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Environmental Policy Flexibility, Search and Innovation*

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Abstract
It has long been argued that the implementation of flexible policy instruments, such as environmentally-related taxes and tradable permits, is likely to lead to greater technological innovation than more prescriptive forms of regulation such as technology-based standards. One of the principle reasons for such an assertion is that they give firms stronger incentives to search for the optimal technological means to meet a given environmental objective. While the theoretical case for the use of flexible policy instruments is well-developed, empirical evidence remains limited. Drawing upon a database of "environmental" patent applications from a cross-section of 73 countries over the period 2001–2003, evidence is provided for the positive effect of "flexibility" of environmental policy regime on innovation. This impact is additional to, and distinct from, the effect of policy stringency.

1. Introduction

Pollution control and innovation are two areas characterized by market failures. Pollution is a negative externality (since elements of the assimilative capacity of the environment are public goods) while innovation is viewed as a positive externality (since elements of the information generated by innovation are public goods). Therefore, without public policies designed to overcome these market failures, firms pollute too much and innovate too little compared with the social optimum. As such, as noted by Jaffe et al. (2005), investments (and thus, innovation) in the development of "green" technology are likely to be below the social optimum because, for such investments, the two markets failures are mutually reinforcing.

It has long been recognized that the characteristics of the environmental policy framework can affect the rate and direction of innovation in pollution abatement technologies. Different policy measures are likely to have different impacts on innovation. For instance, the role of environmental policy stringency on technological innovation has been assessed empirically in a number of recent papers (see, for example, Johnstone and Labonne, 2006). In addition, there is a large body of literature which assesses the role of environmental policy instrument choice on the rate of innovation, with the common finding that market-based instruments are more likely to induce innovation than direct forms of regulation (see Jaffe et al., 2002; Popp et al., 2009 for a literature review). While much of this literature identifies the "flexibility" of market-based instruments as central to this finding, its role is not explicitly addressed. In this paper we seek to assess explicitly the impact of flexible policy regimes on innovative activity with respect to environmental technologies,

* The views expressed here are authors' own and do not necessarily reflect those of the OECD or its members.

using patent data as a proxy for innovation. We define flexibility of policy as a regime which lets the innovator figure out the best way of meeting an objective (whatever that objective might be). We argue that if more "prescriptive" policies are applied, the technology adoption decision is constrained by the precise characteristics of the standard. Thus, in order to induce search for the optimal technology to meet a given environmental objective governments need to allow for more "flexibility" in their policy regimes.

Our analysis considers empirically the role of flexibility of the domestic environmental policy regime on the rate of innovation for environmental technologies. For this purpose, we draw upon a database of patent applications from a cross-section of 73 OECD and non-OECD countries. We find evidence supporting our hypothesis about the significant and independent impact of flexibility on innovative activity. Thus, we show that a more flexible policy regime enhances innovation.

Following this Introduction, Section 2 briefly reviews the anecdotal evidence about the potential role of environmental policy flexibility for innovation. Section 3 describes the data used to measure both innovative activity and policy regulation. Section 4 presents the empirical model and results. Section 5 concludes.

2. Flexibility of Environmental Policy in Practice

When assessing the innovation impacts of different environmental policy instruments, it is helpful to think in terms of the specific characteristics of different environmental policy instruments, and what effect each of these characteristics has on innovation (invention and adoption). Relevant vectors of policy characteristics would include at least the following:

Stringency – i.e. how ambitious is the environmental policy target, relative to the "baseline" trajectory? A stringent policy is more likely to induce innovation than a lax policy since it will increase the opportunity cost of polluting relatively more.[1]

Certainty – i.e. what effect does the policy measure have on investor uncertainty; is the signal consistent, foreseeable, and credible? Given that uncertainty will increase the option value of investments, an uncertain policy will discourage investment in R&D and technology adoption.[2]

Incidence – i.e. does the policy target directly the externality, or is the point of incidence a "proxy" for the pollutant? If the policy targets a proxy for the pollutant, innovation will bend in a direction which is less intensive with respect to the proxy.[3]

Depth – i.e. are there incentives to innovate throughout the range of potential objectives? If the measure does not provide incentives down to zero emissions, the effects on innovation will be blunted.

Flexibility – i.e. does it let the innovator identify the optimal way to meet the objective (whatever that objective may be)? If the policy is inflexible (i.e. prescriptive) there will be little incentive to identify (and adopt) the full range of means of abatement.

[1] This is, of course, just the "environmental" equivalent to Hicks' (1932) induced innovation.

[2] See Johnstone et al. (2009) for a discussion.

[3] See Johnstone et al. (2007).

An environmental policy which is stringent, predictable, targeted, deep and flexible is more likely to induce innovation than one which does not have these characteristics.

Such attributes are often features of market-based instruments. However, while the theoretical case for the use of market-based instruments is well-developed (see, for instance, Jung et al., 1996; Milliman and Prince, 1989; Nentjes and Wiersma, 1987; and Downing and White, 1986), empirical evidence remains limited.[4] Nonetheless, the limited empirical evidence which does exist finds that market-based instruments are effective at inducing innovation. For instance, Popp (2003) finds that following the introduction of the SO_2 permit trading system under the Clean Air Act Amendments in the United States technological innovations led to the improvement in the removal efficiency of scrubbers relative to the situation where the plants were regulated via mandatory standards. Similarly, Newell et al. (1999) find that changes in energy prices (including those induced by taxes) had a positive effect on the commercialization of new more energy-efficient appliances. And finally, the NO_x charge in Sweden induced abatement over a wide range of responses, including fuel switching, modifications to combustion engineering, installation of specific abatement equipment such as catalytic converters and selective non-catalytic reduction, as well as fine-tuning combustion and other processes to minimize emissions (see Millock and Sterner, 2004).

Indeed, it is the "flexibility" of market-based instruments which is often cited as the principal reason for their effectiveness in inducing technological innovation. On the one hand, by encouraging potential inventors to seek out the best means to meet a given environmental objective market-based instruments encourage investment in environmental R&D. On the other hand, by giving the regulated firms the possibility to adopt those technologies which are most appropriate for them they encourage adoption.

However, the juxtaposition between market-based instruments and direct forms of regulation is somewhat misleading. For instance, while a tax on CO_2 is flexible, a differentiated tax for environmentally friendly products is unlikely to be as flexible.[5] In the first case any possible means to reduce CO_2 is potentially attractive, while in the latter case the technological possibilities are constrained by the precise means of tax differentiation. Indeed, to the extent that the criteria for differentiation are based on technological criteria, it could be argued that such a measure would have more similarity with technology-based standards than with a CO_2 tax. Similarly, a performance standard may have more similarities in terms of flexibility with an emissions tax than with a technology-based standard. For instance, if the point of incidence of the performance standard is identical to the base upon which an environmental tax is applied, then they will be equally flexible.[6]

Given that the correlation between broad instrument types (i.e. market-based instruments vs. direct regulation) and instrument characteristics (i.e. stringency, cer-

[4] Popp (2003), Newell et al. (1999), Jaffe and Palmer (1997), and Lanjouw and Mody (1996) demonstrate that environmental innovation responds to incentives such as prices or regulation. Moreover, Popp et al. (2009), Vollebergh (2007), and Jaffe et al. (2002) provide recent reviews of the empirical literature on this theme.

[5] For instance, the application of the "bonus-malus" system on the sales price of motor vehicles in France.

[6] Note, however, that the "depth" of the standard will be shallower since there will be no incentives to innovate beyond the level of the standard.

tainty, incidence, depth, flexibility) is imperfect, it is important to assess empirically the effects of different policy instrument characteristics on innovation. In particular, the role of policy flexibility appears to be central, and the empirical analysis which follows provides some preliminary evidence in the environmental sphere. However, it is important to note that such issues are of relevance in other policy spheres. For instance, both Gann et al. (1998) and Oster and Quigley (1977) discuss the case of effect of building codes and standards on technological innovation.

3. Data Construction and Interpretation

In this section we present the data used in the empirical analysis. In addition to a description of the dependent variable (based on patent counts), measures of policy flexibility and stringency are discussed.

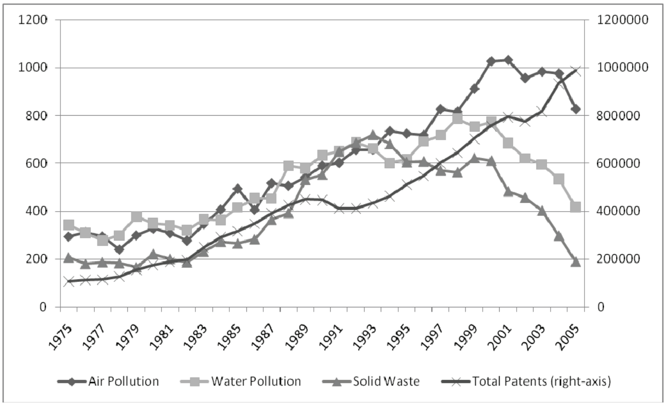
3.1 Environmental Innovation

As noted above, we use patent data to construct a measure of environmental innovation. Patent data have been used as a measure of technological innovation because they focus on outputs of the inventive process (Griliches, 1990; OECD, 2009a). This is in contrast to many other potential candidates (e.g. research and development expenditures, number of scientific personnel, etc.) which are at best imperfect indicators of the innovative performance of an economy since they focus on inputs. Moreover, patent data provide a wealth of information on the nature of the invention and the applicant, the data is readily available (if not always in a convenient format), discrete (and thus easily subject to statistical analysis). Significantly, there are very few examples of economically significant inventions which have not been patented (Dernis and Guellec, 2001). Most importantly for this study, they can be disaggregated to specific technological areas.

Drawing upon existing efforts to define "environmental" activity in sectoral terms, some previous studies have related patent classes to industrial sectors using concordances (e.g., Jaffe and Palmer, 1997). The weaknesses of such approach are twofold. First, if the industry of origin of a patent differs from the industry of use of the patent, then it is not clear to which industrial sector a patent should be attributed in the analysis. This is important when studying specifically "environmental" technology because in this case the demand (users of technology) and supply (inventors of technology) of environmental innovation may involve different entities. Often, "environmental" innovations originate in industries which are not specifically environmental in their focus. For example, technologies aimed at reducing wastewater effluents from the pulp & paper industry are often invented by the manufacturing or chemicals industry (see e.g., Popp et al., 2008). On the other hand, some "environmental" industries invent technologies which are widely applicable in non-environmental sectors (e.g., processes for separation of waste; separation of vapors and gases).

More fundamentally, sectoral classifications are, by definition, based on commercial outputs. As such there will be a bias toward the inclusion of patent applications from sectors that produce environmental goods and services. The application-based nature of the patent classification systems allows for a richer characterization of relevant technologies. Consequently, in this study patent classifications are used, rather than those of industrial or sectoral classifications.[7] Specifically, relevant patents were identified using the International Patent Classification (IPC) system.

Figure 1 General "Environmental" Technologies by Environmental Medium
(Number of patent applications – claimed priorities, worldwide)



Patent data were extracted from the PATSTAT database (EPO 2008) using a search algorithm based on a selection of IPC classes which target specific areas of environment-related technology (see OECD, 2009b for the list of classes included).[8] From the population of patent applications deposited worldwide, we only include the "claimed priorities" because these are considered to be the high-value applications.[9] The patent data are used to construct counts of patent applications in selected areas of environmental technology (air pollution, water pollution, solid waste management), classified by inventor country (country of residence of the inventor) and priority date (the earliest application date within a given patent family). A panel of patent counts for a cross-section of all countries and over a time period of 1975–2006 was obtained.

Figure 1 shows patenting activity in the three environmental domains. Overall, these data suggest a certain level of maturity of this technological field. In particular, innovations related to solid waste management reached a peak in 1993 and have declined since. For water pollution control technologies the peak is in the late 1990s. Finally, only in the case of air pollution control innovations have been increasing rapidly until very recently, keeping pace with the growth in patenting overall (shown on the right-hand axis).

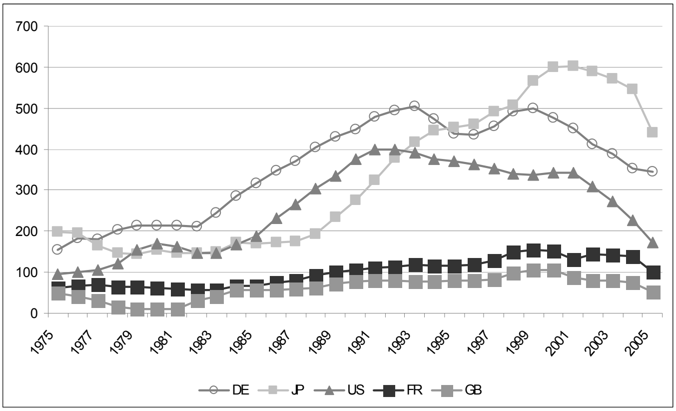
Figure 2 gives patent counts in environmental technology for selected countries which have exhibited significant levels of innovation. Germany had the highest

[7] While Jaffe and Palmer (1997) used patent totals (environmental and non-environmental patents) to study the effect of environmental regulation on innovation, Lanjouw and Mody (1996) and Brunnermeier and Cohen (2003) focus on environmental patents only, and their approach is thus similar to ours. However, in the latter case, details on the selection of IPC classes they used are not provided. Popp (2003) looks at the specific case of NO_x and SO_2 abatement. For a thorough review of the literature and three related empirical papers see OECD (2008).

[8] The selection of classifications benefited from searches developed by Lanjouw and Mody (1996) and Schmoch (2003). Assistance of Julie Poirier and Marion Hemar (ENSAE, Paris) in developing the search strategy is equally acknowledged.

[9] Claimed priority is an invention for which a patent application has been deposited at an additional office to that of the 'priority office'. In other words, these are inventions that have been applied for protection in multiple countries (patent family size > 1).

Figure 2 General "Environmental" Technologies by Inventor Country
(Number of patent applications – claimed priorities, worldwide; 3-year moving average)



number of general environmental patents, with Japan and the US following, until the mid-nineties, when Japan took over leadership. Together with France and the UK, these five countries represent 76% of patent applications in the three domains together. Germany alone is responsible for the highest number of filings in water and waste, while air pollution control is dominated by Japan.

While Germany, Japan, the US, France and the UK are consistently important in environmental technologies examined, other significant innovators in specific areas have included Sweden (air), Canada (water, waste), the Netherlands (water, waste), and Italy (waste). However, a comparison of the productivity of inventive activity across countries needs to account for relative differences in the size of countries' scientific capacity and effort.[10] In *Table 1*, the counts are weighted by country's gross domestic expenditure on R&D to yield a measure of patent intensity. On this basis, a number of smaller countries such as Austria, Finland, or Norway rank high.

3.2 Flexibility of Environmental Policy

In this study we argue that a more flexible environmental policy regime allows firms to search over a wider "space" of abatement options to meet a given environmental objective, and thus to innovate more. Given the heterogeneity of environmental policy regimes both across countries, and within countries across sectors and impacts, it is difficult to construct a general index of the "flexibility" of environmental policy regimes. However, in the period 2001–2003, the *World Economic Forum*'s "Executive Opinion Survey" asked respondents a number of questions related to environmental policy design. The survey is implemented by the WEF's partner institutes in over 100 countries, which include departments of economics in leading universities and research departments of business associations. The means of survey implementation varies by country and includes postal, telephone, internet and face-to-

[10] For example, Madsen (2007) used the ratio of patents and real R&D expenditures as an indicator of countries' research productivity.

Table 1 Environmental Patents per Dollar of General R&D (2001–03)
(Number of "environmental" patent applications – claimed priorities worldwide; Gross domestic expenditures on R&D in USD billions (10e9) using PPP and 2000 prices)

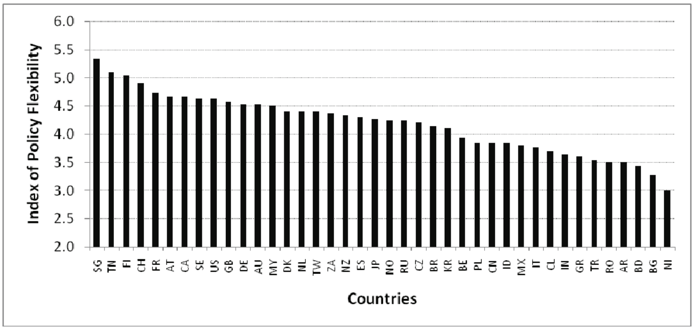
	Air	Water	Waste	Env. tech. combined (AWW)
Germany	**4.49**	**2.03**	1.32	7.68
Austria	1.85	**2.54**	**2.47**	6.33
Finland	1.93	**2.53**	1.82	6.07
Japan	**3.69**	1.26	0.93	5.70
France	1.88	1.46	0.85	4.12
Norway	0.75	1.94	1.02	3.83
Luxembourg	**2.37**	1.19	0.79	3.56
Netherlands	0.59	1.43	1.35	3.40
Belgium	0.83	1.21	1.40	3.32
New Zealand	0.33	1.65	1.32	3.30
Sweden	1.70	0.87	0.75	3.23
Hungary	0.52	1.29	1.55	3.10
Canada	0.83	1.21	1.14	3.00
Czech Republic	0.34	0.80	**1.89**	2.86
Slovak Republic	0.00	0.66	**2.20**	2.86
United Kingdom	0.83	1.23	0.76	2.77
Korea	1.10	1.16	0.65	2.77
Australia	0.33	1.56	1.10	2.76
Italy	0.79	0.88	1.14	2.67
Denmark	0.47	1.22	0.60	2.30
Poland	0.00	1.02	1.04	2.06
Greece	0.00	1.71	0.79	1.98
Spain	0.14	0.96	0.52	1.62
Israel	0.20	0.77	0.47	1.38
Slovenia	0.64	0.64	0.00	1.27
Taiwan	0.30	0.56	0.49	1.23
United States	0.54	0.40	0.24	1.15
Ireland	0.32	0.36	0.48	0.93
Russia	0.25	0.41	0.23	0.83
Singapore	0.12	0.53	0.06	0.65
South Africa	0.28	0.14	0.21	0.63
Mexico	0.26	0.13	0.13	0.52
Iceland	0.00	0.45	0.00	0.45
Romania	0.31	0.00	0.00	0.31
Portugal	0.12	0.12	0.00	0.24
China	0.07	0.10	0.07	0.21
Argentina	0.13	0.00	0.00	0.13

Notes: The top three countries in each field are shown in bold. Note that patent intensity should ideally be calculated using data on "environmental" R&D expenditures; such data however are rarely available.

-face survey. In most years there are responses from between 8,000 and 10,000 firms (see WEF, 2008 for a description of the sampling strategy.)

Specifically, respondents (usually CEOs) were requested to indicate the extent to which they had the freedom to choose different options in order to achieve compliance with environmental regulations. Respondents were requested to assess the degree of flexibility on a Likert scale with 1 = offer no options for achieving compliance,

Figure 3 Index of Flexibility of Environmental Policy Regimes for Selected Countries
(Mean value of the index over 2001–2003)



7 = are flexible and offer many options for achieving compliance. Mean responses for some of the countries included in our sample are provided in *Figure 3*.

3.3 Stringency of Environmental Policy

In previous work on the determinants of environmental innovation, relative policy stringency has been included as the principal environmental policy factor (see, for example, Brunnermeier and Cohen, 2003 and Lanjouw and Mody, 1996). The relative stringency of environmental policy is thought to induce innovation by changing relative factor prices (the idea, discussed in terms of labor costs, goes back to Hicks, 1932). In the context of environmental policy, many regulations take the form of production constraints (rather than explicit price changes), but the effect is analogous. However, measurement of this effect is complicated because cross-country (or cross-sectoral) data on regulatory stringency are rarely available or are not commensurable. Moreover, public policies typically target specific environmental impacts (pollutants) using a specific policy instrument. This paper deals with a broadly-defined (environmental) technology and hence covers multiple impacts and potentially a wide spectrum of policy instruments and sectors. Moreover, it operates in a cross-country context.

In previous studies, data on pollution abatement and control expenditures (PACE) have been used to measure policy stringency. However, in a cross-country study such a variable is inappropriate for two reasons: a) heterogeneity in the definitions used and sampling strategies; b) large numbers of missing observations. In this study, data from the WEF's survey described above are used to measure the stringency of environmental policy. In particular, the degree of perceived stringency of a country's overall environmental regulation was assessed on a Likert scale, with 1 = lax compared with that of most other countries, and 7 = among the world's most stringent. *Table 2* compares the mean responses about the flexibility versus stringency of environmental policy regimes in 40 selected countries.

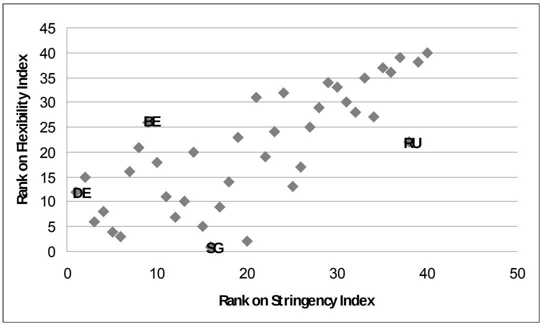
There is a correlation of 0.80 between the two measures of environmental policy. Countries with stringent environmental policies generally are reported to have flexible policies. More obviously, those who rank low in terms of flexibility, also rank low with respect to stringency (with Russia being an exception). However, there are

Table 2 Stringency versus Flexibility of Environmental Policy Regimes
(Mean values of stringency over 2001–2006 and flexibility over 2001–2003)

	Stringency		Flexibility
Germany	6.70	Singapore	5.33
Denmark	6.58	Tunisia	5.10
Austria	6.48	Finland	5.03
Sweden	6.42	Switzerland	4.90
Switzerland	6.40	France	4.73
Finland	6.38	Austria	4.67
Netherlands	6.38	Canada	4.67
Norway	6.22	Sweden	4.63
Belgium	6.07	United States	4.63
New Zealand	6.07	United Kingdom	4.57
Australia	5.90	Australia	4.53
Canada	5.83	Germany	4.53
United Kingdom	5.82	Malaysia	4.50
Japan	5.75	Taiwan	4.40
France	5.73	Denmark	4.40
Singapore	5.73	Netherlands	4.40
United States	5.63	South Africa	4.37
Taiwan	5.28	New Zealand	4.33
Czech Republic	5.10	Spain	4.30
Tunisia	5.03	Japan	4.27
Italy	4.95	Norway	4.23
Spain	4.77	Russian Federation	4.23
Brazil	4.72	Czech Republic	4.20
Chile	4.67	Brazil	4.13
Malaysia	4.65	Korea	4.10
South Africa	4.53	Belgium	3.93
Korea	4.48	China	3.83
Poland	3.98	Indonesia	3.83
Greece	3.97	Poland	3.83
India	3.85	Mexico	3.80
Mexico	3.80	Italy	3.77
Indonesia	3.48	Chile	3.70
Turkey	3.45	India	3.63
China	3.32	Greece	3.60
Romania	3.28	Turkey	3.53
Argentina	3.23	Argentina	3.50
Bulgaria	3.23	Romania	3.50
Russian Federation	3.07	Bangladesh	3.43
Bangladesh	2.58	Bulgaria	3.27
Nicaragua	2.45	Nicaragua	3.00

differences across the two variables. This becomes most clear in the ranking of the countries along the two measures. For instance, while German environmental policy seems to be the most stringent in the sample, the relative lack of flexibility in Germany's policy regulations places the country only twelfth on the flexibility dimension. Belgium also has a relatively inflexible regime in comparison with reported stringency. Singapore and Tunisia are the opposite, with very flexible regulatory frameworks which are not particularly stringent (see *Figure 4*).

Figure 4 Rank of Flexibility and Stringency of the Environmental Policy Regime (mean values)



3.4. Other Explanatory Variables

Aside from public policy, there are other important determinants of patenting activity for environmentally preferable technologies. This includes the propensity to invent technologies in general, and the propensity to obtain any investor protection through existing intellectual property rights (IPR) regimes. Factors such as general scientific capacity, market conditions, openness to trade, etc. will have an important effect on patenting activity in general, and thus also in the specific field of environmental technologies.

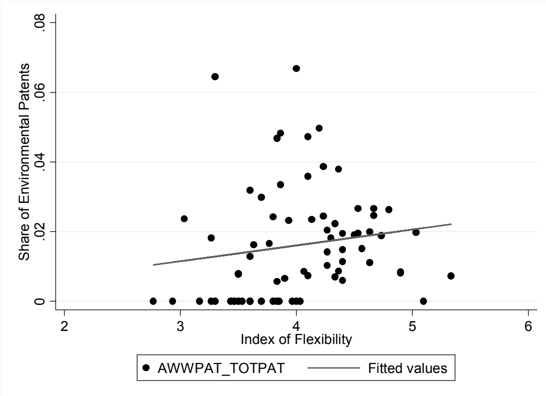
The propensity of inventors from a particular country to patent is likely to change over time, both because different strategies may be adopted to capture the rents from innovation (e.g., Cohen et al., 2000) and because legal conditions may change through time (e.g., Ginarte and Park, 1997). In addition, it is important to control statistically for differences in the propensity to patent across countries. For this purpose, we include a variable reflecting the total number of patent applications (claimed priorities) filed across the whole spectrum of technological fields (not only environmental). This variable thus serves both as a "scale" and as a "trend" variable in that it controls for differences in the effects of the size of a country's research capacity on innovation as well as changes in general propensity to patent over time and across countries. The sign on this variable is expected to be positive.

4. The Model and Empirical Results

In this study we analyze the relationship between the nature of policy regimes and innovation. *Figure 5* shows a scatter plot of the flexibility of environmental policy regimes (mean responses for the period 2001–2003 for 73 OECD and non-OECD countries) and the share of environmental patents on total patents (shown as mean values for the same panel). The plot suggests a positive linear relationship (correlation 0.27, statistically significant at the 1% level).

In addition to flexibility of the policy regime, there are a number of other factors that may affect an individual country's innovative activity with respect to the environment. Most significantly, the stringency of environmental policy plays a role. However, in the previous section we show that the two measures characterizing environmental policy (flexibility and stringency) are highly correlated (0.80). This

Figure 5 Flexibility of Environmental Policy Regimes and "Environmental" Patenting



may lead to multicollinearity if we consider them jointly in a regression. To deal with this potential problem we apply the method of factor analysis to construct a new variable (*FACTOR*). Stringency and flexibility are modeled as linear combinations of the factor plus error term. This variable (*FACTOR*) is normally distributed with a mean of 0 and variance close to 1. In the empirical analysis *FACTOR* will account for the joint impact of flexibility of the policy conditions and stringency of environmental regulations on innovative activity with respect to environmental technologies. It will be possible to identify the individual effect of policy flexibility by comparing the coefficient estimate of *FACTOR* with the one of *STRING*.

Second, general scientific and research capacity and the rate of innovation are likely to change through time due to factors such as strengthening of IPR regimes in many countries. To the extent that increases in patenting in environmental technologies arise out of factors which relate to innovation in general, it is important to control for these country-specific and time-specific effects. This has been achieved by including a variable which reflects innovative activity for all technology classifications. Ideally, we would estimate the model using a two-stage procedure of the form *AWWPAT* = *f*(*ENVPOLICY,TOTPAT*), where total patenting activity is first estimated as *TOTPAT* = *g*(scientific capacity, market conditions, openness, etc.). This approach was followed in OECD (2009b) and it was found that results from the two--stage estimation were closely comparable with those from a reduced-form model. However, in this paper the width of our panel prevents us from following this approach because the sample size shrinks significantly due to lack of data for non-OECD countries. Therefore, we only present results of a reduced-form model where *TOTPAT* is considered to be exogenous. The model takes the following form:

$$AWWPAT_{i,t} = \beta_1 ENVPOLICY_{i,t} + \beta_2 TOTPAT_{i,t} + OECD_i + \alpha_t + \varepsilon_{i,t}$$

where i indexes country and t indexes year. The dependent variable represents the number of patent applications in selected areas of environmental technology – air, water, and waste ($AWWPAT_{i,t}$). In the place of the environmental policy variable, in the "base" model we include a variable which reflects the reported stringency of environmental policy ($STRING_{i,t}$). This is then compared with a model in which the score for the joint stringency/flexibility factor variable ($FACTOR_{i,t}$) is included.

Table 3 Descriptive Statistics (2001–2003

Variable	Unit	Obs	Mean	Std.	Min	Max
AWWPAT	Count	204	29.438	94.218	0	622
FLEX	Index	204	4.016	0.608	1.700	5.400
STRING	Index	204	4.388	1.314	1.200	6.700
FACTOR	Normalized	204	0.000	0.871	-2.895	1.804
TOTPAT	Count	204	1991.419	6542.097	0	41904

In addition, a variable reflecting the propensity to invent and patent technologies in general ($TOTPAT_{i,t}$) is included. Finally, year fixed effects (α_t) account for omitted time-variant effects that influence all countries in the same way. All the residual variation is captured by the error term ($\varepsilon_{i,t}$). Convergence problems and little variation of our policy variables over time prevent us from including country fixed effects; however, we add a dummy indicating membership in the OECD.[11] Given the count nature of the dependent variable, a negative binomial model is used to estimate the model (for details on count data models see e.g., Cameron and Trivedi, 1998; Maddala, 1990; Hausman, Hall and Griliches, 1984).

The variables measuring the characteristics of environmental policy regimes (*STRING, FLEX)* cover a wide range of OECD and non-OECD countries but are only available for a period of six years (2001–2006) and three years (2001–2003), respectively, with corresponding time ranges for the constructed *FACTOR* variable. Another important characteristic of the data is that more than 60 percent of the observations of the dependent variable – the number of patent applications in air, water, and waste – are equal to zero. Descriptive statistics for the "base" estimation sample are provided in *Table 3*.

First, we estimate the model on a balanced sample of 73 OECD and non-OECD countries over the period 2001–2003. *Table 4* reports the empirical results. Models (1a) and (1b) consider the effect of environmental policy regime over the whole sample in a pooled estimation, while models (2a) and (2b) include year fixed effects. In order to isolate the distinct effect of environmental policy flexibility on innovation we compare the coefficients of *FACTOR* and *STRING*. The estimate of *FACTOR* is positive and highly significant in all model specifications estimated. The coefficient of *STRING* is also positive and significant. Most importantly, the coefficient of *FACTOR* is always larger than that of *STRING*, policy stringency. The same holds if we compare the corresponding marginal effects (shown in *Table 6*). These results clearly indicate that policy flexibility has a positive and statistically significant impact on inventive activity in environmental technologies (air, water, waste) that is distinct from, and additional to, the effect of policy stringency. Despite the high correlation between the two policy variables, these are included jointly in a regression in model (3). Both regressors have a positive and significant coefficient estimate, but the statistical significance for flexibility is somewhat lower pointing at the multicollinearity problem. The coefficient of the TOTPAT variable is positive and highly significant suggesting that patenting activity in the selected environmental technologies is also explained by variation in total patenting across countries and over time.

[11] Including a dummy for EU membership yields similar results.

Table 4 Empirical Estimates of the Negative Binomial Regression (2001–2003)

Dependent variable: *AWWPAT_it*	(1a)	(1b)	(2a)	(2b)	(3)
Policy Stringency (*STRING_it*)	0.612*** (0.113)		0.611*** (0.113)		0.342* (0.157)
Policy Flexibility (*FLEX_it*)					0.890* (0.349)
Factor of Policy (*FACTOR_it*)		1.056*** (0.174)		1.082*** (0.176)	
Total Patents (*TOTPAT_it*)	0.144*** (0.028)	0.139*** (0.025)	0.145*** (0.028)	0.138*** (0.025)	0.138*** (0.025)
Intercept	-1.839** (0.538)	1.705*** (0.200)	-1.728** (0.601)	0.871** (0.264)	-4.223*** (1.013)
OECD dummy	0.988*** (0.271)	1.195*** (0.297)	0.993*** (0.271)	1.155*** (0.288)	1.209*** (0.303)
Year fixed effects	No	No	Yes	Yes	Yes
N	204	204	204	204	204
Log Pseudolikelihood	-552.30	-546.56	-552.03	-545.77	-545.72
(Prob>Chi2)	0.000	0.000	0.000	0.000	0.000

Note: Robust standard errors in parentheses. * $p<0.05$, ** $p<0.01$, *** $p<0.001$.

Table 5 Empirical Estimates of the Negative Binomial Regression (2001–2006)

Dependent variable: *AWWPAT_it*	(4a)	(4b)	(5a)	(5b)
Policy Stringency (*STRING_it*)	0.464*** (0.087)		0.483*** (0.083)	
Factor of Policy (*FACTOR_it*)		0.892*** (0.113)		0.912*** (0.109)
Total Patents (*TOTPAT_it*)	0.157*** (0.023)	0.148*** (0.020)	0.161*** (0.024)	0.151*** (0.021)
Intercept	-1.513*** (0.420)	0.576*** (0.158)	-1.308** (0.482)	0.860*** (0.244)
OECD dummy	1.213*** (0.203)	1.180*** (0.208)	1.242*** (0.187)	1.220*** (0.191)
Year fixed effects	No	No	Yes	Yes
N	381	381	381	381
Log Pseudolikelihood	-1010.68	-999.32	-1001.81	-989.64
(Prob>Chi2)	0.000	0.000	0.000	0.000

Note: Robust standard errors in parentheses. * $p<0.05$, ** $p<0.01$, *** $p<0.001$.

Next, we estimate the model on the time period 2001–2006 so that we can fully exploit the availability of the stringency index. In this panel, the stringency variable varies over time (2001–2006) and the *FACTOR* variable is constructed with one component which varies (*STRING*) and one which does not (we take the 2001–2003 average of *FLEX* for each year). The results in *Table 5* suggest that the findings remain robust even if models are estimated on a different panel.

Marginal effects corresponding to the estimated coefficients of the policy variables are reported in *Table 6*.

Finally, we consider estimating the model on averages. Since our measures of environmental policy vary little over time, estimating a panel may be regarded as an unjustified inflation of the sample size. We therefore collapse all variables to their

Table 6 Estimated Marginal Effects

Dependent variable: *AWWPAT_it*	(1)	(2)	(3)	(4)	(5)
Policy Stringency (*STRING_it*)	2.911***	2.890***	1.514*	2.105***	2.087***
Policy Flexibility (*FLEX_it*)			3.931*		
Factor of Policy (*FACTOR_it*)	4.716***	4.786***		3.779***	3.684***

Note: * p<0.05, ** p<0.01, *** p<0.001.

Table 7 Empirical Estimates Using the Average Values (average over 2001–2003)

Dependent variable: *AWWPAT_avg_i*	(6a)	(6b)
Policy Stringency (*STRING_avg_i*)	0.635** (0.191)	
Factor of Policy (*FACTOR_avg_i*)		1.099*** (0.260)
Total Patents (*TOTPAT_avg_i*)	0.148** (0.051)	0.139** (0.043)
Intercept	-2.001* (0.894)	0.418 (0.316)
OECD dummy	0.989* (0.434)	1.125* (0.464)
N	73	73
Log Pseudolikelihood	-190.69	-188.41
(Prob>Chi2)	0.000	0.000

Note: Robust standard errors in parentheses. * p<0.05, ** p<0.01, *** p<0.001.

2001–2003 averages. The results (*Table 7*) concur with our previous findings, thus confirming our principal hypothesis of the positive impact of flexibility of environmental policy on innovation.

In additional analyses, we split the sample into OECD and non-OECD countries, we consider only countries with positive values of patenting activity, we include lagged values of the policy variables as controls, and exclude outliers from the sample such as the largest innovators. All these robustness checks yield similar results both in size and magnitude to the "base" model.[12]

5. Conclusions

Using patent counts as a measure of environmental innovation, empirical evidence has been presented which supports the hypothesis that increased flexibility of environmental policy can result in greater innovation in environmental technologies. For a given level of policy stringency, the more "inflexible" a policy regime, the less innovation takes place. This implies that rather than prescribing certain abatement strategies (such as technology-based standards), governments should give firms stronger incentives to look for the optimal technological means to meet a given environmental objective. This is important because if firms are allowed to search across a wider "space" to identify the means of complying with regulations, the objectives of environmental policy will be met at lower cost.

[12] Estimation output will be provided upon request.

However, it should be emphasized that the evidence presented is preliminary for a number of reasons. Firstly, the measure of policy flexibility (and stringency) is imperfect, based on CEO's subjective "perceptions" of environmental policy flexibility. A more objective measure of policy flexibility would be preferable. Secondly, a "deeper" panel would help to disentangle the correlated effects of policy stringency and flexibility in a more satisfactory manner. The approach adopted in this paper is constrained by the small (and shallow) nature of the sample. And finally, there may be a degree of endogeneity between the measure of general innovation and environmental innovation. Previous work has indicated that this should not result in a significant bias, but it is a concern.

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