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DETERMINANTS OF RENEWABLE ENERGY INNOVATION: ENVIRONMENTAL POLICIES VS. MARKET REGULATION

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Abstract

This paper carries out a comprehensive analysis of renewable energy innovations considering four mechanisms suggested by innovation models: 1. policy-inducement; 2. market structure; 3. demand and social cohesion-mainly proxied by income inequality; 4. characteristics of country knowledge base. For OECD countries and years 1970-2005, we build a unique dataset containing time-varying information on quality-adjusted patent production in renewable energy, the latter being a function of environmental policies, green R&D, entry barriers, knowledge stock, knowledge diversity and income inequality. We develop count data models using the Generalized Method of Moments (GMM) to account for endogeneity of policy support. Our synthetic policy index positively affects innovations especially in countries with deregulated energy markets and low entry barriers. The effect of entry barriers and inequality is negative and of similar magnitude as that of policy. Product market liberalization positively affects green patent generation, especially so when ambitious policies are adopted, when the initial level of public R&D expenditures and when the initial share of distributed energy generation is high. Our results are robust to alternative specifications, to the inclusion of technology-specific effects and to the use of quality-adjusted patents as dependent variables. In the latter case, the estimated effect of lowering entry barriers and of knowledge diversity almost double on citation count relatively to patent count.

JEL Codes **:** Q55, Q58, Q42, Q48, O34.

Keywords: Renewable energy technology, patent, environmental policies, product market regulation, inequality.

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1. Introduction

Innovation is commonly regarded as the best answer to sustaining current life standards while overcoming severe environmental concerns. This is especially relevant in the case of energy, where increasing resource scarcity calls for the rapid development of alternative energy sources, notably renewable energy. Although as of today, renewable energy cannot compete with fossil fuel in terms of production costs; impressive technological progress has paved the way to new promising sources such as biomass, solar and wind, among others.[3]Countries too have developed areas of specialization in specific types of renewable energy sources: For example, Denmark has established a strong technological advantage in wind technologies, Sweden and Germany have specialized in bioenergy, Germany and Spain in solar, Norway and Austria in Hydropower.

In addressing the issue of how technological advantages emerged for renewable energy, the economic literature emphasizes the key role of public policies in fostering environmental innovation. Moving from these premises, assessing the effects of targeted environmental policies and/or energy prices on environmental innovations has been the main goal of most empirical research (Jaffe et al. 2003). For instance, guaranteed price schemes and investment incentives appear to have a major role in the early phase of technological development, whereas for relatively more mature technologies, i.e. wind, obligations and quantity-based instruments appear to be more effective policy tools. (Johnstone, Haščič and Popp 2010, JHP henceforth).

Remarkably less attention has been devoted to the quantification of these inducement mechanisms, first when policies are endogenously determined and second when other institutional factors are considered. On the latter point, the most important institutional change has been the liberalization of the energy sector common to several countries. This process has had a substantial impact on the market structure of the sector of energy, possible altering the incentive mechanism for developing innovation (e.g. Jamasb and Pollitt 2008). In fact, the effect of liberalization on innovation is presumably undetermined: if more competitive markets lower the appropriability of R&D investments, an increase in competition in the energy sector should lower the incentive for innovation. Conversely, more competitive markets may yield greater incentives of investing in R&D in order to escape the increased competition (Aghion et al. 2001). Besides, entry of new players may have spurred innovation as renewable energy involves decentralized energy generation (DG), smaller scale of production and competences far from those of existing incumbents.

On the former point, the approval of well-designed environmental policies is itself endogenous to the choice of technological specialization in renewable energy, both depending on aggregate preference for environmental quality. In particular, environmental policies are likely to be affected both by the level and the distribution of income (Boyce 2003, Magnani 2000) and by political factors, such as the

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3. For example in the most favored geographical locations, wind proves to be almost as competitive as other forms of electricity generation (IEA), whereas solar energy still displays costs significantly higher than fossil fuel energy sources (see, e.g., IEA Experience curve for energy technology).

level of corruption and government quality (e.g. Lopez and Mitra 2000). If environmental quality is considered high in the hierarchical scale, the characteristics of the median voter/consumer are likely to influence both individual and social preferences for a cleaner environment (e.g. Vona and Patriarca 2011). Especially in the decentralized paradigm of energy generation, the level and the distribution of income are also likely to have an impact on the demand for the equipment required to produce energy from renewable sources, i.e. photovoltaic cells.

The empirical analysis of this paper attempts to jointly address the issues of endogeneity of environmental policies and of the impact of liberalization on renewable energy innovation. To address the issue of policy endogeneity, we develop an indicator of renewable energy policy that preserves the informational content of individual policies and, at the same time, is most suitable to be instrumented (Section 3).With the exception of Popp (2002), this paper represents the first attempt of considering policy endogeneity for renewable energy innovation and, therefore, represents a useful complement to the analysis by JHP (2010). To measure the degree of market regulation, we use the time-varying, sector-specific indicator of product market regulation developed at the OECD.

Another empirical issue is related to the combined effects of policy with product market regulation. The most obvious reason for the emergence of synergetic effect relates to the timing of events: the process of liberalization, starting in the 90s, has been accompanied by a greater environmental concern for raising levels of global pollutants, i.e. GHGs, and by the gradual adoption of pro-active environmental policies. Typically, liberalization may have fostered the entry of new innovative firms only if policy interventions decrease the initially high costs of R&D projects. Therefore, one could claim that substantial public investments in basic research should complement private R&D efforts following liberalization. Finally, the initial condition of the energy markets and on the characteristics of knowledge stock are likely to be very important in explaining possibly heterogeneous effects of both variables on innovation. More precisely, both liberalization and environmental policies might spur the entry of new innovative firms only in presence of adequate know-how and organizational capabilities in the DG paradigm of energy production as opposed to the centralized one[4].

At the methodological level, we follow Cameron and Trivedi (2009) and use cluster-robust standard errors to account for mild cases of overdispersion. This choice also fosters the comparison of our baseline Fixed Effect Poisson estimates with GMM Poisson ones where we instrument the policy index. We then carry out several robustness exercises, including area-specific time-trends, clustering

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4. Denmark represents the prototypical example of the factors required to succeed in renewable energy technologies. To summarize, key ingredients of the Danish success in wind were the existence of in-loco complementary knowledge in DG methods of energy production; the entry of small firms and intermediate producers of turbine, also favoured by the earlier entry in the more liberalized Californian market; the strong role of community's ownership, opposition to nuclear power and cooperation among different actors; the importance of balancing hydropower due to the proximity of Norway and Sweden.

data by both country and technology sub-fields and considering accurate measures of the knowledge stock, diversity and of patent quality (Popp 2003, Nesta 2008).

The paper is organized as follows next Section briefly discusses the expected effects of the factors affecting renewable energy technologies. Section 3 describes the main variables of the analysis, while section 4 the empirical strategy. Section 5 the main results and Section 6 the conclusions.

2. Factors affecting renewable energy innovations

The establishment of comparative advantages in given renewable energy technology depends on a host of factors, which we present in this Section. More precisely, Sub-section 2.1 is concerned with the main explanation found existing studies: the effects of energy prices and environmental policies on environmental innovation. Sub-section 2.2 points to market structure and liberalization, which is the main novel factor considered in this paper. Sub-section 2.3 considers additional explanations that are tested jointly with the more traditional one in our empirical analysis.

2.1 Environmental Policies and Energy Prices

Early theoretical studies on the impact of environmental regulation on firms' competitiveness emphasize the trade-off between lowering marginal costs of production and compliance with environmental regulation (see for a review, Jaffe, 1995). In a profit optimizing perspective, in fact, if there are convenient ways of tackling pollution, firm would have already adopted these opportunities, so environmental regulation should lower firms' efficiency. In this perspective, early literature (Pethig 1975, Yohe 1979, McGuire 1982) suggests that a nation's competitive advantage could be influenced negatively by environmental regulation, and that in the long term industry may tend to move from more regulated countries to less regulated ones[5].

Historically, however, the increase in oil prices, brought about by the two crises of the 70s, does not only increase production cost, but also provides the first push for investment in energy efficiency and green R&D. Both historical evidence and increasing environmental concerns inspire a new literature that explicitly considers the dynamic effect of regulation on the incentive of doing innovation and eventually changing consumer's habits. Seminal works of Porter (1991) and Porter and Van der Linde (1995) stressed that the conventional debate of the relationship between competitiveness and regulation was based on the wrong assumption of static technological environment, which is not suitable to understand a relationship characterized by an intrinsic dynamics. The idea is actually a variant of the classical theory of induced innovation (Hicks 1932, Binswanger 1974), maintaining that an increase in the price of an input will stimulate technological change aimed at saving it. In this particular case, allowing technology to respond to higher costs of polluting inputs, the negative effect of regulation on competitiveness in the short-term might be more offset by the positive effect of regulation on innovation.

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[5] Less regulated countries are often called in environmental studies "Pollution Haven" (Copeland and Taylor 2004).

The positive effect can operate through several channels: creating pressure that motivate innovation and energy efficiency, reducing uncertainty on green investment and signaling firms about potential inefficiencies and technological improvements (Porter and van der Linde 1995). Moreover, the positive effect of environmental regulation on innovation can be amplified by feed-back from the latter to the former: innovation lowers generation costs in new technologies and hence allows to accomplish more ambitious environmental targets (Downing and White 1986). Finally, another important channel through which environmental policies can stimulate green technologies is through the adoption of new capital equipment, hence favouring scrapping of old polluting machines can have positive effects on green technology (e.g. Xepapadeas and Zeeuw 1999).

Amore recent strand of theoretical literature examines the 'double externality' problem associated with environmental innovations (Jaffe et al. 2005, Fisher and Newell 2008, Acemoglu et al. 2010). Firms might under-invest in green technologies both because the output of their R&D investment is easily appropriable by their competitors and because compliance to environmental regulation is costly, at least if the innovative choice is not profitable. The main policy implication of these studies is that policy measures targeting only the environmental externality are likely to reduce the competitiveness of the firm even in presence of a good potential for green technologies. As a result, the optimal policy mix consists of two policies, one for each externality: a carbon tax *and* a subsidy to green R&D, which might jointly produce a win-win outcome in terms of competitiveness-sustainability[6]. The need for subsidies and incentives is more pressing when green technologies display a strongly forward-bias profile, i.e. high initial investments in physical capital offset by lower variable costs as for solar and wind energy.

The variety of trade-offs and possible effects highlighted by the theoretical literature makes it difficult to derive clear-cut policy implications and commonly accepted conclusions. The evaluation of the effects of environmental policies on innovation remains mostly an empirical issue. In one of the first contribution, Lanjouw and Mody (1993) found that increasing compliance costs have a positive effect on innovation, with a one to two year lag, for U.S., Japan and Germany. In this case the authors used environmental related patent as proxy for green innovation, and expenditure for compliance with environmental regulation as proxy of environmental policy. For the period 1973-1991, Jaffe and Palmer (1995) exploits the rich information of a panel dataset of U.S manufacturing firms and show that pollution abatement expenditure (PACE) have a significant positive effect on innovation measured as R&D expenditure, but an insignificant effect on R&D measured as number of patents[7].

More recently, Popp (2003) found that the introduction of the clean air act in 1990 increased the SO2 abatement efficiency and lowered the production costs of 186 U.S. plants. Interestingly, another

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[6] Acemoglu et al. (2010) derive this result in a fully-fledged general equilibrium endogenous growth model where the green technology is initially less productive than the polluting one. This optimal policy mix can work in the long-run, but an initial slowdown in productivity, related to the time required to develop the green technology, is unavoidable.

[7] A common critique at these studies is that the authors used overall patent counts and not environmental ones. This may motivate the contradictory result obtain with the two dependent variables.

important driver of abatement efficiency is the type of innovation developed by firms, measured as patent counts in SO2 relevant fields[8]. Brunnermeier and Cohen (2003) conducted an analysis on the determinant of environmental innovation, using as main explanatory variables pollution abatement expenditures, number of air and water pollution control inspections and international competition. They found that both abatement expenditures and international competition are significant driver of environmental patent counts, while the number of inspections is not statistically significant. Another work of Popp(2006) using also patent counts for Germany, the U.S. and Japan, shows how in the case of NOx, national regulation spurred innovation for national firms but not from foreign ones. Moreover, through the use of patent citations he also find that seminal environmental innovations in foreign countries (especially Japan) play an important role in the development of US patents in the field of NOX reduction, confirming the hypothesis that domestic researchers are building on foreign innovations[9]. Along this line, other studies for the US confirm that the environmental regulation had a positive impact on innovation in the paper mills' technology (Gray and Shabagia, 1998) and in the auto industry (Lee et. al. 2011).

The implications of these works are of a particular interest in the case of a growing, but still limited sector like renewables, in which in the absence of a public intervention, production costs are generally higher than the one of fossil fuel derivate. In the last thirty years, many different environmental policies have been introduced in OECD countries in order to reduce this cost gap and to increase the share of renewables in the country energy portfolio. Examples of such measures are: tradable renewable energy certificates, feed-in tariffs, production quotas, and tax credits (see section 3 and the appendix A for details). The effect of these policies on innovation is the aim of JHP (2010), the paper more closely related to ours, which, using a panel dataset covering 25 OECD countries for the period 1978-2003, found that environmental policies play a significant role in determining the flow of patent application in many renewable technologies, with a different intensity among technologies and policy instruments. With regards to the effects of different policies on different technologies, guaranteed price schemes and investment incentives appear to have a major role in the early phase of technological development, whereas for relatively more mature technologies, i.e. wind, obligation and quantity-based instruments work better. This study also controls for the role played by demand related variables (e.g. growth of electric consumption) and energy prices. Interestingly these variables are not significant except in the case of solar renewables, where energy price is associated with a positive and statistically significant coefficient. The related work of Popp et. al. (2011) stressed as policies (mainly the Kyoto protocol) played a fundamental role in promoting the per-capita investment in renewable capacity at country level, for the period 1979-2008. Nevertheless, this overall effect is heterogeneous

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8. Moreover, before 1990, innovation was in fact mainly related to cost-reducing technologies, while it became more oriented towards improving the environmental effectiveness of production after that date.

9. A more recent paper on the effects of knowledge spillovers at the international level is the one of Galeotti and Verdolini (2010).

across renewable sources being strong and significant in the case of biomasses, waste and wind, and weak or even absent, in the case of Solar (PV) technology. Besides this main effect, a variable representing knowledge stock show a positive, but weak, effect on renewable energy investments, while different production structures, like the presence of nuclear power and hydropower are generally associated with lower investment in renewable capacity.

Differently from JHP, positive and significant impact of energy prices on innovation are found in micro studies for the US by Jaffe and Stavins (1995) for thermal insulation in civil buildings and by Newell et al. (1999) for energy-efficient durable goods (air conditioners and water heaters), which show that the direction of innovation responded to both increase in energy prices and energy-efficiency labelling[10]. Using U.S patent from 1970 to 1994, Popp (2002) estimates the effect of time variation in energy prices, public R&D and the existing knowledge stock. Also in this case, energy prices are associated with a statistically significant and positive coefficient, i.e. have a direct effect on innovation, while the knowledge stock is associated with an increase in patenting activities. In particular, he uses two different knowledge stock variables: a simple sum of previous U.S. patents, and a sum of previous U.S. patents weighted by a productivity parameter, which measure the likelihood that patents granted in a given year will be cited by subsequent patents. Possibly, different results on the impact of energy prices have to do with the timing of the events: the impact of the dramatic increase in energy prices of 70s counts more in older studies than in new one where prices back to their long-run value and the policy inducement turns out being paramount.

2.2 Market Structure, Liberalization and Renewable Energy Innovation

The relationship between innovation and competition has been deeply analyzed by vast economic literature on endogeneous growth (e.g. Boone 2000, 2001, Aghion and Howitt 1998). The usual argument put forward by first generation models, claiming imperfect competition to enhance the appropriability of R&D investments, has been challenged by new strand of literature offering a more problematic view of this relationship. Aghion et al. (2001, 2005) developed models where an escaping competition effect counterbalances the standard appropriability effect. In order to retain their market shares, incumbents are induced to invest more in R&D if the competitive pressure of new entrants is higher and they are close enough to the existing technological frontier. On the other hand, higher pressure of new entrants discourages R&D investments of incumbents far from the frontier, whose competences are too distant from the ones needed to imitate leading-edge technologies. As a result of these contrasting forces, the relationship between innovation and competition might result inversely

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[10] Interesting the relationship between technology and energy prices is not smooth in this case. Until beginning of the 70s much innovation was autonomous, but with the rapid increased in energy prices experienced in these years, technological change became always more biased towards energy prices. Moreover, also in this case labelling and governmental standards play a significant role in defining the average energy efficiency of these products menu. The analysis was conducted using U.S. data from 1953 to 1993.

U-shaped with the maximum innovative effort reached when the appropriability and the escaping competition effect counterbalance each other[11].

These models are not informative on which type of market structure is more likely to support radical innovations, i.e. the ones needed to open new trajectories of incremental improvements (Dosi 1988). On this point, Baumol (2002) notices that large oligopolistic firms engaged in routinized R&D and small firms with breakthrough technologies often coexist in many markets. In particular, incumbents and entrants share the innovative labour according to their specific competitive advantages. The advantage of the incumbents is in carrying on innovative activities aimed at incremental improvements of their existing capacity, thereby exploiting their first-mover advantage. Entrants, instead, do not bear the burden of destructive innovations on their existing capacity and hence can more easily undertake radical innovative activities. Since small entrants bear a disadvantage in appropriating the returns of routinized R&D activities, radical innovations are for entrants the only strategy to survive. As a result, during their life-cycle, firms modify the type of innovative activities they carry on and gradually shift to routinized R&D activities (e.g. Winter 1984, Klepper 1996).

In energy markets, there are two issues that render the formulation of *a-priori* hypotheses on the relationship between market structure and renewable energy innovation particularly cumbersome. From a technological viewpoint, renewable energy innovations are radical and destructive for the centralized paradigm of energy production (David and Wright 2003, Elliott 2000, Lehtonen and Nye 2009). In fact, while production of energy from new, more promising renewable sources (e.g. wind, solar, bioenergy) is mainly decentralized in small-medium sized units, the competences of existing incumbents are tied to large scale plants using coal, nuclear or gas as primary energy inputs. Moreover, high sunk costs of large scale generation exacerbate the lock-in of existing incumbents and, together with the expected obsolescence of their assets, feed their political opposition against the DG paradigm (e.g. Neuhoff 2005, Jacobsson and Bergek 2004, Nilsson et al. 2004, Lauber and Mez 2004). As a result, one should expect that new entrants have a comparative advantage in renewable energy technologies and in related infrastructures (i.e. smart grids). Accordingly, the widespread process of liberalization of energy markets, occurred from early 90s, should have contributed to increase innovative efforts in the field of renewable[12].

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[11] Cross country evidence on the effect of competition on innovation is mixed. It is positive, but using time-invariant index of barriers, in Bassanini and Ernst (2002) and negative, but not robust to outliers, in Griffith and Harrison (2004). The inclusion or exclusion of Scandinavian countries affects deeply the shape of the relationship between the mark-up and innovation. Concerning radical innovations, liberal countries do not show a higher propensity to introduce radical innovation w.r.t. regulated ones, but US outlier (e.g. Akkermanns et al. 2009).

[12] Liberalization has generally implied establishment of authority to control for abuse of market power; privatization and ownership fragmentation; promotion of a progressive unbundling of distribution, generation and transmission activities; letting customers to freely choose their favorite supplier. Moreover, transparent approval of procedures for building new plants and easing access to the electricity grid has been particularly important to stimulate entry of new players. The index of product market regulation combines these administrative barriers with the measures of degree of unbundling, market concentration, consumers' choice and privatization. See section 3.

A potential weakness of this argument is well discussed in the paper of Jamasb and Pollitt (2008), who manifest skepticism about the incentives of private companies to be engaged in R&D projects with a long-term payback horizon. Put it differently, liberalizing energy market might have induced new, often private, companies to be engaged in short-term research rather than in fundamental research, needed to develop renewable energy technologies. In liberalized markets, lack of financial support for risky investments can represent another cause of under-investment in renewable energy technology (Nehoff 2005). Finally, the outcome of liberalization is not always a reduction in the scale of operation as market integration might have increased market concentration and favoured the emergence of few large players with excessive market power. For instance, this latter concern applies for Nordpool--the market between Scandinavian countries established in second half of the 90s (see IEA 2005)-- that recently became very concentrated following a series of mergers & acquisition among main national champions. Until now, the empirical evidence supporting a negative effect of liberalization on R&D expenditures has been limited to the US (Dooley 1998) and the UK (Jamasb and Pollitt 2008), but does not directly apply to green R&D and does not seem to hold for patents (Jamasb and Pollitt 2010).

Another critical aspect of the relationship between renewable energy innovation and market structure relates to the complementary factors that might determine which of these contrasting forces eventually prevail. A first important complementarity is the one between existing skills and organizational capabilities in DG, on the one hand, and liberalization, on the other. Rather than replacing state monopolies with few large players that are likely to behave collusively, liberalization could foster decentralized production and entry of new players only in presence of the adequate in loco know-how. The relevant know-how is related to the capacity of self-producing energy and, historically, has been developed in co-generation production, local heating systems and farm and industry self-production[13] (e.g. Granovetter and McGuire 1998, Lehtonen and Nye 2009). Interestingly, even if energy generation was mainly provided in a centralized way when liberalizations started in the late 80s, cross-country differences were remarkable with several Nordic and central European countries maintaining a significant share of DG and a relatively more dispersed ownership[14].

The importance of the initial degree of decentralization in energy production and of entry barriers is evident in many examples. For instance, already in the early 80s--so before the kick-off of the liberalization process, Johnson and Jacobsson (2003), Jacobsson and Bergek (2004) and Nilsson at al. (2004) provide anecdotal evidence of sustained entry of new small producers of wind turbines in

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[13] According to IEA statistics, 80% of self-generation occurs in four industries: chemical, refining, food, and pulp and paper. Historically, the emergence of the paradigm of centralized production at the beginning of the twentieth century depended on various socio-economic and technological factors, i.e. network externalities, beyond the scope of this paper (see David and Bunn 1988, David and Wright 2003, Granovetter and McGuire 1998).

[14] Liberalizations of electricity sector started first in Anglo-Saxon countries in late 80s, then in Scandinavian countries in first half of the 90s, then in central European in the late 90s and finally in southern European countries (Glachant and Finon 2003, IEA 2003). Glachant and Finon (2003) distinguish two models of energy production prevalent in Europe before liberalization: a relatively more dispersed ownership was present in all countries located North-East with respect to the axis London-Paris-Rome-Athens; the opposite for countries located west. Cossent et al. (2009) discuss the effects of the current regulatory regime on DG.

Sweden, Netherlands, Denmark and Germany[15]. Historical accidents played a key role in maintaining alive a DG system in west Denmark where the slow integration into the national grid turned out being an advantage when conversion to renewable was needed. Apart from Denmark, also in other countries quite successful in renewable technologies and cogeneration (i.e. Germany, Netherlands and Sweden) centralized generation does not completely replace industry self-production of energy and localized heating systems using cogeneration, waste and biomass. In Sweden, the local heating systems were very successful in shifting from fossil fuel primary energy to bioenergy as the concern for environment quality emerged (IEA 2008 on Sweden, Nilsson et al. 2004). All in all, existing capacity to produce energy from decentralized sources and to manage two-ways flow of energy in the network (Lehtonen and Nye 2009) appears stronger in countries that, *ex-post*, were able to develop a comparative advantage in renewable energy technology.

Finally, a positive effect of liberalization on renewable energy innovation might prevail only in countries with particularly strict environmental regulation and/or active policies in promoting decentralized sources of energy production. In this view, the combination of liberalized market, organizational skills in decentralized production and active environmental policies would be the optimal configuration to foster renewable energy innovations. Alternatively, further moving along the lines suggested by Jamasb and Pollitt (2008), liberalization might have had positive effect on renewable energy innovations only in presence of a substantial initial public stimulus, i.e. large scale public R&D and demonstration projects. In sum, the complex relationship between degree of competition and innovation in the energy sector requires to look at the potential interaction that an index of competition might have with: 1. Environmental policies, 2. Initial conditions before liberalization in terms of capabilities in DG and public R&D[16].

2.3 Other Factors: Demand and Political Factors

Among the other factors affecting environmental innovations, Beise and Rennings (2005) suggest that demand for green goods and environmentally-friendly production methods play significant role. Related to this, learning by doing has been recognized as a main source of technological development for renewable energy technologies (e.g. Newell and Stavins 2004). Furthermore, the emergence of a sizable demand for green products allows carrying out network investments needed to fully exploit the potential of renewable energy, i.e. micro-grids. Whereas there are historical exceptions where foreign markets have been crucial (i.e. Danish constructors of wind turbines greatly benefited from the exploitation of the Californian market), domestic markets appear particularly important in view of the difficulties to stock and transfer several green goods, i.e. wind turbines (e.g. Lewis and Wiser 2007), eco-building, recycling, bio-food, etc., included renewable energy. As a result, it is important to

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[15] These firms were either entrepreneurial start-ups or mechanical engineering firms (Johnson and Jacobsson 2003).

[16] Also important can be structural breaks associated with market integration, i.e. Nordpool for Scandinavian countries. However, market integration in Europe is still limited and was even more so in the central historical period covered by this paper.

identify the internal factors that, together with targeted policies and the market structure, contribute to create a critical mass of demand for renewable energy.

In principle, as energy is an undifferentiated good, consumption choices should respond only to price signals. However, recent empirical evidence suggest that the willingness to pay higher prices for green energy appears in fact positively related to per-capita income and educational attainments (Oecd2008, Diaz-Rainey and Ashton 2009, Eurobarometer, IEA 2006-Denmark).The observed willingness to pay can be lower for poorer households because the additional price paid for green energy does not offset the higher opportunity cost of giving up consumption of other goods. Income constraints can also prevent households to buy durable goods and equipment with high initial cost, e.g. Photo-voltaic cells (Oecd 2008, Diaz-Rainey and Ashton 2009). These pieces of evidence clarify why environmental quality can be conveniently considered as a good that consumers are willing to buy only after having satisfied more basic needs. Under these circumstances, lowering inequality should positively affect the extent to which a society substitutes polluting goods with green ones depending on the level of per capita income (e.g. Vona and Patriarca 2011)[17]. Higher potential demand for environmental quality can either be translated into political voice to approve a stricter regulation, or affect directly consumption choices and other socio-political aspects usually unobservable to the econometrician. For instance, the willingness to build in-loco DG facilities often depends on the budget of local administrators, which responds to the needs of the local communities and of local stakeholders[18]. Clearly, a smart grid increasing the effectiveness of renewable energy generation is more likely built when each consumer is willing to buy a fraction of the lumpy cost of the grid.

As a higher aggregate demand for environmental quality triggers technological improvements through learning-by-doing on the producer side and learning-by-using on the consumer side, one should observe a negative relationship between inequality and innovation in environmental technologies. Vona and Patriarca (2011) demonstrate that this negative relationship almost disappears in countries with low level of income per-capita: if the median consumer cannot afford the higher initial cost of green goods, only the existence of a fringe of wealthy consumers can sustain a minimum demand threshold. For OECD countries and using many indicators of environmental innovations, existing

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17. For a given level of per capita income, a richer median consumer would be willing to pay a premium for environmental quality and, at the same time, would support stricter environmental regulation, both at the local and at the national level.

18. The Danish case where more than 80% of wind turbines are owned by cooperatives or individual famers is a good example. Another example is the one of Swedish heating districts, which are also owned and managed by cooperatives, small groups or families. There are other mechanisms through which, for a given level of income per capita, a lower income inequality can positively affect the emergence of social preferences for a cleaner environment. First, those who prefer a more equal society often prefer a cleaner environment and care more about future generations (d'Addio 2007). Second, social capital is usually higher in more equal society (Easterly 2001, Easterly et al. 2006). Third, more inequality and social segregation reduce positive behavioral spillovers from the more informed rich people to the less informed poor ones. A good example is the one of hazardous waste sites with poorer communities much more likely to accept these sites in their neighborhoods (Gawande et al. 2001). Four, public sector expenditures are normally higher in more equal societies (e.g. Benabou 1996). However, using school districts in the US as unit of analysis, recent empirical evidence shows that public expenditures increase with the level of inequality (Boustan et al. 2011).

empirical analyses confirm the theoretical predictions that the impact of inequality is generally negative and much stronger for wealthy countries (Magnani 2000, Vona and Patriarca 2011).

In sum, the role of market size and political factors in fostering environmental innovation should vary with both the level of inequality and of per-capita income. Yet their influence on the development of renewable energy technologies depends on radically different reasons. Larger markets act as a guarantee for energy supply, thereby offsetting the intermittencies in wind or solar power production with excess capacity from more traditional sources. The case of the Nordpool market is a good example in place: Norway's hydropower, the best buffer technology for its negligible operating costs, allows the development of Danish wind energy without bearing the cost of installing capacity to compensate for days of low wind[19]. On the contrary, in highly integrated markets, regulatory spillovers are likely to generate positive inducement effects outside the country and push the diffusion of more ambitious environmental policies (see the classical analysis of Popp 2006 and the Norway environmental targets often set on the Danish benchmark).

With regard to political factors, the quality and reliability of policies is of particular importance in uncertain technological field (Marcus 1981). If firms expect large changes in environmental regulation, the payoff function becomes volatile, hence augmenting the propensity to delay investments in new technologies or adopt existing end-of-pipe solutions (Frondel et al. 2004).Again in the Danish prototypical example, main political parties agree on the need to maintain ambitious environmental policies for renewable energy production and energy saving, hence ensuring a long-term commitment to environmental policies (IEA 2006-Denmark). Lack of political commitment for long-term targets is likely to be amplified in countries where public policies are perceived to be ineffective because frequent bribery and corruption (Lopez and Mitra 2000) or simple lack of time consistency. By posing an "option-value" associated with postponing the adoption of a new technology (e.g. Pindyck 2007), an unstable policy environment is expect to have a negative effect on innovation (Johnstone et. al.2010).This tendency is even more pronounced in the case of resource-saving technologies, where the value of such saving depends on future energy prices, which are usually volatile.

Overall, the several channels through which environmental policies, regulation in the energy sector and socio-political factors affect innovation in renewable energy call for the inclusion of a broad set of potential interactions in the empirical specification. Prior to the presentation of our empirical strategy, next Section describes the main variables at stake.

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19. Interestingly, the International Energy Agency puts a lot of emphasis on the importance of balancing hydropower from Norway (99%) and Sweden (40%) for the Danish boom in wind energy. This seemed a fair deal for all: on the one hand, interconnections with Norway and Sweden allow Denmark to balance stochastic variation in wind power; on the other hand, Danish consumers pay the higher energy prices required to finance R&D in wind with positive technological and pecuniary spillovers (lower costs of compliance with the EU regulation) for all Nordic countries. Conversely, in particularly isolated countries facing extreme wheater conditions, unsecure supply could force to use low quality oil and temporarily relax environmental standards, i.e. Italy in the winter 2005-6.

3. Data, measurement issues and descriptive evidence

The set of variables to be included in the empirical analysis concerns a potentially large host of factors, ranging from innovation measurement to policy types, not mentioning the more traditional macroeconomic characteristics. Table 1 summarizes the list of variables and descriptive statistics.

Dependent variable. We use patent counts and citation-weighted patent counts as our proxy for innovation performance. This choice is consistent with prior studies on renewable energy innovations such as Popp (2003), (2006) and JHP (2010). We use patents registered in the nine sub-fields: wind, marine, solar thermal, solar photovoltaic, biofuels, hydroelectric, fuels from waste, geothermal and tidal (tab. 2). We are well aware of the limitations in using patent counts as a proxy for innovation. First and foremost, not all innovations are patented and the propensity to apply for a patent grant may vary a great deal from one firm to another, one sector to another and one country to another. Yet energy generation is likely to become a single global market, and the potential benefits induced by innovation in renewable energy are so vast that we may safely assume homogeneity in patent propensity across country. Patents are not the only proxy for innovation in renewable energy. Installed capacity is another relevant candidate. However, such capacity investments depend highly on factors not related with innovation per see, especially the geographical endowment of a given country[20].

Second, Nehoff (2005) questions the use of patents as a good proxy for innovation in renewable energy. He argues that such technologies consist of a large set of components and require the expertise of several companies. Therefore, a substantial degree of coordination among several actors is required to patents, which in turn inhibits patent applications. Although we concur with this remark, patent information is the only systematic and exhaustive database which is readily available to scientists. Patent information makes it possible to build a series of indicators across countries. Of importance is the availability of the technological content of patent. This allows us to not only distinguish an invention in renewable energy from other invention, but also the identify the type of renewable energy sources it concerns.

A third and last limitation lies in the substantial heterogeneity in the economic value of patents (Archibugi, 1992; Pavitt, 1988). A patented invention may be technology novel with no or only little economic value. Hence patent grasp invention, more so than successful innovation (and past works have repeatedly used quality weighted patent counts to account for their economic value In this respect, the number of citations received by a patent has been shown to embody substantial economic value, although this measure remain somewhat noisy (Gambardella et al., 2008). In this paper, we therefore use of citation weighted patent counts to account for heterogeneity in patent economic value (Hall et al., 2001).

Environmental Policies. We use the database on public policies for renewable energy compiled at the International Energy Agency (IEA) and previously used by JHP 2010. This database and the related

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[20] The degree of correlation between patents in a specific renewable energy field and the installed capacity is however quite high as shown by Popp et al. (2011).

IEA (2000) publications contain detailed fact sheets at the country level that make it possible to construct a chronology of policy adoption for most OECD countries. Figure 1 in Appendix A summarizes the year of adoption of all available policies. In particular in this work, we considered the following policy instruments (further details in the appendix A, see table 3):

1) Research and development expenditures, at national level, taken from taken from the OECD Statistics. We refer in the analysis at both general R&D and sector specific R&D (Solar, Wind and other renewables). We control both for overall R&D expenditures and include in our index a dummy variable for public R&D projects taking value 0 prior to the introduction of the project, 1 thereafter. A second dummy variable has been created for those country which implemented additional R&D programs (or strengthened significantly the existing ones);
2) Investment incentives, i.e. capital grants and all other measures aimed at reducing the capital cost of adopting renewable energy technologies. It may also take the form of third party financial arrangements, where central governments handle part of the risk or provide low interest rate on loans. These are generally provided by State budgets and we used a dummy variable that takes value 0 prior to the introduction, 1 thereafter;
3) Tax measures, used either to encourage production or discourage consumption. They may have the form of investment tax credit or property tax exemptions, in order to reduce tax payments for project owner. An example is the US tax credit for wind (1992). Excises are not directly accounted here unless they were explicitly created to promote renewables (for example excise tax exemptions). Again, we used a dummy variable that takes value 0 prior to the introduction, 1 thereafter;
4) Incentive tariff (feed-in), i.e. guaranteed price above market tariff rates for a certain number of years. The environmental authority sets a premium price to be paid for power generated from renewables. In this case both the dummy variable and the intensity of the tariff are available;
5) Voluntary programs, adopted at country level by different stakeholders involved in the energy sector, i.e. government, public utilities and energy suppliers that agree to buy energy generated from renewable sources. One of the first voluntary programs was in Denmark in 1984, when utilities agreed to buy 100MW of wind power. The variable is also expressed as a dummy variable for adoption;
6) Obligations, which place a requirement on suppliers to provide a share of their energy supply from renewable energy. As in the above, this variable is a dummy variable for adoption;
7) Renewable energy Certificates (RECs). Tradable certificates are generally used to track or document compliance with quota system. At national level part of the total electricity produced generally must be generated by renewables or covered with a renewable energy certificate. In this specific case both a dummy variable and the number of certificates is available.

In this work we are especially interested in having a single variable that represents the overall policy intensity in support of environmental innovation for a given country. In particular, an aggregate policy index is especially suitable for our analysis with our focus on policy endogeneity, rather than on the mere effects of each single policy on different technologies as in JHP (2010). For these reasons, we construct a policy index that attempt to synthesize the regulation intensity for a given country in a given year using all available information regarding the implementation of national related policies. Thus, starting from the information available about the seven types of policies described above, the policy index is a simple average of all available policies expressed as dummy and normalized as to range from 0 to 1. This index is both time-variant and country specific. Similar examples of environmental policy index based on a synthesis of diverse policy performances can be found in Dasgupta et al. (1995), Eliste and Fredrikkson (1998) and Mazzanti and Zoboli (2009).

Clearly a single index built on dummy variables presents several limits. As highlighted by JHP, the ideal policy index would need to be continuous in all its dimensions to capture the intensity of each policy. Moreover, a single index implies a net loss of information as the differential impact of each policy on each sub-field of renewable energy patent cannot be detected, which is especially problematic in presence of a large heterogeneity in the policy-technology linkages (e.g. JHP 2010). In a correlated paper, we demonstrate that the good instruments for our policy index holds for a policy index, which --using a subset of more recent years and EU countries for which we have information on policy intensity-- takes into account of the intensity of different policies (Nicolli and Vona 2012). One can hence conclude that instrumenting the policy index here as in Nicolli and Vona (2012) mitigates the measurement error derived from missing information on policy intensity.

Figures 2-3-4 depict the patterns of the policy index for selected countries showing the generalized and almost everywhere monotonic increase of the index.

Product market regulation. Measuring market competition is certainly an ambitious task, especially because it is difficult to disentangle exogenous and endogenous determinants of effective market competition. With regards to indicators based on opinion surveys, e.g. 'doing business indicator' of the World Bank, the index of Product Market Regulation of the OECD (PMR henceforth) has the advantage of being built on objective policies and regulation specific to certain sectors. Moreover, the issue of endogeneity is less severe for the PMR as policies affecting competition, rather than a direct measure of it, are considered[21]. The index is built following a bottom-up approach that combines different data sources[22]. For each sector, the index combines information on barriers to

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[21] Sources of endogeneity related to the market structure are negligible under the plausible assumption that liberalization and policies favouring the entry of new players are not pushed by powerful incumbents. This source of endogeneity should be weak for renewable energy that represents a small fraction of total installed power and hence--at least in the past--is not likely to affect the liberalization process.

[22] The data sources are for instance the privatization Barometer of the Fondazione Enrico Mattei, the Intergated data Base of the World Trade Organization and interviews with civil servants in particular areas. With regards to the building of the indicator, low level indicators are aggregated in high level ones using principal components analysis. For details on the construction of the index and the weighting scheme see, e.g., Conway et al. (2005).

entrepreneurship and administrative regulation (e.g. licenses and permits, administrative burdens, legal barriers), state control (e.g. price control, ownership), barriers to trade and foreign direct investment (e.g. tariffs, ownership barriers). For the purpose of this paper, the sector of interest is the one of electricity (ISIC 4010) and to a lesser extent Gas (ISIC 4020). The PMR index for electricity and gas essentially combines three sub-indexes ranging from 0 to 6 (maximum anti-competitive regulation). The first is ownership that assumes five values private (0), mostly private (1.5), mixed (3), mostly public (4.5) and public (6).The second is an index of entry barriers that combine information on third party access to the grid (regulated (0), negotiated (3), no access (6)) and minimum consumers' size to freely choose their supplier (from 'no threshold' (0) to 'no choice' (6)). The third component is vertical integration ranging from unbundling (0) to full integration (6). Access to each sub-index of the aggregate index allows evaluating the importance of each element of the process of liberalization in the energy market.

For European countries, another relevant goal of the widespread process of liberalization was the progressive integration of national markets into a unified European one. Whereas integration could give rise to substantial regulatory spillovers across countries, the effective integration into a single wholesale market is proceeding at a slow pace. In last 10-15 years, much stronger integration emerges in European macro-regions: the NordPool for Nordic countries and partially Germany, the APX for the UK and Netherlands, the OMEL for Spain and Portugal, and finally the EuroPEX for central European countries. In these -substantially more integrated- markets, regulatory and policy spillovers are significantly more likely to occur. To jointly account for all possible sources of regulatory spillovers, we include time trends for macro-regions covering the relatively more integrated areas[23]. Figures 5-6 show the patterns of product market regulation for selected countries and make evident the widespread reduction of market regulation especially in the 90s.

Knowledge related control variables. In addition to policy variables, we explain patent generation by the characteristics of country's knowledge base. To measure the knowledge base of a country is tantamount to collecting all the relevant quantitative characteristics that accounts for all its technological competencies. As such, these measures wipe out all the qualitative aspects regarding the national innovation system. But although distinct from broader organizational aspects such as, inter alia, the balance between public and private research, broader public research organizations, university-industry relationships, funding system and incentives environments, we view the country's knowledge base as reflecting indirectly these qualitative aspects. Hence it is not the mastering of a particular technology

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The cross-country rankings of the PMR indicator appears substantially unchanged when using different specifications of the weighting scheme (Conway and Nicoletti 2006) and is in line with rankings derived from other indicators of market competition (Nicoletti and Pryor 2006).

[23] Even if this rough way of capturing regulatory spillovers, one should notice that the major integration occurred quite recently and hence did not contribute explaining establishment of long-term technological advantage. These macro-area trends should be sufficient also to control the balancing capacities, e.g. hydropower.

which makes a country an entity distinct from other countries. It is the set of organizations which sustain a portfolio of technologies which is presumably unique. In our view then, the characteristics of the country knowledge base reflect the country-specific organizational features. More precisely, Nesta (2008) has shown that a knowledge base can be exhaustively described in terms of knowledge stock and knowledge diversity. A given knowledge base can be described to be a function of total knowledge stock K and the number D of technological competencies held by the country. The amendment of K as done traditionally leads to the addition of knowledge diversity as an important component of a country's knowledge base. The existence and relevance of this property is due to the collective nature of knowledge: in order to produce aggregate outcomes, diverse knowledge must be combined and integrated into a coherent whole. Appendix A5 presents the computation of these two measures.

Other control variables. We include the following additional factors: total population, log of total patents, past (average of past three) and present energy prices in logs, past (average of past three) and present R&D in logs plus, in extended specifications, an index of policy uncertainty, a dummy when the Kyoto protocol where first ratified (in 1998), a dummy for government change, a variable for government types (coalition, single party, etc.), the index of perception of corruption of the World resource Institute, the fraction of people with tertiary education and older than 65 to capture the effect of demographic composition on preference for environmental quality. The index of political instability, which appears particularly important, is a 5-year moving average of changes in government characterized by a substantial ideological gap. Including the share of people with tertiary education also allows partially controlling for the human capital endowment, which is a key determinant of innovation. The overall number of patents, instead, is a crude measure of the stock of country technological competencies and propensity to patents. More sophisticated measures of the knowledge stock will be used for the robustness analyses using USPTO patents. See the appendix for the sources of each variable[24].

4. Empirical Strategy

4.1. Baseline Specification

We use fixed effect Poisson regressions with cluster-robust standard errors (country as the cluster unit) that delivers accurate estimates in case of mild overdisperion (Cameron and Trivedi 2009). This allows easing the comparison with GMM Poisson ones where we instrument the policy index. The point is that it is difficult to test whether overdispersion is mild or not, so there is a trade-off between using Poisson regressions instead than Negative Binomial—as would be advocated in our case from standard overdispersion tests. However, since results on the main variables do not strongly change when using Negative Binomial regressions, our cluster-robust Poisson regression seems a reasonable starting point. To further refine our results, we carry on four robustness exercises: 1. including area-

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[24] Differently from JHP (2010), we do not include growth in electricity consumption as it is strongly correlated with population dynamics, the stage of development of a country and energy prices.

specific time-trends, e.g. for Nordic countries, in order to capture unobservable time-varying factors, 2. clustering data by both country, as in the benchmark, and technology sub-field, to account for the large heterogeneity within renewable technologies; 3. Controlling for accurate measures of the knowledge stock using USPTO data[25]--i.e. index of knowledge diversity (Nesta 2008) and/or stocks adjusted for patents' depreciation and diffusion (Popp 2003)-- and of the market structure before liberalization started; 4. considering broad set of political and socio-demographic variables, i.e. political uncertainty, corruption, educational levels, that are likely to affect the preferences for a cleaner environment and hence the effectiveness of policy.

The benchmark specification is:

$$EPO_{Pat_{it}} = \exp(\beta_1 Pol_{it} + \beta_2 PMR_{it} + \beta_3 ineq_{it} + \gamma X_{it} + \alpha_i + \alpha_t + \varepsilon_{it}), \quad (1)$$

where $EPO_{PAT_{it}}$ stands for the number of patents applied for at the European Patent Office for country i at time t, Pol, PMR and $Ineq$ are the three variable of interest and **X** is a set of controls. Note the inclusion of a time fixed effect α_t accounting for a shock common to all countries and a country fixed effects α_i accounting for unobserved but persistent country characteristics. We also augment the baseline specification with the inclusion of a specific trend for more integrated geographic area. Finally, our three main variables of interest, i.e. inequality (Ineq), product market regulation (PMR) and the policy indicator (Pol), are standardized in order to enhance the comparison of their effect on environmental innovation.

The baseline specification with technology-specific effects is:

$$〖EPO_{Pat}〗_{ist} = \exp(\beta_1 〖Pol〗_{ist} + \beta_2 〖PMR〗_{ist} + \beta_3 〖Ineq〗_{ist} + \gamma_s 〖RD〗_{ist} + \gamma X_{it} + \alpha_{ist} + \alpha_t + \varepsilon_{ist}), \quad (1')$$

where now standard errors and fixed effect are calculated on the cluster unit (*i* country, *s* technology). Among the basic controls, we consider R&D expenditures in each specific technological sub-field rather than aggregate R&D for all renewable technologies. In this case, the sample size significantly increase as for each country in each year we have patents in nine technologies, so estimates are more accurate and we have enough degrees of freedom to control for country-specific time trends.

Note that both R&D expenditures and environmental policies raise issue of endogeneity. The former source of endogeneity is, however, mainly related to unobservable country level factors that are included in our analysis. To further mitigate endogeneity issues in this case, we estimate our model using only lagged R&D and results, available upon request, remain unchanged.

Sub-sections 4.2 and 4.3 discuss respectively the choice of instruments for the policy indicator and the correct identification of the effects of PMR and of inequality on patent generation.

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[25] The Patstat data publicly available from the Oecd website contains only the number of patents by year. Therefore, it is impossible to effectively measure patent's quality and building measure of the knowledge stock that accounts for depreciation and diffusion effects. We are in the process of reconstructing these more refined information from the original Patstat dataset, http://www.epo.org/.

4.2. Endogenous Policy

Policy endogeneity represents an unresolved key issue for existing studies on environmental innovations, an exception being the work by Popp (2002). Still, these studies admit that various factors may jointly affect patent intensity and environmental policies. First, there is a mutual reinforcement effect initially recognized by Downing and White (1986): if innovation in environmental technologies follows the implementation of an effective policy support, progress in the generation of renewable energy will, in turn, provide support for that policy. Second, the effect of the policy index is very heterogeneous across countries, implying that unobservable factors affect both the policy and the propensity to patents hence. Hence an omitted variable bias plagues the estimated relationship policy-innovation. Third, renewable energy policies are measured with a substantial error. For most policies, especially the one in place since the 70s and the 80s, lack of detailed information allows only for policy dummies, which at best are only rough proxies[26].

With regards to the choice of instruments, we assume that more ambitious environmental policies are adopted by more developed countries, possibly with lower inequality. This is consistent with the theoretical literature on the environmental Kuznets curve (see Stern 2004, Lopez 1994, Grossman and Krueger 1995) and with empirical evidence (e.g. Dasgupta et al. 2002, Eurobarometer, see tab. 3), Column 3 of Table 4 shows that both the (lagged) first and the second moment of the distribution of income have a significant effect on the index of environmental policy. However, the effect of inequality is positive rather than negative when controlling for lagged GDP pc, which instead is negatively correlated with inequality. Note that inequality has a much weaker effect than per capita GDP and it is not a good single instrument for the policy indicator. This is also evident looking at figure 2: Nordic countries have a level of the policy intensity below the one of the US, Germany and Japan. Additional variables positively correlated with the policy indicator are, as expected, a dummy for government change and the Kyoto dummy, reflecting international pressure for more environmental regulation (see col. 5, tab. 4). Together with lagged GDP per capita, these variables are used in overidentified specifications.

As an alternative best instrument, we also use time of policy adoption under the assumption that, given uncertainty on both technology and policy, a change in policy is more effective when expected benefits in terms of innovation are high. For instance, expected benefits of the policy can be high if a path-breaking innovation opens the opportunity of further discoveries, or when a certain technology acquires social legitimacy and public support. In order to capture the expected gains of innovation and to build our "lead" variable, we use the average discounted number of PCT patents (registered under the Patent Cooperation Treaty) from year t+5 to 2005. Column 1 of Table 4 suggests that the lead variable is the best single instrument for our policy indicator.

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[26] Note that, to a certain extent, aggregating the single policies in a unique index can somehow average away this measurement error by capturing overall policy intensity.

4.3 Identification of the effect of PMR

Identifying the effect of PMR on renewable energy patents raises a couple of issues. First, the effect can conceal not an effective impact of liberalization, but it is due to initial differences in the market structure, the degree of diffusion in DG or can work in a complementary fashion with other policies, especially public R&D and targeted policies. This motivates the inclusion of a full set of interactions: starting from specification (1) and (1'), we consider the interactions between PMR, on the one hand, and the initial share of DG, the degree of centralization in the energy sector, the policy indicator and the per capita investment in public R&D before liberalization. The initial share of DG summarized as a tri-modal variable in Table 5 is essentially derived for our reading of country reports of the IEA and of the books IEA (2005) and Glachant and Finon (2003). Second, each single component of the PMR can have a different effect on patent generation and these effects might offset each other. For instance, while it is intuitive to expect a positive effect of lowering entry barriers on innovation, it is more difficult to believe that private companies are always more motivated than public ones in investing in technologies with forward-biased expected returns. Finally, the widespread process of liberalization could have increased the propensity to patent in the whole energy sector, not only for renewable energy patents. However, using a diff-in-diff approach, results available upon request show that the effect of liberalization has been larger for renewable energy patents than for generic patents in energy even when controlling from area trends and country fixed effects.

5. Results

5.1 Basic

The results of our analysis using specification 1 are presented in Table 6. For the main explanatory variables (energy prices and R&D), we include both current and past levels by taking the moving average of the previous 3-years. The basic controls all have the expected positive effect on patents. Only past energy prices have a negative effect, while current energy prices display the expected positive effect. In regressions available upon request, we show that the combined effect of energy prices, as capture by an average of past and present prices, is not statistically significant, confirming the scarce importance of energy prices as determinant of renewable energy patents (see also JHP 2010). Concerning the impacts of technological inputs, a 1% increase in R&D leads to a 0.35% increase in patents, while the same increase in total patent has a larger .5% impact.

Looking at Column 1, the policy index has the expected positive and significant effect on green patents. This effect remains substantially unchanged when both PMR and inequality are considered (Table 6, Columns 2 to 6), but, as expected, declines substantially when we include year fixed effects (Table 6, Column 3) or socio-political variables (Table 6, Column 6). This implies that both inequality and PMR represent two effective determinants of green technologies. Especially for PMR, however, our data confirm case studies evidence of a negative effect of higher regulation on environmental policies, reflecting the opposition of existing utilities heavily committed in nuclear and carbon energy (e.g . Jacobsson and Bergek 2004, Nilsson at al. 2004, Lauber and Mez 2004, IEA country reviews). This result is robust to the use of either current or lagged policy index, for its e magnitude remains substantially unchanged (Table 6, Column 4). To quantify the effect, note that a one standard deviation increase in the policy index leads to a .23% to .39% increase in expected number of renewable patents. Therefore, all else equal, a country with a policy persistently one-standard deviation below the average score for the past 30 years will accumulate a 10% disadvantage in patent counts in renewable energy.

With regards to our second main variable of interest, i.e. product market regulation, its effect is negative and approximately of the same magnitude as that of the policy. More precisely, the effect of one-standard deviation change in PMR ranges between 0.22% and 0.35%[27]. As in the case of the policy index, the effects of both current and lagged PMR is of similar magnitude. In general, the positive effect of lowering entry barriers on innovation is consistent with case study evidence pointing to the key role of new entrants (e.g. Jacobsson and Bergek 2004). Importantly, part of the positive effect of lowering entry barriers on green patent is mediated by an indirect political-economy effect related to the reduced power of existing incumbents, which are in most cases against the adoption of environmental policies.

Yet we do not claim that liberalization alone can exhaustively account for the increase in green patents. Pre-existing characteristics the energy market could be equally important. Table 7 shows that a substantial fraction of the PMR effect is driven by the share of distributed generation before liberalization and by the level of public R&D in the 70s and 80s[28]. The first result confirms the strategic importance of pre-existing material and immaterial infrastructure in the DG paradigm for the development of renewable energy technologies. The second result sheds light on the strong complementarity between public and private innovative efforts. In particular, the effect of product market regulation turns out significant only in countries that initially supported renewable technologies with public R&D programs. Interestingly, also the index of environmental policy displays a significantly high effect when combined with market deregulation and lower entry barriers. Finally, on the three components of the index, lowering entry barriers is the only statistically significant positive impact on innovation. Unbundling has the expected positive effect but it is only cut-off significant at 85% level, whereas the impact of privatization is negligible and statistically insignificant.

With regards to the other variables, the impact of inequality is consistent with previous findings (Vona and Patriarca 2011, Magnani 2000). Lowering inequality has a positive significant effect on green

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27. Italy or France with relatively strict regulation in the energy sector have a PMR index ¾ of a standard deviation higher than Denmark and Sweden that have moderately unregulated regulation and more than a standard deviation higher than purely liberal countries, i.e. the US and UK.

28. This latter variable is a tri-modal variable: high, medium and low built as terciles of the cross-country distribution of (PPP-adjusted) average public R&D expenditures in the period 1970-1989.

innovation and the effect is of the same order of magnitude as the ones of policy and PMR[29]. However, compared with the other main variables of interest, its effect is less stable across specifications both in term of size and of significance levels (Table 6, Column 2 and Table 9, Column 6). Besides, the impact of inequality does not decrease after the introduction of several controls for the political context and for aggregate preference (Table 6, Column 6) Therefore, inequality should affect green technology through a demand channel rather than a political one. To provide evidence supporting this claim, we estimate the basic specification for different technologies. Table 8 shows that inequality has a much stronger impact on solar technologies, one for which consumer demand matters relatively more. In particular, the effect of inequality is four times as large as the benchmark one for solar PV and twice as large as for solar thermal. For wind energy, Denmark is confirmed to be an outlier as it drives upward both the effect of PMR and the one of inequality.

Finally, among the other variables considered in Table 6, political instability has the expected negative effect on the expected number of patent in renewable technology (Column 6). This result is somewhat consistent with previous ones using a specific index of uncertainty of environmental regulation developed by the World Competitiveness Forum and available for shorter time span (see for example Johnstone et. al.2010). Conversely, government change appears to have a positive influence on technology as possibly less subject to the influence of energy lobbies[30].

5.2 Technology-specific model

With technology specific effects, we explicitly embody the large heterogeneity characterizing the set of technological competencies required in the development of renewable energy. Estimated coefficients could change in this case if part of the variability previously explained by our variables of interest was reflecting a mere technology effect. Table 9 shows that this is not the case and the effect of the variables of interests remains largely unchanged when we consider green innovation in a more detailed fashion.

Note the stability of the term interacting policy with PMR in both Tables 8 and 9. Conversely, the interactions of PMR with both initial condition on DG and R&D loose their significance, but this result should be verified including a wider set of triple interactions PMR-technology-‘initial conditions’. We also estimate the model looking at the effect of single policies. What emerges is that obligations, taxes and feed-in-tariff are the policies that contribute more to renewable energy innovations. These results should be taken with care, since many policies are adopted jointly for several technology fields. Therefore that it is difficult to trace the individual effect for every single technological realm. Finally, Column 7 of Table 9 shows that the policy index is relatively more effective on wind technology and solar PV. These technologies were also the ones experiencing the fastest development in last thirty years.

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[29] Over the time period considered, the gap in inequality between US and Swedish is almost 2 standard deviation. This means that, all else equal, Sweden should have produced 18-20% more patents than the US.

[30] Finally, the index of perception of corruption is never significant and so it is not included in the analysis.

5.3 GMM Regressions

The second issue addressed in this paper concerns the endogeneity of the policy support. Table 10 presents estimates of the basic specification when either lagged GDP or the adoption 'lead' (section 4.2) are used as main instruments. These instruments appear valid in several different specifications, as suggested by the Hansen J test for over-identified restrictions. Combined with our result on the explanatory power of our first-stage regression (see Table XXX), this result suggests that the effect of GDP per capita on renewable technologies is completely mediated by its indirect effect on the policy index in the first place. An equivalent claim cannot be alleged for inequality, which is not a good exclusion restriction to instrument the policy index.

Compared with estimations in Table 6, The policy index appears underestimated according to both our IV strategies. i.e. the one based on 'leads' and the one based on lagged GDP per capita. The magnitude of the estimation bias is about 40% of the original effect in the just-identified case. As expected, the bias in the estimated effect of the policy decreases and almost disappears when more exclusion restrictions are added (e.g. Angrist and Pischke 2009). Nothing changes by including the lagged green patent in the set of explanatory variables (Comlums 3 and 7 of Table 10). Likewise, the effect of the other variables is not directly altered in GMM regressions. Overall, one can conclude that the estimation bias alters neither the sign nor the significance of the policy index, although its effect is significantly underestimated in the Poisson FE setting.

5.4 Robustness using USPTO

With USPTO data, we take advantage of information of the quality of patents and use both citations, received by the patent up to three years after application. Moreover, we extend our measure of country knowledge stock with the inclusion of a scalar regarding knowledge diversity (for details see appendix A). Finally, we distinguish between the knowledge stock in green technologies from the general knowledge stock, proxy of the country level of competencies.

The use of USPTO data constrains us to estimate a model with policy dummies rather than the aggregate index. The reason is that Nordic countries, while having a high patent intensity in the European Patent Office, have a much lower propensity to patent at the US patent office. Hence, the policy index does not explain much of the variation in patent intensity in the US. A caveat follows from this: we estimate our model excluding Denmark, i.e. the leader country in the environmental policy, and all outliers with zero USPTO green patents through the period of interest (Greece, Czech Rep., New Zealand, Poland, Portugal and Turkey)[31].

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[31] Note that the lack of representativeness of country leaders in renewable technologies, such as Denmark, raises concerns about the reliability of USPTO patents in measuring green competencies. Moreover, this does not consent us a full comparison between the result with USPTO and the ones with EPO patents. Also, with USPTO we have data only until 2000 as citations for more recent patents are limited.

Results in Tables 11 and 12 show the effect of our variables of interest on patent count (odd columns) and patent citations (even columns). Tables 12 also displays extended specifications that control for GDP per capita (as a surrogate for the policy index), political variables and Kyoto dummy. In all these specifications, a broad picture emerges: the impact of each variable substantially changes when we consider the citation weighted number of patents rather than mere patent counts. Interestingly, product market regulation turns out being particularly more effective on high quality patents, partially challenging the concerns by Jamasb and Pollitt (2008) on the effect of liberalization on radical innovations. In particular, the effect of PMR reaches around 1.2 if only top 20% patents are considered. However, results might be driven by the US and by the low reliability of US patents in capturing effective competencies in green technologies. Also, other variables have a significantly higher impact on citations: R&D, inequality and the knowledge-related measures, especially knowledge diversity whose effect almost doubles. With regards of the policies, Kyoto, trade certificates and investment incentives have both a significantly larger effect on green citations. In line with theoretical research (e.g. Jaffe and Stavins 1995, Jaffe et al. 2003, Fisher and Newell 2008), obligations appear to affect negatively high quality innovation as they do not provide an incentive to go beyond regulation.

6. Conclusions

This paper contributes to the growing literature on determinants of environmental innovations in two ways. First, we provide a careful evaluation of the impact of liberalization of the energy market on renewable energy technologies. In particular, we show that lowering product market regulation can have a significant positive impact on renewable energy technologies. This effect is consistent with several case studies, which show that lowering entry barriers is more beneficial to green innovation than the promotion of private ownership. We also find that deregulation fosters innovation significantly more when the initial level of R&D is sufficiently high and the initial share of energy produced by DG. A more ambitious environmental regulation is also more effective when combined with lower entry barriers, promoting the entry of new players into the market. Still, an apparently optimal combination of ambitious environmental policies and liberalized energy markets remains fairly risky for the asymmetric degree of commitment associated with the two policies: very high for liberalization, very low for environmental policies that are more sensitive to electoral cycles. A major concern is the recent trends of market integration in EU countries that have brought about excessive concentration with few large players dominating the market, e.g. EDF, ENI, E-ON, Vattenfall.This process may undermine the entry of new innovative players and the development of the DG paradigm. Whether preventing entry has a positive or a negative impact on innovation, depends crucially on the stage of development of the renewable energy industry.

Second, we show that the impact of policies might be underestimated in fixed effect Poisson regressions with respect to GMM ones. GMM estimates suggest that the effect of GDP per capita on innovation is fully mediated by its effect on the approval of more ambitious policies. In turn, income inequality does not affect substantially environmental policies, but lowering inequality positively impacts innovation, especially in technologies where consumers' involvement is more important, i.e. solar. Our results are robust to various specifications, notably adding technology-specific effects and variables of political context. Using more sophisticated measures of the knowledge stock and considering quality-adjusted patents reinforces our results. In this case, entry barriers and inequality keep having a relevant effect only on high-quality patents, while the effect of knowledge diversity almost doubles when citations are considered.

Appendix A- Descriptive Stats and Additional Information

A1. Data sources

Key variables

- Entry barrier, time-varying indicator of Product Market Regulation (Oecd).
- Inequality, Standardized World Income Inequality Database (SWIID)
- Synthetic indicator of environmental policy (IEA, and other sources)
- Knowledge stock weighted by citations (USPTO)
- Knowledge diversity –number of tech. field- conditioned to the number of patents (USPTO)

Basic controls

- Total patent activity (Oecd)
- Current and past electricity prices (IEA, International Energy Agency)
- Current and past R&D in renewable energy (IEA)
- Population

Additional controls

- Index of country political instability (Comparative Political Data Set I)
- Woman participation in parliament (Comparative Political Data Set I)
- Share of tertiary educated (Cohen and Soto dataset)
- Share of people above 65 (Comparative Political Data Set I)
- Perception of Corruption (world resource institute dataset)

Table 1: list of variables and descriptive statistics

Acronim	Description	Obs	Mean	St. Dev.	Min	Max
EPO 3	Total Renewable patents at EPO (EPO 3); i.e. Wind, Solar Thermal, Solar Photovoltaic, Solar thermal hybrids, Geothermal, Marine energy, Hydro new (e.g. Tidal), Hydro Conventional, Biofuel	1008	10.402	28.41	0	350.5
EPO 2	Total Renewable patents at EPO (EPO 2); i.e. EPO3 plus Energy from non-fossil fuel.	1008	10.940	29.594	0	366.5
Solar Photovoltaic	Patent at EPO	1008	3.976	14.391	0	143
Solar thermal	Patent at EPO	1008	1.630	4.092	0	52
PV	Patent at EPO	1008	.0962	.40005	0	5
Wind	Patent at EPO	1008	1.627	6.253	0	79
Hydro energy Conventional	Patent at EPO	1008	.5982	1.571	0	24
Population	Habitants/1000	1008	35245.1	50897.7	339.17	295753
Total Patent	Total patent at EPO	1008	1854.85	4819.46	0	35569.95
R&D (Ren.)	Total RD&D in Million USD (2010 prices and PPP)	617	51.324	130.52	.008	1560.916
Energy Prices	Energy end use price, USDppp/unit (Households)	813	.108	.046	.019	.256
Policy Index	Standardized in the analyses	1008	.23041	.2416	0	1
PMR Electr.	Standardized in the analyses	791	.4709	.178	.074	1
Gini coeff.	Standardized in the analyses	957	28.974	6.625	15.061	53.922
Government Chan.	Number of changes in government per year; termination of government due to (a) elections, (b) resignation of the Prime Minister, (c) dissension within government, (d) lack of parliamentary support, (e) intervention by the head of state.	775				
Political Instability	Political instability index, moving average over previous five years of the number of government change characterized by a significant ideological gap	721	-.0001	.455	-3	3
Goverment Type	Type of Government. Classification: (1) single party majority (2) minimal winning coalition (3) surplus coalition (4) single party minority (5) multi party minority (6) caretaker government	730	2.436	1.276	1	6
Elderly	Log % population 65 and over	787	2.5828	.188	1.955	3.003
Education	Log % pop. aged 15 or over with complete higher education	1008	.103	.071	0	.285

A2. Patent classes

Table 2: renewable energy patents

Class	**Brief Descriptions**
Wind energy	Wind currents can be used to generate electricity by using wing-shaped rotors to convert kinetic energy from the wind into mechanical energy and a generator to convert the resulting mechanical energy into electricity.
Solar thermal energy	Heat captured from the sun is used for residential heating or industrial processes or for thermal power generation. Technologies involved in solar thermal energy production include solar heat collection, heat storage, systems control, and system design technologies
Solar photovoltaic (PV) energy	Specially adapted semiconductor devices are used to convert solar radiation into electrical current. Related technologies include solar cell design, storage battery, and power conversion technologies.
Geothermal energy	Thermal energy derived from magma heat and stored in soil, underground water, or surface water can be used for heating or cooling buildings by means of a ground coupled heat pump system. Such systems operate by having a heat exchange embedded in a borehole supply the energy for the evaporation and condensation of a refrigerant. Geothermal liquid can also be used to drive turbines and thus generate electricity.
Marine energy (excluding tidal)	Energy From waves.
Hydro energy - tidal, stream or damless	The energy from incoming and outgoing tides can be harnessed togenerate electricity using, for instance, turbines.
Hydro energy – conventional	Electricity can be generated through the conversion of potential energy of water contained in a reservoir using a turbine and a generator.
Biofuels	Bioenergy generally refers to energy produced from biomass, that is to say organic matter including dedicated energy crops and trees, agricultural food and feed crops, agricultural crop wastes and residues, wood wastes and residues, aquatic plants, animalwastes, municipal wastes, and other waste materials.
Fuel from waste (e.g. methane)	Household and other waste can be processed into liquid or solid fuels or burned directly to produce heat that can then be used for power generation ("mass burn"). Refuse derived fuel (RDF) is a solid fuel obtained by shredding or treating municipal waste in an autoclave, removing non-combustible elements, drying, and finally shaping the product. It has high energy content and can be used as fuel for power generation or for boilers.

Source: WIPO. Patent Based Technology analysis Report.

A3. Policy Index

Table 3: further details on the components of the policy index

The policy index used in this analysis is based on a Data base on public policy aimed at supporting renewable energy adoption developed by the International Energy Agency, and summarized in the table below.

Instrument	Brief explanation	Variable Construction
Investment incentives	Capital Grants and all other measures aimed at reducing the capital cost of adopting renewable energy technologies. May also take the form of third party financial arrangements, where central governments assume part of the risk or provide low interest rate on loans. They generally provided by State budgets.	A dummy variable that takes on a value of 0 prior to introduction of the policy, and 1 thereafter
Tax Measure	Used either to encourage production or discourage consumption. They may have the form of investment tax credit or property tax exemptions, in order to reduce tax payments for project owner. An example is the US production Tax credit for wind (1992). Excises are not directly accounted here unless they were explicitly created to promote renewables (for example excise tax exemptions).	A dummy variable that takes on a value of 0 prior to introduction of the policy, and 1 thereafter
Incentive tariff	Guaranteed price systems that guarantee above market tariff rates. In such cases, the Environmental authority generally sets a premium price to be paid for power generated from renewables	A dummy 0-1
Feed-in Tariff	Guaranteed price that may vary by technology	Feed-in tariff Level.
Voluntary program	One of the first voluntary program was in Denmark in 1984, when utilities agreed to buy 100MW of wind power. These programs generally operate through agreement between government, public utilities and energy suppliers.	A dummy variable that takes on a value of 0 prior to introduction of the policy, and 1 thereafter
Obbligation	Obligation are generally quota systems that place an obligation on suppliers to provide a share of their energy supply from renewable energy.	A dummy 0-1
Tradable Certificate	Renewable energy Certificates (RECs), are generally used to track or document compliance with quota system. At national level part of the total electricity produced generally must be generated by renewables or covered with a renewable energy certificate.	A dummy 0-1
Research and Development Support	Public financed R&D program	A dummy 0-1. In this case a second dummy has been created for these countries that implemented a second R&D program.

Figure 1: patterns of policy adoption

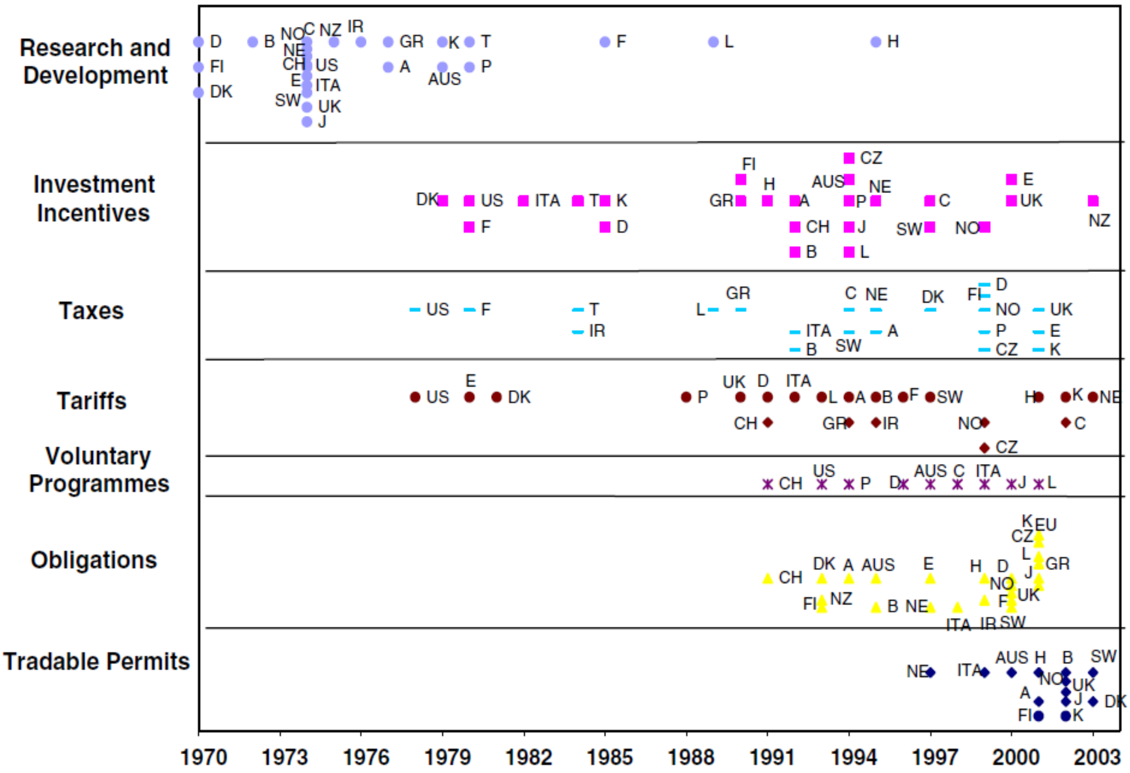


Figure 2: correlation GDP-WTP for environmental quality (Eurobarometer)

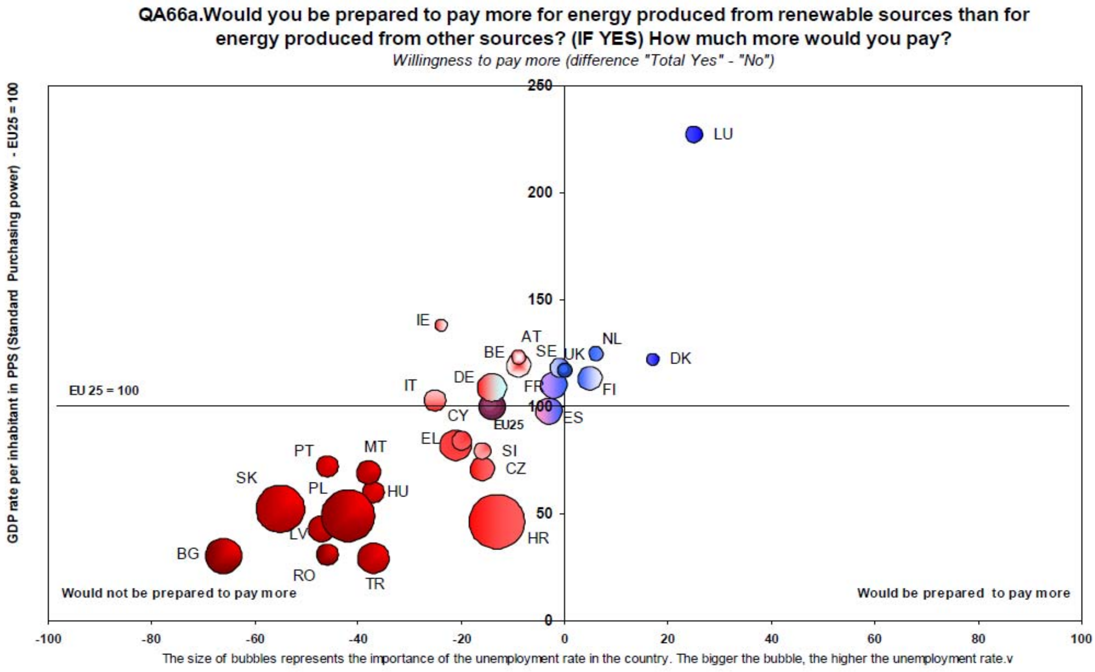


Figure 3: Policy Index

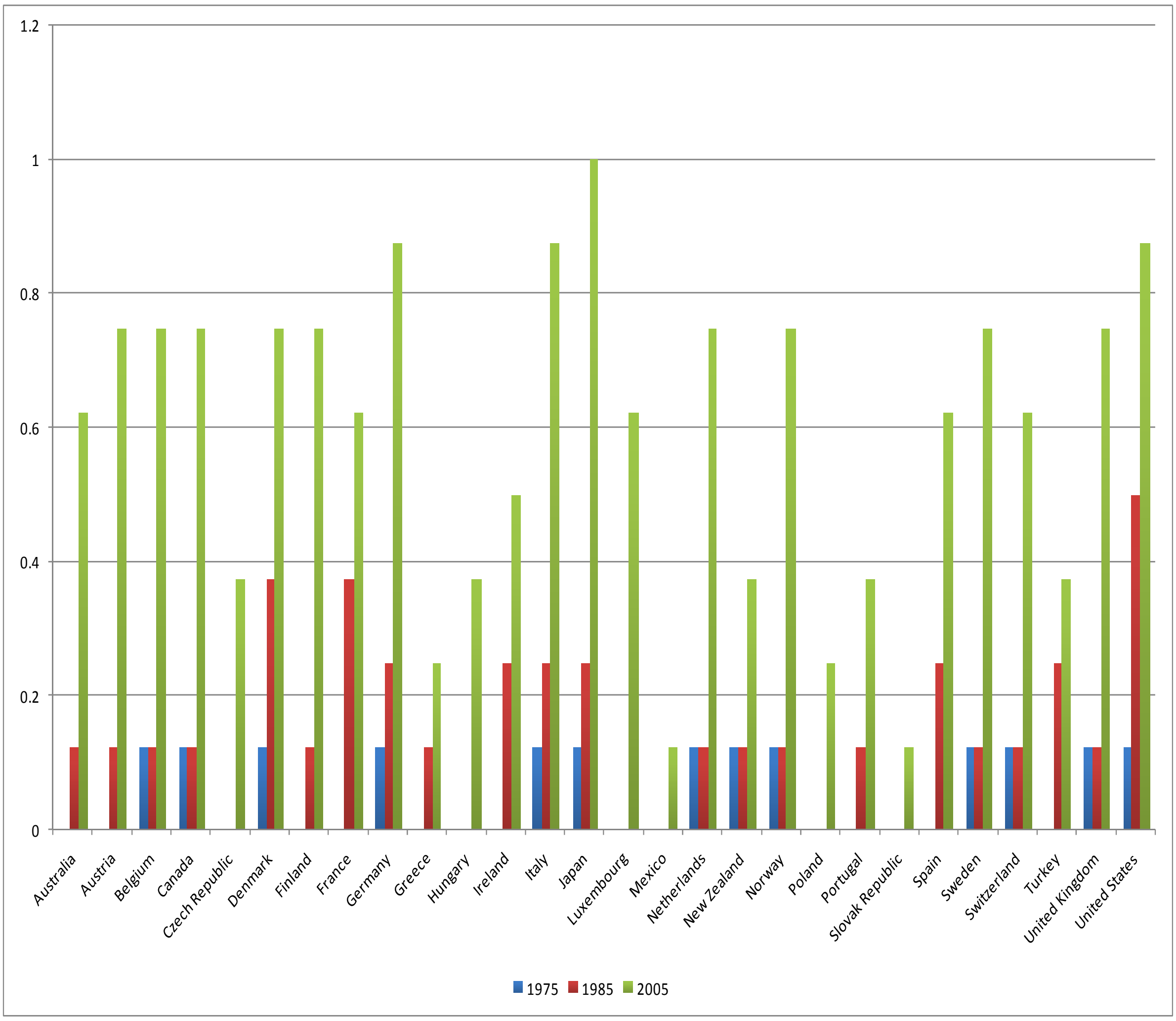


Figure 4: trends in the policy index, selected countries

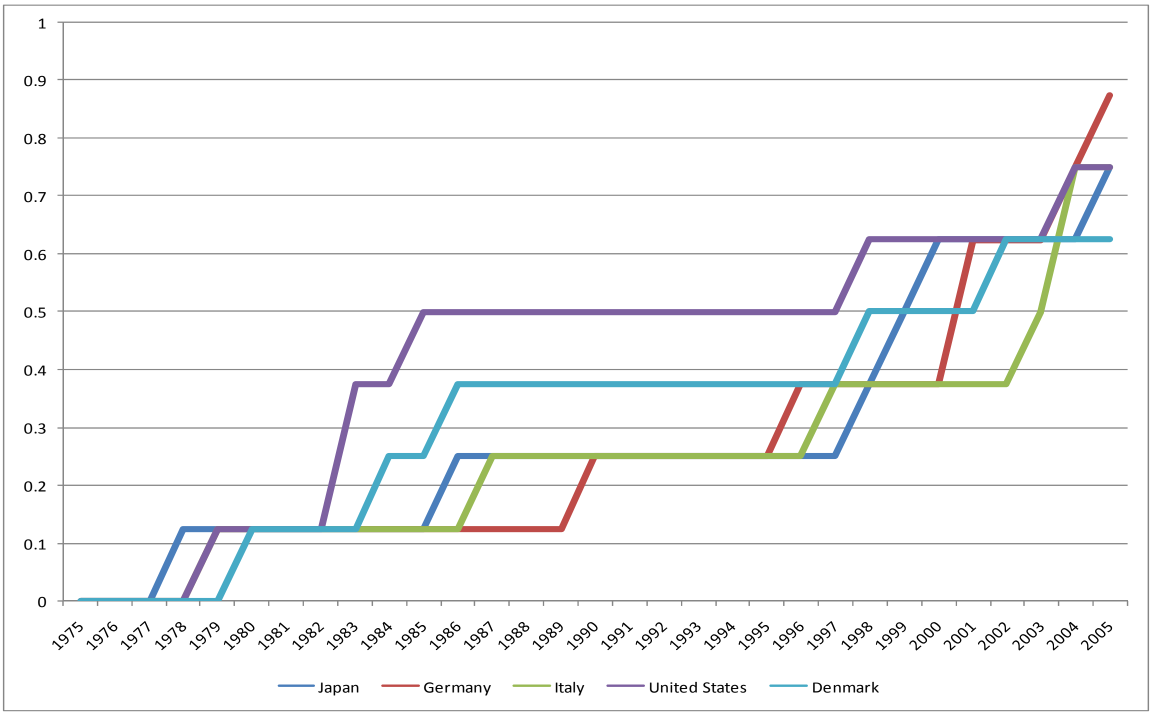


Figure 5: trends in the policy index, selected countries

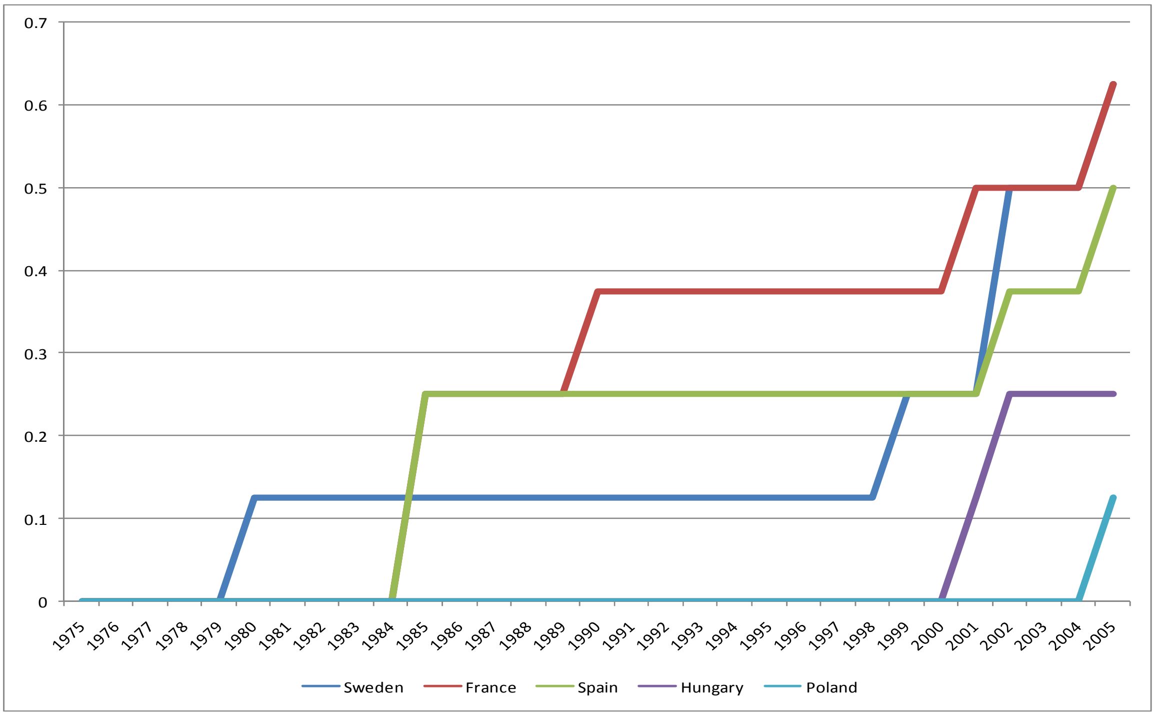


Table 4

Determinants of the Policy Index

Variable	Only best instrument	Only 2' best instrument	role of inequality	Both best instruments	Variables pol. Context
Adoption lead	14.7875			10.8762	9.5313
	0.4765			0.4831	0.6691
GDP pc(t-1)		0.00001	0.00001	0.00001	0.00001
		0.000	0.000	0.000	0.000
inequality			0.229		
			0.026		
gov. change					0.0107
					0.008
kyoto					0.21
					0.0157
constant	-0.0302	-0.1202	-1.6045	-0.1965	-0.0714
	0.01	0.0153	0.0658	0.0128	0.0182
N	1008	943	898	943	756
R^2	0.4886	0.4181	0.4689	0.6216	0.7041

A4. Energy Markets and Liberalization

Table 5

Energy markets before liberalization

Country	Share of DG before liberalization	Non monopoly system before liberalization
Australia	0	0
Austria	1	1
Belgium	0	1
Canada	0	0
Czech Republic	1/2	1
Denmark	2	1
Finland	0	1
France	0	0
Germany	2	1
Greece	0	0
Hungary	0	1
Ireland	0	0
Italy	0	0
Japan	0/1	0
Luxembourg	0	1
Mexico	0	0
Netherlands	2	1
New Zealand	1	1
Norway	0	1
Poland	1	1
Portugal	1	0
Slovak Republic	0	1
Spain	1	0
Sweden	2	1
Switzerland	0	1
Turkey	0	1
United Kingdom	0	0
United States	0	0

DG=Distributed generation, 2 is high share, 0 low

Monopoly before liberal.: 0 no, 1 yes, shadow: difficult to classify
Sources: IEA country reviews, IEA 'Lesson from lib. Mkt.' Glanchant and Finon (2003)

Figure 6: trends in PMR, selected countries

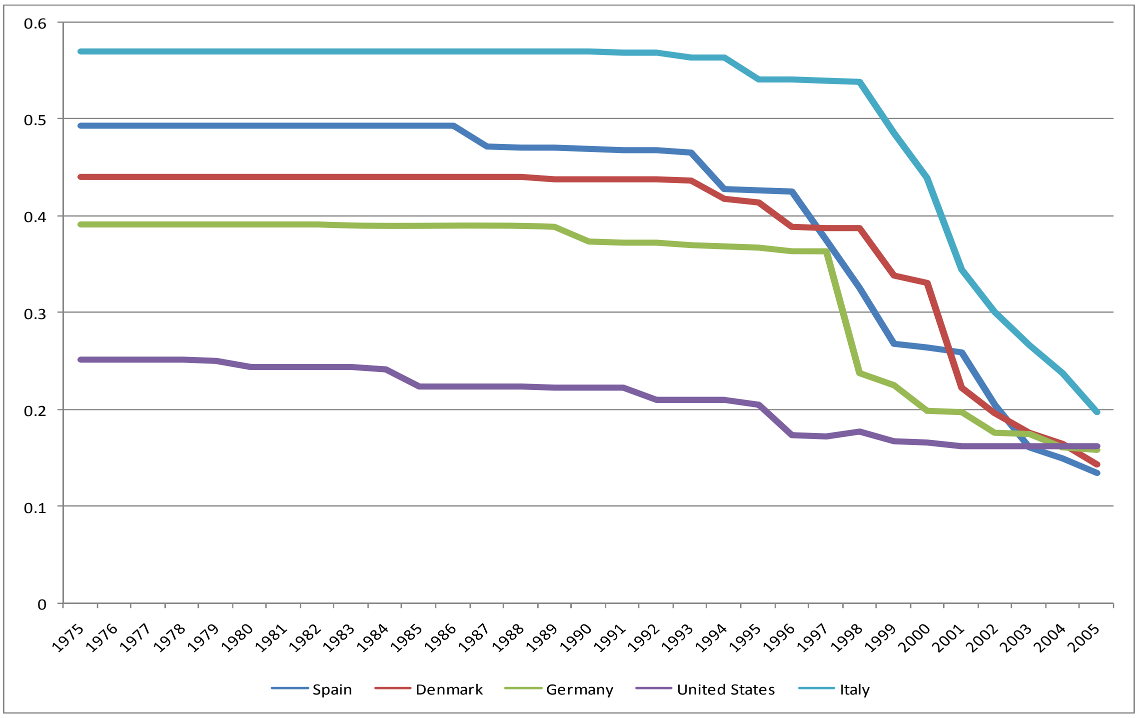
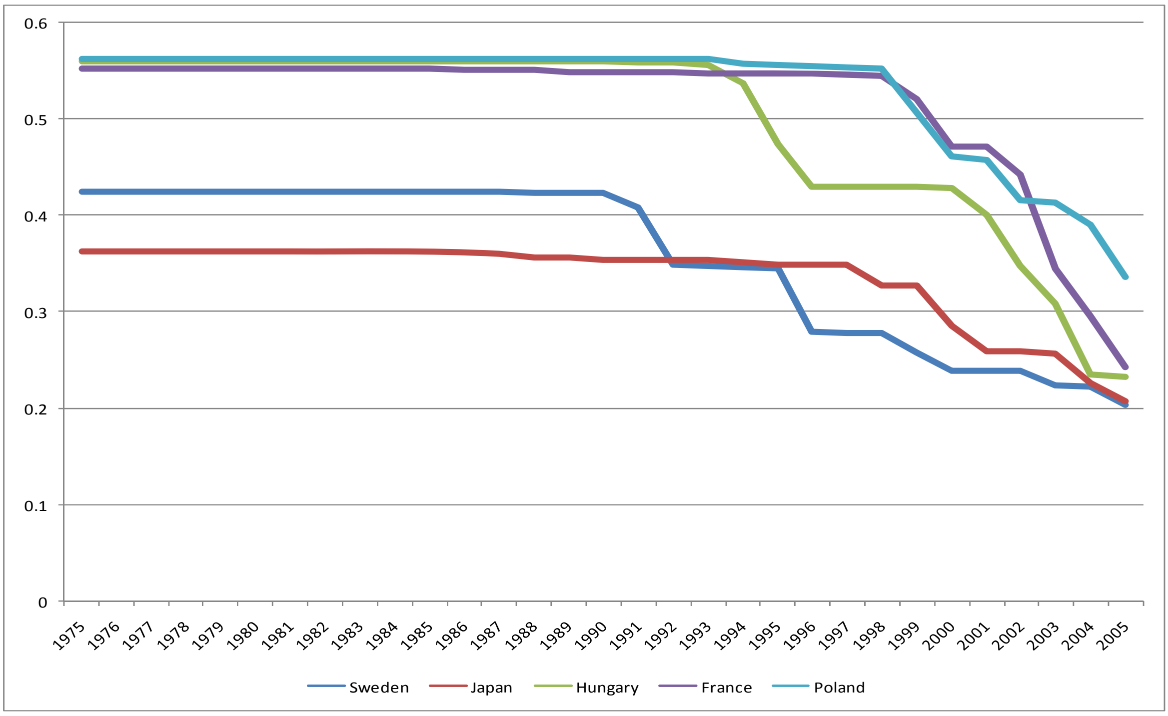


Figure 7: trends in PMR, selected countries



A5. Measuring knowledge stock and knowledge diversity

The knowledge base of a given country can be described by means of systematic attributes. First, we measure knowledge capital of country i at time t based on Popp (2003) as follows: $K_{it}^{POPP} = \sum_{s=0}^{s=\infty} e^{-\beta_1(s)}\left(1 \quad e^{-\beta_2(s+1)}\right) \times p_{it}$, where β_1 is the rate of knowledge obsolescence, β_2 captures knowledge diffusion and p is the number of patents applied for by firm i in year t . In our work, we set the rate ofknowledge obsolescence to $0.1\,(\beta_1 = 0.1)$, and the rate of knowledge diffusion to $0.25\,(\beta_1 = 0.25)$. An alternative method is the so-called permanent inventory method, and measures the cumulated stock of past patent applications as follows: $K_{it}^{PIM} = p_{it} + (1 - \beta_1) \times K_{i,t\;1}^{PIM}$, where again β_1 is the rate of knowledge obsolescence set to 0.15 . For both measures we expect a positive impact of accumulated knowledge on patent production.

Importantly, patent statistics provide information on technology classes in which firms develop technological competencies. This information is essential in experimenting for the expected positive role of knowledge diversity on patent generation. Diversity affects output by increasing the number of new knowledge combinations, that is, the potential number of innovations. However, not all innovations arise from radical new knowledge. Cross fertilisation processes arise when new basic knowledge about the principles at work in a given scientific fieldbecome correspondingly relevant in other research areas. We state that internal knowledge spillovers, i.e. knowledge flows amongst different research programmes conducted within a single country, contribute significantly to innovative performance.

We measure knowledge diversity as follows. Let p_{kit} be the number of patents applied for by country i at time t in patent technology class k . In order to compensate for changes in a countries technological policy, we introduce some rigidity in its set of technological competencies and define P_{kit} as the sum of all patent applications over the past five years: $P_{kit} = \sum_{\tau=0}^{\tau=4} p_{k,i,t-\tau}$. Now let $d_{kit} = 1$, if the country has developed competencies in patent technology class k , $(P_{kit} > 0)$, 0

otherwise. Knowledge diversity D is simply the number of patent technology classes in which firms develop scientific competencies: $D_{it} = \sum_k d_{kit}$, over the past five years.

Appendix B- Tables of results

Table 6: All Renewables. Dependent variable: Renewable EPO Patents

Specification	**I**	**II**	**III**	**IV**	**V**	**VI**
Population	0.0001**	0.0001**	0.0001***	0.0001**	0.00001**	0.0001***
	(4.48e-06)	(5.78e-06)	(4.24e-06)	(5.85e-06)	(5.79e-06)	5.89e-06
Log Total Patent	0.5182**	0.5068**	0.8452***	0.5636**	0.4176**	0.2598
	(0.249)	(0.227)	(0.152)	(0.220)	(0.198)	0.213
Log R&D (Ren.)	0.3879***	0.3607***	0.1654***	0.3953***	0.3379***	0.2827***
	(0.061)	(0.054)	(0.049)	(0.063)	(0.062)	0.040
Log Past R&D (Ren.)	0.0382	0.0948	0.1499***	0.0661	0.1202*	0.1187**
	(0.120)	(0.081)	(0.053)	(0.066)	(0.074)	0.054
Log Energy Prices	11.507***	7.934**	5.6539**	4.8395*	8.8126**	5.6522*
	(4.196)	(3.851)	(2.524)	(2.633)	(3.717)	3.066
Log Past En. Prices	-14.277*	-12.986**	-3.7999	-10.713**	-12.657**	-8.7103**
	(7.706)	(6.029)	(4.008)	(4.961)	(5.729)	4.405
Policy Index (Std)	0.3986***	0.3355***	0.2307***		0.2473***	0.2348***
	(0.080)	(0.084)	(0.064)		(0.090)	0.076
PMR Electr. (Std)		-0.351***	-0.252***		-0.2888***	-0.336***
		(0.1003)	(0.079)		(0.106)	0.094
Gini coeff. (Std)		-.3152	-0.2029*	-0.332***	-0.2322	-0.5629**
		(0.208)	(0.121)	(0.211)	(0.216)	0.256
Policy Index$_{t-1}$				0.3175***		
				(0.075)		
PMR Electr.$_{t-1}$				-0.398***		
				(0.106)		
Kyoto Dummy					0.3310***	0.2922***
					(0.093)	0.085
Government Chan.						0.0947**
						0.037
Political Instability						-0.1620*
						0.089
Goverment Type						0.0867
						0.062
Log Elderly						0.6376
						0.464
Log Education						2.3999
						2.005
Country FE	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	No	No	Yes	No	No	No
Observation	567	543	543	542	543	490
Log likelihood	-1679.76	-1568.43	-1411.41	-1561.16	-1542.66	-1427.55
χ^2	1.3e+05	52040.21	1.8e+05	48870.93	44801.81	2.2e+06

Dependent variable: Total Renewable patents at EPO (EPO 3); i.e. Wind energy, Solar Thermal energy, Solar Photovoltaic energy, Solar thermal (PV) hybrids, Geothermal energy, Marine energy, Hydro Energy (Tidal, Stream or Dameless), Hydro energy Conventional, Biofuel.
Poisson Estimations, cluster-robust standard error in parenthesis. Cluster unit: Country
*,**,*** indicate significance at respectively 10%, 5% and 1% level.

Table 7: All Renewables. Dep. variable: Renewable EPO Patents. PMR & Interactions

Specification	I	II	III	IV	V
Population	0.0001***	0.0001***	0.0001***	0.0001*	0.0001**
	(4.27e-06)	(4.36e-06)	(4.17e-06)	(3.96e-06)	(4.33e-06)
Log Total Patent	0.485**	0.4873***	0.5220**	0.505**	0.488**
	(0.236)	(0.228)	(0.234)	(0.227)	(0.235)
Log R&D (Ren.)	0.3538***	0.376***	0.3946***	0.338***	0.3558***
	(0.053)	(0.0604)	(0.061)	(0.065)	(0.055)
Log Past R&D (Ren.)	0.1091	0.1138	0.1265	0.1189	0.0839
	(0.101)	(0.106)	(0.101)	(0.092)	(0.103)
Log Energy Prices	9.196***	6.301	5.9967	7.364***	8.5025**
	(3.535)	(3.949)	(4.097)	(2.471)	(3.49)
Log Past En. Prices	-14.072**	-12.776**	-13.245**	-11.129**	-13.373**
	(6.006)	(5.601)	(5.35)	(5.079)	(5.451)
Policy Index (Std)	0.2968***	0.276***	0.2693***	0.0110	0.2867***
	(0.079)	(0.077)	(0.081)	(0.11)	(0.072)
PMR Electr. (Std)	-0.3323***	-0.271***	0.1140	-0.2007***	
	(0.112)	(0.071)	(0.172)	(0.058)	
DG * (1-PMR)		0.133**			
		(0.064)			
R&D * (1-PMR)			0.2209**		
			(0.092)		
Policy*(1-PMR)				0.1383***	
				(0.042)	
PMR entry					-0.0416*
					(0.024)
PMR public owned					-0.0389
					(0.046)
PMR vertical integration					-0.0565
					(0.036)
Country FE	Yes	Yes	Yes	Yes	Yes
Year FE	No	No	No	No	No
Observation	550	550	550	550	567
Log likelihood	-1610.74	-1596.1	-1595.17	-1575.36	-1620.65
χ^2	54924.62	1.0e+05	1.2e+05	2.1e+05	77238.11

Dependent variable: Total Renewable patents at EPO (EPO 3); i.e. Wind energy, Solar Thermal energy, Solar Photovoltaic energy, Solar thermal (PV) hybrids, Geothermal energy, Marine energy, Hydro Energy (Tidal, Stream or Dameless), Hydro energy Conventional, Biofuel.

Poisson Estimations, cluster-robust standard error in parenthesis. Cluster unit: Country

*,**,*** indicate significance at respectively 10%, 5% and 1% level.

Table 8: Renewable Energy Technologies Separated. Dep. variable: Renewable EPO Patents

Specification	Solar Photovoltaic	Solar thermal	PV	Wind	Hydro energy Conventional
Population	-0.0001**	0.0001**	0.0001**	0.0001***	0.0001***
	(7.07e-06)	(4.80e-06)	0.00001	(0.00001)	(8.32e-06)
Log Total Patent	0.9810***	0.18481	-0.4728	0.5463	0.5717***
	(0.328)	(0.119)	0.633	(0.372)	(0.187)
Log R&D (Field)	0.2817***	0.5378***	0.9224***	0.0975	0.3584**
	(0.067)	(0.108)	0.262	(0.140)	(0.179)
Log Past R&D (Field)	0.0401	-0.1192	-0.4909	-0.0555	0.0896
	(0.088)	(0.129)	0.346	(0.090)	(0.1046)
Log Energy Prices	7.8367***	13.3042***	-8.3458	5.703	7.6997
	(2.849)	(4.281)	18.754	(3.525)	(7.7020)
Log Past En. Prices	-5.698	-22.1288***	45.819**	-13.499	-14.693
	(4.967)	(5.059)	21.91	(9.321)	(10.185)
Policy Index (Std)	0.2460***	0.1054	0.4277***	0.7099***	0.1767
	(0.081)	(0.072)	0.15	(0.156)	(0.119)
PMR Electr. (Std)	-0.2027**	-0.6483***	0.0044	-0.4664*	-0.2654**
	(0.103)	(0.139)	0.417	(0.278)	(0.137)
Gini coeff. (Std)	-0.277**	-0.6020***	-1.190**	-0.9924*	-0.3091
	(0.143)	(0.190)	0.607	(0.567)	(0.488)
Policy No Denmark	0.246***	0.1345*	0.4277***	0.8264***	0.1915
	(0.082)	(0.071)	(0.150)	(0.139)	(0.117)
PMR No Denmark	-0.2007**	-0.5963***	0.0044	-0.1868	-0.2338*
	(0.103)	(0.132)	(0.417)	(0.202)	(0.140)
Gini No Denmark	-0.2771**	-0.5156***	-1.190**	-0.3620	-0.2566
	(0.143)	(0.184)	(0.607)	(0.465)	(0.505)
Country FE	Yes	Yes	Yes	Yes	Yes
Year FE	No	No	No	No	No
Observation	419	525	319	477	508
Log likelihood	-653.44	-741.80	-115.82	-730.21	-499.66
χ^2	62976.03	1184.69	7052.43	32009.18	6376.08

Poisson Estimations, cluster-robust standard error in parenthesis. Cluster unit: Country
*,**,*** indicate significance at respectively 10%, 5% and 1% level.

Table 9: Technology Fixed Effect Model. Dependent variable: Renewable EPO Patents

Specification	I	II	III	IV	V	VI	VII
Population	0.0001**	0.0001*	0.0001*	0.0001*	0.0001	0.0001***	0.0001**
	(6.34e-06)	(6.47e-06)	(5.93e-06)	(5.54e-06)	(5.72e-06)	(5.46e-06)	(4.47e-06)
Log Total Patent	0.5389***	0.8174***	0.4482**	0.509***	0.5403***	0.5263***	0.4170***
	(0.1702)	(0.158)	(0.181)	(0.163)	(0.177)	(0.127)	(0.136)
Log R&D (Field)	0.42107***	0.2179**	0.4045***	0.4034***	0.3993***	0.4476***	0.3724***
	(0.1088)	(0.092)	(0.113)	(0.116)	(0.117)	(0.1008)	(0.082)
Log Past R&D (Field)	-0.0479	-0.0564*	-0.0055	-0.0033	-0.0150	-0.0526	-0.033
	(0.037)	(0.032)	(0.035)	(0.036)	(0.038)	(0.033)	(0.036)
Log Past R&D (Ren.)	-0.0073	0.0781	0.0318	0.0191	0.0241	0.0309	0.0298
	(0.092)	(0.064)	(0.104)	(0.103)	(0.104)	(0.097)	(0.076)
Log Energy Prices	6.2168**	6.0828**	7.8409**	7.174**	5.5372*	4.7385	7.512***
	(3.412)	(2.773)	(3.867)	(3.699)	(3.298)	(3.265)	(2.769)
Log Past En. Prices	-11.955***	-4.7698	-12.264***	-12.702***	-10.602**	-7.4038**	-10.916***
	(3.891)	(3.350)	(4.187)	(4.314)	(4.150)	(3.801)	(3.337)
Policy Index (Std)	0.3623***	0.2026**	0.3179***	0.3006***	0.1142		-0.1351*
	(0.0748)	(0.098)	(0.071)	(0.069)	(0.088)		(0.074)
PMR electr. (Std)	-0.3827***	-0.2709***	-0.3331***	-0.4402**	-0.1939**	-0.3233***	-0.3127***
	(0.0972)	(0.100)	(0.081)	(0.230)	(0.079)	(0.092)	(0.079)
Gini coeff. (Std)	-0.4552**	-0.3261**				-0.2503	-0.4223***
	(0.1863)	(0.171)				(0.189)	(0.119)
DG * (1-PMR)			0.1227				
			(0.134)				
R&D * (1-PMR)				-0.0512			
				(0.119)			
Policy * (1-PMR)					0.1239***		
					(0.029)		
Feed in Level (Field)						0.8468**	
						(0.366)	
Share of REC						-0.0023	
						(0.021)	
Tax						0.5129***	
						(0.187)	
Incentive Investment						-0.0360	
						(0.101)	
Voluntary Program						-0.0467	
						(0.158)	
Obligation						0.4061***	
						(0.131)	
Kyoto							0.3971***
							(0.088)
Wind * policy							0.7448***
							(0.086)
PV * policy							0.4749***
							(0.046)
Geothermal * policy							0.1914***
							(0.060)
Hydro * policy							0.3289***
							(0.106)
Marine * policy							0.3769**
							(0.154)
Biofuel * policy							0.4011***
							(0.102)
Techn * Cnt FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	No	Yes	No	No	No	No	No
Area trend	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Observation	3563	3563	3608	3608	3608	3563	3563
Log likelihood	-4414.05	-4278.17	-4497.63	-4500.16	-4488.51	-4386.21	-4154.66
χ^2	712.03	1450.91	605.57	481.59	626.83	944.75	3322.97

Poisson Estimations, cluster-robust standard error in parenthesis. Cluster unit: Country*technology
*,**,*** indicate significance at respectively 10%, 5% and 1% level.

Table 10: Endogenous Policy Index, FE GMM Poisson. Dep. Variable: Renewable EPO Pat

Specification	I	II	III	IV	V	VI	VII	VIII
Population	0.0001***	0.0001***	0.0001***	0.0001***	0.0001***	0.0001***	0.0001***	0.0001***
	(5.04e-06)	(2.39e-06)	(2.53e-06)	(5.14e-06)	(2.66e-06)	(3.71e-06)	(2.16e-06)	(2.07e-06)
Log Total Patent	0.3376	0.5622***	0.6045***	0.3667	0.7524***	0.9099***	0.6730***	0.6259***
	(0.245)	(0.155)	(0.105)	(0.257)	(0.175)	(0.155)	(0.155)	(0.138)
Log R&D (Ren.)	0.2920***	0.3616***	0.3241***	0.3042***	0.4168***	0.4017***	0.4135***	0.4343***
	(0.092)	(0.053)	(0.074)	(0.110)	(0.080)	(0.072)	(0.084)	(0.074)
Log Past R&D (Ren.)	0.1247	0.2049***	0.1206***	0.1193	0.2505***	0.1117**	0.2590***	0.2994***
	(0.080)	(0.058)	(0.044)	(0.091)	(0.063)	(0.056)	(0.069)	(0.079)
Log Energy Prices	6.0483	6.704*	5.0600*	6.3664	5.6977	5.725*	4.4331	1.4902
	(4.937)	(3.824)	(2.906)	(5.435)	(4.265)	(3.275)	(4.407)	(5.171)
Log Past En. Prices	-11.702*	-15.76***	-13.75***	-11.907*	-16.52***	-15.97***	-14.76***	-13.31***
	(7.061)	(4.849)	(3.839)	(7.187)	(5.440)	(5.663)	(5.154)	(4.571)
Policy Index	0.5287***	0.2792***	0.2608***	0.4942**	0.2190***	0.1360**	0.2153***	0.2233***
	(0.181)	(0.075)	(0.074)	(0.227)	(0.075)	(0.071)	(0.078)	(0.086)
PMR Electr.	-0.24**	-0.609***	-.4432***	-0.2599*	-.6108***	-.4432***	-0.462***	0.3607
	(0.125)	(0.125)	(0.086)	(0.156)	(0.133)	(0.081)	(0.101)	(0.2086)
Gini coefficient	-.4479**	-.5355***	-.4833***	-.4240*	-.5940***	-.4958***	-0.445***	-0.3695**
	(0.232)	(0.198)	(0.150)	(0.250)	(0.191)	(0.155)	(0.165)	(0.151)
Lagged Depend. Var.			0.0024***			0.0030***		
			(0.0008)			(0.0009)		
DG * (1-PMR)							0.1478***	
							(0.064)	
R&D * (1-PMR)								0.4213***
								(0.105)
Country FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Observation	544	524	524	544	524	524	524	524
GMM criterion	1.228e-26	0.0135	0.0103	4.737e-26	0.01417	0.0107	0.0135	0.0122
Hansen test	1.00	0.2136	0.3639	1.00	0.1150	0.2297	0.1318	0.1696
Instruments	Adoption Lead	Kyoto, one year lag GDP, two year lag GDP, Adoption Lead, Gov. Change	Kyoto, one year lag GDP, two year lag GDP, Adoption Lead, Gov. Change	one year lag GDP	Kyoto, one year lag GDP, two year lag GDP, Gov. Change	Kyoto, one year lag GDP, two year lag GDP, Gov. Change	Kyoto, one year lag GDP, two year lag GDP, Gov. Change	Kyoto, one year lag GDP, two year lag GDP, Gov. Change

Dependent variable: Columns I, II, III, IV: Total Renewable patents at EPO (EPO 3); i.e. Wind energy, Solar Thermal energy, Solar Photovoltaic energy, Solar thermal (PV) hybrids, Geothermal energy, Marine energy, Hydro Energy (tidal, Stream or Dameless), Hydro energy Conventional, Biofuel.

Poisson Estimations, cluster-robust standard error in parenthesis. Cluster unit: Country.

*,**,*** indicate significance at respectively 10%, 5% and 1% level.

Table 11: Quality of Patents. Dependent Variable: Renewable USPTO Patents

Specification	**I**	**II**	**III**	**IV**
Dependent Variable	Patent Counts	Green Citations	Patent Counts (Without outliers & Denmark)	Green Citations (Without outliers & Denmark)
Know. Stock (std)	0.0858***	0.1265***	0.0874***	0.1293***
	(0.020)	(0.048)	(0.020)	(0.049)
Green Know. (std)	0.2890***	0.4676***	0.2916***	0.4629***
	(0.0790)	(0.170)	(0.074)	(0.171)
Know. Diver. (std)	0.0790***	0.1644***	0.0837***	0.1613***
	(0.023)	(0.048)	(0.024)	(0.049)
Population	-0.0001**	2.15e-06	-.0001***	2.66e-06
	(7.63e-06)	(0.00001)	(6.78e-06)	(0.00001)
Log R&D (Ren.)	0.0881	0.2893***	0.0746	0.2848***
	(0.086)	(0.093)	(0.090)	(0.092)
Log Past R&D (Ren.)	-0.1193*	-0.3531***	-0.1113*	-0.356***
	(0.064)	(0.053)	(0.065)	(0.054)
Log Energy Prices	0.0586	1.986	-1.0871	2.0257
	(4.960)	(6.615)	(5.181)	(6.648)
Log Past En. Prices	4.5056	7.244	4.0703	7.8008
	(7.347)	(9.683)	(7.823)	(9.795)
PMR electr. (Std)	-0.1243	-0.6544***	-0.1093	-0.648***
	(0.114)	(0.207)	(0.115)	(0.2094)
Gini coeff. (Std)	0.2566	-0.5984	0.3224	-0.6143
	(0.315)	(0.423)	(0.313)	(0.429)
Time trend	-0.057***	-0.0757***	-0.056***	-0.076***
	(0.017)	(0.021)	(0.018)	(0.021)
Feed in Level (Average)	-1.8403	-4.8006	-1.8118	-4.8591
	(1.596)	(3.164)	(1.705)	(3.154)
Dummy R&D Plan	-0.7013	-1.0179	-0.608	-1.069
	(0.542)	(0.768)	(0.559)	(0.775)
Dummy R&D Grant	0.5005***	0.4933**	0.5314***	0.4850**
	(0.121)	(0.240)	(0.132)	(0.241)
Trade Certificate	0.4054*	1.1735**	0.5370**	1.1702**
	(0.228)	(0.490)	(0.222)	(0.519)
Tax	0.1203	0.0255	0.0914	0.012
	(0.091)	(0.111)	(0.092)	(0.107)
Investment Incentive	0.1280**	0.1672***	0.1486**	0.1683***
	(0.064)	(0.055)	(0.063)	(0.056)
Economic incentive	0.1426	0.5163***	0.1665	0.5371***
	(0.134)	(0.157)	(0.133)	(0.152)
Voluntary Program	0.0761	0.1432	0.0825	0.1437
	(0.060)	(0.143)	(0.057)	(0.144)
Obligation	0.2584	-0.6728*	0.1778	-0.6740*
	(0.165)	(0.385)	(0.160)	(0.404)
Country FE	Yes	Yes	Yes	Yes
Year FE	No	No	No	No
Observation	434	361	351	338
Log likelihood	-640.865	-703.30	-597.70	-691.84
χ^2	4.2e+09	7.6e+15	1.5e+16	-1.0e+17

Dependent variable: Patent count at USPTO, Citations in green patent
Poisson Estimations, cluster-robust standard error in parenthesis. Cluster unit: Country
*,**,*** indicate significance at respectively 10%, 5% and 1% level

Table 12: Quality of Patents. Dependent Variable: Renewable USPTO Patents - II

Specification	**V**	**VI**	**VII**	**VIII**
Dependent Variable	Patent Counts (no outliers & Denmark)	Green Citations (no outliers & Denmark)	Patent Counts (no outliers & Denmark)	Green Citations (no outliers & Denmark)
Know. Stock (std)	0.0905***	0.1411***	0.1415***	0.1750***
	(0.023)	(0.0405)	(0.041)	(0.055)
Green Know. (std)	0.3358***	0.6173***	0.0290	0.3579
	(0.076)	(0.156)	(0.109)	(0.267)
Know. Diver. (std)	0.1308***	0.3167***	0.0437	0.2235***
	(0.031)	(0.053)	(0.032)	(0.072)
Population	-0.0001**	0.00001*	0.00002**	0.00005**
	(6.16e-06)	(8.45e-06)	(0.00001)	(0.00002)
Log R&D (Ren.)	0.0892	0.3339***	0.1551	0.4405***
	(0.110)	(0.119)	(0.107)	(0.111)
Log Past R&D (Ren.)	-0.1133	-0.347***	-0.1150	-0.388***
	(0.073)	(0.071)	(0.080)	(0.076)
Log Energy Prices	0.7049	6.8474	5.6380	17.541
	(6.188)	(8.160)	(8.129)	(11.985)
Log Past En. Prices	3.2362	6.087	4.8311	3.9009
	(8.302)	(8.866)	(10.207)	(8.391)
PMR electr. (Std)	-0.1032	-0.630***	-0.287***	-0.807***
	(0.107)	(0.184)	(0.071)	(0.178)
Gini coeff. (Std)	0.3726	-0.3495	0.0456	-0.7955**
	(0.304)	(0.357)	(0.232)	(0.364)
Time trend	-0.0624**	-0.107***	-0.128***	-0.195***
	(0.029)	(0.038)	(0.026)	(0.032)
Feed in Level (Average)	-1.7182	-3.398	0.61635	-0.8670
	(1.466)	(2.217)	(0.5071)	(1.305)
Dummy R&D Plan	-0.6146	-0.9576**	-0.9150**	-1.158**
	(0.564)	(0.756)	(0.462)	(0.586)
Dummy R&D Grant	0.5115***	0.4275**	0.3488***	0.2936*
	(0.127)	(0.211)	(0.085)	(0.176)
Trade Certificate	0.4467**	0.9188**	0.7195***	1.2808***
	(0.234)	(0.387)	(0.239)	(0.452)
Tax	0.0942	0.0635	-0.0593	-0.0246
	(0.094)	(0.108)	(0.107)	(0.153)
Investment Incentive	0.1493**	0.1882**	0.0826	0.1112
	(0.067)	(0.086)	(0.057)	(0.086)
Economic incentive	0.1299	0.3435**	0.0935	0.3550***
	(0.117)	(0.135)	(0.082)	(0.122)
Voluntary Program	0.0503	0.0477	0.0114	-0.0179
	(0.068)	(0.087)	(0.069)	(0.088)
Obligation	0.1464	-0.726**	0.2077	-0.6518*
	(0.155)	(0.371)	(0.172)	(0.367)
Log GDP	-0.1511	-0.1656	-0.8053	-0.6627
	(0.919)	(1.590)	(0.978)	(1.800)
Kyoto	0.2509***	0.7899***	0.1466*	0.6756***
	(0.091)	(0.1808)	(0.087)	(0.175)
Political instability			0.2832***	0.2388
			(0.099)	(0.147)
Log elderly			3.097***	2.213**
			(0.763)	(1.117)
Woman Partecipation			0.333***	0.502***
			(0.0985)	(0.113)
Log education			-0.3430	3.246
			(3.061)	(3.798)
Country FE	Yes	Yes	Yes	Yes
Year FE	No	No	No	No
Observation	351	338	347	334
Log likelihood	-595.27	-669.12	-566.64	-645.32
χ^2	3.5e+16	1.0e+18	-2.7e+16	9.9e+15

Poisson Est., cluster-robust std. err. in parenthesis. *,**,*** indicate significance at respectively 10%, 5% and 1% level

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