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# INNOVATION AND ENVIRONMENTAL STRINGENCY: THE CASE OF SULFUR DIOXIDE ABATEMENT

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# Innovation and Environmental Stringency: The Case of Sulfur Dioxide Abatement*

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**Abstract**

A weak version of the Porter hypothesis claims that strict environmental policy provides positive innovation incentives, hence triggering improved competitiveness and securing environmental quality. In a comparative way, this paper empirically tests this hypothesis across countries by linking environmental stringency to innovation – proxied by patents – in the field of $SO_2$ abatement over the period 1970-2000. Three different models of environmental stringency are examined. Two of these models do not reveal a positive significant effect on innovation as a result of increased stringency. In the theoretically preferred model, however, a positive relationship between environmental stringency and innovation is obtained.

**Keywords:** patents, pollution control, environmental stringency, sulfur dioxide, innovation

**JEL classification:** L51, L94, O31

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## 1 Introduction

One of the salient features of the world economy is the increased tendency of liberalization and deregulation of markets, both at the national and the international level. Concurrently, the issue of sustainability comes to the fore more prominently. Several important questions arise in this respect. A first question is whether these developments are in conflict with each other. One can argue that an increase in international trade will lead to more pollution and an increased exploitation of natural resources, which is at variance with sustainable development. A counterargument would be that trade increases income, which may lead to more care for the environment.[1] A second question, to which the present paper is related, refers to the link between environmental policy and international trade.

There are two opposing views on this relationship. One view is that environmental regulation raises the costs to firms, hence affecting competitiveness adversely. In the absence of trade policy options, a "too" lax environmental policy might be used for strategic reasons. In this respect one can see environmental policy as a substitute for trade policy (see e.g., Elbers and Withagen (2003) for an assessment of ecological dumping). In the other view, prominently expressed by Porter (1991) and Porter and Van der Linde (1995a, 1995b), appropriate environmental regulation enhances innovation as well as efficiency by firms, thereby improving their competitiveness. The two views have been subject to fierce debates; theoretical as well as empirical research projects have dealt with the issue (e.g., Kalt, 1988; Tobey, 1990; Jaffe et al., 1995; Palmer et al., 1995; Xepapadeas and De Zeeuw, 1999; Mohr, 2002; Mulatu, 2004). However, systematic empirical tests of the Porter hypothesis are still very scarce. The aim of this paper is to reduce this gap in a cross-country setting.

The central question concerns the relationship between the strictness of environmental policy and the level of innovativeness of firms that are subject to it. To address this question properly, one needs to define and operationalize the concepts of environmental stringency and innovativeness. On an aggregate level, a commonly used indicator for innovation is R&D expenditures. However, R&D expenditure data comprise inputs in the innovation process rather than successful outputs. In addition, R&D expenditures are not comprehensively available, because they mostly come from a subset of larger firms. Moreover, the data are inaccurate since the available data are not broken

[1] See Copeland and Taylor (2003) for an excellent review of the debate.

down by technology group (Lanjouw et al., 1998). For these reasons, R&D expenditure data are not well suited for a cross-country analysis with an explicit focus on specific pollution abatement technologies.

Another way of measuring innovative output is by means of the number of patent applications. Although not all patents will lead to innovation in practice and innovation does not yield a competitive edge per se, in a comparative way patents still provide information on innovative activities undertaken. Moreover, "it is the unique combination of detail and coverage found in patent data which make them particularly well-suited to studies of the efficacy of policies tailored to particular technological areas…" (Lanjouw et al., 1998, p. 406). This is exactly what the current study is covering, i.e., the impact of environmental policy on differential inventiveness in pollution control, in particular sulfur dioxide ($SO_2$) abatement.

In an extensive survey, Griliches (1990, p. 1661) mentions at least three advantages of patent statistics. First, patents statistics are available. This feature is particularly attractive in the light of the aforementioned inadequacy of R&D expenditure data for investigating differential inventiveness in international settings, i.e., across countries. Second, patents are by definition related to inventiveness. Third, they are based on an objective and slowly changing standard, because they are granted on the basis of novelty and utility.

However, there are also problems associated with the use of patents for economic analyses. Two major problems are: classification and intrinsic variability (Griliches, 1990). Classification refers to the problem of how to allocate patent data into economically relevant industry or product groupings. Intrinsic variability refers to the technical and economic value of patents. Some patents are highly valuable, whereas others are of minor value only.[2] In this respect, patents are "indicators of success of the underlying inventive activity or R&D program" (Griliches, 1990, p. 1679). Since we are primarily interested in the degree of innovation induced by environmental policy, intrinsic variability is not so important for our study. Further, due to the high aggregation level of the current study, classification does not pose a problem either; it would have become a problem as soon as different industries within countries were considered. In Section 3 we outline more precisely how we dealt with it.

There is abundant evidence showing that the diffusion of environmental innovations has increased considerably over the past decades; also the share of environmental patents

[2] See Lanjouw et al. (1998) for a method to explore patent renewal data in order to capture the economic value of patents.

has increased as a percentage of total patents (Lanjouw and Mody, 1996). However, the time patterns differ among countries. An analysis linking stringency of environmental policy and patents might be one possible explanation for these patterns.

In the present paper we focus on a case study for $SO_2$ abatement. We provide a systematic analysis of the environmental policy effects on innovation related to $SO_2$ abatement. Since the vast majority of the literature on this issue solely focuses on the U.S.,[3] we conduct a thorough investigation of patents over the period 1970-2000 for a much larger set of countries (in total 14). In this way we contribute to the insight into the effect of differential environmental policy on the incentive to innovate, as measured by the number of patent applications.

The common approach of measuring environmental stringency is by using "Pollution Abatement and Control Expenditures" (PACE), which reflect pollution abatement capital expenditures[4] and operating costs. The idea is that an increase in PACE is (partly) due to an increase in the environmental policy burden, i.e., firms are expected to spend more on pollution abatement when they encounter more strict regulatory measures. However, all significant changes in PACE must be reviewed with care, as PACE may also increase because of improved sectoral coverage and data availability. Inter-country comparisons should therefore be limited to orders of magnitude. Moreover, PACE data are only available for a limited set of countries and sectors. Given the broad international perspective of our study, PACE is thus an unsuitable candidate for measuring environmental stringency.

Therefore, we had to rely on other measures of environmental stringency, which will be discussed in more detail below. In sum, the main finding is that in the theoretically preferred model, quite strong innovation incentives exist as environmental policy becomes more stringent. The intuition of this model is that high emission levels induce the pursuit of a strict environmental policy, which in turn provides a positive incentive to undertake innovative activities.

The outline of the paper is as follows. In Section 2 we survey the empirical literature on the link between patents and the strictness of environmental regulation. Section 3 presents a description of the data, for patents as well as for stringency. Moreover, it simultaneously discusses the different models. Section 4 presents the results of the econometric analyses. Section 5 concludes.

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[3] An exception is Popp (2004), who considers the U.S., Germany and Japan.

[4] Pollution abatement capital expenditures include rental and depreciation costs and *not* the actual amount of investment in environmental R&D itself.

## 2 Environmental policy and patents: previous literature

In this section, we briefly review earlier work on environmental patents. The number of papers on this issue is rather limited. To the best of our knowledge, we were able to identify only 5 papers, which will be discussed chronologically.

Lanjouw and Mody (1996) were the first to address the issue of increased regulatory stringency and environmental patenting empirically. First of all, they show that the amount of environmental patents has increased considerably in the period 1971-1988. Furthermore, considerable technology transfer has occurred in the form of trade in pollution control equipment. Second, they built a patent database, based on a search method by means of keywords. We will discuss this way of data acquisition in the next section. The data refer to countries (in particular the U.S., Japan and Germany) rather than to industries. The analysis of the data leads to conclusions related to the types of pollution to which the patent refers. There is evidence, be it non-econometric, that innovations are responsive to domestic environmental regulation. Third, attention is also paid to foreign patenting in developing countries. It turns out, among other things, that foreign patents in developing countries are not particularly tailored to these countries.

Jaffe and Palmer (1997) distinguish several versions of the Porter hypothesis. The "narrow" interpretation reflects that certain types of environmental regulation trigger innovation. The "weak" version states that regulation stimulates innovations directed towards reducing the cost of regulatory compliance. The "strong" version stresses that regulation causes a shock that induces firms to rethink their strategies and bring them closer to profit maximizing behavior. In the latter interpretation firms will indeed increase profits or reduce costs. Apart from conceptual problems with this "strong" interpretation, evidence for it is difficult to find from published data. Therefore, Jaffe and Palmer only try to establish a relationship between stringency and innovation. Innovation is measured in two ways: industry-wide R&D expenditures (a route we will discuss no further) and patents. Patents are considered as proportional to unobserved innovative output. The model Jaffe and Palmer estimate then reads as follows:

$$\begin{aligned} log\ PATENTS_{it} = {} & \alpha_i + \mu_t + \gamma_1\, log\, VALUE\ ADDED_{it} + \gamma_2\, log\ FOREIGN\ PATENTS \\ & + \gamma_3\, log\ PACE_{i,t-1} + \varepsilon_{it} \end{aligned}$$

The data refer to a set of U.S. manufacturing industries in the period 1977-1989. The variable *PATENTS* refers to the number of successful patent applications by industry $i$ in year $t$. Formally, this presupposes that the U.S. Patent Office is able to identify the applying firm in terms of industry according to the SIC classification. But this is not the case. The Patent Office does, however, classify applications according to certain classes of the technological nature of the application and imputes applications to industry groups following a "concordance". We have gone into some detail here because this is relevant for our research as well. Jaffe and Palmer note that there are two difficulties with this approach. First, it might be the case that inventions made in an industry are not assigned to that industry. Second, many inventions relate to new processes that are embodied in capital goods. But is the invention then assigned to the capital supplying industry or to the capital demanding industry? *VALUE ADDED* is a size-scaling variable and refers to industry value added. As already mentioned above, *PACE* denotes pollution abatement control expenditures. *FOREIGN PATENTS* denote the successful patent applications assigned to a foreign inventor. This variable is included in order to shed light on the question whether U.S. firms that are subject to regulation innovate more relative to foreign firms. Moreover, patents will vary over time and across industries, possibly due to variations in variables that affect the decision to apply for a patent. One may argue that these effects can at least partially be captured by assuming that these factors apply to foreign firms as well. In addition to a time variable, Jaffe and Palmer also include possible fixed effects for industries.

Jaffe and Palmer find a statistically significant result for *FOREIGN PATENTS* and *VALUE ADDED*, but the *PACE* variable is statistically insignificant for all variants of the model. A suggestion for future research is to try to obtain more disaggregated data on patents, a better classification of patents into industries, and an alternative, more output oriented measure of stringency.

Bhatnagar and Cohen (1998) extend the analysis of Jaffe and Palmer (1997) in several respects. Whereas Jaffe and Palmer consider *all* patents, Bhatnagar and Cohen focus on environmentally related patents. To add another element of stringency, they also consider the role of environmental monitoring by the government. Moreover, they include the market structure by means of a concentration measure. More specifically, their model reads:

$$PATENTS_{it} = \alpha_i + \gamma_1 VALSHIP_{it} + \gamma_2 VISITS_{i,t-j} + \gamma_3 PACE_{i,t-j} + \gamma_4 CONC_{it} + \gamma_5 CAPINT_i + \gamma_6 EXPINT_{it} + \varepsilon_{it}$$

*VALSHIP* refers to the value of industry shipments, *VISITS* to pollution related inspections. *CONC*, *CAPINT* and *EXPINT* are measures of industry concentration, capital intensity and export intensity respectively. For *PACE* the authors incorporate pollution abatement capital and operating costs. The period covered in Bhatnagar and Cohen's study is 1983-1992 and includes 146 industries. The patent variable refers to successful patent applications. The authors are not clear on how "environmental technologies" are identified. The allocation of such patents to industries basically suffers from the same problems as in Jaffe and Palmer (1997), because the classification was made on the basis of the "primary line of business" of the organization of the first named assignee in the patent application. Contrary to Jaffe and Palmer, the stringency variable is now highly statistically significant. Inspection does not play a major role overall, but it does in the chemical and the automobile industry, both of which are given extra attention.

The previous paper led to a published article by Brunnermeier and Cohen (2003), where essentially the same model is employed with a few extensions added. The results of the previous paper regarding the significance of the environmental stringency variable remain with the introduction of a time dummy. In other versions of the model explicit account is taken of the fact that the dependent variable is a positive integer. The conclusion with respect to *PACE* is unaltered.

Taylor et al. (2003) focus on $SO_2$ control, in particular flue gas desulfurization (FGD). Their study is based on the time path of $SO_2$-related patents over 100 years (1887 till 1995), expert interviews, data from the International Energy Agency, and patent lists of the major players in the FGD market. One of the results they obtain is that persistently most patents were issued in the period after 1970 when $SO_2$ regulation came in place. These regulations are well documented in terms of requirements as contained in legislation. Second, capital costs of FGD equipment have decreased considerably, arguably the consequence of stricter regulation and possibly an effect in line with Porter's hypothesis.[5]

Popp (2004) is a recent and closely related paper. Alike the present study, his main focus is on $SO_2$ (together with $NO_x$). While Popp considers the number of patent applications in a triple-country setting (U.S., Japan and Germany), we incorporate a maximum of 14 countries. Compared to our contribution, there are other major differences too, which mainly refer to the way data are gathered (to which we will come back in Section 3.1) and to the research question addressed. Popp's interest is twofold. First, he

[5] This optimistic view is not shared in an econometric analysis performed on FGD by Bellas (1998).

aims to obtaining a relationship between stringency of domestic environmental regulation and patenting. It is found that more stringent regulation in a country indeed enhances domestic patenting by domestic inventors, but not by foreign investors. This result is obtained by casual inspection of time series rather than by an econometric analysis, as we will conduct below. A second and more important objective is to investigate the link between domestic and foreign patents. It turns out that domestic innovation mainly occurs via domestic firms, in spite of the fact that foreign abatement equipment might have been available earlier. But domestic inventors rely strongly on foreign patents in developing their new equipment.

The empirical literature teaches us two lessons. First, there is a need for additional and more systematic attempts to empirically test a possible link between environmental stringency and innovation. Second, using patents as a proxy for innovative output as a consequence of environmental policy requires a quite specific search for relevant patents. That is, since innovation in emission control equipment is rather pollutant specific, accuracy in the retrieval of patents is extremely important.

## 3 Data description and modeling

In this section we describe the data used for our analysis. We have two types of data: data that refer to environment-related patents and those that refer to the stringency of environmental policy. We start with patents in subsection 3.1, followed by an examination of different measures of environmental strictness in subsection 3.2.

### 3.1 Patents

Our main data source has been the European Patent Office (EPO) in The Hague. EPO's database can be accessed in two ways. A first access mode is the online database *esp@cenet*.[6] Second, one can consult the EPO directly by contacting experts at the office. We followed the latter procedure and we will explain below the advantages of this approach.

The patents are classified according to the European Classification System (ECLA). For example, B01D53/50 refers to the class containing patents on the chemical or

[6] The online database can be entered via http://www.espacenet.com/.

biological processes to reduce $SO_2$. Since our analysis particularly focuses on sulfur dioxide, we are only interested in patents aiming at reducing $SO_2$. Furthermore, because the international environmental policy agenda with regard to $SO_2$ was basically initiated around the 1970s, we restrict our attention to the period 1970-2000.

EPO's database can provide patents counted by the so-called priority date, which is the earliest year of application. Using priority dates allows us to construct a time series that embodies information concerning actual innovative output, i.e., priority dates actually give an indication of the time the innovator perceives the invention as potentially valuable. This is independent of any differences in application rules set by the different patent offices. So priority dates provide uniformity in measuring innovate output and make an accurate comparison of innovation across countries possible.

Following Lanjouw and Mody (1996), Taylor et al. (2003) and Popp (2004), we make use of keywords in order to find the appropriate patents. We first construct a base set by means of general keywords (step 1) and then impose combined group-related keywords (step 2). Step 1 and step 2 yield a preliminary set of *potentially* relevant patents, which are then individually screened on the basis of patent abstracts (step 3). After reading each single patent abstract it was determined whether it explicitly relates to $SO_2$ abatement or not. If not, the patent was eliminated from the set; it remained in the set otherwise. The third step in the patent retrieval procedure is a distinctive feature of our database. The final step in the procedure (step 4) implies the search for so-called "family members" of each patent in the clean set as obtained through the screening in step 3. Patents are family members if they are based upon the same *priority*, which means that these are patents that comprise the same claim. It indicates in how many countries a patent with the same priority is applied for. This is particularly relevant because of the multi-country focus of this paper. Let us outline the whole procedure in more detail.

*Step 1*

Since the focal point of the analysis is $SO_2$, the search in EPO's database was first restricted to the use of the following combination of keywords: $SO_2$ or $SO_x$ or +SULFUR+ or +SULPHUR+.[7] The result is the base set that identifies those patents related to "sulfur". At the date of the first search, the base set contained a total number of 121,913 patents.[8]

*Step 2*

There are many different ways to control or abate $SO_2$ emissions. A technique with a long history in $SO_2$ reduction is scrubbing, which is a key-representative of end-of-pipe technologies. In addition, next to improvement of existing technologies, R&D can be directed towards the development of new technologies. A potentially new technique suitable for $SO_2$ reduction – and which is currently still in the experimentation stage – is called oxidative desulfurization. Given the large range of technical options, we make use of the technological distinctions included in the well-known RAINS model as developed at the International Institute for Applied Systems Analysis. The RAINS model distinguishes the following $SO_2$ abatement categories (see Cofala and Syri, 1998):

1. The use of low-sulfur fuels, including fuel desulfurization;
2. In-furnace control of $SO_2$ emissions (e.g., through limestone injection or with several types of fluidized bed combustion);
3. Conventional wet flue gas desulfurization processes;
4. Advanced, high efficiency methods for capturing sulfur from flue gas;
5. Measures to control process emissions.

The base set is then used for subsearches based on the aforementioned RAINS classification. These are searches based on the group-related keywords as contained in Table 1. The first subsearch was based on the use of low-sulfur fuels, including fuel desulfurization. The keywords applied for this class are: FUEL, DESULP and DESULF.[9] Subsearch 2 focused on in-furnace control of $SO_2$ emissions by imposing the keywords

[7] To be complete in the patent search, we had to be explicit in using the English and American writing style and, therefore, had to distinguish between "sulphur" and "sulfur". Moreover, a "+" put in front of or after a keyword implies that when the search engine browses through the database also those words that contain the original words are included. For example, "sulfur+" also yields "desulfurization".

[8] The first search was conducted on September 26, 2003. The search date is important because EPO's database is dynamic in the sense that every day new patents may be included. A new search at another time probably yields more patents in the base set.

[9] The "and" term between keywords refers to a combination of keywords in the search, whereas "or" statements refer to synonymous expressions of the associated keyword.

COMBUST, BURN, INCINER, LIME, LIMESTONE, CA and CALCIUM. Furthermore, in subsearch 3 we combined classes 3 and 4 of the RAINS classification by simultaneously employing the keywords FLUE and GAS. Note that class number 5 (measures to control process emissions) is a difficult one and may comprise various techniques. Therefore, we did not specify this class in detail. But as already noted above, a relatively new way to cut back $SO_2$ emissions is oxidative desulfurization. In subsearch 4 we emphasized this new process by using the keywords OXIDATIVE and DESUL.

**Table 1: Used keywords (in caps) and combinations of keywords per search (keywords)**

| Subsearch | Keywords |
|---|---|
| 1 | FUEL and DESULF+ or DESULP+ |
| 2 | COMBUST or BURN+ or INCINER+ and LIME or LIMESTONE or CA or CALCIUM |
| 3 | FLUE and GAS |
| 4 | OXIDATIVE+ and DESUL+ |

*Step 3*

The subsearches mentioned above led to a pool of potentially relevant patents; in total 4,243. However, in order to obtain a set of adequate data, for each of these potentially relevant patents the abstract was carefully read in order to determine whether it is really environmentally relevant or not. The total number of rejected patents, including double counts, was 1,105 (26%). The adjusted patent yield thus was 3,138 (4,243-1,105).

*Step 4*

A final step in the data acquisition procedure required the retrieval of the so-called family members of each of the patents in the adjusted set (step 3). Patents are family members if they are based upon the same priority. Once an inventor files its patent application for the first time (the priority date, i.e., the earliest application date) in a certain country, it has some time (maximum one year) to also file its application in other countries. In our case, taking account of these family members yielded a series of 5,323 patent applications over 1970-2000.

The major difference with the previously mentioned studies is step 3, where each individual patent is screened for its environmental relevance. The usual procedure is to work with keywords, as we did. But then one looks for those ECLA classes that contain a majority of environmentally related patents. In the further analysis it is then assumed that all patents in these classes are environment related. This might pose serious problems if the composition of patents within a class changes over time, so that for certain years the class is relevant, but no longer for other years. Moreover, even if in a certain class environmental patents are only a minority, they still may be relevant. Therefore, we think that individual inspection of the abstracts is preferable above relying on working with entire classes.

Appendix A contains a complete overview of the data. In total we distinguish 14 countries: United States, Germany, United Kingdom, France, Finland, Austria, Denmark, Sweden, Canada, The Netherlands, Poland, Italy, Luxembourg and Switzerland. Table 2 summarizes some patent application statistics for each of these countries and accounts for patents that are based upon the same priority (family members).

**Table 2: Patent application statistics for $SO_2$ control technologies per country (1970-2000)**

| | Total | US | DE | UK | FR | FI | AT | DK | SE | CA | NL | PL | IT | LU | CH |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Total** | 5323 | 2488 | 1722 | 162 | 161 | 156 | 152 | 139 | 113 | 53 | 44 | 42 | 41 | 30 | 20 |
| **Mean** | 171.71 | 80.26 | 55.55 | 5.23 | 5.19 | 5.03 | 4.90 | 4.48 | 3.65 | 1.71 | 1.42 | 1.35 | 1.32 | 0.97 | 0.65 |
| **St.dev.** | 66.55 | 36.09 | 36.92 | 6.87 | 6.74 | 11.72 | 7.61 | 6.71 | 6.77 | 2.15 | 3.69 | 2.63 | 3.22 | 2.85 | 2.46 |
| **Min** | 34 | 23 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **Max** | 296 | 152 | 135 | 26 | 20 | 63 | 27 | 27 | 25 | 8 | 13 | 11 | 12 | 11 | 12 |
| **Share** | 1 | .467 | .324 | .030 | .030 | .029 | .029 | .026 | .021 | .010 | .008 | .008 | .008 | .006 | .004 |

US: United States, DE: Germany, UK: United Kingdom, FR: France, FI: Finland, AT: Austria, DK: Denmark, SE: Sweden, CA: Canada, NL: The Netherlands, PL: Poland, IT: Italy, LU: Luxembourg, CH: Switzerland

Figure 1 illustrates the evolution of the aggregate number of patent applications included in our set. From 1970 on, it shows an increase in the number of applications with a peak in the mid 1980s. Then the amount of applications exhibits a decreasing tendency. Overall, the trend is positive.

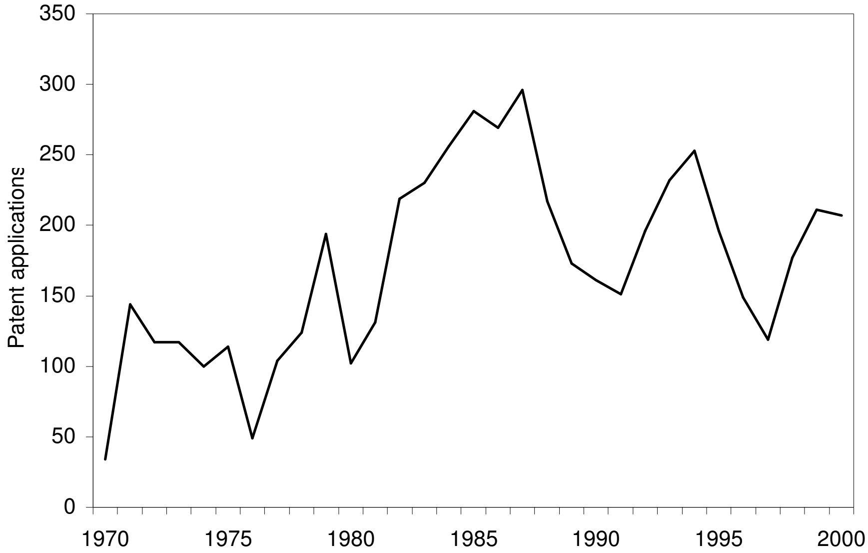


**Figure 1: Aggregate patent applications for $SO_2$ control equipment**

A more differentiated picture is given in Figure 2, which shows the development of patenting activity in the four biggest countries in terms of the number of patent applications (85.2%)[10], viz. the U.S., Germany (DE), United Kingdom (UK), and France (FR). If we compare patent activity in the U.S. with that in Germany, we see from Figure 2 that in both cases patent activity features an irregular pattern, but that the "global" pattern is more or less bell shaped for Germany with a clear peak in the mid 1980s. That is, in Germany the number of patent applications basically tends to increase from 1970 on, reaching its peak around 1985, and then falls down again to a much lower level. If we add a linear trend line to the time series of the U.S. and Germany, we derive in both cases a positive slope; however, for Germany the slope is somewhat smaller (1.395) than that of the U.S. (2.0).

[10] The U.S. and Germany account for 79.1% of the total number of patent applications.

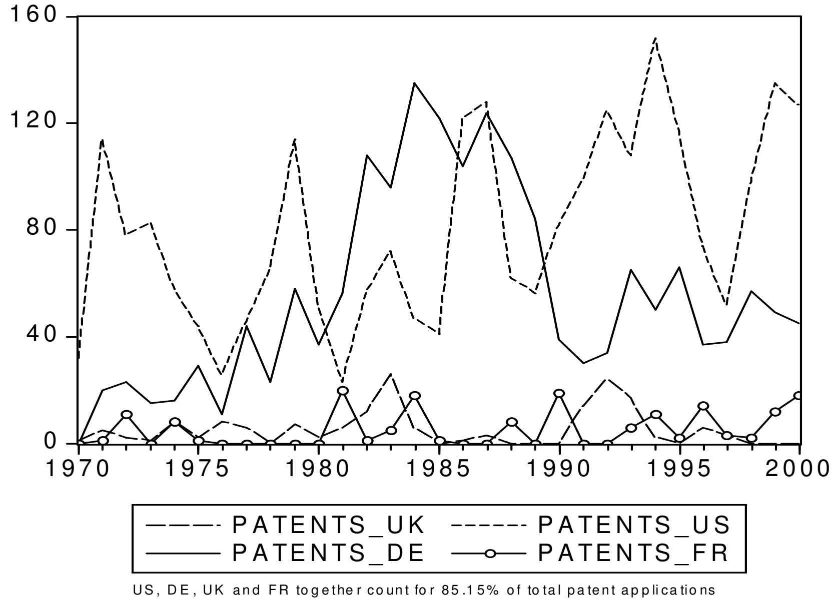


**Figure 2: Patent activity in the US, Germany (DE), United Kingdom (UK) and France (FR)**

It is, of course, difficult to derive any conclusions on the relation between environmental policy and patenting activity based on a graph like the one depicted in Figure 2. At this stage we can only highlight the main developments in environmental policy as related to the control of $SO_2$ emissions. As stated before, the general encountering of environmental problems occurred in the early 1970s. From that time on also the $SO_2$ oriented policy measures developed more extensively.

Because the online database poses limits on the total number of patents one can retrieve[11], for our approach it was necessary to cooperate with EPO. An example of the major differences in data obtained is the U.S. patents for $SO_2$ reduction. We find a significant increase in the number of patent applications in the U.S. in the period 1997-1999, whereas the number of patent applications in this interval is relatively stable in Popp (2004). Another difference in the time series applies to the period 1979-1981. Also here the level of U.S. patent applications are relatively stable in Popp (2004), while in our case there is a significant decrease in the number of patents in the U.S. Perhaps this difference is partly explained by the fact that Popp restricts himself to power plants. However, it is unlikely that this accounts for the entire difference, because also in our database power plants play an important role.

[11] The limit is 500 patents.

## 3.2 Environmental stringency

Now we have outlined the innovation part of the problem as measured by the number of patent applications, the next issue we have to address is the stringency of environmental policy with regard to $SO_2$. A distinction will be made between 3 approaches, leading to six different model specifications. In general, all models are linear fixed effects models, which in our case implies that the country-specific intercepts (the fixed effects) capture all the permanent inter-country variation in innovation. That is, differences in variation in patenting activity (technological opportunity) can be examined quite well for inter-country analyses.

***Model I***

In this model we assume that the strictness of environmental policy is captured by international agreements, which become more stringent over time. Compliance with these agreements by individual signatories requires more stringent domestic policy. From the sequence of relevant regulatory designations with respect to sulfur abatement as summarized below, one sees that the stringency of emission goals has increased through the years:

- 1979: Protocol to the convention on long-range transboundary air pollution.
- 1985: Helsinki protocol on the reduction of sulphur emissions or their transboundary fluxes (entered into force 1987). It entails emission reduction obligations for 1994. The reduction target for $SO_2$ emissions is more than 30% compared to 1980 levels.
- 1994: Oslo protocol on further reduction of sulphur emissions (entered into force 1998). Differentiation of emission reduction obligations (base year 1980 levels).
- 1999: Gothenburg protocol to abate acidification, eutrophication and ground-level ozone (not yet into force). It includes a differentiation of emission reduction obligations for 2010. The overall reduction target for $SO_x$ emissions in Europe amount to at least 63% compared to 1990 levels.

The sequence of the protocols highlights the main developments in environmental policy as related to the control of $SO_2$ emissions and shows that since the recognition of environmental problems in the early 1970s, the subsequent encountering of problems associated with $SO_2$ emissions (e.g., acid rain), have resulted in a more stringent pursuit of emission targets. In order to capture this development, we consider two modeling variants: I-a and I-b. Model I-a reads as follows:

$$PATENTS_{it} = \alpha_i + \beta_0 TREND + \beta_1 D79 + \beta_2 D85 + \beta_3 D94 + \varepsilon_{it}. \qquad (1)$$

The dependent variable (*PATENTS*) refers to the number of patent applications in country *i* in year *t*. On the RHS of (1) we include fixed country effects $\alpha_i$ and a general trend variable (*TREND*). Additionally, we have dummies for the years 1979 (*D*79), 1985 (*D*85) and 1994 (*D*94).[12] Coefficients $\beta_1, \beta_2, \beta_3$ capture the increased perceived stringency as a consequence of the protocol to the convention on long-range transboundary air pollution, the Helsinki protocol, and the Oslo protocol respectively. $\varepsilon_{it}$ is a random disturbance term.

In order to elucidate the anticipatory effects to future policy implementations, in the estimations we have also looked at several alternative modeling versions with a lag structure applied to the dummies. The results are provided and discussed in the next section.

Compared to version I-a, model I-b does not include dummies for the exact date of the protocol. Instead, the dummies in I-b capture the intermediate range (time interval) between two different protocols in order to capture the effect of environmental stringency as imposed in individual countries after the signing of the international agreements. More specifically,

$$PATENTS_{it} = \alpha_i + \beta_1 D7178 + \beta_2 D7984 + \beta_3 D8593 + \beta_4 D9400 + \varepsilon_{it}, \qquad (2)$$

where *D7178* is a dummy with value 1 for the years 1971-1978 and value 0 otherwise. The same routine applies to *D7984*, *D8593* and *D9400*. Since these dummies basically cover the whole period under consideration, we do not include a general time trend since that would introduce redundancy in terms of time variables. Again, $\varepsilon_{it}$ is a random disturbance term. Models I-a and I-b differ from Jaffe and Palmer (1997) and

[12] Because our data goes until 2000, we did not include a dummy for the 1999 Gothenburg protocol.

Brunnermeier and Cohen (2003) in the sense that their models include time dummies for all years in order to remove the effects from time-dependent determinants of innovation like inflation and tax law changes. Moreover, both studies use PACE data at the industry level.

***Model II***

In the second model (model II) we assume that stringency differentials between countries are constant over time. This approach is based on recent work by Cagatay and Mihci (2003), who develop an "Index of Environmental Sensitivity Performance" (IESP). The IESP consists of several subindices, among which an index referring to acidification. Their analysis is based on the pressure-state-response indicator developed by Hammond et al. (1995) and which is used by the OECD. The pressure indicators for acidification are $SO_x$ and $NO_x$ emissions. The state indicators are emissions of these gases per unit of real GDP from several sources – including power stations – and industrial and domestic fuel combustion. The response indicator is the share of pollution abatement and control expenditures aiming at the reduction of pollution.[13] We adopt the IESP to test whether in a country that can be characterized as "stringent", relatively more patents (appropriately scaled) are applied for.

The basic econometric specification of model II is as follows:

$$PATENTS_{it} = \alpha_i + \beta_0 TREND + \beta_1 GDP_{it} + \beta_2 DSTRICTNESS_{it} + \beta_3 RDPERS_{it} + \varepsilon_{it}, \qquad (3)$$

where *TREND* is again a general trend variable, GDP represents gross domestic product and acts as a scaling variable, and *RDPERS* refers to the number of people active in R&D. The variable *DSTRICTNESS* is a dummy indicating a country's environmental policy strictness with respect to $SO_2$ emissions, which is based upon the corresponding IESP for acidification. *DSTRICTNESS* takes value 1 if a country is classified as "strict" or is 0 otherwise. This dummy thus determines the marginal value of a strict environmental policy regime with respect to patent activity.

Cagatay and Mihci calculate an IESP for acidification, among others (climate change, waste management, water resource usage). Their acidification IESP was calculated on the interval 1990-1995. Unfortunately, this rather limited time span posed

[13] So expenditures on natural parks and the supply of drinking water are not included.

some restrictions on exploiting the potential econometric information included in our extensive time series (1970-2000). Due to this limitation we estimated (3) for the period 1990-2000.

The corresponding IESP levels in Cagatay and Mihci (2003) were categorized in different stringency regimes ranging from the extremes "strict" to "tolerant". More precisely, they distinguish six categories: strict, strict to moderate, moderate to strict, moderate, moderate to tolerant, and tolerant. In total 23 countries were included in their analysis and each country was put into one of the categories based on the corresponding IESP score. If we had adopted their categorization directly, in our set of countries only Austria would fall into the "strict" group. However, since the value of the acidification IESP for Austria is also a "borderline" case according to their categorical confinement, it could as well be classified as "strict to moderate". This would then imply than no country from our set could be classified as purely "strict". In turn, little variation within categories exists. In order to secure variation for the purpose of our study, we therefore redesigned Cagatay and Mihci's classification by defining only two classes: "strict" and "tolerant". Country $i$ is classified as "strict" if $50.1 < IESP_i \leq 100$, whereas it is "tolerant" if $0 < IESP_i \leq 50.0$. Table 3 shows the values of the IESP acidification for the various countries and the corresponding classification within our modeling framework.

**Table 3: Acidification IESP for different countries and corresponding classification based on own classification**

| Country | IESP | Classification |
|---|---|---|
| United States | 50.00 | tolerant |
| United Kingdom | 41.67 | tolerant |
| Canada | 25.00 | tolerant |
| France | 75.00 | strict |
| Italy | 58.33 | strict |
| Germany | 66.67 | strict |
| Poland | 25.00 | tolerant |
| The Netherlands | 83.33 | strict |
| Sweden | 75.00 | strict |
| Finland | 58.33 | strict |
| Austria | 83.33 | strict |
| Denmark | 50.00 | tolerant |
| Switzerland | 75.00 | strict |

Source: Cagatay and Mihci (2003), Table B8, p. 240

The borderline value of 50.1 is the value that corresponds to Cagatay and Mihci's classification. So, formally speaking, according to our binary classification (1 for strict and 0 for tolerant), countries with an IESP level of 50 (in our case the U.S. and Denmark) should be classified as "tolerant". But because the difference is only 0.1 at the margin, at the same it could as easily be put in the group "strict". Thus, the caveat of model II lies in defining the arbitrary swap value of going from "strict" to "tolerant". Therefore, various econometric analyses were conducted on classifying the "IESP borderline countries" U.S. and Denmark. In model II-a, the U.S. and Denmark were classified as "strict", whereas in II-b they were treated as being "tolerant". In the final case (model II-c), the U.S. and Denmark were excluded from the sample. The statistical results are given in subsection 4.2.

***Model III***

In the preceding models we implicitly assumed that environmental stringency was, to some extent, directly observable by international environmental protocols and an environmental sensitivity performance index. However, both measures of environmental stringency are imperfect; they only provide a limited view on environmental stringency. Therefore, in the current model we take for granted that the strictness of environmental policy is not directly observable, a priori. That is, environmental stringency is a latent variable.[14]

Xing and Kolstad (2002) study the effect of environmental policy strictness on foreign direct investment and also face the latency problem of environmental strictness. Their analysis concerns sulfur emissions and the methodology they use for revealing environmental strictness can be applied to our model as well. In our case, the model would look as follows:

$$PATENTS_{it} = f_i(Z_{it}, STRICTNESS_{it}) + \varepsilon_{it}, \tag{4a}$$

$$EMIS_{it} = g_i(X_{it}, STRICTNESS_{it}) + \eta_{it}, \tag{4b}$$

where patents (*PATENTS*) in country $i$ at time $t$ are a function of a vector of exogenous variables $Z$ and of the unobserved environmental policy strictness (*STRICTNESS*). Sulfur

[14] See e.g., Zellner (1970) and Goldberger (1972) for more general details about estimating equations with unobserved and observed variables.

dioxide emissions (*EMIS*) depend on another vector of exogenous variables *X* and on strictness as well. Assuming that the function $g_i$ is invertible in the degree of environmental stringency, i.e., $STRICTNESS_{it} = g_i^{-1}(X_{it}, EMIS_{it})$, one obtains:

$$PATENTS_{it} = h_i( X_{it}, Z_{it}, EMIS_{it} ) + \xi_{it}, \tag{5}$$

which is the equation to be estimated. Note that estimating (5) by OLS yields biased results because the error term $\xi_{it}$ is correlated with *STRICTNESS*. We will come back to this below.

More specifically, assume that the economy-wide $SO_2$ emissions depend on aggregate output measured in terms of gross domestic product (*GDP*) and on the industrial structure, which we model via value added (*VALADD*). In our case, *VALADD* is the value added contributed by 13 different sectors relative to the total value added of all industries. The included sectors are:[15] Food products, beverages and tobacco (15-16); Wood and products of wood and cork (20); Pulp, paper, paper products, printing and publishing (21-22); Chemical, rubber, plastics and fuel products (23-25); Other non-metallic mineral products (26); Basic metals and fabricated metal products (27-28); Machinery and equipment (29-33); Transport equipment (34-35); Manufacturing nec recycling (36-37); Electricity, gas and water supply (40-41); Construction (45); Transport and storage (60-63); Energy producing activities. Consequently, equation (4b) becomes:

$$EMIS_{it} = g_i( GDP_{it}, VALADD_{it}, STRICTNESS_{it} ). \tag{6}$$

Given the invertibility of $g_i$ we get:

$$STRICTNESS_{it} = h_i( GDP_{it}, VALADD_{it}, EMIS_{it} ). \tag{7}$$

So environmental strictness is contingent on gross domestic product, the industry structure and the level of $SO_2$ emissions.

[15] The ISIC codes of the included sectors are in parentheses.

In the line of (5), the specific equation to be estimated now reads:

$$PATENTS_{it} = \alpha_i + \beta_1 GDP_{it} + \beta_2 VALADD_{it} + \beta_3 EMIS_{it} + \beta_4 RDPERS_{it} + \xi_{it}, \quad (8)$$

where the composite error term $\xi_{it}$ is uncorrelated with any of the RHS variables in (8) and has zero mean. Furthermore, the variances of this error term will vary across countries. These observations call for an instrumental variable approach. Following Xing and Kolstad (2002), we include as instruments all the exogenous variables and population density. The latter could serve as an indicator of congestion and the ability of pollutants to naturally disperse away from population centers (Xing and Kolstad, 2002, p. 11).

The intuitive relationship between environmental stringency and emissions is that if a country has a relatively high level of $SO_2$ emissions, environmental stringency in that country will be relatively more intense. As a consequence, we would expect the number of patent applications to be positively related with $SO_2$ emissions. The role of national income is ambiguous. On the one hand, a higher national income will lead to more emissions. On the other hand, environmental policy may also be negatively related to national income.[16] Hence, it is difficult to speculate on the sign of the *GDP* coefficient ex ante.

## 4 Empirical results

The description of the empirical results follows the order of the models as discussed above. All models are are estimated by means of a pooled least-squares method with White heteroskedasticity-consistent standard errors and covariance.

### 4.1 Results model I

Table 4 presents the results of model I-a and I-b. In both models the time trend is highly significant. In model I-a the dummies are all statistically insignificant. Furthermore, in both I-a and I-b the fixed effects show considerable variation over the distinguished countries. The U.S. and Germany have relatively high fixed effects compared to the other countries. Jaffe and Palmer (1997) use GDP as a scaling variable. Next to calculations

[16] See e.g., Copeland and Taylor (2003) for a discussion on endogenous environmental policy.

with real GDP, we also conducted analyses with a general trend variable; however, both variables generated the same positive effect and did not affect the dummy variables significantly. In other words, GDP and the trend variable essentially provide the same statistical results.

Instead of using real GDP as a scaling variable, we also conducted econometric analyses by using a scale variable measured in terms of the number of personnel that is involved in the R&D processes of different countries. When it comes to patents (innovation), such a scaling variable may be even more appropriate since it proxies the size of the R&D sector (by the number of researchers and technicians) as well as a countries' technically oriented educational basis, i.e., the intellectual assets in terms of highly qualified personnel (researchers and technicians). For this variable we only found data from 1980 onwards. We did some econometric analyses with this, but found that the inclusion of highly trained workers does not increase the significance of the dummy variables. On the other hand, as expected, it reduces the differences in fixed effects.

Note that Germany has high fixed effects relative to the U.S., i.e., the difference in fixed effects is relatively small between these two countries if you consider the U.S. "large" compared to Germany. However, compared to the U.S., in Germany a relatively high number of people are working in R&D. This could explain (partially) the relatively small difference in fixed effects. Moreover, in addition to the number of R&D personnel, another reason of Germany's high fixed effect could be due to its relatively stringent policy regime. In case of the 1994 Oslo protocol, which allowed for differentiated emission reduction targets, Germany pursued the most stringent emission goals of all countries, namely reduction targets of 83% (87%) of 1980 $SO_x$ emissions by the year 2000 (2005). With respect to the 2000 targets, the other countries' reduction goals range from 30 to 80 percent.

**Table 4: Effects of environmental protocols on patent applications: model I-a and I-b**

| Variable | Coefficients Model I-a | Coefficients Model I-b |
|---|---|---|
| *TREND* | 0.266 (3.845) | - |
| *D79* | 3.700 (1.413) | - |
| *D85* | 8.321 (1.211) | - |
| *D94* | 3.931 (0.753) | - |
| | | |
| *D7178* | - | 5.330 (1.114) |
| *D7984* | - | 11.048 (2.231) |
| *D8593* | - | 13.254 (2.729) |
| *D9400* | - | 10.959 (2.275) |
| | | |
| ***Fixed effects*** | | |
| United States | 75.760 | 70.422 |
| Germany | 51.051 | 45.712 |
| United Kingdom | 0.728 | -4.611 |
| France | 0.696 | -4.643 |
| Austria | 0.406 | -4.933 |
| Finland | 0.535 | -4.804 |
| Sweden | -0.852 | -6.191 |
| Denmark | -0.014 | -5.352 |
| Canada | -2.788 | -8.127 |
| Italy | -3.175 | -8.513 |
| Poland | -3.143 | -8.482 |
| The Netherlands | -3.078 | -8.417 |
| Luxembourg | -3.530 | -8.869 |
| Switzerland | -3.852 | -9.191 |
| | | |
| $R^2$ | 0.728 | 0.733 |
| Adjusted $R^2$ | 0.717 | 0.722 |
| Log likelihood | -1770.98 | -1767.20 |
| Mean patents | 12.265 | 12.265 |

NB: *t*-statistic in parentheses

The statistical insignificance of the dummy variables in model I-a comes as no surprise. The dummies refer to the establishment of important international treaties on $SO_2$. It is, however, difficult to argue that these treaties have had an instantaneous effect on the number of patent applications. Alternative arguments are that the international agreements lead to more stringent policies in the individual countries that come into effect much later than the signing of the treaties. In contrast, one could also argue that firms anticipate to more stringent policies long before the actual international agreements are implemented. In order to test for the first possibility, which sounds rather plausible, we have introduced dummies for periods (model I-b) rather than for specific years when international agreements occurred (model I-a). Concurrently, for reasons of comparison, we also conducted several calculations with different lag specifications of the dummies in model I-a. In general, we found for a one, two, three and four period lag structure no statistically significant results for the dummies *D79*, *D85* and *D94*.

With the exception of dummy *D7178*, in model I-b all dummies are highly significant and have the expected positive sign. Obviously, based on this model specification we cannot conclude that international environmental agreements enhance innovation, even though at first sight the Helsinki Protocol seems to have triggered more innovation than the other protocols. Unfortunately this cannot be concluded; based on a Wald test we could not reject the null-hypothesis $\beta_2 = \beta_3 = \beta_4$, i.e., there are no significant differences between the dummies *D7984, D8593* and *D9400*. On the other hand, when including *D7178*, the null-hypothesis $\beta_1 = \beta_2 = \beta_3 = \beta_4$ is rejected, implying that dummy *D7178* has a significantly smaller effect on patenting activity than dummies *D7984, D8593* and *D9400*. Based on these results we might conclude that innovation in terms of patent applications has increased significantly since the 1979 Protocol to the convention on long-range transboundary air pollution.

Based on the above results one can hypothesize that countries are willing to sign protocols if they can achieve the environmental targets relatively easily, that is, with little effort and with little investment in R&D. For instance, when we take a closer look at the 1985 Helsinki protocol, where the countries agreed upon a reduction of $SO_2$ emissions by at least 30 percent, only Canada, France and Luxembourg did not meet their national targets by 1993.[17] The 1994 Oslo protocol subscribes the hypothesis even better; with the exception of the U.S. who did not ratify the protocol, all countries in the sample did meet their targets quite easily before the target year 2000, ranging from 1989 (Switzerland) to 1998 (Denmark, the Netherlands).

[17] Canada, France and Luxembourg met the Helsinki targets in 1999, 1994 and 1995 respectively. In our sample only Poland and the United Kingdom did not ratify the Helsinki protocol.

## 4.2 Results model II

The findings for model II and its different versions are displayed in Table 5. Recall that version II-a (II-b) classifies the U.S. and Denmark as "strict" ("tolerant"). In II-c they were both excluded. Taking a look at the impact of environmental stringency on the number of patent applications, we see that the sign of the estimated coefficients are invariant of whether environmental policy in the U.S. (and Denmark) is characterized as strict or tolerant. *DSTRICTNESS* has a negative effect in model II-a as well as II-b, though it is not significant. Thus in all cases the marginal value of a strict environmental policy is insignificant. However, when the sample is adjusted for "borderline countries" (II-c), the marginal value is positive and comes close to statistical significance, implying that the pursuit of a more stringent environmental policy likely enhances innovative activities.

Further, the effect of GDP on innovation is in all three cases very small and statistically insignificant. Also the size of the R&D population (*RDPERS*) has in all three versions a small effect on patent output. However, the effect is significant and, as expected, positive. In other words, when more people get involved in the R&D sector (a higher aggregate level of R&D effort), the more likely it is that patent activity increases. Finally, the *TREND* is negatively related to innovation and is significant.

**Table 5: Effects of environmental stringency on patent applications: model II**

| Variable | Model II-a | Model II-b | Model II-c |
|---|---|---|---|
| *TREND* | -0.211 (-3.360) | -0.189 (-3.002) | -0.187 (-3.076) |
| *GDP* | 0.0056 (1.075) | 0.0055 (1.151) | -0.0078 (-1.771) |
| *DSTRICTNESS* | -0.563 (-0.283) | -1.453 (-0.730) | 1.866 (1.072) |
| *RDPERS* | 0.062 (2.506) | 0.063 (2.641) | 0.107 (4.964) |
| $R^2$ | 0.712 | 0.713 | 0.603 |
| Adjusted $R^2$ | 0.702 | 0.703 | 0.588 |
| Mean patents | 8.885 | 8.885 | 7.733 |

NB: *t*-statistic in parentheses

## 4.3 Results model III

Table 6 contains the estimation results of equation (8) based on the instrumental variable estimation procedure in order to obtain consistent, unbiased and efficient estimates. Variables can serve as instrument only if they are correlated with the unobservable variable of environmental strictness (*STRICTNESS*), but at the same time are uncorrelated with the disturbance term $\xi_{it}$. Therefore, as commonly applied in the literature, we incorporated the exogenous variables *GDP*, *VALADD*, and *RDPERS*. Note that *EMIS* cannot serve as an instrument due to the endogeneity of $SO_2$ emissions. Concurrently, also per capita GDP and population density acted as instruments, which are also unlikely to be correlated with $\xi_{it}$.

Because we did not find any adequate time series data on *RDPERS* en *VALADD* prior to 1980, we estimated model III for the period 1980-2000. From table 6 we see that *GDP*, *VALADD* and *EMIS* have a significant positive effect on patent applications. Environmental stringency, as measured through *EMIS*, has a strong significant effect on innovation, i.e., the number of patent applications. When emissions go up, hence inducing a more stringent environmental policy, innovation tends to be stimulated. Further, alike *GDP*, the industry structure as measured by *VALADD* also has a positive impact on patenting.

Regarding the number of personnel involved in the R&D process (*RDPERS*), one would expect it to be positively related with innovation. That is, if the size of the R&D population increases, more effort is put into the overall R&D activities and therefore also more patent output could be expected. From table 6 we see that the data indeed reveals a positive relationship between innovation and *RDPERS*, though the effect is statistically insignificant and relatively small.

**Table 6: Effects of environmental stringency on patent applications: model III**

| **Variable** | **Coefficient** |
|---|---|
| *GDP* | 0.014 (2.531) |
| *VALADD* | 0.687 (2.911) |
| *EMIS* | 8.528 (5.993) |
| *RDPERS* | 0.068 (1.311) |
| | |
| ***Fixed effects*** | |
| United States | -240.986 |
| United Kingdom | -76.218 |
| Canada | -66.884 |
| France | -62.358 |
| Italy | -56.953 |
| Germany | -48.434 |
| Poland | -46.160 |
| The Netherlands | -29.959 |
| Sweden | -27.361 |
| Finland | -26.007 |
| Austria | -23.139 |
| Denmark | -22.262 |
| Switzerland | -10.471 |

NB: *t*-statistic in parentheses

## 5 Conclusions

The primary purpose of the present paper was to investigate the relationship between stringency of environmental policy regarding sulfur dioxide ($SO_2$) and innovativeness at the country level over the period 1970-2000. We have considered several ways of measuring environmental policy strictness. The incentive to innovate was measured by means of patent applications. As was to be expected, due to the lack of adequate time series regarding pollution abatement control expenditures for the set of countries under consideration, finding plausible measures of stringency posed a major problem. For that reason we had to rely on approaches that are not entirely satisfactory. The first approach is rather naïve in making no distinction between countries. It relies on the assumption that major international agreements on $SO_2$ reductions provide incentives for innovations. The analysis suggests that innovation has increased since the start of the 1979 Protocol to the convention on long range transboundary air pollution. In a second model we classify countries as strict or tolerant over the period 1990-2000, thereby not allowing for increased or decreased stringency over time at the country level in this specific period. Several cases were analyzed, since the bimodal classification of countries in strict and tolerant is not straightforward. However, innovation could not be shown to have a significant relationship with stringency. Finally, we relied on an indirect approach advocated by Xing and Kolstad (2002). In this setting we find quite a strong positive relationship, through emissions. Here the underlying idea is that high emission levels trigger strict environmental policy, which in turn provide an incentive for innovation.

The overall conclusion one is tempted to draw is that, at least in the theoretically preferred model, there is a case for what we would like to call the weak version of the Porter hypothesis. This means that it has not been established that strict environmental policy creates win-win situations, because this is not really measured by innovation. But there is an indication that strict environmental policy with regard to $SO_2$ induces new abatement technologies.

The merits of our approach mainly concern the meticulous identification of patents that contribute to solving the sulfur dioxide problem. In this process we have benefited from the database of the European Patent Office, to which we had direct access. This is important because it seems that working with their public database *esp@cenet* has a number of drawbacks which might lead to flawed results, since not all relevant patents can be found.

Future research will concentrate on other pollutants such as carbon dioxide ($CO_2$), nitrogen oxide ($NO_x$) and volatile organic compounds (VOCs). In that research we employ the same methodology with respect to the screening of patents, since we think that this innovative feature is worthwhile pursuing further.

## Appendix A: Data

**Table A1: Patent applications for sulfur abatement technology per year per country***

| Year | Total | US | DE | UK | FR | FI | AT | DK | SE | CA | NL | PL | IT | LU | CH |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1970 | 34 | 32 | | 1 | | | | | | 1 | | | | | |
| 1971 | 144 | 114 | 20 | 5 | 1 | | | | | 4 | | | | | |
| 1972 | 117 | 78 | 23 | 2 | 11 | | | | | 3 | | | | | |
| 1973 | 117 | 83 | 15 | 1 | | | | | 10 | | 8 | | | | |
| 1974 | 100 | 58 | 16 | 8 | 8 | | | | | 1 | 2 | | | 7 | |
| 1975 | 114 | 44 | 29 | 2 | 1 | 8 | | | | 5 | 13 | | | | 12 |
| 1976 | 49 | 26 | 11 | 8 | | 1 | | | | 3 | | | | | |
| 1977 | 104 | 46 | 44 | 6 | | | | 7 | | 1 | | | | | |
| 1978 | 124 | 65 | 23 | | | | | 27 | | 2 | | | | | 7 |
| 1979 | 194 | 114 | 58 | 7 | | 7 | | 7 | | 1 | | | | | |
| 1980 | 102 | 51 | 37 | 2 | | | | 7 | | 4 | | 1 | | | |
| 1981 | 131 | 23 | 56 | 6 | 20 | | 13 | 13 | | | | | | | |
| 1982 | 219 | 57 | 108 | 12 | 1 | | 17 | 9 | 7 | 8 | | | | | |
| 1983 | 230 | 72 | 96 | 26 | 5 | | 27 | 1 | | 3 | | | | | |
| 1984 | 256 | 47 | 135 | 6 | 18 | 13 | 5 | 1 | 20 | 1 | | | | 10 | |
| 1985 | 281 | 41 | 122 | | 1 | 63 | 25 | 16 | 5 | 7 | | | | 1 | |
| 1986 | 269 | 122 | 104 | 1 | | | 3 | 17 | 10 | 1 | | | | 11 | |
| 1987 | 296 | 128 | 124 | 3 | | 6 | 17 | 6 | 10 | 1 | | | | 1 | |
| 1988 | 217 | 62 | 107 | | 8 | 13 | 8 | 3 | | 1 | | 5 | 9 | | 1 |
| 1989 | 173 | 56 | 84 | | | 17 | 7 | | | | | 8 | 1 | | |
| 1990 | 161 | 82 | 39 | | 19 | 7 | 12 | 1 | | | | 1 | | | |
| 1991 | 151 | 99 | 30 | 14 | | 1 | 3 | 2 | | | | | 2 | | |
| 1992 | 196 | 125 | 34 | 24 | | 1 | | | | | | 1 | 11 | | |
| 1993 | 232 | 108 | 65 | 17 | 6 | 5 | | | 25 | 2 | | 1 | 3 | | |
| 1994 | 253 | 152 | 50 | 2 | 11 | | 8 | | 19 | | | 11 | | | |
| 1995 | 196 | 117 | 66 | | 2 | | 3 | | 4 | | | 2 | 2 | | |
| 1996 | 149 | 74 | 37 | 6 | 14 | | 2 | | | | | 4 | 12 | | |
| 1997 | 119 | 52 | 38 | 3 | 3 | 6 | | | 3 | | 13 | | 1 | | |
| 1998 | 177 | 98 | 57 | | 2 | 7 | | | | | 8 | 5 | | | |
| 1999 | 211 | 135 | 49 | | 12 | 1 | | 13 | | | | 1 | | | |
| 2000 | 207 | 127 | 45 | | 18 | | 2 | 9 | | 4 | | 2 | | | |
| Total | 5323 | 2488 | 1722 | 162 | 161 | 156 | 152 | 139 | 113 | 53 | 44 | 42 | 41 | 30 | 20 |

* US: United States, DE: Germany, UK: United Kingdom, FR: France, FI: Finland, AT: Austria, DK: Denmark, SE: Sweden, CA: Canada, NL: Netherlands, PL: Poland, IT: Italy, LU: Luxembourg, CH: Switzerland

NB: An open entry implies zero patent applications

**Table A2: SOx emissions per year per country (1000 tonnes)***

| Year | US | DE | UK | FR | FI | AT | DK | SE | CA | NL | PL | IT | LU | CH |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1970 | **29006** | **7368** | **5810** | **2819** | **460** | **355** | **292** | **357** | **4279** | **590** | **2659** | **4137** | **7** | **135** |
| 1971 | **27633** | **7296** | **6023** | **2744** | **420** | **347** | **243** | **350** | **4465** | **533** | **2799** | **4005** | **12** | **121** |
| 1972 | **28288** | **7100** | **5149** | **2696** | **405** | **365** | **227** | **324** | **4661** | **547** | **2928** | **3913** | **15** | **104** |
| 1973 | **29558** | **7143** | **5455** | **2858** | **419** | **372** | **249** | **323** | **4856** | **575** | **3031** | **4122** | **15** | **130** |
| 1974 | **27955** | **7117** | **4949** | **3028** | **473** | **383** | **277** | **367** | **4898** | **561** | **3097** | **4265** | **30** | **143** |
| 1975 | **26074** | **6891** | **5272** | **2690** | **472** | **352** | **270** | **381** | **4746** | **479** | **3407** | **3517** | **27** | **101** |
| 1976 | **26468** | **7009** | **4994** | **2786** | **444** | **349** | **255** | **427** | **4520** | **507** | **3583** | **3447** | **31** | **85** |
| 1977 | **26643** | **6964** | **4797** | **2937** | **535** | **336** | **304** | **438** | **4829** | **511** | **3775** | **3794** | **26** | **97** |
| 1978 | **25018** | **6748** | **4704** | **2802** | **496** | **342** | **309** | **447** | **4228** | **456** | **3908** | **3636** | **23** | **86** |
| 1979 | **25078** | **7238** | **4661** | **3118** | **556** | **371** | **376** | **476** | **4490** | **506** | **4047** | **3928** | **18** | **103** |
| 1980 | 23501 | *7514* | 4880 | 3208 | 584 | *344* | 452 | 508 | 4643 | 495 | 4100 | *3760* | 24 | 116 |
| 1981 | 22600 | *7441* | 4431 | 2588 | 534 | *304* | 364 | 422 | 4291 | 468 | **4152** | *3330* | 20 | *108* |
| 1982 | 21400 | *7440* | 4208 | 2490 | 484 | *289* | 368 | 362 | 3612 | 394 | **4193** | *2850* | 16 | *100* |
| 1983 | 20800 | *7346* | 3861 | 2095 | 372 | *217* | 312 | 303 | 3625 | 319 | **4233** | *2460* | 14 | 92 |
| 1984 | 21500 | *7633* | 3719 | 1867 | 368 | *201* | 296 | 287 | 3955 | 302 | **4273** | 2240 | 14 | 84 |
| 1985 | 21463 | *7732* | 3750 | 1473 | 382 | *183* | 339 | 266 | 3704 | 254 | 4300 | 1963 | 16 | 76 |
| 1986 | 20700 | *7641* | 3895 | 1348 | 331 | *163* | 278 | 263 | **3419** | 273 | *4200* | 2074 | 14 | 68 |
| 1987 | 20400 | *7397* | 3898 | 1288 | 328 | *141* | 249 | 241 | 3800 | 267 | *4200* | 2010 | 14 | 62 |
| 1988 | 20700 | *6487* | 3818 | 1223 | 302 | *105* | 242 | 213 | **3874** | 259 | *4180* | 2006 | 12 | 56 |
| 1989 | **21215** | *6165* | 3699 | 1272 | 242 | *94* | 193 | 174 | **3401** | 218 | *3910* | *1850* | 12 | 49 |
| 1990 | 21481 | *5322* | 3754 | 1269 | 260 | *79* | 181 | 136 | 3305 | 202 | 3210 | 1719 | 15 | 42 |
| 1991 | 20906 | *3995* | 3568 | 1379 | 194 | *72* | 239 | 116 | 3316 | 172 | 3156 | 1606 | **13** | 41 |
| 1992 | 20696 | *3307* | 3447 | 1201 | 141 | *59* | 186 | 104 | 3167 | 172 | 2820 | 1501 | **13** | 38 |
| 1993 | 20388 | *2945* | 3105 | 1040 | 122 | *58* | 152 | 94 | 3035 | 163 | 2725 | 1368 | 15 | 33 |
| 1994 | 19845 | *2472* | 2665 | 985 | 115 | *52* | 157 | 96 | 2668 | 146 | 2605 | 1320 | 13 | 31 |
| 1995 | 17407 | *1939* | 2348 | 926 | 97 | *52* | 149 | 90 | 2806 | 142 | 2376 | 1262 | 9 | 34 |
| 1996 | 17109 | *1340* | 2010 | 905 | 105 | *51* | 179 | 96 | 2721 | 132 | 2368 | 1205 | 8 | 30 |
| 1997 | 17566 | *1039* | 1637 | 764 | 99 | *46* | 110 | 88 | 2691 | 118 | 2181 | 1075 | 6 | 26 |
| 1998 | 17682 | *835* | 1567 | 837 | 89 | *43* | 75 | 83 | **2627** | 107 | 1897 | 1039 | 4 | 28 |
| 1999 | 17116 | *738* | *1230* | 735 | 85 | *39* | 55 | 71 | **2597** | 100 | 1719 | 923 | 4 | 26 |
| 2000 | 15176 | *638* | *1190* | 659 | 76 | *38* | 28 | 58 | **1254** | 91 | 1511 | *758* | 3 | 19 |

**Sources and calculation information:**

- OECD Environmental Data Compendium 1992, 2002
- Italic numbers: Expert emissions (EMEP) from the Cooperative Programme for Monitoring and Evaluation of the Long-Range Transmission of Air Pollutants in Europe
- Boldface numbers: Own estimates based on average (1980-2000) country-specific sulfur emission ratios

  Next to a few missing entries for some countries, direct *sulfur dioxide* emissions prior to 1980 were also not available. We solved this by using *sulfur* emissions (see Table A3), which were obtained from David Stern's website (http://www.rpi.edu/~sternd/datasite.html). The procedure is as follows. Sulfur emissions data from David Stern go back until 1970. For each country in the set, these sulfur emissions were obtained for the period 1970-2000. Since we had sulfur dioxide emissions for each country in the period 1980-2000 (with the few exceptions), a sulfur ratio (sulfur emissions/SOx emissions) was calculated for each single year and each country (see Table A4). Then averaging sulfur ratios over 1980-2000 yields country-specific sulfur ratios. Subsequently, the estimated sulfur dioxide emissions for country $i$ at time $t$ were estimated by multiplying the country-specific sulfur ratio with the sulfur emissions of country $i$ at time $t$.
- Figures for Germany (DE) represent Unified Germany (former Federal Republic of Germany and former German Democratic Republic)

**Table A3: Sulfur emissions per year per country (1000 tonnes)***

| Year | US | DE | UK | FR | FI | AT | DK | SE | CA | NL | PL | IT | LU | CH |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1970 | 14158 | 3748 | 2905 | 1454 | 230 | 178 | 147 | 164 | 2083 | 295 | 1325 | 2035 | 4,0 | 67,5 |
| 1971 | 13488 | 3711 | 3012 | 1415 | 210 | 174 | 123 | 161 | 2173 | 266 | 1395 | 1970 | 7,2 | 60,7 |
| 1972 | 13808 | 3612 | 2575 | 1390 | 203 | 183 | 114 | 149 | 2269 | 273 | 1459 | 1925 | 8,9 | 51,9 |
| 1973 | 14428 | 3633 | 2728 | 1474 | 210 | 186 | 125 | 148 | 2364 | 287 | 1511 | 2028 | 8,8 | 64,8 |
| 1974 | 13645 | 3620 | 2475 | 1562 | 236 | 191 | 139 | 169 | 2384 | 280 | 1544 | 2098 | 17,5 | 71,5 |
| 1975 | 12727 | 3505 | 2636 | 1387 | 236 | 176 | 136 | 175 | 2310 | 239 | 1699 | 1731 | 15,5 | 50,3 |
| 1976 | 12920 | 3565 | 2497 | 1437 | 222 | 175 | 129 | 196 | 2200 | 253 | 1786 | 1696 | 17,8 | 42,6 |
| 1977 | 13005 | 3542 | 2399 | 1515 | 268 | 168 | 153 | 201 | 2351 | 255 | 1882 | 1867 | 15,0 | 48,5 |
| 1978 | 12212 | 3433 | 2352 | 1445 | 248 | 171 | 156 | 205 | 2058 | 228 | 1948 | 1789 | 13,5 | 43,2 |
| 1979 | 12241 | 3682 | 2331 | 1608 | 278 | 186 | 190 | 219 | 2186 | 253 | 2018 | 1933 | 10,6 | 51,4 |
| 1980 | 11770 | 3757 | 2427 | 1631 | 292 | 172 | 226 | 246 | 2322 | 245 | 2050 | 1879 | 12,0 | 58,0 |
| 1981 | 11086 | 3721 | 2199 | 1282 | 267 | 152 | 185 | 216 | 2146 | 232 | 2070 | 1665 | 11,6 | 54,0 |
| 1982 | 10408 | 3720 | 2093 | 1229 | 242 | 144 | 189 | 186 | 1806 | 202 | 2090 | 1425 | 11,1 | 50,0 |
| 1983 | 10141 | 3673 | 1923 | 1012 | 186 | 108 | 161 | 153 | 1813 | 162 | 2110 | 1232 | 10,7 | 46,0 |
| 1984 | 10664 | 3817 | 1849 | 903 | 184 | 100 | 153 | 148 | 1978 | 150 | 2130 | 1057 | 10,2 | 42,0 |
| 1985 | 10582 | 3866 | 1859 | 754 | 191 | 91 | 170 | 133 | 1886 | 129 | 2150 | 951 | 9,8 | 38,0 |
| 1986 | 10114 | 3821 | 1939 | 689 | 166 | 81 | 144 | 136 | 1665 | 132 | 2100 | 965 | 9,3 | 34,0 |
| 1987 | 9983 | 3698 | 1937 | 681 | 164 | 71 | 128 | 114 | 1844 | 132 | 2100 | 1015 | 8,9 | 31,0 |
| 1988 | 10260 | 3244 | 1905 | 628 | 151 | 53 | 125 | 112 | 1886 | 125 | 2090 | 982 | 8,4 | 28,0 |
| 1989 | 10355 | 3083 | 1848 | 710 | 122 | 47 | 98 | 80 | 1656 | 102 | 1955 | 927 | 8,0 | 24,5 |
| 1990 | 10477 | 2661 | 1860 | 662 | 130 | 39 | 90 | 53 | 1605 | 101 | 1605 | 826 | 7,5 | 21,0 |
| 1991 | 10158 | 1998 | 1767 | 720 | 97 | 36 | 119 | 50 | 1788 | 87 | 1498 | 770 | 7,5 | 20,5 |
| 1992 | 10025 | 1654 | 1730 | 638 | 71 | 30 | 93 | 44 | 1547 | 86 | 1410 | 697 | 7,5 | 19,0 |
| 1993 | 9884 | 1473 | 1557 | 555 | 62 | 29 | 76 | 39 | 1278 | 82 | 1363 | 667 | 7,5 | 17,0 |
| 1994 | 9691 | 1237 | 1338 | 528 | 57 | 26 | 78 | 40 | 1246 | 73 | 1303 | 636 | 6,5 | 15,5 |
| 1995 | 8453 | 997 | 1182 | 496 | 48 | 26 | 74 | 36 | 1317 | 74 | 1188 | 661 | 4,5 | 17,0 |
| 1996 | 8348 | 703 | 1015 | 484 | 53 | 26 | 90 | 48 | 1267 | 68 | 1184 | 603 | 4,0 | 15,0 |
| 1997 | 8554 | 564 | 835 | 410 | 50 | 23 | 55 | 35 | 1269 | 59 | 1091 | 538 | 3,0 | 13,0 |
| 1998 | 8602 | 450 | 804 | 423 | 45 | 21 | 37 | 34 | 1279 | 54 | 949 | 520 | 2,0 | 13,8 |
| 1999 | 8014 | 416 | 614 | 362 | 44 | 19 | 27 | 27 | 1264 | 52 | 860 | 462 | 1,9 | 12,8 |
| 2000 | 7408 | 319 | 594 | 327 | 37 | 19 | 14 | 29 | 611 | 46 | 756 | 379 | 1,5 | 9,6 |

Source: David Stern, Sulfur emissions data, available at http://www.rpi.edu/~sternd/datasite.html

**Table A4: Sulfur emission ratios per year per country (sulfur emissions/SOx emissions)**

| Year | US | DE | UK | FR | FI | AT | DK | SE | CA | NL | PL | IT | LU | CH |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1980 | 0,501 | 0,500 | 0,497 | 0,508 | 0,500 | 0,499 | 0,500 | 0,483 | 0,500 | 0,495 | 0,500 | 0,500 | 0,500 | 0,500 |
| 1981 | 0,491 | 0,500 | 0,496 | 0,495 | 0,500 | 0,499 | 0,509 | 0,511 | 0,500 | 0,496 | | 0,500 | 0,578 | 0,500 |
| 1982 | 0,486 | 0,500 | 0,497 | 0,494 | 0,500 | 0,499 | 0,515 | 0,512 | 0,500 | 0,513 | | 0,500 | 0,694 | 0,500 |
| 1983 | 0,488 | 0,500 | 0,498 | 0,483 | 0,500 | 0,500 | 0,517 | 0,503 | 0,500 | 0,506 | | 0,501 | 0,761 | 0,500 |
| 1984 | 0,496 | 0,500 | 0,497 | 0,484 | 0,500 | 0,500 | 0,516 | 0,516 | 0,500 | 0,495 | | 0,472 | 0,729 | 0,500 |
| 1985 | 0,493 | 0,500 | 0,496 | 0,512 | 0,500 | 0,500 | 0,501 | 0,500 | 0,509 | 0,508 | 0,500 | 0,484 | 0,609 | 0,500 |
| 1986 | 0,489 | 0,500 | 0,498 | 0,511 | 0,500 | 0,500 | 0,518 | 0,517 | | 0,484 | 0,500 | 0,465 | 0,664 | 0,500 |
| 1987 | 0,489 | 0,500 | 0,497 | 0,528 | 0,500 | 0,501 | 0,512 | 0,473 | 0,485 | 0,493 | 0,500 | 0,505 | 0,632 | 0,500 |
| 1988 | 0,496 | 0,500 | 0,499 | 0,513 | 0,500 | 0,502 | 0,517 | 0,526 | | 0,483 | 0,500 | 0,489 | 0,700 | 0,500 |
| 1989 | | 0,500 | 0,500 | 0,558 | 0,504 | 0,500 | 0,510 | 0,460 | | 0,468 | 0,500 | 0,501 | 0,663 | 0,500 |
| 1990 | 0,488 | 0,500 | 0,495 | 0,521 | 0,500 | 0,500 | 0,497 | 0,389 | 0,486 | 0,500 | 0,500 | 0,480 | 0,500 | 0,500 |
| 1991 | 0,486 | 0,500 | 0,495 | 0,522 | 0,500 | 0,500 | 0,499 | 0,428 | 0,539 | 0,503 | 0,474 | 0,479 | | 0,500 |
| 1992 | 0,484 | 0,500 | 0,502 | 0,531 | 0,500 | 0,500 | 0,500 | 0,422 | 0,488 | 0,500 | 0,500 | 0,464 | | 0,500 |
| 1993 | 0,485 | 0,500 | 0,502 | 0,534 | 0,504 | 0,500 | 0,500 | 0,417 | 0,421 | 0,503 | 0,500 | 0,487 | 0,500 | 0,515 |
| 1994 | 0,488 | 0,500 | 0,502 | 0,536 | 0,496 | 0,500 | 0,497 | 0,417 | 0,467 | 0,500 | 0,500 | 0,481 | 0,500 | 0,500 |
| 1995 | 0,486 | 0,514 | 0,504 | 0,536 | 0,495 | 0,500 | 0,498 | 0,405 | 0,469 | 0,518 | 0,500 | 0,524 | 0,500 | 0,500 |
| 1996 | 0,488 | 0,524 | 0,505 | 0,535 | 0,500 | 0,500 | 0,500 | 0,503 | 0,466 | 0,511 | 0,500 | 0,500 | 0,500 | 0,500 |
| 1997 | 0,487 | 0,542 | 0,510 | 0,537 | 0,500 | 0,500 | 0,497 | 0,396 | 0,472 | 0,500 | 0,500 | 0,500 | 0,500 | 0,500 |
| 1998 | 0,486 | 0,538 | 0,513 | 0,506 | 0,506 | 0,500 | 0,496 | 0,406 | | 0,505 | 0,500 | 0,500 | 0,500 | 0,493 |
| 1999 | 0,468 | 0,563 | 0,500 | 0,492 | 0,512 | 0,500 | 0,491 | 0,383 | | 0,516 | 0,500 | 0,500 | 0,478 | 0,490 |
| 2000 | | 0,500 | 0,499 | 0,496 | 0,483 | 0,501 | 0,495 | 0,493 | | 0,503 | 0,500 | 0,500 | 0,515 | 0,507 |
| Average | 0,488 | 0,509 | 0,500 | 0,516 | 0,500 | 0,500 | 0,504 | 0,460 | 0,487 | 0,500 | 0,498 | 0,492 | 0,580 | 0,500 |

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