Environmental Policy Characteristics and Technological Innovation

by Nick Johnstone, Ivan Haščič and Margarita Kalamova

1. Introduction

Inducing environmental innovation is a significant challenge to policymakers. On the one hand, pollution is a negative externality (since elements of the assimilative capacity of the environment are public goods). On the other hand innovation is a positive externality (since elements of the information generated by innovation are public goods). Therefore, without public policies designed to overcome these two 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 can affect the rate and direction of innovation in pollution abatement technologies. For instance, the role of environmental policy on technological innovation has been assessed empirically in a number of recent papers (see, for example, Johnstone - Labonne, 2006). However, different policy measures are likely to have different impacts on innovation. 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).

However, there can be as much variation within policy types, as between them. Two market-based instruments (i.e. a tax on carbon emissions relative to environmentally-motivated product tax differentiation) may be as different from each other as each is in relation to some forms of direct regulation.

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Therefore, the stark juxtaposition between market-based instruments and direct forms of regulation is somewhat misleading. It is more helpful to think in terms of attributes of characteristics of different policies, and what effect each of these characteristics has on innovation. Relevant attributes would include at least the following: stringency; depth; incidence; flexibility; and stability.

The key point is that correlation between instrument types and policy design attributes is imperfect. Any incentives for innovation arise out of the underlying policy attributes and not the broad policy type *per se*. As such, it is important to assess incentives for innovation in terms of the underlying policy attributes rather than by broad instrument type. Because of this imperfect correlation, it is necessary to disentangle the distinct effect of each of these attributes empirically. Until recently the empirical literature has not generally examined the specific role of these different policy attributes on environmental innovation.

Drawing upon the EPO/OECD World Patent Statistics (PATSTAT) database of patent applications from over 80 national patent offices we empirically examine the individual effects of three of these factors (stringency, stability and flexibility), as measured by the World Economic Forum Survey on environmental policies. Evidence is found that both stability and flexibility have distinct effects on innovation above and beyond the effect of policy stringency.

The paper is structured as follows: following this brief introduction, Section 2 reviews the literature and presents the hypotheses to be tested; Section 3 presents the data on «environmental» innovation derived from the database; Section 4 presents the model and the results; and in Section 5 the paper concludes with a discussion of the policy implications.

2. Review of the Literature and Principal Hypotheses

Assessing the determinants of «environmental» innovation (as reflected in patenting activity) requires an understanding of the determinants of innovation more generally. Indeed, aside from environmental policy, there are, of course, other important determinants of innovation for environmentally preferable technologies. Factors such as general scientific capacity, market conditions, openness to trade, etc. will also have an important effect on innovation in general, and (see Jaumotte - Pain, 2005 for some recent evidence). Such factors are also likely to influence the specific field of environmental technologies.

Moreover, not all inventions are patented, and this may vary across time and countries. For instance the characteristics of intellectual property rights (IPR) regimes are likely to have a significant effect on the propensity to seek protection through the IPR regime rather than by some other means (e.g. industrial secrecy). 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 - Park, 1997).

However, relative to other fields of innovation, it is evident that in the case of environmental technologies the regulatory framework plays a particularly important role. In general, a strong case has been made for the use of market-based instruments (e.g. taxes, tradable permits), rather than direct regulation (e.g. technology-based controls, performance standards) in order to induce innovation (see Jaffe *et al.*, 2002; and Popp *et al.*, 2009, for a review)[1]. In particular, it is argued that the rate of innovation under market-based instruments is likely to be greater, since a greater proportion of benefits of technological innovation and adoption will be realised by the firm itself than is the case for many direct forms of regulation. Moreover, since market-based instruments are not usually «prescriptive», they are more likely than many types of direct regulation to ensure that the direction of technological change is cost-minimising with respect to the avoidance of damages[2]. This usual taxonomy is sometimes complemented by review of measures designed to address related (but distinct) market failures, i.e. information-based measures, technical assistance, etc.

However, the stark juxtaposition between market-based instruments and direct forms of regulation is somewhat misleading. It is more helpful to think in terms of vectors of characteristics of different instruments, and what effect each of these characteristics has on innovation. Relevant vectors would include at least the following:

– *Stringency* – i.e. how ambitious is the environmental policy target, relative to the «baseline» emissions trajectory?;

– *Predictability* – i.e. what effect does the policy measure have on investor uncertainty; is the signal consistent, foreseeable, and credible?;

– *Flexibility* – i.e. does it let the innovator identify the best way to meet the objective (whatever that objective may be)?;

– *Incidence* – i.e. does the policy target directly the externality, or is the point of incidence a «proxy» for the pollutant?; and

– *Depth* – i.e. are there incentives to innovate throughout the range of potential objectives (down to zero emissions)?.

There is no precise mapping from instrument type to each of these vectors. For instance, different environment-related taxes may have very different attributes. A tax on CO_2 is flexible, targeted, deep, and often predictable. However, a differentiated tax for «environmentally friendly products» is not very flexible, targeted or deep. Indeed, depending upon how the tax rate is determined, such a measure may actually have more similarity with technology-based standards than with an emissions tax.

More generally, a performance standard with a similar point of incidence (i.e. on the pollutant itself) and degree of flexibility may have more similari-

[1] OECD (2008) assesses the role of six different instrument types on innovation in renewable energy.

[2] See Jaffe *et al.* (2002).

ties with a tax than with a technology-based standard. While it does not provide the same «depth» of incentive – i.e. there is no incentive to go beyond the standard[3] – in other respects it is likely to have similar innovation impacts as an emissions tax.

The effect of **stringency** on innovation is a correlate to the Hicksian notion that a change in the relative prices of factors of production will motivate firms to invent new production methods in order to economise the use of a factor which has become relatively expensive. Originally developed in the context of labour economics, this idea came to be known as the «induced innovation hypothesis». Applied to the environmental policy framework, it implies that if governments could affect relative input prices, or otherwise change the opportunity costs associated with the use of environmental resources, firms' incentives to seek improvements in production technology which save on these inputs would be increased. Since markets often fail to put a price on environmental resources, the opportunity costs of many environmental assets is to a large extent formed by government regulation.

By imposing a price (whether explicitly or implicitly) on the costs of pollution emissions, or by otherwise changing the opportunity costs associated with environmental assets, environmental policy is likely to induce innovation – because firms seek to meet the policy objectives at least cost. Of course, different policy measures may be more or less likely to induce innovation. Irrespective of the nature of the instrument applied, some innovation is likely to be induced. However, as argued previously, policy stringency is only one aspect of the public policy regime which affects the rate of innovation. Other potentially important aspects are discussed next.

While theoretical work has shown that stringent environmental regulation may provide incentives for technological improvements, empirical evidence on the effect of stringency of environmental policy on innovative behaviour remains limited (for recent reviews of the empirical literature on this theme see Popp *et al.*, 2009; Vollebergh, 2007; Jaffe *et al.*, 2002). The major reason is that the effect is unobservable to a researcher; hence, its measurement is complicated. As a consequence, 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.

A number of imperfect proxies have been used in the literature. This includes reported data on pollution abatement and control expenditure measured at the macroeconomic (e.g., Lanjouw - Mody, 1996) or sectoral level (e.g., Brunnermeier - Cohen, 2003), the frequency of inspection visits (e.g., Jaffe - Palmer, 1997), parameterisation of policy types (e.g., Fischer - Newell, 2008), or various derived measures based on the point of policy implementation (e.g., Johnstone *et al.*, 2010 and Johnstone - Labonne, 2006). In general

[3] Unless it is assumed that the standard itself will change as a consequence. See Milliman - Prince (1989).

the results which are consistent with stringent environmental policy will induce environment-saving innovation.

Policy **predictability** can reduce uncertainty for investors. This is important since it is well-known that economic uncertainty can be a significant «brake» on investment (see Pindyck, 2007; Dixit - Pindyck, 1994). However, this may be particularly true of investments in R&D, which are by nature risky and with uncertain outcomes. This is compounded by the fact that such investments are irreversible; should market conditions change, «sunk costs» cannot be recovered in the market. Both characteristics (uncertainty and irreversibility) thus give rise to a commercial risk associated with innovative activities. Investment in R&D is therefore often sub-optimal. For instance, in a panel data study of nine OECD countries covering the period 1981-1992, Goel - Ram (2001) find a much sharper adverse effect of uncertainty on R&D investments than on non-R&D (and aggregate) investments.

In the case of «environmental» innovations, this market uncertainty can be compounded by environmental policy uncertainty. This may arise due to concerns over the «stability» of the policy framework, as well as of the signals provided by the policy itself. In such cases, predictable signals and «irreversible» investments give rise to great option values, implying strong incentives to postpone investments[4]. Recent work at the IEA (2007) has examined this issue in the context of climate policy uncertainty.

As such, it might be supposed that governments which do not provide clear signals about policy intentions over the duration of firms' planning horizons will retard investment in innovation. In particular, if the future trajectory of the costs associated with policies is uncertain, individual firms may choose to wait before undertaking investments which seek to identify means of reducing this cost (i.e. before investing in environmental R&D). Since expectations concerning the path of future environmental policy can be a key determinant of perceived uncertainty over the firm's planning horizon, policy predictability can play an important role in inducing environmental innovation, and one which is distinct from that played by policy «stringency».

The effect of policy uncertainty on innovation with respect to environmental technologies has not been examined empirically. (For a recent paper which looks at the role of policy uncertainty on abatement investment decisions, rather than innovation *per se*, see Löfgren *et al.*, 2008.) However, there is significant anecdotal evidence in the area of renewable power development to support the hypothesis that policy stability has played at least as important a role as policy stringency (see Söderholm *et al.*, 2007; Wiser - Pickle, 1998; Barradale, 2008). For instance, Barradale (2008) argues that in the case of the United States, uncertainty concerning the annual renewal of the

[4] In the environmental context, irreversibilities are partly a function of the nature of investments – i.e. end-of-pipe abatement vs. change-in-production processes.

federal production tax credit (PTC), discouraged investment in renewable energy. This finding is supported by anecdotal evidence presented in Wiser - Pickle (1998) concerning both wind and solar power. In a comparison of wind power development in Denmark, Germany and Sweden, Söderholm *et al.* (2005) argue that the relatively slow pace of development in Sweden is due to instability in the policy framework, more than the actual level of support, with a number of different subsidy programmes implemented successively for short periods of time.

The effects of frequent policy changes on long-term investments can, therefore, be considerable. Since the planning horizon for investments in innovation is particularly long, such investments are likely to be significantly affected by policy instability. A history of abrupt policy changes can discourage investment, and this is likely to be exacerbated by the perception that such instability is likely to continue. Interestingly, Barradale (2008) provides evidence that perceived uncertainty is correlated with instrument choice. Investors in the sector believed that renewable energy portfolio standards were more likely to stay in effect long enough to influence long-term investment decisions than depreciation rules, tax credits, feed-in tariffs or production subsidies.

The role of the **flexibility** of environmental policy measures on innovation has also not been examined closely. In this paper we assess whether more flexible policies (of equal stringency) induce more innovation than prescriptive policies. The hypothesis is that if more «prescriptive» policies are applied, technology invention and adoption decisions are 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 should seek to allow for more flexibility in their policy regimes when this can be achieved at reasonable administrative cost.

The most prominent example of a flexible environmental policy is the US Clean Air Act Amendments (CAAA) of 1990 which sought to reduce SO_2 emissions by implementing a tradable permit system in place of direct regulations. The programme was designed to encourage the electricity industry to minimize the cost of reducing emissions. The industry is allocated a fixed number of total allowances, and the firms are required to surrender one allowance for each ton of sulphur dioxide emitted by their plants. Firms may transfer allowances among facilities or to other firms, or bank them for use in future years.

Prior to the CAAA, plants were required to use the best available technology for pollution control, which was a scrubber. As a result, while there were incentives for innovation that would lower the cost of installing and operating scrubbers, there would be little incentives for innovation to improve the efficiency of the scrubbers (that is, ability to actually remove pollutants) (see Bellas, 1998.) Moreover, the most significant benefits of the trading system was that it gave firms the freedom to search for all possible technologies to reduce SO_2 emissions (see Burtraw, 2000).

As an alternative example, consider the NO_X charge in Sweden. The introduction of a rather stringent tax on NO_X emissions, supported by close monitoring, created a strong incentive for polluting firms to search for abatement options. Most significantly, the tax 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 noncatalytic reduction, as well as fine-tuning combustion and other processes to minimize emissions (for more detail on the Swedish NO_X charge, see Millock - Sterner, 2004).

Both of these examples relate to market-based instruments: tradable permits; and, environmentally-related charges. However, it is important not to conflate market-based instruments with policy flexibility and direct regulations with inflexibility. Some market-based instruments can be prescriptive (e.g. differentiated value-added taxes based upon technical criteria of the product) and some direct forms of regulation can be flexible (e.g. performance standards in which the point of incidence is the pollutant itself). In such cases the direct regulation may well provide greater space for potential technologies than a market-based instrument, thus inducing more innovation.

Drawing upon the PATSTAT database of patent applications, we argue that the different types of environmental policy regimes have an important and distinct role in encouraging innovation. The principal hypotheses to be examined are:

– H_1: policy stringency has an effect on invention.

– H_2: policy stability has an effect on invention above and beyond that of stringency.

– H_3: policy flexibility has an effect on invention above and beyond that of stringency.

– H_4: policy stability and flexibility have a joint effect on innovation above and beyond that of stringency.

These hypotheses are tested by drawing upon the WEF survey data on policy attributes and the EPO/OECD PATSTAT database of patent documents.

3. Data on Environmental Innovation and Policy

3.1. *Environmental Innovation*

In order to test these hypotheses data on the extent of innovation across time and countries is required. This section describes trends across countries and over time for selected general environmental technologies (including air pollution control, water pollution control, and solid waste management) as well as climate change mitigation using patent data. The data were extracted from the PATSTAT database (EPO, 2008) using a search algorithm devel-

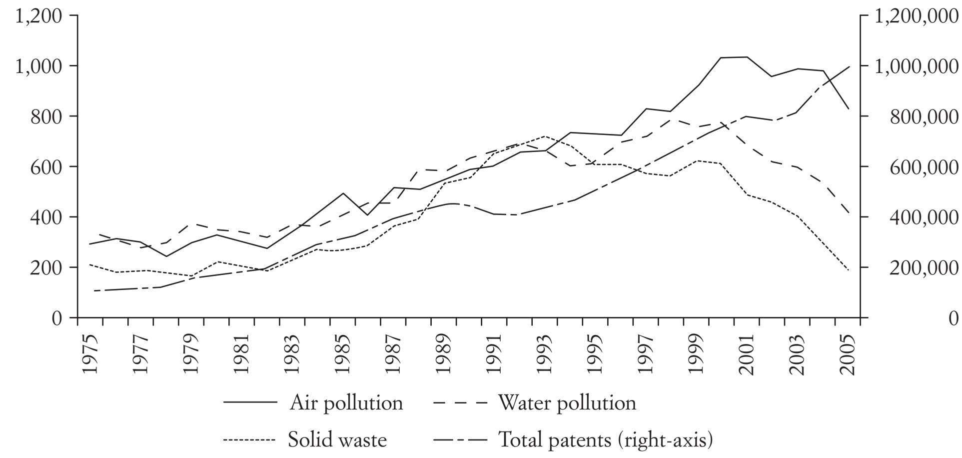

FIG. 1. General «environmental» technologies by environmental medium (number of patent applications-claimed priorities, worldwide).

oped at the OECD and based on a selection of IPC classes (see www.oecd.org/env/cpe/firms/innovation)[5].

Indicators of innovation were constructed based on counts of patent applications (claimed priorities, worldwide) in the selected areas of environmental technology, classified by inventor country (country of residence of the inventor) and priority date (the earliest application date within a given patent family). In order to ensure that only high-value patents are included only applications in which protection has been sought in at least two offices (i.e. «claimed priorities») are included[6]. A panel of patent counts for a cross-section of all countries and over a time period of 1975-2007 was obtained.

Search strategies were developed for different areas, including:

– air pollution abatement from stationary sources;
– wastewater effluent treatment;
– solid waste management (landfill disposal, recycling, incineration and some aspects of prevention); and,
– climate change mitigation.

Data on the first three categories are presented in Figure 1 relative to the rate of patent activity overall. The data suggest a recent stagnation in the rate of innovation in these areas. In particular, innovations related to solid waste management reached a peak in 1993 and have declined since. For water pollu-

[5] The selection of classifications benefited from searches developed by Lanjouw - Mody (1996) and Schmoch (2003). Assistance of Julie Poirier and Marion Hemar (ENSAE, Paris) in developing the search strategy is equally acknowledged. See www.oecd.org/environment/innovation/indicator for a discussion of the search strategies.

[6] See Guellec - van Pottelsberghe (2000) and Harhoff *et al.* (2003) for empirical evidence supporting this approach.

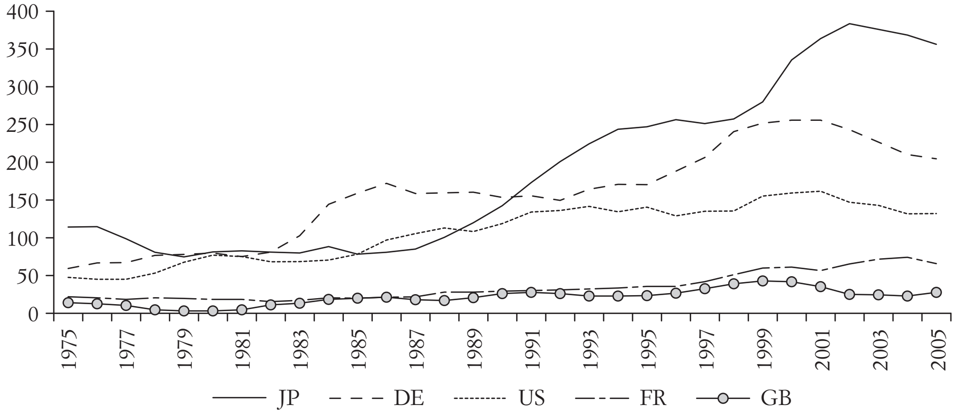

FIG. 2. Air pollution abatement and control technologies (number of patent applications-claimed priorities, worldwide; 3-year moving average).

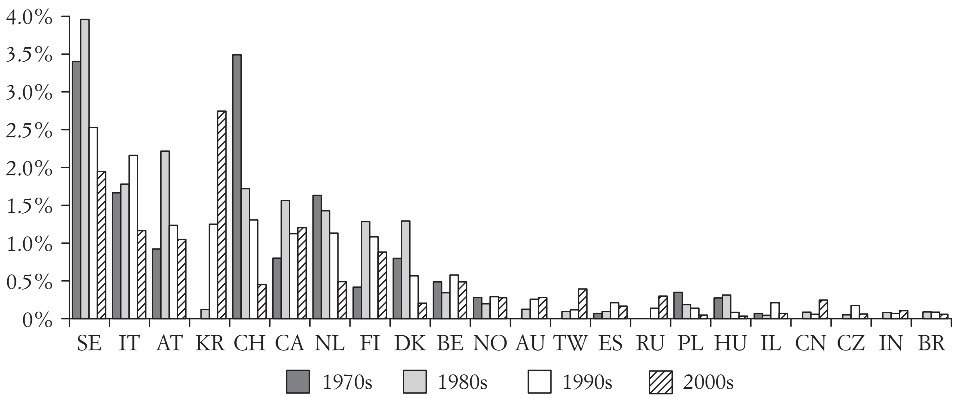

FIG. 3. Air pollution abatement and control technologies (share of world patenting by inventor country).

tion control technologies, the peak occurred in the late 1990s. Only 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).

The domain of air pollution abatement and control includes technologies that limit emissions of local air pollutants from stationary sources (e.g., SO_X, NO_X, PM). Figure 2 gives patent counts for selected countries with the highest levels of innovation in air pollution abatement, including Germany, Japan, the US, France, and the United Kingdom. While these countries are consistently important in environmental technologies examined, other significant innovators in air pollution control have included Sweden, Italy, Austria, and very recently also Korea (Fig. 3).

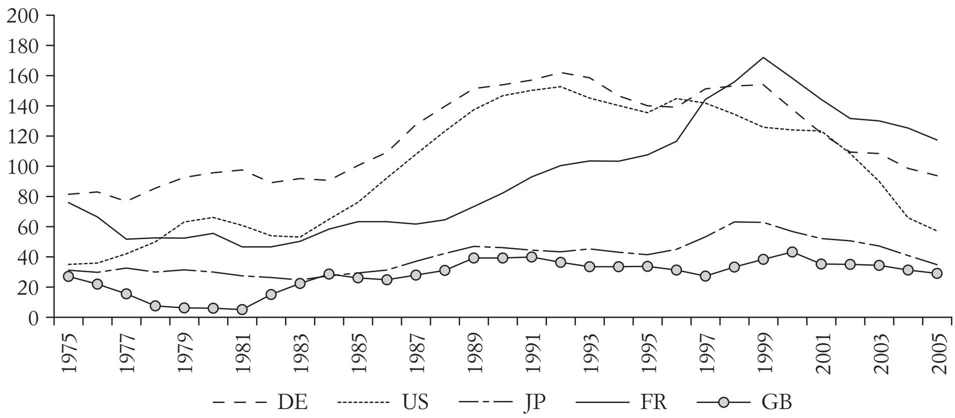

FIG. 4. Water pollution abatement and control technologies (number of patent applications-claimed priorities, worldwide; 3-year moving average).

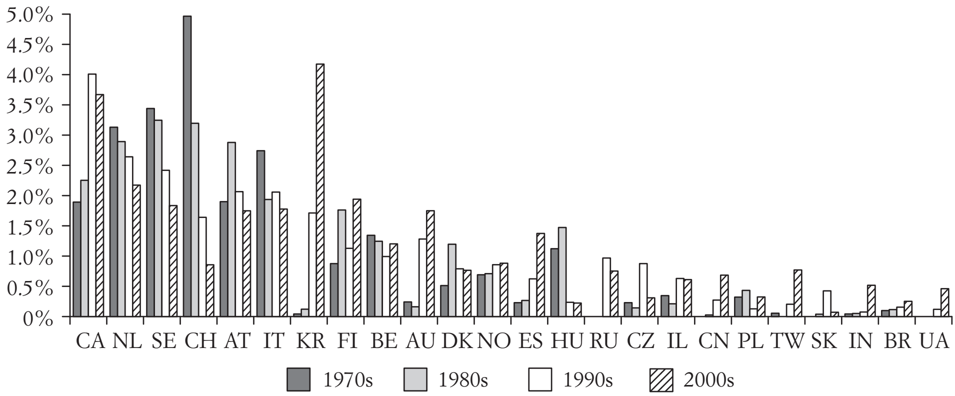

FIG. 5. Water pollution abatement and control technologies (share of world patenting by inventor country).

The water pollution abatement and control technologies identified here include all wastewater treatment techniques – primary (mechanical), secondary (biological) and tertiary (chemical) treatment technologies. Figure 4 gives patent counts for the five major inventor countries, suggesting that Germany and the US have historically been the major innovators, with Japan taking the lead more recently. Other significant innovators in this field have included Canada, the Netherlands, Sweden, and more recently Korea, Australia and Spain (Fig. 5). The rate of growth of this type of innovation in Korea and especially in China in recent years has been startling, increasing four-fold in the period 1999-2004. This is in marked contrast to developments else-

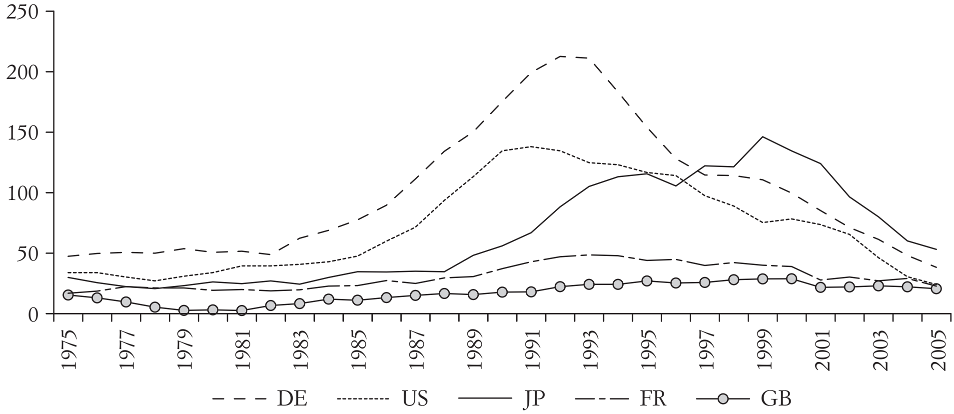

FIG. 6. Solid waste management technologies (number of patent applications-claimed priorities, worldwide; 3-year moving average).

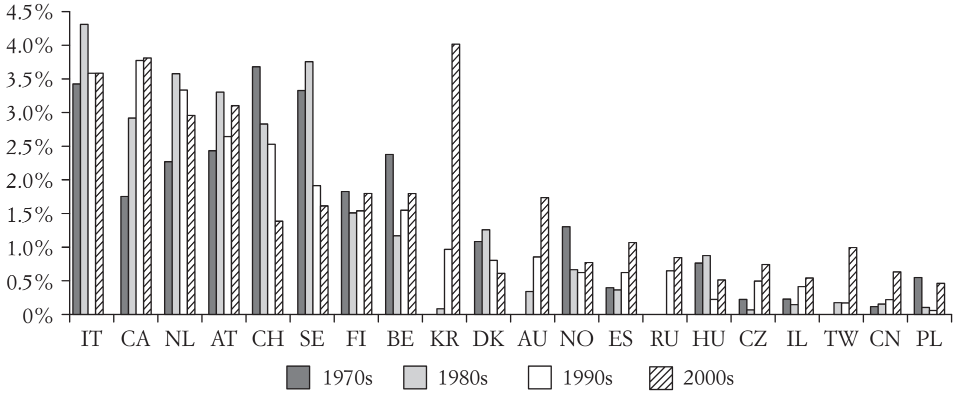

FIG. 7. Solid waste management technologies (share of world patenting by inventor country).

where, with patent counts for most of the large innovating countries actually decreasing in recent years.

The domain of solid waste management includes technologies that relate to waste disposal and landfilling, as well as incineration, energy recovery, material recycling and some aspects of waste prevention. As can be seen in Figure 6, there has been a marked decrease in patent activity in this area since a peak in the early 1990s, with German inventors dominating the field throughout the 1980s and 1990s. Among the medium-sized inventor countries (Fig. 7), Italy and Canada have sustained a relatively strong performance. Fast growth rates in the sector have recently been recorded by inventors in Korea, Taiwan, China, and Poland.

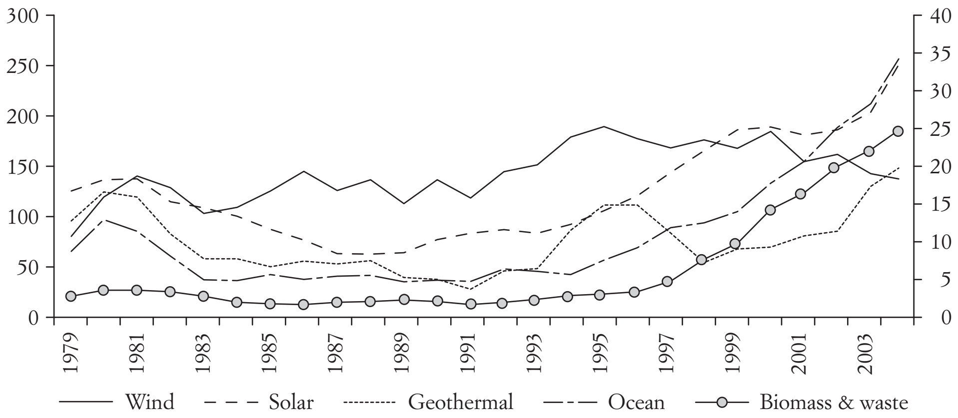

FIG. 8. Patenting activity for renewables by type of technology (number of EPO patent applications, 3-year moving average).

Notes: Geothermal, ocean, and biomass/waste are shown on the right axis due to relative magnitudes.

The observed decline in the rate of innovation with respect to solid waste management may be due in part to the difficulty associated with defining search strategies for some aspects of energy recovery, material recycling and waste prevention, which may result in a downward bias in the figures. This is likely to be particularly important in recent years as countries have focussed more of their efforts in these areas.

Figure 8 shows the total number of patent applications for five renewable energy sources (solar, wind, ocean, geothermal, and biomass/waste). As expected wind and solar power (left axis) have the highest counts. Solar power counts exhibit a U-shaped path, with growth since the early 1990s, and particularly since the turn of the century. In the case of wind power, growth rates picked up markedly from the late 1990s. There has also been high growth in ocean energy patenting recently, but from a very low base. And finally, there appears to have been little growth in innovation levels in the area of geothermal and biomass/waste-to-energy since the 1970s.

Figure 9 compares total patent applications for a selection of OECD countries which have exhibited significant levels of innovation. Germany, followed by the United States and Japan have the highest number of patents, but it must be noted that there is a degree of «home bias» associated with German counts when using EPO applications. France and the UK also have relatively high counts, but it is significant that France has only recently returned to the levels reached in the early 1980s. The Figure also includes data for Spain and Denmark – countries which have been leading innovators in solar and wind power respectively in recent years. The Netherlands, Switzerland and Italy also have relatively high counts.

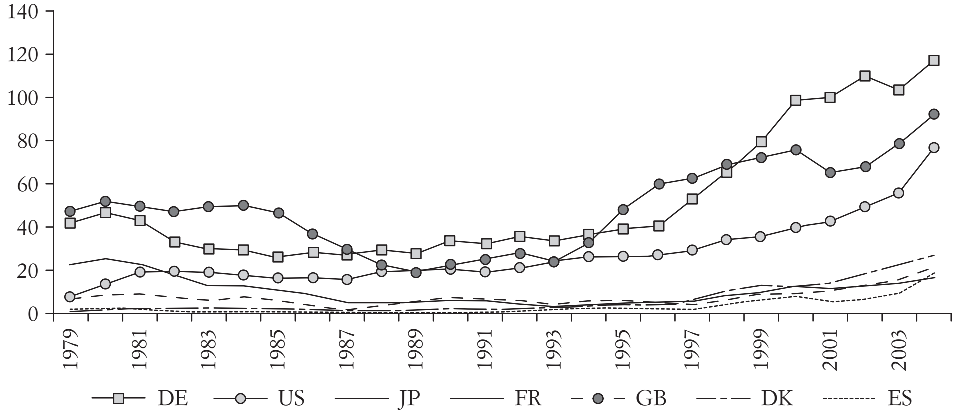

FIG. 9. Patenting activity for renewables by inventor country (number of EPO patent applications, 3-year moving average).

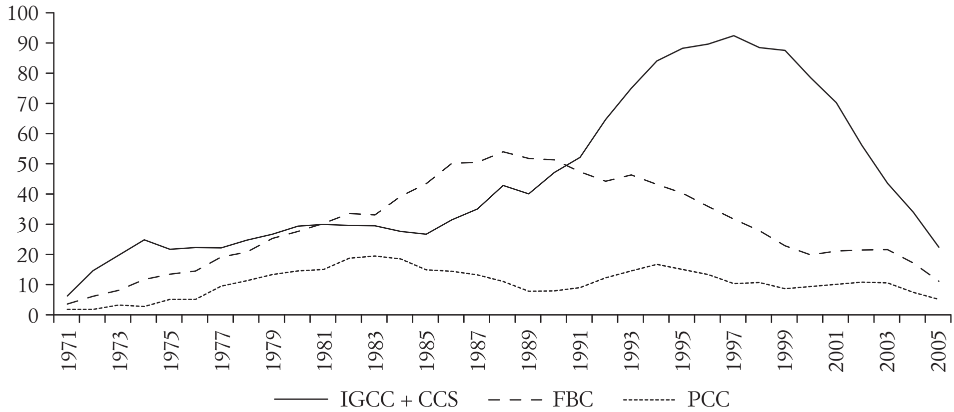

FIG. 10. Patenting activity in selected «clean coal» technologies (number of patent applications-claimed priorities, worldwide; 3-year moving average).

The greatest share of electricity generation is based on the combustion of conventional fossil fuels. This share amounts to 70%, and coal accounts for more than half of that. Coal is projected to remain an important resource for the production of electricity in the near future. It is unlikely that renewable sources will be able to substitute fossil energy carriers completely. «Clean coal» technologies seem to offer one possibility to achieve the aims of using coal as energy carrier and simultaneously reducing greenhouse gas emissions.

Figure 10 gives patent counts for such technologies. Over the time period considered here, the different technologies peaked at different points in time. Pulverised coal combustion reached its highest patenting level in the early

1980s, fluidised bed combustion in the late 1980s, and integrated gasification combined cycle/carbon capture and storaged patents peaked in the mid to late 1990s. Moreover, since the late 1990s, all patent counts have decreased. Voigt *et al.* (2009) argue that this may be a consequence of the shift toward innovation in renewable energy sources following the signing of the Kyoto Protocol.

In summary, it is interesting to note that patent activity is declining in most of the fields covered. The exceptions are selected renewable energy sources and, to a lesser extent, air pollution abatement. Some of this is likely due to the relative maturity of some fields (e.g. solid waste management, wastewater abatement). However, within such fields there are areas which remain relatively dynamic. For instance, the use of nanotechnology and biotechnology in these two fields is growing rapidly[7].

3.2. *Environmental Policy*

As noted above, the role of policy incentives is also likely to be important. In this paper we focus on the stringency, flexibility and stability of the regimes. To disentangle the distinct effect of each policy attributes empirically, we use data obtained from the World Economic Forum's Executive Opinion Survey, where respondents are asked a number of questions related to environmental policy design. The survey was implemented by the WEF's partner institutes in over 100 countries, which include departments of economics at leading universities and research departments of business associations. The means of survey implementation varied by country and included postal, telephone, internet and face-to-face survey.

In most years, there were responses from between 8,000 and 10,000 firms (see WEF, 2008 for a description of the sampling strategy.) In order to ensure representativity, the sampling follows a dual stratification based on the size of the company and the sector of activity. In the first instance, the partner institutes are requested to prepare a «sample frame», which includes firms representing the main sectors of the economy. The frame is then split in two, with one that includes only large firms, and a second list that includes all other firms (both lists representing the various economic sectors). A random selection of firms from the two lists is then selected to receive the Survey (see WEF, 2009).

Given the heterogeneity of environmental policy regimes both across countries, and within countries across sectors as well as through time, it is difficult to construct a general index of the stringency of environmental policy regimes. However, in the WEF Survey, respondents (usually CEOs) were requested to indicate the «stringency» of a country's overall environmental

[7] See http://www.oecd.org/document/40/0,3343,en_2649_37015404_42323688_1_1_1_1,00.html.

regulation. More specifically, they were requested to assess the degree of stringency on a Likert scale, with 1 = lax compared with that of most other countries, 7 = among the world's most stringent.

To test the second principal hypothesis (concerning the relationship between policy stability and environmental innovation), we need an appropriate measure of policy stability. Given the heterogeneity of environmental policy regimes – both across countries, and within countries across sectors and impacts (as well as through time) – it is difficult to construct a general index of the «stability» of environmental policy regimes. However, for 2001-2006, the WEF Survey also asked respondents about their perceptions of the «stability and clarity» of the environmental policy regime in different countries. Respondents were requested to indicate on a Likert scale whether environmental regulations were «confusing and frequently changing» (1) or «transparent and stable» (7).

In order to test our third principal hypothesis (about the relationship between policy flexibility and environmental innovation) we use the flexibility index from the WEF Survey over the period 2001-2003. In particular, respondents were requested to assess the degree of flexibility on a Likert scale, with 1 = offer no options for achieving compliance, 7 = are flexible and offer many options for achieving compliance. Mean responses for some of the countries included in the sample discussed here are provided in Figure 11.

4. Empirical Model and Results

An empirical model is developed to test the hypotheses set out in Section 2. The following reduced-form equation is specified and estimated for stringency, stability, and flexibility as policy design attributes:

$$AWWPAT_{i,t} = \beta_1 ENVPOLICY_{i,t} + \beta_2 TOTPAT_{i,t} + \varepsilon_{i,t} \quad (1)$$

where i indexes country and t indexes year. The dependent variable is measured by the number of patent applications in selected areas of environmental technology which was described above. However, due to the nature of the questions posed, only inventions which relate to air and water pollution abatement and solid waste management are included. Nonetheless, general lessons learned are likely to be applicable to other fields (i.e. climate change mitigation). ENVPOLICY accounts for the different attributes of countries' environmental policy regimes (stringency, stability, flexibility), and the construction of these variables is discussed below.

As noted above, it is important to control statistically for differences in the propensity to innovate and patent across countries. In order to capture the effect of such factors (which are not specific to environmental technologies), we include the variable TOTPAT reflecting the total number of patent applications (claimed priorities) filed across the whole spectrum of techno-

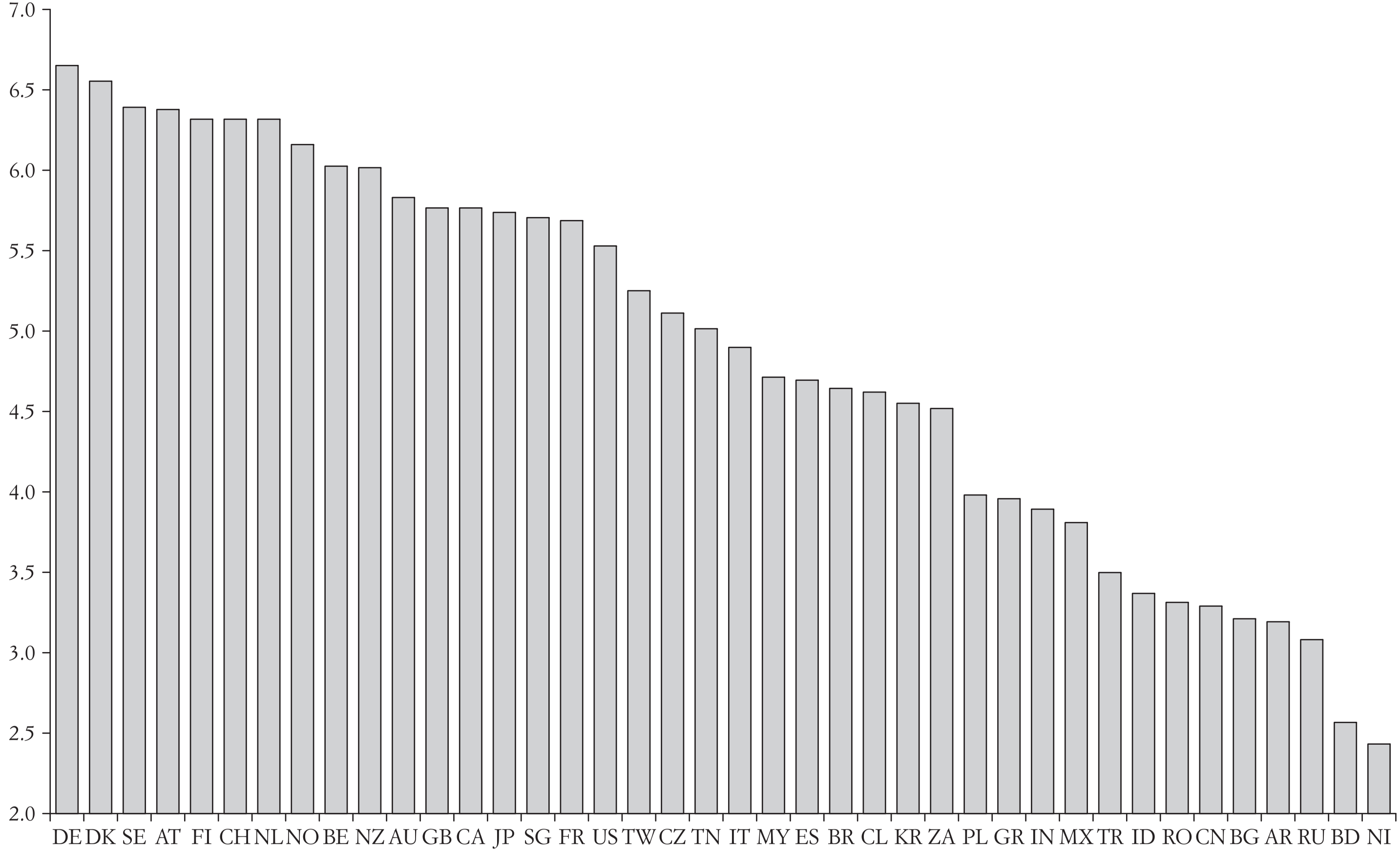

FIG. 11A. Stringency of environmental policy regimes in selected countries (mean value of the index over 2001-2007).

Notes: Environmental policies in your country are 1 = lax compared with that of most of other countries, 7 = among the world's most stringent.

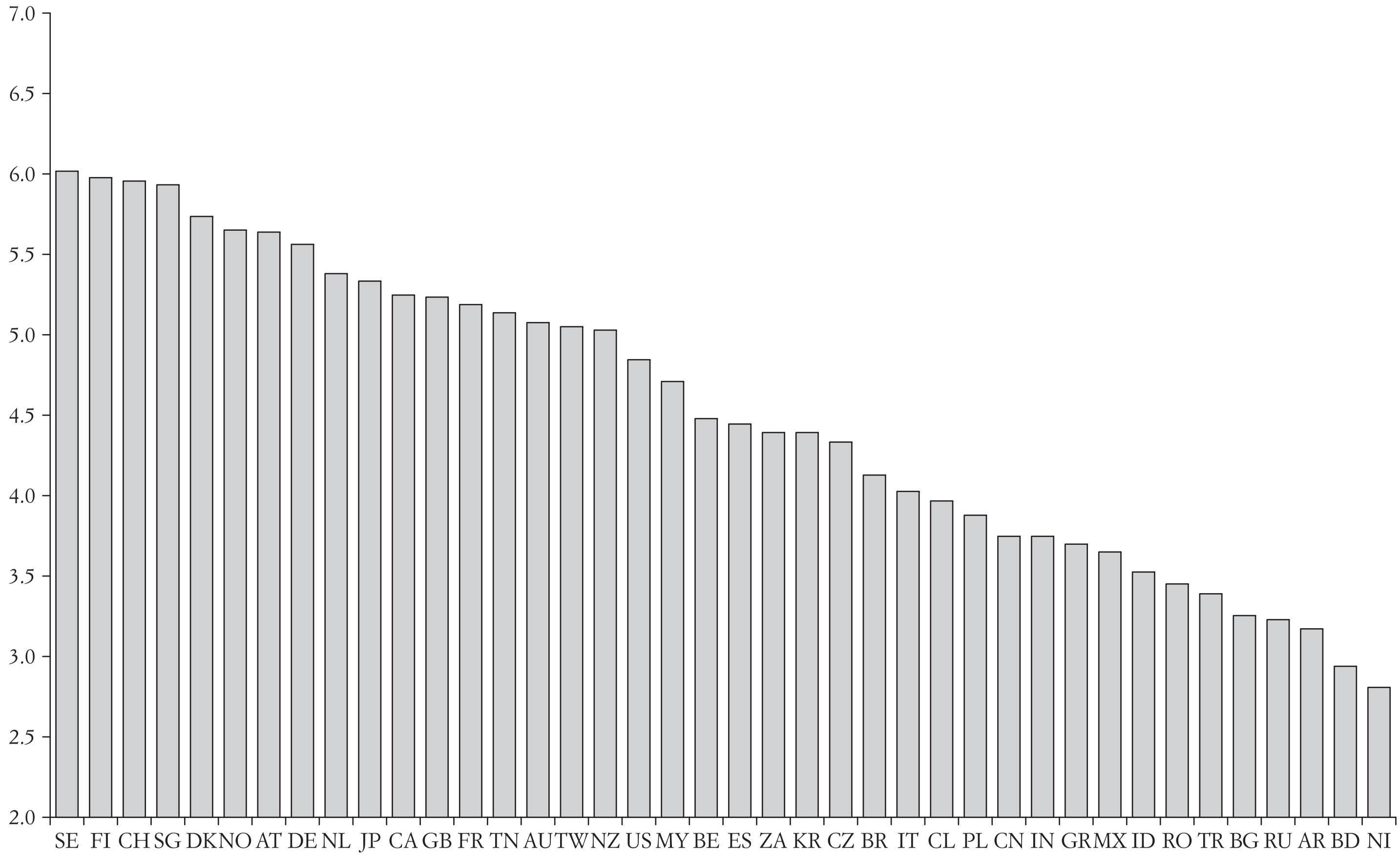

FIG. 11B. Stability and transparency of environmental policy regimes (mean value of the index over 2001-2006).

Notes: Environmental policies in your country are 1 = confusing and frequently changing, 7 = transparent and stable.

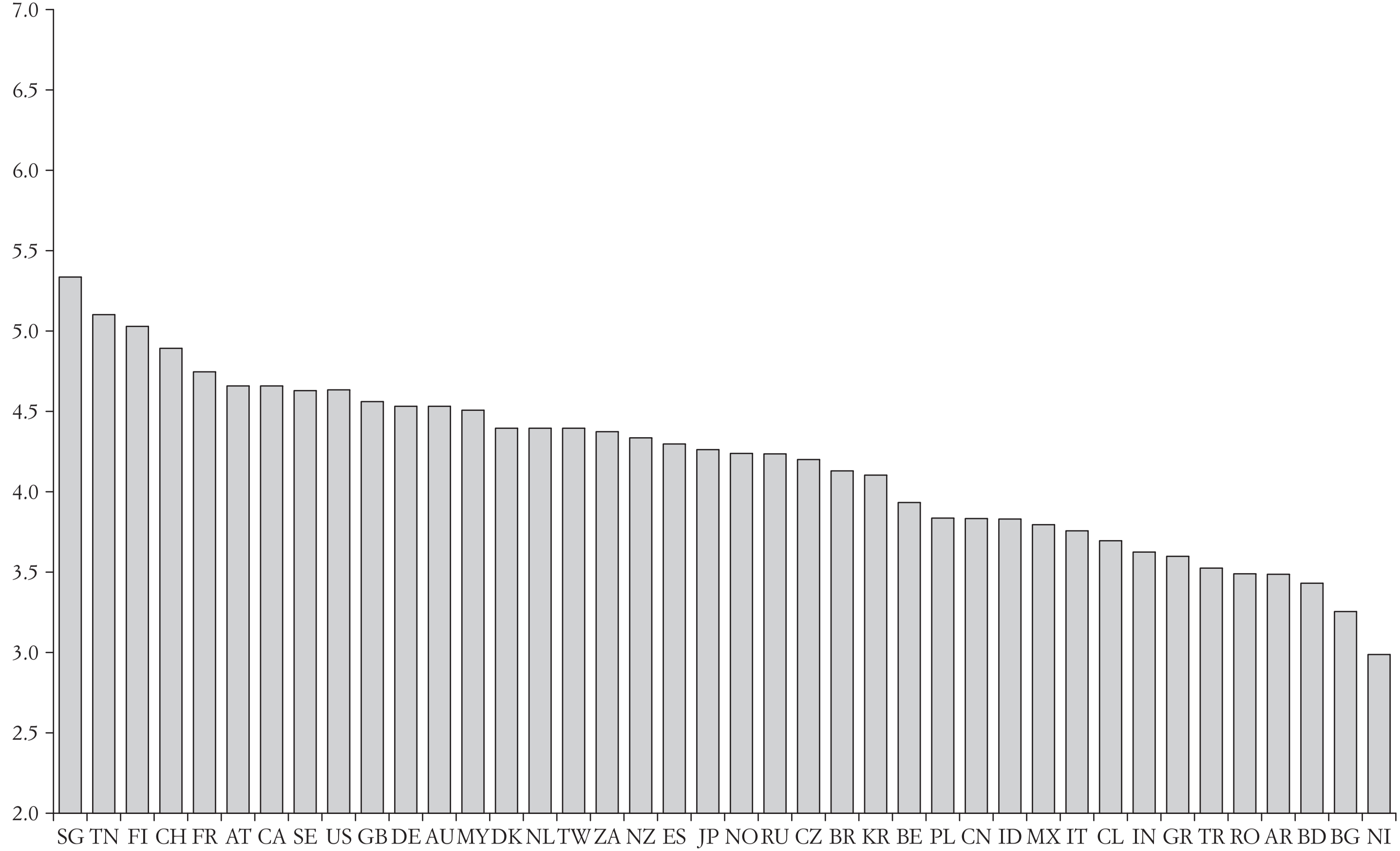

FIG. 11C. Flexibility of environmental policy regimes (mean value of the index over 2001-2003).

Notes: Environmental policies in your country are with 1 = offer no options for achieving compliance, 7 = are flexible and offer many options for achieving compliance.

logical 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. All the residual variation is captured by the error term ($\varepsilon_{i,t}$). A negative binomial model is used to estimate the model.

However, since the different measures characterizing environmental policy (stringency, flexibility and stringency) are highly correlated (> 0.80), considering them jointly in a regression may lead to multi-collinearity. We tackle the potential problem by applying the method of common factor analysis. In the following, we construct variables (*FACTOR*) – normally distributed – which are linear combinations of the correlated environmental policy measures plus an error term. Thus, in the empirical analysis *FACTOR* will account for the joint impact of stability and stringency (models 2 and 3), flexibility and stringency (models 4 and 5), as well as the three types of environmental policy included together (models 4 and 6). It will be possible to identify the individual effect of policy stability or flexibility, and their joint effect by comparing the coefficient estimates of each factor with a model in which only stringency is included.

However, the different policy questions were not asked for the same years. Therefore, in order to ensure that the comparison with the model including only the stringency variable is made on the same sample the models are re-estimated in each case. Column (1) in Table 1 covers the period 2001-2007, columns (2) and (3) report results for 2001-2006, while the last three columns cover only the years 2001-2003.

The results (Table 1) confirm all our principal hypotheses. Stringency has a positive impact on environmental patent activity in the base models (1, 2 and 4) for each sample. Moreover, when the factor variable is created, its coefficient is significant, positive, and greater in magnitude than the coefficients for the stringency variable. Therefore, these results clearly indicate that policy stability and flexibility have a positive and statistically significant individual impact on inventive activity in environmental technologies (air, water, waste) that is distinct from, and additional to, the effect of policy stringency[8]. Furthermore, column (6) shows that flexibility and stability have also a joint positive impact on innovation, while we control for stringency at the same time (see column 4). And finally, 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.

[8] It would be useful to compare the impact of policy attributed on the three different areas of environmental innovation activity considered in this paper (air, water, waste). However, the lack of data on stability and flexibility at the sectoral level hinders such an empirical exercise.

Tab. 1. *Results of negative binomial model*

	1	2	3	4	5	6
Stringency of env. policy (STRING)	0.850***	0.838***		0.891***		
	(0.069)	(0.072)		(0.101)		
Factor of env. policy (with stability)			1.089***			
			(0.097)			
Factor of env. policy (with flexibility)					1.534***	
					(0.152)	
Factor of env. policy (with stability and flexibility)						1.446***
						(0.233)
Total patents (TOTPAT)	0.191***	0.185***	0.184***	0.163***	0.164***	0.201***
	(0.023)	(0.029)	(0.028)	(0.039)	(0.038)	(0.051)
Intercept	−2.411***	−2.328***	1.560***	−2.529***	1.435***	1.486***
	(0.432)	(0.450)	(0.230)	(0.582)	(0.211)	(0.252)
N	440	386	386	204	204	204
Log pseudolikelihood	−1083.09	−1019.5	−1023.57	−556.8 3	−552.83	−570.04
(Prob > Chi2)	0	0	0	0	0	

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

5. Discussion and Policy Implications

There is some empirical evidence that market-based instruments such as environmentally-related taxes and tradable permits are more likely to induce innovation than direct regulations such as technology-based standards. However, juxtaposing the incentives associated with market-based instruments with direct regulations in broad terms may be misleading since there is no necessary mapping from instrument type to each of the characteristics listed above.

Any incentives for innovation arise out of the underlying policy characteristics. As such, it is important to assess incentives for innovation in terms of their specific characteristics rather than by broad instrument type. Because of this imperfect correlation, it is necessary to disentangle the innovation effect of each of these characteristics. Drawing upon a worldwide database of patent applications, the effects of three of the most important characteristics (stringency, stability, and flexibility) are examined.

This study presents evidence that policy stringency plays a significant role in inducing innovation. More specifically, based on evidence from a broad cross-section of countries over the period 2000-2007 it is found that policy stringency has a positive impact on the likelihood of developing innovative means of air and water pollution abatement and solid waste management. A more «stringent» policy will provide greater incentives for polluters to search for ways to avoid the costs imposed by the policy.

All «environmental» policies – whether they be taxes, subsidies, regulations, information – attach a price to polluting. By increasing the «price» of polluting, it is hardly surprising to find that the more stringent the policy the greater the effect on innovations which have the effect of reducing emissions. However, this is not to say that different policy measures of equal stringency will not have different effects on the rate and direction of innovation. Policy stringency is only one aspect of the public policy regime which affects the rate of innovation, and it is important to examine some of the other characteristics of policy regimes as well.

If there is uncertainty associated with a country's environmental policy, this will result in less innovation in environmental technologies. Conversely, the more stable and predictable a policy regime, the more innovation is likely to take place. This implies that governments should behave in a predictable manner if they wish to induce innovations that achieve environmental objectives at lower cost. Frequently changing policy conditions come at a cost, and to the extent that these arise out of reasons that are unrelated to new information concerning market or ecological conditions, such instability should be avoided.

Why does this arise? Uncertain signals give investors strong incentives to postpone investments, including the risky investments which lead to innovation. There is an advantage to «waiting» until the policy dust settles. As such, by adding to the risk which investors face in the market, policy uncertainty can serve as a «brake» on innovation, both in terms of technology invention and adoption. Empirical evidence over the period 2001-2006 supports our hypothesis that policy stability has a distinct impact on innovation. This implies that governments have an interest to behave in a predictable manner if they wish to induce innovations that achieve environmental objectives at lower cost.

However, it must be recognised that in some cases policy instability can arise from the acquisition of information. Damages may be higher or lower than initially foreseen, encouraging the use of more or less stringent policies. Similarly, abatement costs may be higher or lower than initially foreseen. In such cases, there is a trade-off between changing environmental objectives to reflect the new information and keeping incentives constant in order to reduce uncertainty.

The third aspect of policy design that is examined empirically in this report is policy flexibility, which can be characterised as technology-neutrality. The results presented for panel data over the period 2001-2003 indicate that, for a given level of policy stringency, the more «inflexible» a policy regime, the less innovation takes place. In other words, the more «flexible» policy regime will induce more innovation than a regime which is «prescriptive» in nature. This implies that rather than prescribing certain abatement strategies (such as technology-based standards), wherever possible governments should give firms stronger incentives to look for the optimal technological means to meet a given environmental objective.

Since both governments and firms cannot foresee future trajectories of technological change, it is important to give innovators the incentive to search across a wider «space» to identify potential means of complying with regulations. Flexibility «unleashes» the search for new innovations, some of which may be only marginal (but environmentally significant) improvements on existing technologies. Therefore, by encouraging potential innovators to devote resources to identify the best way of achieving a given environmental objective, policy flexibility provides incentives for innovation above and beyond those provided by policy stringency.

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Summary: Environmental Policy Characteristics and Technological Innovation (J.E.L. Q55, Q56, Q58, O31, O33)

This paper focuses on the issue of innovation and technology transfer in the areas of air pollution abatement, wastewater effluent treatment, solid waste management, and climate change mitigation. The paper describes the trends in innovative activity related to selected areas of pollution abatement and control technologies and their transfer internationally. It also discusses characteristics of environmental policy regimes that are amenable to encouraging innovation of environmental technologies, and provides empirical evidence on the role of various determinants (including general characteristics of countries' environmental policy regimes) in encouraging innovation.