate R&D in the field of renewable energy as well as for the adoption of the new technologies later on. It is therefore unsurprising that policy makers have introduced different policy instruments, each designed to stimulate innovation and its dissemination in a different, specific way.

The policy instruments can broadly be distinguished by the manner in which they affect the expected profits from investments. Firstly, they may reduce the up-front costs from R&D expenditures or installation costs. Secondly, they may be market-based, i.e. the policy instruments change the relative prices for either the inputs or the output.³

After the first oil price shock in 1973, several countries introduced R&D programs expressly to search for more efficient ways to harness renewable energy resources. These programs directly or indirectly reduced the R&D (up-front) costs and were one of the first policy instruments to stimulate renewable energy technology.⁴ Choosing a non-market based policy instrument to stimulate innovation in the field of renewable energy technology was appropriate during the late 1970s and 1980s. Electricity suppliers were believed to be natural monopolies due to the immense fixed costs and network costs. The market was heavily regulated and electricity suppliers were state owned in many countries.⁵ As competition in the electricity market did virtually not exist and prices were more or less determined by government authorities, policy instruments that rely on the price mechanism were unnecessary. The R&D programs gradually phased out during the mid and late 1980s.

² According to the EEA (2009, p. 48), the majority of the EU-27 member states will most likely have some competitive wind power potential by 2020.

³ Isoard and Soria (2001, p. 631) distinguish between supply-push policies such as R&D and demand-pull policies in a similar way.

⁴ R&D programs would directly reduce the R&D costs for private enterprises if the firms receive direct funding. The indirect effects of R&D programs stem from the public goods characteristics of knowledge. Once an invention has been made, the re-creation is possible at lower costs. Patent laws regulate the use of patented knowledge. However, experimentation alone, especially for the purpose of further developments, does frequently not constitute a patent infringement (Weiss, 2010).

⁵ In some countries such as Germany, the market was divided into geographically distinct sub-markets; and each sub-market was served by a monopoly.

As more and more countries chose to open the electricity market for competition, new policy instruments had to be created as firms now acted in a competitive environment where customers respond to price differences. There are arguments both for and against the hypothesis that stronger competition is conducive to increased innovation. Schumpeter (1942) argues that firms in a competitive environment lack the profits to pursue R&D. Arrow (1962a) on the other hand points out that stronger competition may well induce firms to seek more efficient production methods in order to gain advantage over their competitors. Although we expect that the liberalisation of the electricity market will have a positive effect on the innovative activity for wind turbines, we also believe that the relationship between liberalisation, regulation and innovation is complex.⁶

Some of the regulation instruments such as taxation, R&D funding and providing grants or low interest loans for installing wind turbines have been extensively used even before the energy market liberalisation. Other instruments, such as e.g. certain tax exemptions for consumers seem to appear only after markets have been opened to competition. Therefore, we expect that certain policy instruments will be more effective if markets are already open to competition. It is reasonable to assume that policy instruments that affect prices will depend more on competition than non-price-based instruments.

Wind as an energy source has been used for centuries. Yet, the technology was extremely inefficient to generate electricity. Substantial technological progress was necessary to bring production cost even close to the cost for generating electricity from traditional sources. These technological achievements are largely a consequence of the first oil price shock and the associated efforts to become less dependent on oil imports.

When a technology is still relatively young and large improvements are made, being the first firm in a market ensures a large market share.⁷ Since wind is a ubiquitous resource and because the technological knowledge was at least initially not widely available, foreign demand for wind turbines might increase R&D and therefore patenting activities. The argument is supported by the fact that wind quality widely differs so that wind turbines developed for Europe might be less efficient in e.g. India or China. Consequently, it might be necessary to adapt wind turbine technology to local conditions. Usually, firms that export valuable technology will patent their technology in the importing country. Table 1 below shows that there are remarkable differences in foreign patenting activities between the countries.

2.2 The model

Since innovation activities itself cannot be measured, it has become common practice to use either inputs for or outputs of innovation activities instead.⁸ Input measures build on the hypothesis that increasing e.g. R&D expenditures will increase the number of inventions and innovations. On the other hand, innovative activities may result in patentable inventions. Assuming that on average a fixed proportion of inventions is patented, patent applications or patent grants are an appropriate output measure for innovation activities. In recent years, researchers have increasingly relied on patent counts. Because of the availability of data as well as the amount of additional information, e.g. on patentees, in an *internationally standardised* form, we decided

⁶ Swezey and Bird (2000) stress the role for liberalisation in electricity markets for the rise in the supply of green power in the US. As Bird and Sumner (2010, p. 21) point out: "Initially, green power marketers in competitive markets were often forced to offer existing renewable energy sources because of a lack of new renewable energy supplies, but most marketers now offer primarily new renewable energy".

⁷ According to Kristinsson and Rao (2007), Danish firms have a world market share of about 40 per cent.

⁸ See e.g. Griliches (1990) for a discussion on the relative strengths of both methods.

to use the number of patent applications to study the effects of environmental regulations on the progress of renewable energy technologies.

Poisson processes are often thought of describing random arrival events. Because of the obvious similarity to innovation processes, they have been used in the theoretical literature on innovation and patent races.⁹ For random variables governed by a Poisson process, residuals would not be normally distributed so that standard least squares regressions would yield biased results. Therefore, a Poisson regression is a better choice. However, a Poisson regression presumes that the mean and the variance for the (count) random variable are identical. This assumption is rather restrictive and often violated in patent count estimations, i.e. we might encounter the problem of over-dispersion. Therefore, a negative binomial regression is usually used (Allison and Waterman, 2002).

We know that patent counts will depend on country-specific differences, i.e. mainly on country size and on the inclination to patent. Therefore, a panel data negative binomial regression with country fixed effects would be appropriate regression model. According to Allison and Waterman (2002) and Guimarães (2008), the negative binomial regression model of Hausman et al. (1984) which has been incorporated into a number of statistical software programs relies on an assumption that is rarely met. Allison and Waterman (2002) therefore suggest to use the unconditional negative binomial regression model with country dummy variables to account for the fixed effects. We follow the suggestion of Allison and Waterman (2002) and use the following, simplified version of our estimation equation:

$$\ln E(\text{PatCnt}_i) = \ln(\text{pop}_i) + \beta(\text{Policy}_i) + \gamma(\text{Market}_i) + \delta(\text{Investment}_i) + \alpha_i \iota. \quad (1)$$

$E(\text{PatCnt}_i)$ denotes the expected total patent applications. Since larger countries tend to apply more often for patents, we explicitly account for the differences in country size by including the natural logarithm of the population $\ln(\text{pop}_i)$ for observation i in the estimation. Further, we use a number of *Policy* variables as well as controls for innovation incentives that are naturally present in the *Market* and direct *Investment* incentives such as R&D expenditures (see below). β , γ and δ are the vectors of the estimation coefficients associated with the *Policy*, *Market* and *Investment* variables. $\alpha_i \iota$ represent the country dummies for observation i .

In the next section, the variables that are included in the estimation are discussed in detail.

3 Data

3.1 Patent data

Patent applications collect a vast number of information about the invention as well as the inventors and assignees. We use the number of all patent applications for wind motors that were made by nationals or firms from Denmark (DK), France (FR), Germany (DE), Japan (JP), the Netherlands (NL), Spain (ES), Sweden (SE), the United Kingdom (GB) and the US as a dependent variable. To generate the patent count data (PatCnt), we extract all patent applications whose applicants resided in the considered countries and that were filed under the international patent classification number F03D (wind motors) between 1970 and 2009 from the worldwide patent database of the European Patent Office (PATSTAT).¹⁰ Due to the nature of patents and

⁹ See e.g. Loury (1979) for an early example, and Reinganum (1992), Scotchmer (2004) or Weiss (2010) for overviews over innovation and patent race models.

¹⁰ Due to missing data for some of the explanatory variables, the estimation includes only patent applications made between 1980 and 2008.

Table 1: Summary statistics for wind turbine patent applications between 1980 and 2008

Country	Number	Mean	Min	Max	per mil pop
Germany (DE)	3638	125.45	16	389	1.58
US (US)	2636	90.90	18	348	0.33
Denmark (DK)	1041	35.90	1	205	6.64
France (FR)	669	23.07	2	57	0.39
Spain (ES)	641	22.10	0	100	0.52
UK (GB)	592	20.41	2	87	0.34
Japan (JP)	563	19.41	0	91	0.15
Netherlands (NL)	406	14.00	0	60	0.88
Sweden (SE)	399	13.76	1	41	1.56

certain peculiarities of the PATSTAT database, a number of issues arise that have to be addressed. Firstly, patents that are not related to the wind energy technology might be included in the data set. This particular problem is minimal since the technology class F03D is exclusively for wind motors.

Second and more importantly, relevant patents might not have been included in the data set. This problem might e.g. occur with basic technologies where all fields of application are not yet known. The patent for the broad technology would not be included in our data set if it is discovered only after the patent was granted that the technology can also be applied to wind turbines. Again, there is no reason to believe that wind turbine inventions are systematically more prone to the exclusion of relevant patent applications than other technology fields so that it will not unduly bias our estimation. Another, more serious reason for the exclusion of relevant patents is due to missing information on the patent applicant's country of residence. In fact, there are quite a few cases in which the applicant's country information is missing. There is no obvious way to deal with the problem. Dechezleprêtre et al. (2011) e.g. assign patents without country information proportional to the overall distribution of patent application across all countries. We decided against this approach and used only those patent applications that can unambiguously be traced to applicants of the considered countries. We believe that the proportion of missing relevant patent applications due to missing assignee country information is small since our data set accounts for almost half of the patent applications in the world.

Finally, applicants may apply for patent protection for the same invention in different countries. Since we do not restrict patent applications to those made in a single country, our initial patent data include multiple applications for the same invention. Fortunately, applicants have to indicate whether they applied for the same invention in a different country before and, thus, claim priority for the first application.¹¹ This makes it possible to eliminate the multiple counts for an invention from the initial patent data.

Table 1 summarises the patent application data for the nine countries considered here. As it can be seen, the total number of patent applications for wind turbines differ remarkably between countries. Sweden has the fewest number of patent applications for wind turbines. Yet, it has almost twice as many patent applications per million inhabitants as the Netherlands. On the other hand, although Germany has even more wind turbine patent applications than the much larger US, it has only slightly more patent applications per million inhabitants than Sweden. In this respect, Denmark is the most remarkable country which has accumulated more than six patent applications per million population over a time period of almost 30 years. Undeniably,

¹¹ See e.g. Merges and Duffy (2002) or Weiss (2010) for a description of priority.

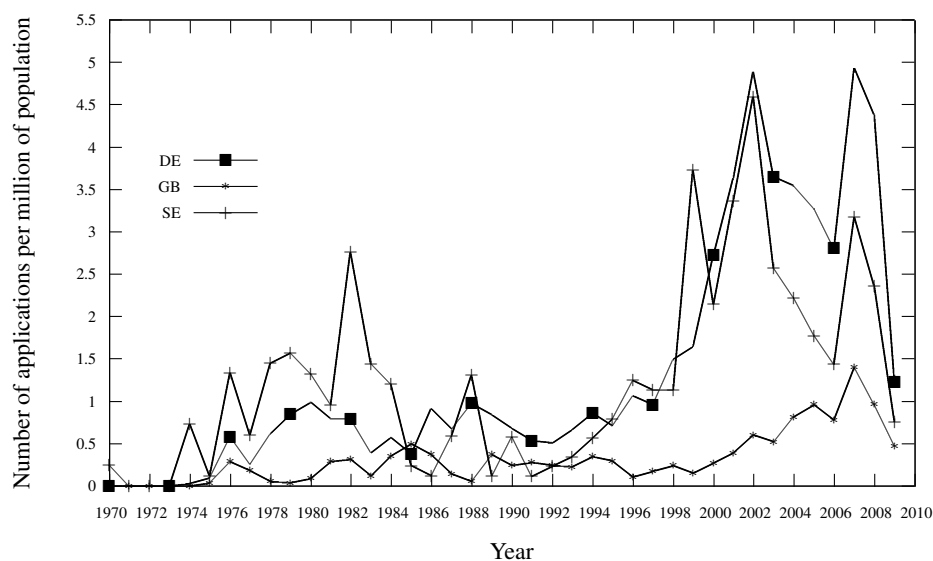


Figure 1: Patent applications per million of inhabitants in Germany, Sweden and the UK

Table 2: Patent applications by region of application between 1970 and 2009

	North Am	(US)	M&S Am	Asia	(China)	Europe	Own	Total
	in per cent							
DE	4.69	(3.40)	0.95	8.58	(5.95)	84.81	51.69	3798
DK	8.98	(5.99)	1.54	15.06	(14.07)	72.96	38.66	1102
ES	5.33	(3.75)	2.31	8.93	(8.07)	82.13	61.53	694
FR	3.86	(3.41)	0.34	1.93	(1.14)	93.52	79.09	880
GB	8.10	(6.85)	0.78	4.98	(3.58)	85.51	61.99	642
NL	5.71	(3.88)	0.23	7.76	(7.31)	85.39	36.99	438
SE	6.80	(6.14)	1.75	4.39	(1.97)	86.40	62.72	456
JP	21.71	(19.32)	0.85	62.91	(16.07)	14.53	34.53	585
US	53.98	(51.07)	2.11	11.31	(8.30)	31.86	51.07	3227

country size as measured by its population explains part of the observed difference in the number of patents. However, it is equally clear that other factors affect patenting activities.

Figure 1 illustrates the argument by displaying the number of wind motor patent applications per million inhabitants in Germany, Sweden and the UK. Especially in Sweden and to a lesser degree in Germany, a rise in the number of patents per million inhabitants can be observed in the years following the oil price shocks in the 1970s and again from the mid 1990s on. Other countries, such as the United Kingdom show little variation in the number of patents per million inhabitants.

Table 2 shows where the applicants patent. Again, we find an astonishingly diverse international patenting pattern. Except for Danish applicants, more than 80 per cent of patent applications with European applicants are made within Europe. The majority of European patent applications with European assignees are exclusively made in their own country. On average, less than 20 per cent of patent applications with European assignees are made in non-European countries first. In contrast, over 30 per cent of applications with either Japanese or US American

assignees are made outside their own continent. While for Japanese applicants the most important destinations are other Asian countries and North America, Europe is the most important patenting region for US American assignees.

Two factors may help to explain the pattern of international patent applications. Firstly, sharing a common language and cultural links explain part of the observed pattern. Usually, patent applications have to be translated into the language of the application country. For a British inventor, it is thus less costly to apply for a patent in the US instead of e.g. in Mexico. The reverse will be true for Spanish inventors. Secondly, the observed patent application pattern might mirror international trade patterns. Inventors naturally wish to protect their intellectual property in the countries to which they expect to export their wind turbines. Therefore, expected demand for wind turbines might also be a factor that stimulates innovative activities, especially because it might be necessary to adapt technology to local (wind) conditions.

3.2 Explanatory variables

3.2.1 Policy instruments

Over the past decades, policy makers have developed a large variety of policy instruments which are designed to increase the use of environmental friendly technologies. Usually, the instruments aim at increasing the expected profits from investments into environmentally friendly technologies in a specific way, e.g. by reducing investment costs or by increasing the price for electricity that is generated from non-renewable sources. Therefore, most countries use a combination of different instruments to facilitate research and development of environmental friendly technologies on the one hand as well as their deployment and also the demand for electricity from renewable resources.

To assess the different policy instruments, we construct six policy variables. The first variable is *feed-in tariffs (FIT)* which some countries, notably Germany, Spain and the Netherlands have introduced. Different from premium prices (see below) feed-in tariffs are fixed prices that electricity producers receive if they rely on renewable resources. They are designed to reduce the cost disadvantage that renewable energy technologies still have vis-à-vis traditional electricity generating technologies in a predictable and reliable manner. Since the 'new' renewable technologies differ immensely in their cost efficiency, tariffs usually differ across technologies.

Feed-in tariffs are paid for a certain period of time and may be constant or decreasing over time as e.g. in Germany. Since the duration over which the feed-in tariffs are paid differs across countries as well as within countries at different times, we decided to use the annuity of the stream of paid tariffs instead of the tariff for the first year as in e.g. Johnstone et al. (2010). This enables us to account for the decreasing feed-in tariffs over time which Germany introduced from the very beginning. This degression has expressly been introduced to encourage continued technological progress in the field of renewable energy and has been sharpened repeatedly over the years.

To construct the FIT variable for Germany, IEA data are used for the years 1989 to 2000.¹² From 2000 on, we relied on various versions of the Renewable Energy Source Act (*Gesetz für den Vorrang Erneuerbarer Energien*, 2000). A series of *Royal Decrees* provided the information on the Spanish feed-in tariffs. Finally, the data for the Netherlands has been obtained from the NL Agency.¹³

Including too many binary variables may cause problems with collinearity so that it is always preferable to use continuous variables. However, due to the large number of different policy

¹² See IEA (2011) for the years 1989 and 1990 and IEA (2004, p 310) for the years 1991 to 2000.

¹³ See NL Agency (2011) and SDE (2009) for the tariffs.

instruments it is not possible to construct continuous variables for the remaining five policy variables. The binary variables below take the value one when the particular policy instrument was active in the particular country and year and zero otherwise. Again, we mainly rely on the policy database of the International Energy Agency (IEA) to construct the following policy variables:¹⁴ premium prices (PP), grants, investment tax credits (ITax), tax exemption for consumers (DTax) and renewable energy certificates (REC).

Premium prices (PP) also compensate firms for the cost disadvantages that renewable energy technologies still have vis-à-vis traditional electricity generating technologies. Different from feed-in tariffs however, firms that use renewable energy sources for the production of electricity receive a premium over the market price rather than a fixed price.¹⁵ Consequently, when electricity prices fall e.g. due to a decrease in the world market prices for coal, natural oil or gas, the price received for 'green' electricity decreases as well. In principle, nothing prevents the prices for 'green' electricity to fall below the costs of producing it.¹⁶ This may encourage continued R&D to discover more cost effective technologies, but it will also raise uncertainty for investors.

Grants or low interest-rate loans are used by all countries included in our study. They directly lower the (up front) costs for extending the capacity of wind energy and thereby increase the expected profits for investors.

Investment tax credits (ITax) are another, less often used policy measure. They can take different forms. In the Netherlands, the *VAMIL Depreciation scheme* leaves the decision to firms as to when they want to depreciated the investments into renewable energy technologies. The US also allow special depreciation schemes for renewable energy equipment. In addition, firms are also eligible for certain tax exemptions in the US.

Another option to indirectly increase the price a firm can charge for electricity generated from renewable resources is a *tax exemption for consumers (DTax)*. This policy measure is usually introduced with an energy tax. Different from Germany, Dutch and Swedish consumers of renewable energy are exempt from energy taxation. This gives electricity producers the opportunity to charge consumers a premium of at most the energy tax over the electricity generated in the traditional way.

In recent years, many countries introduced a certification system and tradeable *Renewable Energy Certificates (REC)*. The former intends to guarantee that the electricity is indeed generated from renewable resources. This is especially important since electricity suppliers may wish to import electricity that was generated from renewable resources. Some of the REC systems, however, are purely voluntary and seem not to have any effect beyond certifying that the electricity has renewable resources as an origin. We therefore include only the REC schemes of the United Kingdom, the Netherlands, Sweden, Japan and the US because either producers or consumers have to buy certificates.¹⁷

In addition to the policy variables above, two additional binary variables are used to capture the potential effects of the ratification of the Kyoto Protocol (*Kyoto*) and electricity market liberalisation (*Lib*).

Many countries introduced different forms of *energy/environmental taxes (EnvTax)*. These taxes are likely to change the relative prices between traditionally produced electricity and electricity generated by renewable energy technology in favour of the latter. Therefore, they are likely to change the incentives to innovate in all renewable energy technologies. As a further

¹⁴ See IEA (2004) for policies up to 2004 and IEA (2011) for more recent regulations.

¹⁵ Premium prices may be indirect, e.g. in form of a energy tax exemption as in Sweden and the United Kingdom.

¹⁶ Interestingly, most countries specify a upper limit for the market price for which the premium price is still paid. For any market price exceeding this limit, firms are only paid the market price. In contrast, countries rarely specify a lower limit that guarantees a fixed minimum price for the production of electricity using renewable resources.

¹⁷ See Plumb and Zamfir (2009) for a more detailed information on the REC systems for the European countries.

proxy, we therefore include *environmental tax revenues* (*EnvTax*) in million €. For the European countries, we use the data from the Statistical Office of the European Commission (Eurostat) which is available for the years 1980-2008. For Japan and the US, we constructed a variable that corresponds to Eurostat's definition of environmental tax revenues from the OECD database on taxes (OECD, 2010c). Table 3 gives an overview over the statistical properties of the variables to be included in the estimation.

Table 3: Descriptive statistics of explanatory variables (1980-2008)

Variable	Obs.	Mean	SD	Min	Max
PP (B)	261	0.364	0.482	0	1
DTax (B)	261	0.096	0.295	0	1
REC (B)	261	0.215	0.411	0	1
Price (B)	261	0.456	0.499	0	1
FIT (€cents/kWh)	261	0.017	0.031	0	0.101
Price 2 (B)	261	0.582	0.494	0	1
Grants (B)	261	0.490	0.501	0	1
ITax (B)	261	0.203	0.403	0	1
NPriceP (B)	261	0.563	0.497	0	1
Lib (B)	261	0.264	0.442	0	1
Kyoto (B)	261	0.215	0.411	0	1
EnvTaxpc (€)	261	542.23	420.87	63.39	2481.47
WRDpc (€)	250	0.44.2	0.641	0	4.739
Open (%)	261	44.31	21.26	13.19	114.77
Im71 (bil USD)	261	0.422	0.462	0.070	1.716
ExR71 (USD/ per mil GDP)	256	0.041	0.046	0.000	0.204
EnPI (2005 = 100)	261	74.195	23.607	21.108	141.420
NetEImpc (Mtoe/ mil pop)	261	1.731	1.182	-1.939	3.750
OilP (€/1000l)	261	392.96	213.82	68.09	1237.16

B: Binary variable; Mtoe: Megaton oil equivalent

3.2.2 Other explanatory variables

Policy instruments that aim at stimulating innovation activities in renewable energy technologies are usually introduced because the natural market incentives are believed to be too weak to achieve the desired results. To obtain reliable estimation results, we therefore control for a number of variables that are likely to affect the incentives to innovate. Foremost among them are technology-specific R&D expenditures, which are likely to have the most direct effect on the number of patent applications. It can be expected that the number of patent applications will rise when more resources are spent on wind energy R&D. We use IEA data on total R&D expenditures per capita (*WRDpc*) in € at prices of 2009.

As mentioned above, the expected foreign demand for wind turbines may be an additional incentive to innovate, especially since it might be necessary to adapt the wind turbine technology to local characteristics. Ideally, we would like to have a measure for the expected future total demand for wind turbines. Since we do not have information on firms' expectations, we use one of three variables as proxy. For the first variable *ExR71*, we collect data on exports for commodity group 71888, which includes wind turbines, in million US\$ (OECD, 2010d). To account for differences in country size, we use the ratio of the exports to million of the gross national product in US\$ and current prices (OECD, 2010a). This variable has the disadvantage that it measures the part of the total world demand that a countries has satisfied rather than

the world demand itself. Therefore, we construct a second variable *Im71* by calculating the imports in billion US\$ of commodities in group 71888 of all OECD countries that originate from OECD countries (OECD, 2010d). The variable *Im71* does not include the demand for non-OECD countries. Since most of the trade in commodity group 71888 actually takes place between industrialised countries, we feel confident the OECD demand for wind turbines is a good proxy for the world demand. Unfortunately, data on both variables are not available for a number of countries, especially in the 1980s. Because the aggregate trade figures are more reliable than imports and export in a single five digit commodity group, we also include the imports and exports in per cent of the GDP in current prices (*Open*) (OECD, 2010a,d).

We also include the consumer price index for energy (*EnPI*) to account for changing national energy prices (OECD, 2010b). Since the consumer price index for energy is calculated from total consumer prices, it does not only increase with rising energy prices, but also with increasing taxes. Finally, we control for countries' self sufficiency concerning domestic energy provision. Firms in countries that are insufficiently endowed with traditional energy resources might have anticipated that world energy prices are increasing and that these increases in turn will raise the profitability of renewable energy technologies. A good measure of self sufficiency is the net energy imports in Mtoe per million inhabitants (*NetImpc*) which is provided by the IEA (2010a). In addition, we include the price for 1000 litre light oil (*OilP*) in € as a proxy for the expected world market price developments.

4 Estimation results

4.1 The effect of electricity market liberalisation

We estimate different specifications of equation (1). The base *model B1* is presented in the first column of Table 4. In addition to investment, market and policy variables we include the dummy variable for the ratification of the Kyoto Protocol.

We find a positive and significant effect of wind-technology-specific R&D expenditure per capita (*WRDpc*) on the number of wind turbine patents. This result is unsurprising since R&D expenditures are the most important input factor for any research process. We also find that total demand for wind turbines in OECD countries (*IM71*) has a large, positive and highly significant effect on innovations. This confirms our hypothesis, that the first-mover advantage on the world market exerts a powerful incentive to innovate and possibly adapt the wind energy technology that has mainly been developed for European countries and the US to local circumstances. As expected, ratifying the Kyoto Protocol exerts a positive influence on innovation activities. From an international policy perspective, the significance of the Kyoto Protocol can hardly be over-estimated. After long and difficult negotiations, a majority of countries finally acknowledged that greenhouse gas emissions have large and global negative external effects; now, they were prepared for cautious action. The signing and ratification of the Protocol certainly signalled a policy shift in many countries. It became clear that relative (energy) prices would irreversibly change and that a reversal of environmental policy measures was rather unlikely. The Kyoto Protocol has induced policy makers to introduce new policy instruments. Consequently, it changed the expectations on the profitability of renewable energy technology which is likely to increase innovative activities.

At the first glance, it might seem surprising that we find a negative and significant effect of the energy price index (*EnPI*) on the patenting behaviour. After all, using renewable energy technology to generate electricity is more profitable when prices are high. However, the negative sign may simply indicate that firms are actively looking for more efficient wind turbines

Table 4: Estimation results: Effect of electricity market liberalisation

	B1	B2	B3	B4	B5	B6
WRDpc	0.3248* (0.034)	0.3954** (0.009)	0.3399* (0.026)	0.2292* (0.041)	0.3398* (0.040)	0.3376* (0.027)
Im71	0.8742*** (0.000)	0.7415*** (0.000)	0.9163*** (0.000)	1.0562*** (0.000)	1.0563*** (0.000)	0.9039*** (0.000)
Kyoto	0.6126*** (0.000)	0.6363*** (0.000)	0.6416*** (0.000)	0.5360*** (0.000)	0.5372*** (0.000)	0.6219*** (0.000)
EnPI	-0.0086* (0.048)	-0.0087* (0.047)	-0.0063 (0.227)	-0.0127** (0.007)	-0.0129** (0.007)	-0.0078 (0.099)
OilP	0.0006 (0.386)					
NetEImpc		-0.0040 (0.967)				
Year		0.0229 (0.188)				
EnvTaxpc	0.0013*** (0.000)	0.0011* (0.015)	0.0014*** (0.000)	0.0011*** (0.000)	0.0011*** (0.000)	0.0013*** (0.000)
Lib				0.5504*** (0.000)	0.5508*** (0.000)	
FIT					0.9173 (0.575)	
FIT, Lib = 0						-0.8312 (0.581)
FIT, Lib = 1						5.7662* (0.025)
LogLik	-944.4	-942.5	-945	-938.4	-938.3	-941
AIC	1921	1920	1920	1909	1911	1916
N	250	250	250	250	250	250

p-value in parentheses

* : $p < 0.05$; ** : $p < 0.01$; *** : $p < 0.00$

when energy prices are low. As expected, the coefficient for environmental tax revenues (EnvTaxpc) is positive and significant. They change the relative prices for energy and electricity in favour of ‘green’ energy sources. As a consequence, expected profits from innovations in wind technology increase and investments may be redirected from more traditional research projects to e.g. innovation for more efficient wind turbines.

Finally, the coefficient for the oil price (OilP) is positive, but insignificant. Therefore, we may conclude that countries which are naturally poor in traditional energy resources do not systematically put higher efforts into innovations in renewable energy resources.

In *model B2* used net energy imports per capita (NetEImpc) as a measure of lacking self sufficiency. In addition we also included a time trend (year). In *model B1* this was unnecessary since the oil price is highly correlated with time. The results confirm that changing the measure for a country’s exposure to ‘costly’ energy imports from the oil price to net energy imports per capita does not change the estimation results. Net energy imports per capita do not seem to have an effect on wind turbine innovation. There is also no evidence that patenting activities are independently increasing over time. All other variables are found to have an effect similar in magnitude and significance as in *model B1*. We therefore drop the oil price, the net energy imports and the time trend from further consideration. The resulting model configuration is found in *model B3*. Again, we find that the effects have a similar magnitude and significance as

the variables in model B1.

For *models B4 and B5*, theoretical results are compatible with a positive as well as a negative coefficient for the energy market liberalisation (Lib). We find a strong positive and significant coefficient which would support the findings of Arrow (1962b). However, the coefficient for the feed-in tariffs (Fit) is positive but insignificant. The positive sign of the coefficient supports the findings of Söderholm and Klaassen (2007) who stress the importance of feed-in tariffs in the innovation and diffusion process. Other studies such as e.g. Johnstone et al. (2010) find little empirical evidence for a strong and positive effect of feed-in tariffs on innovation.¹⁸

We might expect that price-based policy instruments such as feed-in tariffs are more effective if the energy market is open to competition. We test this hypothesis in *model B6*. Here we find again an insignificant effect of feed-in tariffs when energy markets are not open to competition. In contrast, feed-in tariffs have a strong and significant effect if there is competition, i.e. after the energy market liberalisation.

4.2 Price and non-price based policy instruments

We are first studying the interaction between energy market liberalisation and different price-based policy instruments. The results are presented in Table 5 in the Appendix. For convenience, we reproduced the results for the interaction between feed-in tariffs and liberalisation from Table 4 as *model P1* and *P2*.

In *models P3* and *P4*, we repeat the exercise for premium prices PP. Except for Spain, most countries use either premium prices or feed-in tariffs to stimulate the deployment of wind energy technology. In Spain, firms that are under the special regime can choose between both options. As explained above, the variable PP does not only record which country introduces premium prices, but also includes policy measures such as e.g. an exemption from energy tax or the value-added tax that would have the same effect as premium prices. When neglecting any interaction between energy market liberalisation and premium prices, we find the now familiar pattern. Both variables have a positive coefficient but only liberalisation has a significant influence on the patenting activities. *P4* reports the results for the model specification that takes the interaction between premium prices and market liberalisation into account. Again, we find that liberalisation alone has a positive and significant effect on innovation. Premium prices in absence of energy market liberalisation have a positive, but insignificant coefficient. In contrast, the combined effect of premium prices and energy market liberalisation on innovation activities is large and significant.

Finally, consider *models P5* and *P6* which test the same hypothesis for the price policy dummy variable (PriceP), which combines a dummy variable for feed-in tariffs, premium prices, renewable energy certificates and tax exemptions for consumers. Different from the models *P1* and *P3*, the price policy variable has a positive and significant effect on the number of patents even if the interaction between price-based policy instruments and energy market liberalisation are disregarded. Model *P6* again shows a positive but and weakly significant effect for the price policy variable when markets are not open to competition. The combined effect of price-based policy variables and energy market liberalisation is much larger and highly significant. Therefore, we conclude that market-based policy instruments are more efficient when energy markets have been liberalised.

Observe also that the individual price-based policy instruments in models *P1-P4* have almost the same explanatory power. In contrast, combining all price-based policy variables in *P5* and

¹⁸ In Johnstone et al. (2010), feed-in tariffs are consistently positive and significant only for solar energy and across all renewable energy sources. For wind energy the feed-in tariffs either have the wrong sign or are insignificant.

P6 leads to a slightly better fit. This suggests that none of the price-based policy instruments shows a clear superiority over other price-based alternatives. Rather, it seems important that they have been implemented and preferably in an energy market that is open to competition.

In Table 6 in that Appendix, we compare the results for no interaction between energy market liberalisation and certain non-price-based variables with the results for an assumed interaction between both variables. *Model N1* shows that both grants and energy market liberalisation have a positive and significant effect on innovation activities. *Model N2* confirms that the coefficients for grants and low interest rate loans remain positive and significant independent whether or not the energy markets are open to competition. *Models N3* and *N4* show that essentially the same holds true for the broader non-price dummy variable (NPriceP), which combines investment tax credits and grants as policy variables. Comparing models N1 to N4 we find that even the size of the respective coefficients are very similar. The presented results confirm our hypothesis that non-price based variables are also effective in absence of energy market liberalisation.

Including non-price-based policy instruments instead of prices-based variables increases the fit of the model. This leads us to combine price-based and non-price-based instruments in Table 7. Again we find the now familiar pattern. *Model PNI* shows that the coefficient for grants is positive and highly significant. Feed-in tariffs have a large and significant effect on innovation activities when energy markets are liberalised. However, combining both, price and non-price policy instruments does not improve the fit of the model.

5 Conclusion

We provide a panel data study to assess the impact of environmental policy instruments on innovation activities for wind turbines in a selection of European countries, Japan and the US between 1980 and 2008. Our study contributes to the existing literature in explicitly controlling for the effects that energy market liberalisation had on innovative activities. Experience indicates that liberalisation in the energy sector tends to affect the deployment of renewable energy supply (see e.g. Swezey and Bird, 2000, for experiences in the US). By using patent count data for selected countries, we pursue the task of determining which policy instruments and conditions are most favorable in bringing about innovation and technological change in wind energy technology.

We did not find any evidence that resource-poor countries systematically invest more in renewable energy technology. We therefore conclude that world energy markets are performing well enough and that there are no systematic price differences. The development of oil prices seems to have little effect on innovation activities for wind turbines. In contrast, environmental tax revenues were found to have a positive and highly significant effect on patent activity. These findings seem plausible, especially since we consider environmental tax revenues to be a proxy for the extent of relative energy price changes in favour of electricity generated by renewable resources.

As in previous studies, we find strong evidence that technology-specific R&D expenditures increase patenting activities. Margolis and Kammen (1999) e.g. describe a strong correlation between public and private investments in energy R&D and energy related patents in the US between 1976 and 1996 and criticise the decline of energy R&D funding, both in scale and diversity, throughout the industrialized world during this period. Fortunately, as the IEA (2010b) recently reported, public investment in low-carbon technology research, development and demonstration is increasing again in the industrialized world, but it estimates that in order to prevent dangerous climate change, respective government funding will need to be much higher than current levels. We also find a strong positive effect of the ratification of the Kyoto Protocol on

patent activity in the renewable energy sector.

At the outset we formed three hypotheses. Firstly, we argued that energy market liberalisation has an effect on innovation activity. Secondly, we surmised that energy market liberalisation may have a direct and an indirect effect on innovation activities. Opening up the energy markets to competition may have made price-based policy instruments such as feed-in tariffs or premium price more effective. Lastly, we expected that total world demand for wind turbines may also affect innovation activities for wind energy technology.

Total foreign demand seems indeed to increase the number of patent applications. As suggested by the international patenting pattern, patentees holding wind turbines patents seem to protect their technology in export markets. This would confirm the related findings of Kristinsson and Rao (2007). Since efficient wind energy technology is relatively young, the motive of reaping profits from a first-mover advantage might be the driving force.

Concerning the effect of energy market liberalisation, we find very strong evidence for the hypothesis that single price-based policy variables as e.g. feed-in tariffs as well as a combination of price-based policy instruments are more effective in energy markets that allow for competition. This might suggest that the price-based policy instruments encourage firms to continue in seeking more efficient technologies to harness wind energy. The same effect could not be found for the non-price-based policy instruments. This confirms our supposition that non-price-based policy instruments are largely independent of whether or not energy markets are open to competition.

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Appendix

Table 5: Estimation results for price-based policy instruments
(a) Feed-in tariffs (b) Premium prices

	P1	P2		P3	P4
WRDpc	0.3389* (0.031)	0.3376* (0.032)	WRDpc	0.3402* (0.023)	0.3336* (0.42)
Im71	1.0563*** (0.000)	0.9039*** (0.000)	Im71	1.0773*** (0.000)	1.0828*** (0.000)
Kyoto	0.5372*** (0.000)	0.6219*** (0.000)	Kyoto	0.5384** (0.000)	0.5365*** (0.001)
EnPI	−0.0129** (0.007)	−0.0078 (0.070)	EnPI	−0.0134** (0.005)	−0.0134** (0.009)
EnvTaxpc	0.0011*** (0.000)	0.0013*** (0.000)	EnvTaxpc	0.0011*** (0.000)	0.0011*** (0.000)
Lib	0.5508*** (0.000)		Lib	0.5233*** (0.001)	
FIT	0.9173 (0.557)		PP	0.0859 (0.592)	
FIT, Lib = 0		−0.8312 (0.591)	PP = 1, Lib = 0		0.0192 (0.911)
FIT, Lib = 1		5.7662* (0.023)	PP = 0, Lib = 1		0.4529* (0.025)
			PP = 1, Lib = 1		0.6221** (0.001)
LogLik	−938.3	−941	LogLik	−938.3	−938.2
AIC	1911	1916	AIC	1911	1912
N	250	250	N	250	250

Table 5: Estimation results for price-based policy instruments
(a) Price policies

	P5	P6
WRDpc	0.3746* (0.018)	0.3746* (0.027)
Im71	1.0117*** (0.000)	1.0117*** (0.000)
Kyoto	0.5128*** (0.001)	0.5128** (0.002)
EnPI	-0.0129* (0.012)	-0.0129* (0.018)
EnvTaxpc	0.0009*** (0.000)	0.0009*** (0.000)
Lib	0.4744** (0.002)	
PriceP	0.2893* (0.014)	
PriceP = 1, Lib = 0		0.2893* (0.015)
PriceP = 0, Lib = 1		
PriceP = 1, Lib = 1		0.7637*** (0.000)
LogLik	-935.6	-935.6
AIC	1905	1905
N	250	250

Table 6: Estimation results for non-price-based policy instruments
(a) Grants (b) Non-price policies

	N1	N2		N3	N4
WRDpc	0.3821* (0.016)	0.3897** (0.008)	WRDpc	0.4034* (0.016)	0.4075* (0.020)
Im71	0.9271*** (0.000)	0.9125*** (0.000)	Im71	0.9716*** (0.000)	0.9655*** (0.000)
Kyoto	0.4952*** (0.000)	0.5128** (0.001)	Kyoto	0.4053** (0.000)	0.4240* (0.000)
EnPI	-0.0133** (0.004)	-0.0131* (0.010)	EnPI	-0.0119* (0.027)	-0.117* (0.016)
EnvTaxpc	0.0011*** (0.000)	0.0011*** (0.000)	EnvTaxpc	0.0010*** (0.000)	0.0010*** (0.000)
Lib	0.5270*** (0.000)		Lib	0.4753** (0.002)	
Grants	0.3212** (0.002)		NPriceP	0.3840** (0.001)	
Grants = 1 & Lib = 0		0.3439** (0.001)	NPriceP = 1 & Lib = 0		0.4061** (0.002)
Grants = 0 & Lib = 1		0.6006** (0.003)	NPriceP = 0 & Lib = 1		0.5714** (0.002)
Grants = 1 & Lib = 1		0.8293*** (0.000)	NPriceP = 1 & Lib = 1		0.8327*** (0.000)
LogLik	-933.8	-933.6	LogLik	-933.7	-933.5
AIC	1902	1903	AIC	1901	1903
N	250	250	N	250	250

Table 7: Estimation results for price-based and non-price-based policy instruments
 (a) Feed-in tariffs and grants (b) Price- and non-price-based instruments

	PN1		PN2
WRDpc	0.3882** (0.010)	WRDpc	0.4099** (0.004)
Im71	0.7617*** (0.000)	Im71	0.9642*** (0.000)
Kyoto	0.5680*** (0.000)	Kyoto	0.4184** (0.007)
EnPI	-0.0086* (0.046)	EnPI	-0.121* (0.019)
EnvTaxpc	0.0013*** (0.000)	EnvTaxpc	0.0013*** (0.000)
FIT, Lib = 0	-2.1043 (0.226)	PriceP = 1 & Lib = 0	0.1472 (0.301)
FIT, Lib = 1	5.1489* (0.038)	PriceP = 1, Lib = 1	0.5958** (0.002)
Grants	0.3686*** (0.001)	NPriceP	0.3135* (0.0018)
LogLik	-935.2	LogLik	-933.1
AIC	1906	AIC	1902
N	250	N	250

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