INCITING PROTOCOLS*

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Abstract

Using a uniquely constructed patent data set on SO_2 abatement technologies filed in 15 signatory and non-signatory countries in the period 1970-1997, this paper studies patenting decisions by firms in relation to the negotiation and signing of international environmental agreements. Our data enable us to track intended knowledge flows by separating so called mother patents, or original inventions, from family patents, which represent the same invention but are patents filed in foreign countries. Our results suggest that not only local regulations matter for knowledge investment decisions. International agreements are likely to reduce investment uncertainty for inventing firms and provide an additional signal about new opportunities for profitable investmenst in new inventions as well as where to transfer this new knowledge.

Keywords: International environmental agreements, Inventions, Knowledge transfers, Patents, Acid rain

JEL Codes: D7; D8; O31; Q5

1 Introduction

This paper offers a new perspective on the currently dominant view that international environmental agreements (IEAs), such as the Convention on Long-Range Transboundary Air Pollution (LRTAP), have little additional impact on local efforts to reduce international environmental spillovers. This important IEAs in environmental policy aims at reducing emissions of sulphur dioxide (SO_2) and nitrogen oxides (NO_X) and recent empirical and anecdotal evidence suggests that this IEA has added little in addition to what local governments were already planning to do (e.g. Levy (1993), Murdoch and Sandler (1997), Murdoch et al. (2003) and Finus and Tjøtta (2003)). In addition, Popp (2006) has shown that inventors of SO_2 (and NO_X) pollution control technologies essentially respond to environmental regulatory pressure in their own country, rather than to foreign environmental regulations, let alone IEAs.

We challenge the view that protocols have been unsuccessful in contributing to the large reductions in SO_2 emissions. Even though IEAs in general may not be indicative for inducing emission reductions directly, we present evidence that the sulfur protocols have played a role on their own. Using a unique international patent data set we explore the conjecture that IEAs change expectations of innovating firms about their product market, and that innovating firms are strongly inclined to designate patent protection of technologies employed for reducing SO_2 emissions in countries that consider signing the protocol. We will look specifically at protection behavior by firms by means of so called *intended* knowledge flows, or transfers through 'family' patents (e.g., Lanjouw and Mody, 1996, Lanjouw and Schankerman, 2004). We use the distinction between 'mother' and 'family' patents in SO_2 abatement technologies as well as the panel characteristics of our data set to study the responsiveness of patenting behavior of innovating firms for signals as provided by IEAs and in relation to local regulation.

The key hypothesis we explore is that negotiations and signing of IEAs provide a clear (public) signal to inventing firms about new opportunities for a profitable exploitation of their new or existing inventions, for instance because countries that agree on the cooperation to reduce emissions are likely to introduce more stringent environmental policy pressure directed towards their local emitters soon. Thus a country that participates in negotiations that aim at an IEA typically reduces investment uncertainty of inventing firms, whether they are located at home or abroad. In particular in the absence of any previous local regulation, this may induce inventors to increase effort in new research as well as to consider knowledge transfers to the countries that (are likely to) participate in the IEA. In the analysis we mainly focus on run-up effects because we expect negotiations on protocols to have the largest impact on firms' inventing and knowledge transfer decisions. However we also look at more permanent treatment effects after the signing of the IEA.

We believe that our analysis provides clear indications that IEAs in the case of SO_2 emission regulation provide an additional signal to inventing firms about new opportunities for profitable exploitation of their inventions in countries that participate in the protocols and that it is unlikely that the same amount and distribution of innovation across countries and time would have occurred were the Helsinki and Oslo protocols never adopted. For instance, the Helsinki protocol seems to have provided an excellent opportunity for German firms to work somewhat longer on new inventions to reap potential benefits at the time of the actual signing of the protocol. Also an additional effect on family patents seems hard to deny such as the remarkable difference in the value of the mother patents (measured by the number of families for a given mother patent) before and after the negotiations started to sign a binding protocol. Moreover these effects are particularly strong in the countries that cooperate through the IEAs, i.e., the signatory countries.

Our analysis is based on an innovative construction of a patent data set on SO_2 abatement technologies for 15 countries in the period 1970-1997. Several of these 15 countries did not cooperate under LRTAP and the period we study covers the phase-in period of LRTAP coordination for which the 1985 Helsinki and 1994 Oslo protocols are landmarks. The questions our database allows us to address are: (i) have the SO_2 protocols had a significant effect on the incentives to innovate as well as on the decision where to apply for patent protection; (ii) if such incentives exist, do they differ between signatory and non-signatory countries; and (iii) to what extent can differences between the filing of mother patents and patent families be explained by local regulation or international cooperation?

The next section provides a background analysis of our case study. Section 3 describes local and international regulation of SO_2 emissions and our data collection procedure. Section 4 presents a first look at the (distribution of) patent counts. Section 5 describes the econometric model and section 6 presents results for our main hypothesis. Section 7 discusses endogeneity and identification problemas and section 8 some robustness issues. Section 9 concludes.

2 Inventions, knowledge flows and IEAs

Recent empirical evidence confirms the old Hicksian idea that inventions are triggered by changes in the relative prices of the factors of production (Hicks, 1932; Acemoglu, 2001). For example, Popp (2002) provides evidence that rising oil and gas prices induce patents for fossil-fuel saving technologies. Technology groups such as fuel cells, use of waste as fuel or for heat production, and coal gasification have clearly benefitted from the rise in fossil fuel energy prices over time. Similarly, environmental policy —whether implemented through a standard or a specific tax— influences technological change because a policy program signals to (new) producers that it is beneficial to be engaged in R&D directed to meet the requirements of the standard or to reduce tax payments. This is precisely what Popp (2006) found for the linkage between (local) emission standards for NO_X and SO_2 and patent counts of air pollution control equipment that abates those emissions. In addition, he reports that the most important inventing countries in this technological field, the U.S., Germany and Japan, essentially respond to environmental regulatory pressure in their own country between 1970 and 2000 building on existing knowledge from abroad and at home, but not to foreign environmental regulations.

Patent filings are well-known for their usefulness as an observable indicator of knowledge generation.[1] When it comes to study the transfer of knowledge between countries, knowledge flows are usually traced by looking at patent citations (e.g., Jaffe and Trajtenberg, 2002; Keller, 2004; Popp, 2006). These citations reflect technology externalities (spillovers), or disembodied knowledge flows. Knowledge is disembodied if it is not physically 'attached' to labor or products, and it flows unintended if an invention at some place and time inspires other inventions, e.g., if researchers 'stand on the shoulders' of other researchers.[2] If such knowledge flows cross borders they are labelled international knowledge spillovers. As they are not deliberately chosen by the inventor, most knowledge flows under patent citations are beyond the control of the original inventor and are best treated as *unintended*

[1] Measuring invention of new technologies through patents has drawbacks too. For instance, firms may not always patent to protect their rents or may 'over-patent' as a strategic deterrence device (Jaffe and Trajtenberg, 2002).

[2] We explicitly distinguish between (international) knowledge transfers and technology diffusion to make the difference between disembodied and embodied spillovers clear from the beginning. The large literature on international technology spillovers usually focuses on embodied technology diffusion (e.g., Eaton and Kortum, 1999). International technology diffusion in this framework captures the notion that *product* quality innovations in country i become available in country n at some rate ε_{ni}, for example through labor transfer of knowledge workers.

knowledge flows.

In this study we follow a somewhat different approach and focus on what Keller (2004) has labelled 'market-based' international technology diffusion, or knowledge transfers according to our terminology. Market-based transfers are what we call *intended* knowledge flows: the inventor intentionally creates a family of his nationally protected (mother) invention in other countries as long as he believes that the potential gains of additional protection in foreign markets outweigh their investment costs (see also Eaton et al., 2004). Since patent protection is country-specific, i.e., inventors need to apply for patent protection in each country they want to enforce the patent in, the geographical designation of patents is likely to contain important information on market-based expectations.

We exploit the detailed information contained in a patent filing not only to learn more about the technological details of the invention, but also about the associated intended international knowledge flows. To this end we distinguish the original ('mother') from its identical copies filed in other countries ('family'). A mother patent is the original patent filed first in a certain year. This first year of filing is the so-called priority year. Mother patents are usually filed in the home country of the inventor (or inventing company). However, the inventor can file exactly the same patent also in other countries up to one year after the filing of the mother patent. Patent applications designated to other countries are therefore referred to as family members of the mother patent. Thus, family patents comprise the same claim(s) as the mother patent.

As a result the *same* knowledge or invention spreads across countries because of the decision of the firm to seek protection abroad. Clearly this type of international diffusion of knowledge is not a typical externality, because it is the result of a reasoned decision by the supplier of the knowledge. Therefore, patent families lack the public good characteristics that are typical for unintended knowledge flows. The knowledge *per se* is a public good, but the use of an existing invention is constrained to those who pay for it. The designation of these patent flows can be exploited to study geographical or time related distributional patterns. By explicitly separating 'mother' and 'family' patents, we are able to study not only whether the number or location of original inventions correlates with regulatory signals like local regulation or the signing of an IEA, but also whether the number and designation of the families of a given invention is sensitive to such events.[3]

[3] Only Lanjouw and Mody (1996) and Lanjouw and Schankerman (2004) exploit the distinction between mother and family patents. The first paper illustrates that they indeed play an important role in the diffusion of abatement technologies to developing countries.

How would IEAs, such as the Helsinki and Oslo protocols, have an impact on new inventions of firms and their decisions to transfer their knowledge across borders? Inventing firms typically face huge investment uncertainty, in particular in markets that heavily depend on government regulation, such as SO_2 abatement equipment. The decision to invest in new knowledge and its (local and international) protection by patents is likely to be not only affected by the existence of local regulations (see Popp, 2006) but also by expectations about its future development. Perspectives of firms on the profitable exploitation of new (or existing) technologies and their protection crucially depend on the perceived likelihood that governments either introduce new regulations or increase the stringency of existing ones. The same holds for the international designation of this protection, i.e. the number of countries where to seek protection. In global markets with free trade these expectations are not only conditional on (expected) regulatory interventions by the government in the home country but are also likely to be affected by similar decisions abroad.[4]

This is where IEAs are likely to play a role. Negotiations on IEAs provide a clear (public) signal to inventing firms about new opportunities for profitable exploitation of their new or existing inventions. For instance, cooperating countries are more likely to introduce environmental policy pressure directed towards their local emitters and this will also probably happen sooner than in the absence of an IEA. Thus a country that participates in negotiations that aim at an IEA typically reduces investment uncertainty of inventing firms. In the absence of any previous local regulation, this may, in turn, induce inventors at home to increase effort in new research if no such technology is available or existing technologies can be improved. Inventors abroad, whether its country participates or not, will also see an IEA as a signal of an upcoming enlargement of their market and invest in new research as well as exporting new or already existing knowledge to participating countries. With local regulation already in force in a country that itself does not consider to participate, inventors could gain from market expansion in foreign countries created by their likely participation in an IEA.

One would expect this effect to be particularly strong if no previous regulation exist because signing a protocol is likely to be followed by more stringent local regulations and therefore creates large opportunities for the firm. Thus by increasing expectations on the profitable expansion of the international product market for SO_2 abatement technologies, IEAs are likely to also induce larger family sizes for a given

[4] Note that the market size of a typical local invention is not restricted to the home country, but also depends on other countries introducing similar stringent emission restrictions as well. See also Acemoglu et al. (2009).

number of mother patents.[5] When an IEA is already in force, lasting incentives for new inventions and their transfers are created only when permanent incentives for new inventions are created. Finally, expectations will be formed already in the advent of the actual signing of an IEA because negotiations on IEAs signal the likelihood of an upcoming change in local environmental policy in the period after the signing of the protocols.[6] The patent data set we collected allows us to explore such effects of IEAs on the development of new technologies and intended knowledge transfers by comparing differences in mother and family patent filing behavior of firms in both signatory and non-signatory countries surrounding the years of signing the protocols.

3 SO_2 regulation and patent data

To examine the effects of SO_2 policy on new inventions and knowledge transfers we have constructed a panel of SO_2 abatement technology patents for 15 OECD countries over the period 1970-1997. This period covers almost entirely the years of take-off and increasing stringency of SO_2 policies in both signatory and non-signatory countries. This section first discusses developments in both national and international regulation of SO_2 emissions and then explains our patent counts in detail.

3.1 Regulation of SO_2 emissions

Regulation of SO_2 emissions dates back to the late 1960s and early 1970s. At that time Japan and the U.S. took the lead with their implementation of regulatory schemes for (coal-fired) power plants. It took another decade, however, before international cooperation was established under the auspices of the United Nations Economic Commission for Europe (ECE), an organization that includes member states from both Western and Eastern Europe. In particular Scandinavian countries and Canada suffered severely from acid rain in the late seventies, because the

[5] Indeed family size is as indicative of the value of a specific patent as patent citations (see Harhoff et.al., 2003, p.1358). The mere existence of family members for a given patent as a measure of value has also been recognized by the use of so called claimed priorities (see, for instance, Popp, 2006). Claimed priorities are patents that are claimed in at least one other country. Patents that are claimed would be more valuable than those that are not. However, this approach does not exploit the information contained in the number and designation of the claims.

[6] Moreover, public officials of countries with innovating firms may also have a clear stake in negotiating protocols with countries without innovating firms.

soils lack limestone. Hence, they were especially vulnerable to acid deposition (Barrett, 2003, p.7ff). Because acid rain crosses borders, a complex relationship exists between polluters and victims. Not only the prevailing western wind produced acid deposits in vulnerable areas, like Scandinavia, but sulfur imports also found their origin in Eastern European states. Although individual interests of countries may differ considerably due to large differences in the balance between imports and exports of acid emissions, only joint effort to reduce emissions is likely to create a Pareto improvement.

The first treaty that reflects successful efforts in international cooperation has been the Convention on LRTAP in 1979 (see section 1). This treaty provided the framework under which several protocols have been established that regulate specific pollutants, starting with the reduction of sulfur oxides to reduce acidification. At this time there was political reluctance to enter into binding commitments to reduce emissions. With growing awareness in the early 1980s in Scandinavian countries, the Netherlands, and particularly Germany, the political tide turned, leading to the Helsinki protocol, signed in 1985 and entered into force in 1987, on the reduction of sulfur emissions or their transboundary fluxes (Sliggers and Kakebeeke, 2004). This protocol entails emission reduction obligations for 1994. For all signatories the reduction target for SO_2 emissions is more than 30% compared to 1980 levels. The next major event that explicitly aims to further contribute to the reduction of sulfur emissions has been its follow up protocol signed in Oslo in 1994. This 'Oslo Protocol on Further Reductions of Sulfur Emissions' introduced differentiation of emission reduction obligations (base year 1980) due to enhanced knowledge of the complexity of the international emission-deposition-damage chain as well as the aim to find cost-efficient emission reduction regulation.[7]

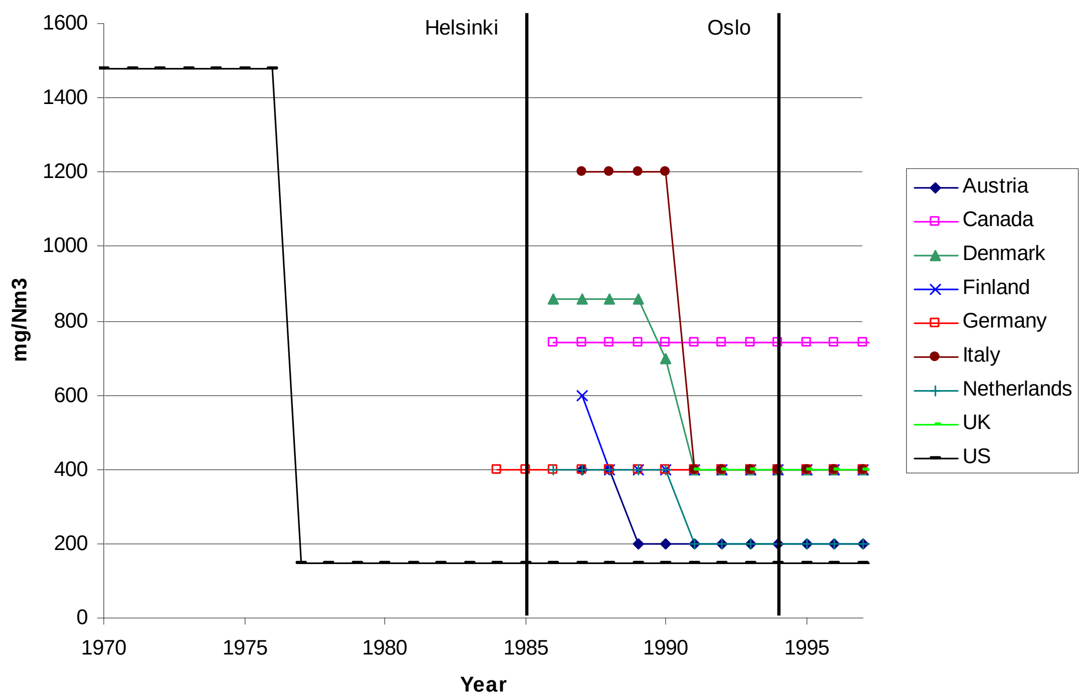
Since the adoption of the Convention in 1979 exchange of technology and operational experience has been an important part of the international coordinated effort to reduce acid rain. With a 5 year interval, starting in May 1981 in Salzburg, Austria, seminars on the exchange of technology have been organized (Sliggers and Kakebeeke, 2004, p.52ff)). The seminars review available efficient control technolo-

[7] The final event relevant for the specific regulation of SO_2 emissions is the Gothenburg protocol signed in 1999. This protocol is a comprehensive regulatory device that not only reduces acidification, but also eutrophication and ground-level ozone. It includes a differentiation of emission reduction obligations for 2010. The overall reduction target of SO_2 emissions in Europe amounts to at least 63% compared to 1990 levels. Ratification of the Gothenburg protocol has taken a lot of time with formal enforcement only in 2005. Because we have patent data only until 1997 we exclude the Gothenburg protocol from our analysis.

gies and the agenda followed the need to integrate technical knowledge into the protocols' annexes, such as the FGD (flue gas desulfurization) technology in 1981. Most of the technical task forces and expert groups were organized by lead countries, such as Germany, United Kingdom and the Netherlands. Valuable information was gathered relating to technical details, cost data, performance of installations, etc.

The countries in our data set that have been involved in coordinated effort from the beginning are Austria, Canada, Denmark, Finland, France, Germany, Italy, Luxemburg, the Netherlands, Sweden and Switzerland. Almost all participating countries ratified the Helsinki protocol already in 1987 which is also the formal year of enforcement (see Appendix A for further details). Ratification of the Oslo protocol has been more slowly and enforcement took effect in 1998. The UK and Poland participated only in the Oslo protocol, for which negotiations started in 1991. The UK was also involved in the negotiations on the Helsinki protocol, but in the end decided not to join. Finally, the U.S. and Japan kept out of international efforts for cooperation under both the Helsinki and the Oslo protocol.

Figure 1: Regulatory standards for coal fired power plants (in μgg/Nm3)



Abatement efforts for SO_2 emission reduction have been targeted predominantly at (coal-fired) power plants.[8] Figure 1 shows the stringency levels for a typical (large) coal-fired power plant as well as its timing for several participating and non-participating countries in our data set in the period 1970-1997.[9] The non-participating countries Japan and the U.S. implemented the first regulatory schemes. Japan set emission standards that varied from plant to plant already in 1968 and the U.S. imposed a first limit on emissions under the Clean Air Act (CAA) in 1970. In practice, however, Japanese and U.S. regulations do not differ substantially (see Popp, 2006, p.49). Standards were tightened by amendments in 1970 and 1974 in Japan. Under the CAA the U.S. imposed a technology-forcing regulation in 1977 by requiring a 90% removal efficiency of SO_2 emissions for new power plants. This type of regulation was designed to ensure that the standards were met by using FGD technology, rather than by switching to clean coal. Thus, the environmental target was unchanged, but the government specified how to reach it.

The countries that decided to cooperate under the LRTAP framework in 1979, however, did not implement their first restrictions on emissions until the 1980s. Indeed, it took until 1 June 1983 before Germany implemented emission standards for large plants (>50 MWt). The regulations in Germany were at a level of 400 mg/m^3 for new plants. The other signatory countries typically imposed their regulations in 1986 or 1987, i.e., *after* their own ratification of the Helsinki protocol, usually at less stringent levels compared to Germany. Except for the U.S., who maintained the advanced 1977 stringency levels, most of the countries in figure 1 increased their stringency levels again up to three years before the 1994 Oslo protocol mainly by applying similar standards now to existing and also smaller plants. In Germany, for instance, the scope of the original restriction of 400 mg/m^3 for new power plants was widened to existing plants in 1993.

[8] We restrict ourselves to policies regarding power plants, because our patent counts are mainly linked to these regulations. Moreover, these regulations are easily comparable across countries. Popp (2006) offers a detailed account of policy interventions in the U.S., Japan and Germany. Information on country-specific regulation of coal power plants has been obtained from Placet et al. (1988), Vernon (1988) and Sloss (2003). See Appendix A for further details.

[9] We exclude Japan from this graph because of its heterogeneous plant-by-plant regulations. Given the heterogeneous character of country, type and capacity of power plants, the standards in the graph apply to large power plants (usually >300 MW). See appendix A for the various types that were used for constructing the graph.

3.2 Patent counts of SO_2 abatement technologies

Patent counts are usually obtained from selecting relevant patent classes, where the classes themselves are identified by using keywords. As explained in detail by Popp (2006), the use of European Classification (ECLA) instead of the commonly used International Patent Classification (IPC) system has the advantage that changes in classes over time are no longer problematic, because patents are reclassified as classes change.[10] Popp (2006) identified the relevant classifications pertaining to pollution control by using keywords —in his case based on technological information on SO_2 and NO_X abatement technologies— which were extracted from various sources. Given the search outcomes, some individual patent documents were subsequently screened to tally frequently occurring ECLA classes, where the classes were assessed on their relevance for pollution control technologies (see p.B2 of Appendix Popp, 2006).

In constructing our patent data set we took a different approach (see Appendix B for a detailed description). As Lanjouw and Mody (1996) have observed, the commonly followed procedure based on patent classes might suffer from type 1 and type 2 errors, i.e., the possibility to obtain whole subclasses of patents that contain technologies not relevant for the specific field, and the possibility to loose relevant patents that are minorities in certain subclasses not selected by the keyword search. To avoid these errors we fed the entire European Patent Office (EPO) online search engine *esp@cenet* database with keywords in order to identify all relevant *individual* patents. The keywords were extracted from SO_2 abatement technologies as explicitly described in the well-known RAINS model, developed at the International Institute for Applied Systems Analysis (Cofala and Syri, 1998). Subsequently, we screened every single patent that came out of our search in *esp@cenet*. The patents we obtained in this way cover abatement technologies such as the use of low-sulfur fuels, including fuel desulfurization, in-furnace control of SO_2 emissions (e.g., through limestone injection or with several types of fluidized bed combustion), conventional wet flue gas desulfurization processes, advanced high efficiency methods for capturing sulfur from flue gas and measures to control process emissions. These patents clearly represent efforts to reduce SO_2 emissions by coal-fired power plants, which was the main industry to be regulated under the Oslo protocol.

We find clear indications that the classification-based search strategy performs rather differently relative to our keyword-based search strategy. Comparing our data with the number of counts reported by Popp (2006) for Germany, Japan and

[10] Nowadays also the IPC accounts for this.

the U.S., we find remarkable differences. For all countries absolute levels are much higher with the classification strategy, in particular for Japan. Furthermore, only for Germany the trend is similar given a correlation coefficient of 0.83 between Popp's total counts and ours. The much lower coefficient for Japan and the U.S., respectively 0.47 and 0.59, reconfirms Lanjouw and Mody's (1996) warning for type 1 and 2 errors.[11]

In the next step we distinguish between a mother and a family patent based on their application and priority number. When a patent is filed at a national patent office it receives a unique application number, whereas the priority numbers refer to other patents owned by the inventor serving as the basis for the new patent. If the patent filing concerns a new or improved technology, the application number is added to the list of priority number and therefore identified as a 'mother' patent. Family members, which protect exactly the same invention as the mother patent, can be identified as having exactly the same priority number(s) as the mother patent, but for which a different application number is used, because it is filed in another country. The overall number of family members of a mother patent is likely to differ across technologies depending on the perceived value of the patent by the inventor who seeks protection abroad.

Our patent database consists of three types of patents: National patents (NP), European patents (EP) and International patents (WO). EP and WO are single patents, providing protection of intellectual property in multiple countries selected by the inventor.[12] To capture all flows of knowledge we decomposed the EP and WO patents by assigning a count to each of the countries selected by the inventor in the year of filing the EP or WO patent. In order to prevent double counting, e.g., when both a NP and an EP are filed for the same technology, we ranked the patents lexicographically in the above stated order. Hence, we registered knowledge flows covered by an EP only if they were not yet captured by national patents. The same holds for WOs: these knowledge flows were registered only if protection was not yet granted through a NP or EP.[13]

Table 1 summarizes our counts and their distribution across countries for both mother and family patents separately. Not only the numbers differ considerably between countries, but also the distribution across countries for mother and family patents is entirely different. Together, Germany, Japan and the U.S. produced 92% of all mother patents, whereas only 26% of all family patents were filed in these

[11] We thank David Popp for making his data available to enable this comparison.

[12] Note that EP and WO applications must still be acted upon by local patent offices.

[13] Some specific cases are discussed in appendix B.

countries. Hence, new inventions are concentrated in these three countries, of which only Germany has been involved in the SO_2 protocols. In contrast, family patents spread remarkably equal across the countries in our sample. As the bulk (70%) of the inventions can be found in non-signatory regions —i.e., Japan and the U.S.— it is hardly surprising that the share of family patents is much lower in these countries (7%).

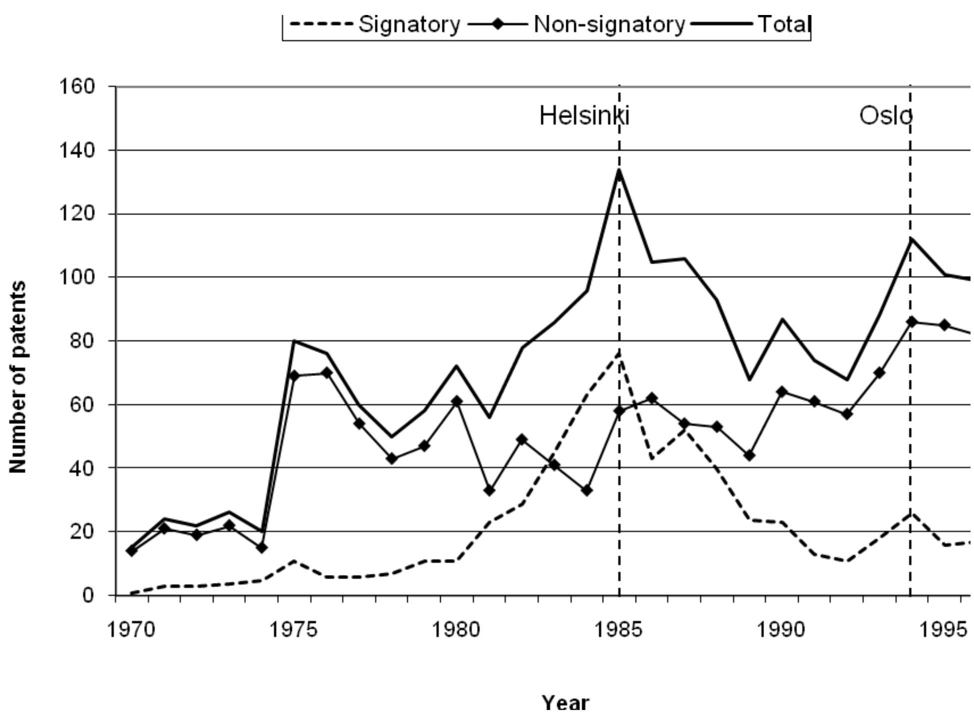
Table 1: Patent counts for 'mother' and 'family', 1970-1997

	Mother		Family	
	Total	Share (%)	Total	Share (%)
Austria	17	0.8	190	6.1
Canada	19	0.9	135	4.3
Denmark	10	0.5	121	3.9
Finland	16	0.8	65	2.1
France	19	0.9	308	9.9
Germany	483	23.6	299	9.6
Italy	8	0.4	278	8.9
Japan	933	45.6	241	7.7
Luxemburg	3	0.1	151	4.8
Netherlands	3	0.1	260	8.3
Poland	26	1.3	68	2.2
Sweden	9	0.4	211	6.8
Switzerland	3	0.1	164	5.3
United Kingdom	36	1.8	375	12.0
U.S.	460	22.5	257	8.2
Total	2045	100.0	3123	100.0
Signatory	603	29.5	2292	73.4
Non-signatory	1442	70.5	831	26.6

4 A first look at the data

If an IEA would have an effect on either new inventions or knowledge transfers or both one would expect a clear difference in both mother and family filings in the run-up to the signing of the agreement and also afterwards if the IEA is not limited to a once and for all ban or limitation of specific emissions. Indeed, local regulation on SO_2 emissions in all but one country, Germany, was yet to be introduced before the signing of the SO_2 protocol for Helsinki. Around Oslo the situation was different because the Helsinki protocol was only renegotiated and never seriously questioned. In particular, the negotiations for the Oslo protocol, focused on cost-efficient, country specific emission reduction in combination with a Best Available Technique (BAT) requirement for the participating countries (Sliggers and Kakebeeke, 2004).

Figure 2: Mother patents in signatory and non-signatory countries

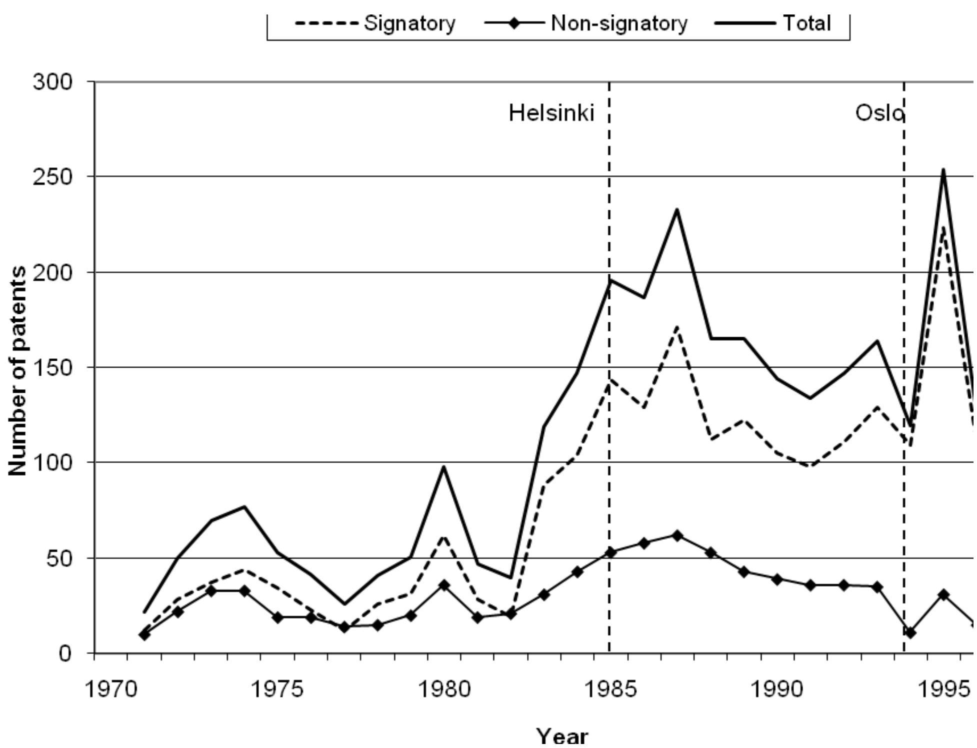


When we plot the distribution of both types of patent filings over time, we indeed find indicative support for our main hypotheses (see Figures 2 and 3). The two figures depict the overall efforts to protect R&D results in SO_2 abatement technologies in both signatory and non-signatory countries through mother patents and their families between 1970 and 1997. Very different profiles emerge for mother and family patents in both signatory and non-signatory countries and across time. Figure 2 clearly has two peaks for mother patents both around Helsinki and Oslo. After an initial steep rise of mother patents in non-signatory countries in 1975[14], the

[14]In a personal communication Matsuno argues that our counts for this period are probably too

overall number of inventions starts to rise again sharply in 1981 until a clear peak around the Helsinki protocol. A second peak arises around Oslo though less sharp. Interestingly, the patterns of inventive activity are very different between signatory and non-signatory countries. The sharp rise in mother patents in 1975 is explained almost only by additional activity in non-signatory countries, whereas the rise before Helsinki is largely attributable to the rise in signatory countries, in particularly Germany. Indeed, within the signatory countries little happens in the 1970s and only after 1979 the number of new mother patents rose sharply with a very strong peak in 1985, i.e., around the signing of the Helsinki protocol. After Helsinki fewer and fewer new patents are filed in signatory countries whereas inventive activity in non-signatory countries continues until 1992 when patenting started to rise again in both signatory and non-signatory countries.

Figure 3: Family patents in signatory and non-signatory countries

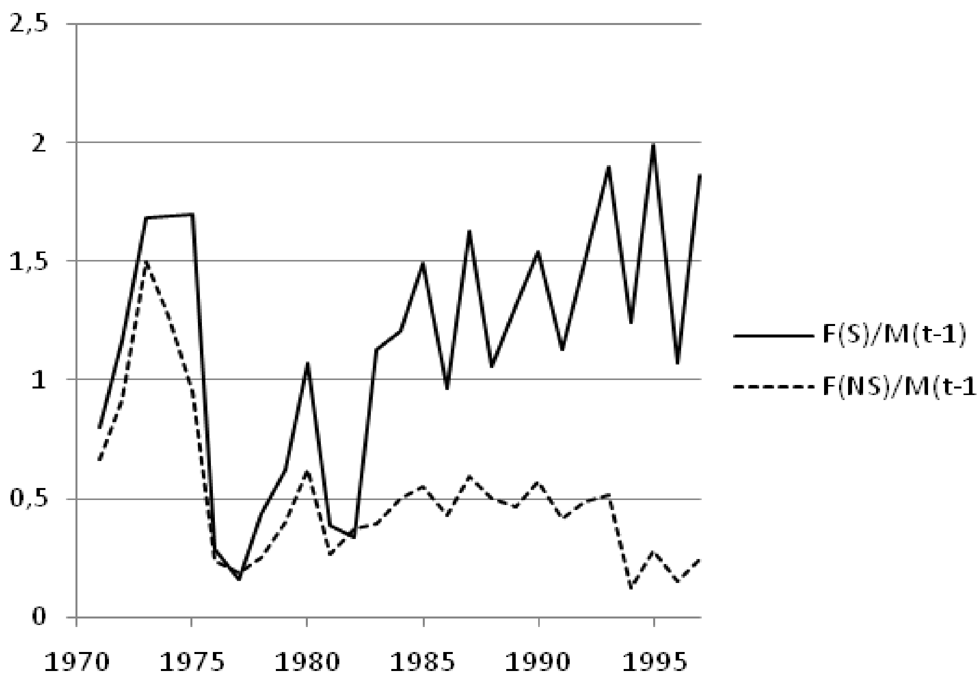


The figure for family patents is also telling (see Figure 3). The overall number of

small due to language problems.

family patents is low on average before the Helsinki protocol and then rises sharply in the run-up to the signing of this protocol in 1985 and remains high afterwards. Peaks can be observed around 1987 as well as just one year after the signing of the Oslo protocol.[15] Interestingly, the difference in patenting activity between the signatory and non-signatory countries is less remarkable except for the fact that the overall number of family patenting in signatory countries grows very fast in the run-up period to Helsinki and remains high since The mean of family filings between 1983-1997 is three times as large as in the period 1971-1982. We do not observe a similar increase of family patenting activity in the advent to Oslo, but the activity level remains rather high despite its erratic pattern at the end of our observation period.

Figure 4: Ratio of region specific family patents to all one year lagged mother patents



The decision to transfer technology is conditional on new technologies being available. So if protocols would stimulate mother patents, than any increase in patent family counts would simply occur because there are more mother patents to

[15] As one might expect the peaks for family patents are somewhat later compared to mother patents because of the built-in time lag of 12 months that applies to filing such patents relative to their mother patents.

transfer. Figure 4 provides a first indication that the increase in family patenting is not just the result of the overall increase in mother patents. The difference in the ratio of family patents relative to all one lagged year mother patents in signatory versus non-signatory countries confirms the remarkable break around 1983.[16] Both series follow a more or less similar pattern until 1983 but then start to diverge strongly.[17] This suggests that even if the Helsinki protocol would have promoted more mother patents, also the decision to transfer technology seems to be affected. Indeed the value of a new invention as measured by the number of families relative to an invention in signatory countries has increased strongly after the negotiation and signing of the Helsinki protocol.

Hence, our data suggest a clear effect of the international negotiations on SO_2 abatement technologies, in particular since the run-up to the binding Helsinki protocol. The protocols indeed appear to provide an incentive for firms to invest in new technologies in their advent, and, when a new technology was invented, to ascertain its potential benefits through additional (family) patenting activity in those countries where firms expect more stringent regulation based on the protocols. Such an effect is at variance with the claim by Popp that only domestic environmental policy determines patenting by domestic firms (Popp, 2006). We not only observe mother patents to peak around both protocols in signatory countries, but also family patenting to rise in those countries before the signing of both protocols —though to a lesser extent around Oslo— and to remain persistently high after Helsinki. Our counts indeed suggest that innovating firms respond to changing prospects across countries and over time. However, also local regulatory interventions play a role. For instance, the big spike in the mid 1980s in signatory countries is largely attributable to German patents, which is likely to be influenced by new German legislation for coal-fired power plants in 1983. Also the U.S. introduced the Clean Air Act (CAA) in 1990 and announced its emissions trading program to be phased-in in 1995 which more or less coincides with the signing of the Oslo protocol in 1994. In the sequel we investigate whether the patterns found in our aggegate data are confirmed by a closer scrutiny at the country level as well as in relation to developments in local regulation.

[16] We apply a lag to the mother patents because family patents can be filed with delay up to a maximum of one year.

[17] Also the peak around 1980 is related to the signing of the non-binding agreement under the LRTAP. The high level of the ratio in the first half of the 1970s is due to the low number of Japanese mother patents in our data base.

5 Econometric specification and estimation

In this section we present the econometric model applied to test whether a differential effect of patent filings in both signatory and non-signatory countries exists in the advent of both the Helsinki and Oslo protocols. For this purpose we model the protocols as events to identify potential differences in impact of the protocols on new patents ('mothers') and their intentional transfers ('family') in designated countries, i.e., in those countries that also participated in the SO_2 protocols.[18] The dependent variables are the aggregate numbers of filed mother and family patents of major SO_2 abatement technologies in 15 OECD countries between 1970 and 1997. We focus on the run-up effects because we expect negotiations on protocols to have the largest impact on firms' inventing and knowledge transfer decisions, in particular if no binding protocol yet exists. But even after a protocol is in force and new negotiations are initiated, firms are likely to expect these negotiations to have a beneficial effect on their inventions because they increase the market prospect for new inventions. As explained in section2 these effects may hold in global markets irrespective of where the inventing firm is located.

Because both our dependent variables are counts of filed abatement technologies, we apply a conditional fixed effects Poisson panel model.[19] We assume the following conditional mean function for the SO_2 abatement patents:

$$E\left[P_{it}|c_i, \theta_t, \mathbf{X}_{it}\right] = \exp(c_i + \theta_t + \gamma\mathbf{X}_{it} + \delta \cdot PROTSIG_{it}), \tag{1}$$

where E is the expectations operator, P_{it} is the number of mother (or family) patents filed in country i in year t, c_i represents country fixed effects, θ_t specifies year effects capturing any common time component and the vector $\mathbf{X}_{it}$ contains country-specific control variables. Our main variable of interest is the event variable $PROTSIG$. As explained before, inspection of Figures 2 and 3 suggest that firms already become active in the advent of the protocols and a permanent effect on . To identify the differences in filing behavior, we study the effect of the protocols by using a dummy called

[18]Note we do not model patent filings by country of origin or designation. We restrict our econometric analysis to the *total* amount of mother or family patents on SO_2 abatement in a given country. Accordingly, estimations do not discriminate between the origin of the (mother and family) patents filed in a particular country. They might originate from both domestic and foreign firms. However, our distinction between mother and family patents implicitly accounts for origin and designation because mother patents are typically filed in the inventors' *own* countries and family patents in *other* countries. Also the distribution across countries of both mother and family patents is asymmetric with a concentration of mother patents in the U.S., Japan and Germany.

[19]A similar approach is used by Acemoglu and Linn (2004). See Wooldridge (2002), p.674ff for details on this estimation strategy.

$PROTSIG$. We exploit different specifications depending on whether we study the run-up or permanent effects. To study the run-up effect we assume $PROTSIG$ to be non-zero for signatory countries in the years of signing the Helsinki and Oslo protocols as well as during a predefined anticipation period preceding the protocols. We parameterize δ flexibly to control for the individual effects of the Helsinki and Oslo protocol.[20] We also study a permanent effect by assuming $PROTSIG$ to be non-zero for the whole period between the signing of the Helsinki and Oslo protocol.

To get rid of unobserved heterogeneity represented by the country fixed effects in our panel estimation we follow Hausman et al. (1984). Accordingly, we factor out the heterogeneity component (c_i) through the conditional logit transformation to obtain a multinomial distribution for P_{it} of the form:

$$E[P_{it}|\theta_t, \mathbf{X}_{it}, \bar{P}_i] = \frac{\exp\left(\theta_t + \gamma \mathbf{X}_{it} + \delta \cdot PROTSIG_{it}\right)}{\sum_{\tau=1}^{T} \exp\left(\theta_\tau + \gamma \mathbf{X}_{i\tau} + \delta \cdot PROTSIG_{i\tau}\right)} \bar{P}_i, \tag{2}$$

where $\bar{P}_i = \sum_{\tau=1}^{T} P_{it}$ is the total number of filed patents in country i over the entire sample period. This transformation allows consistent estimation of our main variable of interest δ by applying Quasi Maximum Likelihood. We estimate (2) using heteroskedastic robust standard errors.

If the protocols have a differential effect on the number of new inventions or knowledge transfers between signatory and non-signatory countries in the run-up to the signing of the protocols, we expect δ to be positive and significant. This parameter measures to what extent firms' R&D leads to more patenting in the surge to the protocols in the countries that actually signed those protocols relative to those that did not sign.[21] Throughout we exploit the potentially exogenous effect of negotiations about protocols on new inventions (mothers) as well as the transfer of knowledge by inventing firms (families) because we expect the negotiations about the protocol and its renewal to have a positive impact on the inventing firms' expectations on the size of their product market. The exact timing of the surge is open and ultimately depends on the prospective behavior of the innovating firms. We expect that the technology seminars organized by LRTAP have played an important role (see section 3.1). Potential innovators could update their information on inventions before deciding to further explore new directions of research or to transfer knowledge across different (participating) countries. The timing of these seminars (1981,

[20] Note that we cannot use first differencing together with count data, because our estimation procedure requires nonnegative integer values.

[21] Note that a one unit change in $PROTSIG$ leads to a proportional change in the conditional expected number of filed patents.

1986 and 1991) is such that a lag of more than 3 years is unlikely. We focus on a 2 year lag and set our event dummy equal to one in 1983-1985 and 1992-1994 for only those countries that actually signed the Helsinki and Oslo protocol respectively (see Table 2).[22] We also check robustness of our results with alternative specifications of the length of the event variable as well as changes in patent filing rules including an increase of the use of European and/or international patents.

Table 2: Treatment dummy for signatory countries (PROTSIG) in anticipation to the signing of the protocols

	Dummy Helsinki	Dummy Oslo
Austria	1983-1985	1992-1994
Canada	1983-1985	1992-1994
Denmark	1983-1985	1992-1994
Finland	1983-1985	1992-1994
France	1983-1985	1992-1994
Germany	1983-1985	1992-1994
Italy	1983-1985	1992-1994
Japan	No	No
Luxemburg	1983-1985	1992-1994
Netherlands	1983-1985	1992-1994
Poland	No	1992-1994
Sweden	1983-1985	1992-1994
Switzerland	1983-1985	1992-1994
United Kingdom	No	1992-1994
U.S.	No	No

As country-specific control variables we employ, first of all, the share of coal-based electricity in total electricity. The share of coal-based electricity accounts for local differences in specific emission generating processes for which abatement technologies provide potential solutions. For instance, flue gas desulfurization is important for coal-based electricity plants. We also expect coal share to be particularly important where the protocol is in effect and therefore also interact coal share with the protocol dummies. Furthermore, we also include the overall number of patents for all types of technologies filed in each country as a scaling variable. Countries

[22] If the seminar is successful, i.e., leads to transfer of information on state of the art technology, patenting of *new* inventions is likely to be delayed with (at least) one more year (relative to the seminar).

may differ systematically in rates of acceptance of patent applications, in how much research they do or — given the amount of inventing activity — how active firms are in patenting. The alternative indicator for scale in inventive activity, i.e., R&D investment expenditures (see Hausman et al., 1983), is available on a country specific basis only for the period 1981-1997. Therefore we run estimations using (lagged) R&D as a measure of the importance of inventive activity within our sample only for robustness purposes. Finally, we include a (common) time trend that captures partly unobservable variation over time.

Table 3 provides some descriptive statistics.

Table 3: Descriptive Statistics, 1970-1997

Variable	Number	Unit	Mean	St.Dev	Min	Max
Mother Patents	420	count	4.87	11.62	0	69
Family Patents	405	count	7.71	6.34	0	26
Coal Share	420	% electricity production	0.34	0.30	0	0.97
Total Patents	420	count	3.78	6.99	0	34.73
Research	206	% GDP	0.02	0.01	0.01	0.03

6 Main results

This section presents our econometric results for a potentially differential effect in patent filings between signatory and non-signatory countries of both the Helsinki and Oslo protocols. We start with our analysis of mother patents. Note that for the Helsinki protocol no noticable changes in regulation in the main inventing countries, Japan, Germany and the United States, can be observed. Only German innovators faced the introduction of new stringent regulations on newly build coal power plants in 1983. In other countries we do not observe changes in local regulations before 1986 and mostly even later, i.e. after the Helsinki protocol was signed and even ratified.[23] Around the Oslo protocol the situation was very different. Most signatory countries had already regulation in force and gradually increased its stringency over time as well as its applicability. The signing of the Oslo protocol appears important not so much because there was clear follow up in terms of more stringent measures, but

[23]Indeed, our country-specific local regulation inventory reveals that most local standards for coal power plants are dated in 1986 or 1987 (see also Appendix A).

it reconfirmed the lasting importance of this market in combination with a Best Available Technique (BAT) requirement for the participating countries. Around Oslo, however, there is likely to be some interaction with the changes in local policy in the US in 1995, i.e. the introduction of new CAA regulation on SO_2 emissions trading in the U.S. in 1995.

Table 4 shows whether the number of filed *mother* patents in both periods differs systematically between signatory and non-signatory countries. The first column provides indicative evidence for a significant upward effect on the number of filings in signatory countries in relation to the Helsinki protocol. Although the overall number of patents rises in both signatory and non-signatory countries in both periods (see Figure 2), the likelihood to observe additional patent filings in the signatory countries is considerably higher only around Helsinki and not in the run-up to Oslo. The expected number of filed mother patents in the period before the Helsinki Protocol increases by 148% in signatory countries. For the Oslo protocol this effect is even negative, though not significant at the 10% level.[24] Coal share as a proxy of local regulation has no impact in this simple specification. Adding interaction terms with the protocol dummy, however, shows that coal share has strong explanatory power when interacted with the protocol dummy. Apparently, a strong rise in new inventions can be observed in signatory countries, in particular in the countries with a large coal share in the electricity sector.

Column 3 presents the results of a specification that also controls for the changes in local environmental policy in both Germany and the U.S. The local policy dummies are set equal to 1 for the period 1981-1983 in Germany and 1993-1995 for the U.S., both run-up periods toward fundamental changes in the local enactment of regulation. The results are illuminating for our main hypotheses. For Germany we basically find support for Popp's finding that local regulation induces new inventions, but the strongly positive Helsinki effect also shows that the inventive activity in Germany continued *after* this regulation was already enforced. By contrast, however, we find a strongly significant *negative* correlation of the U.S. policy dummy on the filing of additional mother patents. Apparently changes in regulation do not nec-

[24] A third event that might have influenced patenting activity is the Convention on Long-Range Transboundary Air Pollution (LRTAP) in 1979. The U.S. was also involved in these negotiations. To see whether this event might have had similar effects we estimated our model with an extended specification of our $PROTSIG$ dummy to include an anticipation period for LRTAP as well. This dummy is equal to 1 in 1977-1979 for all countries except Japan, that never signed the convention. The basic results for this specification as reported by our main specification are not influenced at all. Results are available upon request.

Table 4: Two year lag effect of protocols on mother patents

	(1)	(2) Interact	(3) Incl local policy	(4)	(5) Excl GER
Protsig_Helsinki	1.48 (0.15)***	0.64 (0.34)*	1.41 (0.15)***	0.69 (0.32)**	0.84 (0.22)***
Protsig_Oslo	- 0.36 (0.22)	- 0.26 (0.71)	- 0.42 (0.22)*	- 0.34 (0.71)	0.10 (0.30)
Policy_Germany			0.55 (0.16)***	0.50 (0.19)***	
Policy_U.S.			- 0.33 (0.08)***	- 0.33 (0.08)***	
Coal share	- 0.53 (1.75)	- 0.79 (1.73)	- 0.94 (1.77)	- 1.12 (1.76)	1.42 (0.74)*
Prots_H*Coal sh		1.44 (0.52)***		1.26 (0.48)***	
Prots_O*Coal sh		- 0.22 (1.42)		- 0.17 (1.39)	
Total patents	0.00 (0.01)	0.00 (0.01)	- 0.00 (0.01)	- 0.00 (0.01)	0.00 (0.01)
Log likelihood	-608	-604	-600	-468	-468
Number of obs	420	420	420	420	392
Groups	15	15	15	15	14

essarily always induce new inventions and the impact of new regulation also seems to depend on the circumstances that apply before this regulation is introduced. For Germany an end came to a previously more or less unregulated phase, whereas strict environmental laws were already enforced in the U.S. and the new regulation aimed at similar requirements on old existing plants in combination with more flexibility in attaining such *given* standards.

These results do not change if we also allow for the interaction term with coal share (see column 4), except for the direct effect of the Helsinki protocol. Like the other estimate that includes these interaction terms (column 2) Helsinki is most important for new inventions if countries have a high coal share in their electricity power sector. Finally, an estimate without the inclusion of Germany confirms a significant impact on the number of new inventions within the other signatory countries around Helsinki and this basically implies that the impact is not merely restricted to the main inventor within the signatory countries.

Our findings for the Oslo protocol are very different compared to Helsinki. Even though we observe a peak in patenting activity in signatory countries in 1994 (see Figure 2), our estimates reflect no evidence for additional activity within the signatory countries, rather the opposite. Indeed, mother patenting activity in the advent to both Oslo and the new CAA regulation on emissions trading in the U.S. in 1995 is mainly concentrated in Japan. Both the upward effect in Germany and the U.S.

around that time, pales into insignificance compared to the additional activity in Japan before and in 1995. Given these trends in the three major inventing countries it is hardly surprising that we do not find any effect for the Oslo protocol.[25]

This result is also in concordance with Popp's (2006) observation that Japanese patents were the only case where foreign patents were increasing when U.S. regulations tightened. However, the additional activity in Japan could also, or in addition, be triggered by an expected increase (in stringency) of regulation in signatory countries. In that case we would expect a significant impact in the number of *family* filings within the signatory countries from these mother patents. To this as well as other effects to the filing of family patents we now turn.

If IEAs are key to the higher value of a given mother patent, one would expect knowledge tranfsfers to be strongly correlated with our protocol dummies. In the run-up period of the signing of a (new) protocol, firms - whatever their location - are likely to expect more profit from filing a family patent in a country where the transfer is most likely to become profitable, i.e. a signatory country. The results for our *family patents* indeed provide evidence for such a role of the protocols: the expected number of filed family patents in signatory countries in the years before and the year of the signing of the protocols increases by 22% on average for Helsinki, though the effect is insignificant, and even 69% for Oslo (see Table 5 column 1). Again coal shares on their own have no significant effect on filing behavior in this simple specification. Family patenting is negatively correlated with the total number of patents filed in specific countries, but this is precisely what one would expect. Countries with a large inventive sector attract fewer families *ceteris paribus*.

The Helsinki effect is not only much larger but also strongly significant if we include the interaction terms with coal share (see column 2). Also family patent filings are now more likely in countries with a high coal share in the electricity sector. However, signatory countries without a high coal share also become relatively attractive for knowledge transfers which explains the negative effect of the interaction term. These results are almost similar if we also control for changes in environmental policy at the national level (column 3 and 4 in table 5). The introduction of local regulation in Germany in 1983 does not correlate with additional family patents. Somewhat surprisingly we find that the shifts in U.S. regulation did attract significantly less family patents by changing its national policy at the time of the Oslo protocol while the signatory countries did attract more family patents relative to the non-signatory countries.

[25] This result is confirmed for a subpanel without Germany and the U.S. Results are available upon request.

Table 5: Two year lag effect of protocols on family patents

	(1)	(2)	(3)	(4)	(5)
		Interact	Incl local policy	Interact	Excl GER
Protsig_Helsinki	0.22 (0.14)	0.43 (0.13)***	0.23 (0.14)	0.45 (0.13)***	0.25 (0.14)*
Protsig_Oslo	0.69 (0.14)***	0.66 (0.15)***	0.62 (0.10)***	0.59 (0.12)***	0.73 (0.14)***
Policy_Germany			- 0.00 (0.09)	0.17 (0.13)	
Policy_U.S.			- 0.25 (0.10)**	- 0.25 (0.10)***	
Coal share	0.97 (0.63)	1.09 (0.63)*	0.97 (0.63)	1.09 (0.63)*.	0.76 (0.72)
Prots_H*Coal sh		- 0.80 (0.28)***		- 0.84 (0.28)***	
Prots_O*Coal sh		0.10 (0.28)		0.10 (0.27)	
Total patents	- 0.05 (0.02)***	- 0.05 (0.02)***	- 0.05 (0.02)***	- 0.05 (0.02)***	- 0.05 (0.01)***
Log likelihood	-919	-913	-919	-912	-854
Number of obs	405	405	405	405	405
Groups	15	15	15	15	14

The general picture that emerges is that the Helsinki protocol is strongly correlated with additional activity in both mother and family patents within the signatory countries. For the Oslo protocol we do not observe mother patenting in signatory countries to be significantly different at the time, whereas the number of designated family patents in signatory countries actually is. Some concerns remain, however. Apart from some caveats such as differences in the prospensity to patent and yet to be discussed, also some more fundamental concerns remain. In particular one might question to what extent countries just decide to participate in an IEA because they would simply benefit from the new pool of knowledge becoming available. Furthermore, one might still be concerned that no real IEA effect exist because it coincides (up to some point) with anticipation by firms of the enactment of local regulation in the participating countries. These and other issues will be discussed in more detail in the next section.

7 Endogeneity and identification problems

Our analysis so far is subject to a fundamental endogeneity issue which is closely linked to a fundamental identification problem. First of all, it is entirely plausible that the countries that had an incentive to reduce SO_2 unilaterally are the same countries that signed the IEAs, and that the same amount and distribution of innovation would have occurred were the treaties never adopted. Moreover, the results obtained so far might also be spurious if they are simply the result of an identification problem. Indeed, firms could equally well just have anticipated changes in local regulation three to four years in advance. Together both arguments amplify each other.

7.1 Endogeneous participation decisions

We start by noting that we do not claim that the IEAs have induced countries to reduce more emissions than they would otherwise have done unilaterally. At the same time we also think it is quite unlikely, however, that countries would only participate in an IEA in the SO_2 case to get access to the pool of knowledge with the protocols themselves adding little to the number and timing of new inventions and knowledge tranfers. If anything we learn from our distinction between mother and family patents it is that inventing *firms*, not countries, are responsive to the changing market conditions in different countries created by a country negotiating and signing an IEA or not. For inventing firms IEAs are just risk reducing devices, in particular in global markets - such as the market for SO_2 abatement equipment -. Apart from being sensitive to regulatory signals at their home market inventing firms consider an IEA as an early signal of upcoming regulations in (newly) participating countries or a continuous signal for a lasting market abroad.

By contrast *countries* make their participation decisions, first of all, in relation to whether or not they can organize reduction commitments properly. Victim countries try to commit polluters which gets complicated if the externality is not bilateral such as in the case of the United Kingdom. Furthermore, endogeneity is likely to be a problem if patterns between non-signatory and signatory countries would not be similar before the event. In fact, they are similar before and fundamentally different since negotiations on the Helsinki protocol (see figure 3). To look whether the post-Helsinki period implies a fundamental break for the signatory countries compared to the period before the negotiations about this binding agreement, we re-estimated our basic specification including also a dummy equal to 1 for signatory countries between 1985-1997. Table 6 shows that the dummy is (weakly) significant for both mother and family patents. Thus we observe a greater likelihood that firms file both mother and family patents more often after the signing of the Helsinki protocols in the signatory countries.

A second reason why participation would not be necessary for countries to benefit from a technology pool is participation is not a precondition for inventing firms

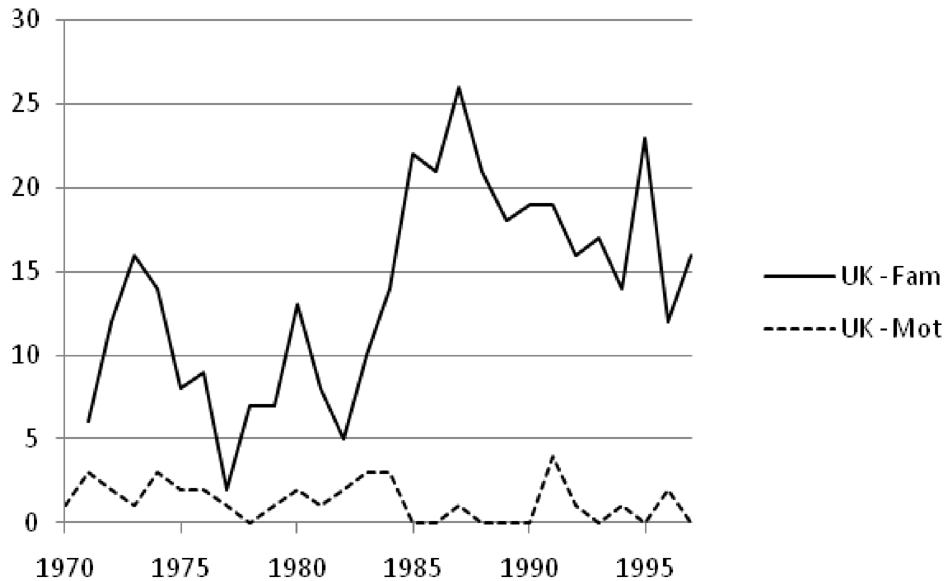
Table 6: Robustness analysis

	(1)	(2)	(3)	(4)
Dependent Variable	Mother Patents Permanent	Family Patents Permanent	Mother Patents Ratification	Family Patents Ratification
Protsig_Helsinki	0.85 (0.32)**	0.50 (0.14)***	0.17 (0.42)	0.39 (0.11)***
Protsig_Oslo	- 0.43 (0.67)	0.54 (0.13)***	- 0.36 (0.42)	- 0.32 (0.21)
Policy_Germany	0.76 (0.25)***	0.21 (0.13)***	1.17 (0.10)***	0.01 (0.09)
Policy_U.S.	- 0.20 (0.11)*	- 0.20 (0.09)**	- 0.26 (0.15)*	- 0.50 (0.10)***
Permanent	0.75 (0.33)**	0.28 (0.15)*		
Coal share	0.79 (1.51)	1.28 (0.76)*	- 0.88 (1.27)	1.30 (0.68)*
Prots_H*Coal sh	1.04 (0.47)**	- 0.86 (0.28)***	1.86 (0.69)***	- 0.87 (0.27)***
Prots_O*Coal sh	- 0.14 (1.33)	0.13 (0.28)	- 0.81 (0.74)	0.97 (0.67)
Total patents	0.01 (0.02)	- 0.04 (0.02)***	- 0.01 (0.01)	- 0.06 (0.02)***
Log likelihood	-586	-907	-600	-905
Number of obs	420	405	420	405
Groups	15	15	15	15

to benefit from the larger market size implied by a protocol. Indeed, main inventing countries like the US and Japan have always stayed outside the coalition. Interestingly also is that our estimation with the permanent effect seems to suggest that more inventive activity can be observed in most signatory countries in the post-protocol period. Furthermore, a permanent effect on family patenting is also there, but it is smaller and significant only at the 10% level.

Finally, the role of the UK provides further evidence that our analysis is not perverted by endogeneity problems. If the goal for the UK would have been access to the knowledge pool, it should certainly have participated. Because of its large share of coal based electricity generation one would expect the UK to sign for sure. In fact the UK did not sign the Helsinki protocol and only decided much later to participate in the Oslo protocol. Also serious stringent local regulation of coal power plants had to wait until 1991 when the UK was obliged to implement the EU coal combustion plant directive. Interestingly, close inspection of our data show a remarkable picture (see Figure 5). Inventive activity within the UK has always been there in the pre-Helsinki period, but dropped to zero when it became clear that the UK did not participate in the Helsinki protocol despite its active participation in the treaty negotiations. The number of family patents in the UK, however, has always been highest of all countries in our data set and also closely followed the trend in other signatory countries. Indeed, inventors have expected that the UK would sign the Helsinki protocol for quite a long time and therefore also included this country in their knowledge transfer considerations. And even after the protocol was signed, the UK continued to be an important target because the 1988 EU Large Combustion Plant Directive made it plausible that the country had to adapt its policies anyway. These observations are confirmed when we re-estimate our basic specification with the UK included as a signatory country.[26]

Figure 5: The filing of mother and family patents in the UK



7.2 Protocol versus regulatory effects

A closely related problem is the identification of protocol effects from the regulatory effects. Clearly our basic specification already controls for the major local policy effects in countries that host most important inventors, typically Germany and the U.S.[27], as well as a coal share variable as a proxy for (anticipated) local policy effects in other countries. An alternative way to potentially control for this problem is

[26] This only has a small effect on the coefficients and never changes our findings in a fundamental way. Remember our event variable defines the UK as a non-signatory country around the Helsinki protocol, but as a signatory country for the Oslo protocol. Also excluding the UK from our sample has no significant effect on the results.

[27] **EXPLAIN JAPAN**

using ratification dates as a proxy for the introduction of increased local stringency. Therefore we experimented with what we call a 'ratification' dummy. This dummy reflects the possibility that firms only anticipate local regulation which is likely to become more stringent only after ratification and not because of the countries' negotiating and signing of the IEA as such. For this purpose we use as our event dummy country-specific information on the year of ratification by the protocol participants applying a 2 year lag. For instance, $PROTSIG$ for Austria is equal to 1 in the years 1985-1987 respectively 1996-1997 because Austria ratified the Helsinki protocol in 1987 and the Oslo protocol in 1998 (see Appendix A for details).[28]

The estimations based on this ratification dummy generate weaker results compared to our run-up dummy for negotiations (see Table 6 column 3 and 4). For mother patents we now only observe a significant positive effect for Helsinki when the ratification dummy is interacted with coal share. For Oslo we observe that the interacted effect is now even strongly negative (though significant only at the 10% level). This suggests that ratification in the case of mother patents has less explanatory power than our protocol dummy which is more closely connected with the negotiation process. This more or less confirms what we have observed before: the Helsinki negotiations are heavily influenced by the participation of Germany which took the lead not only with its early introduction of local regulation but also with a continuous stream of new inventions until the protocol was actually signed. Because family patents could be filed up to one year after the mother has been patented, it is also hardly surprising that ratification is still correlated with family patenting around Helsinki (see Table 6 column 4).

In our view the run-up effect we find for Helsinki is unlikely to be similar to a counterfactual without any negotiation about this IEA. In particular the main *inventing* firms in Germany had a clear interest in these negotiations as they provide a promising outlet for their invented technologies. Indeed, the newly developed FGD control technology in Germany was key to compliance with new local restrictions on coal-fired power plant SO_2 emissions such as those codified in the initial regulation in Germany in 1983. With this guaranteed demand for their FGD technology, the German firms continued their successful search at a level not seen before in any period or country in the run-up to the Helsinki protocol. The only reason to continue this activity beyond the level necessary for compliance with local regulations in Germany is negotiations on the Helsinki protocol providing a potential outlet for

[28] From the appendix it is clear that ratification for Helsinki in particular is a good proxy for increased local stringency. Ratification often happened in the same year or one or two years before the introduction of more stringent local measures.

new inventions. Indeed, as documented by people involved in the negotiations on LRTAP, a continuous search for state of the art technologies was promoted already before the signing of the Helsinki protocol (Sliggers and Kakebeke, 2004). However, when the negotiations culminated in the signing and ratification of the Helsinki protocol it became clear that no further inventions would be necessary for participating countries to comply with the negotiated targets. So we conclude that the German inventions enhanced the possibility to finally boost LRTAP negotiations which culminated in the Helsinki protocol, but that targets negotiated and codified in the protocol itself did not require new inventions because the local regulations envisaged by the participating countries to comply with the protocol could already be met with the existing FGD technology.

The results for the ratification dummy once more illustrate the important difference between decisions on new inventions (mothers) and knowledge transfers (families) by firms. Indeed, the fading incentives for new inventions do not immediately affect the interest of the inventing firm in knowledge transfers. Many participating countries still had to introduce regulation at a level already enforced in Germany. Therefore the interest for the inventing firms to protect their newly acquired knowledge in the countries that signed or were expected to sign the Helsinki protocol continued after the signing of the protocol itself.[29] Also our results for the permanent effect shown in the previous section suggests that more family patenting was going on in most signatory countries in the post-protocol period. To neglect this finding and to attribute the remarkable rise in family patents starting already in 1982 *only* to inventing firms anticipating stricter local regulatory interventions 4 to 5 years earlier seems to be hard to defend.[30] An interpretation that gives credit to the negotiations as providing credibility to upcoming market expansion in non-inventing signatory countries, usually through stricter national measures, seems more convincing. This interpretation also finds support in the fact that inventing firms in the U.S. and Japan suddenly increased their family patenting in signatory countries while they did not really expanded their inventive activity around Helsinki (measured by a rise in their mother patents). Whatever the mechanism is here, all of these findings shows that inventing firms not only respond to what happens in their home country, but certainly also to developments in other countries.

[29] Note that also the UK was an attractive target because of its participation in the negotiations.

[30] Note that the stringency of the local standards themselves are also likely to be conditional on the IEA itself. However, whether or not the Helsinki protocol has lead to stricter local regulations than those that would have been obtained under unilateral action is an open question as well (see Barrett, 2003).

A final and related issue that deserves closer scrutiny is the difference in impact between Helsinki and Oslo. All our findings suggest that the run-up to Oslo has less of an impact on new inventions within the signatory countries whereas family patenting remains important. In fact, these findings provide another reason why it is unlikely that major changes in new inventions and knowledge transfers could be attributed to responses in shifts in local regulation *only.* First of all, the Helsinki protocol provided more of a break with the past than the Oslo protocol. Before Helsinki most participating countries had almost no regulation of SO_2-emissions. After Helsinki was signed the protocol provided continuous pressure on the diffusion of the FGD technology because regulation was regularly updated in all participating countries, in particular also by pushing existing power plants to also adapt this technology (see also Appendix A for details). By contrast Oslo is not followed by a similar increase in specific standards and would therefore offer an excellent opportunity to explore the difference. Unfortunately, our sample does not extend beyond 1997. Moreover, developments around Oslo also coincide up to some point with important changes in U.S. regulation. Finally, a fundamental change can be observed in the location of new inventions across our sample and to this we now turn in more detail

According to the negotiatiors on LRTAP (Sliggers and Kakebeke, 2004) after Germany conquered the world with its FGD technology and guaranteed a profitable market size through the Helsinki protocol, the main new inventive activity gradually shifted towards Japan, a non-signatory country. The shift in new inventions is clearly visible in the pattern for mother patents in Figure 2. The dominance of German inventions in the early 1980s shows up in the spike of signatory countries at the time, whereas the rise in Japanese inventive activity in the 1990s drives the overall number of non-signatory mother patents to an all-time high in 1995 when both Oslo and the U.S. CAA entered a new phase. The developments in the advent to the Oslo protocol resemble the circumstances before Helsinki, but now with Japan in the leading inventor role. The number of mother patents for Japan rose from 28 in 1989 to 68 in 1995. In contrast, this number in Germany peaked at 69 in 1985 and then gradually dropped to as low as 5 in 1992, one year before regulatory standards for existing coal-fired power plants were tightened in Germany. The new legislation in 1993 only required existing plants to comply with the standards that new power plants already had to comply with since 1984 and therefore illustrates that no serious benefits were expected from new improvements in the FGD technology itself. German inventors, after their initial first mover advantage, seem to have been outcompeted by Japanese inventors who were mainly responsible for further improvements of FGD technology around that time.

Indeed, Japanese firms, strongly supported by the Japanese government, have worked both consistently and continuously on further improvements of FGD inventions with a strong focus on finding opportunities for technology transfer in the 1990s. According to Imura (2005, p.350) Japan was very conducive to the creation of a so-called 'eco-industry' which produced and supplied various pollution control technology. Between 1990 and 1995 expenditures on FGD equipment rose strongly due to the introduction of newly built coal fired power plants to the Japanese grid and the newly developed wet scrubbers became the dominant FGD technology in the 1990s. This development was further enhanced by the implementation of Japan's Basic Environmental Law in 1993. The main difference of this new law with previous legislation is that it took a more global perspectives on environmental problems (Imura, 2005, p.358) and focused on long term environmental targets and national action plans.

Developments in regulations abroad, i.e., within the U.S. and the countries that cooperated under the LRTAP, provided ample opportunities for the Japanese strategy. In the U.S. the new CAA regulation on emission trading in 1995 shifted attention in technological advances considerably (Farrell et al., 2000, p.IV-24ff). In particular, the introduction of the cap-and-trade system starting off in 1995, fueled the firms' interests to reduce emissions as much as possible. This is typically provided by wet scrubbers. Also reliability of the process became a major concern and routine control effectiveness was improved to over 95% through several new technologies. The major other option for knowledge transfer in the 1990s were the countries preparing for the Oslo protocol. Negotiations at that time aimed to provide strong incentives for further improvements of new inventions. In particular, the negotiations for the Oslo protocol, focused on cost-efficient, country specific emission reduction in combination with a Best Available Technique (BAT) requirement for the participating countries (Sliggers and Kakebeeke, 2004). Apart from this general BAT provision, the 1994 Sulfur protocol also imposed emission limit values on new and existing large stationary combustion sources based on earlier EU legislation, the 1988 EU Large Combustion Plant Directive.

Looking at our data, the main designated countries of the Japanese inventions between 1992-1994 were, apart from Germany, the UK, Italy and France, all involved in the negotiations for the Oslo protocol. Designation for the U.S. peaked in 1995 when the U.S. implemented the first phase of its new acid rain program.[31] At the

[31] The additional number of families from Japan to the U.S. in the year 1995 alone was 22 and this is two times the number of patents in the whole period 1992-1994.

same time designation of inventions by U.S. firms is targeted at signatory countries, though they spread more equally across signatory countries. Finally, the peak in family patents in 1995 is mainly due to U.S. firms designating almost an equal number of families in signatory countries in 1995 as in the whole period of 1992-1994. These knowledge transfer patterns explain our estimation results for family patents as well as the patterns visualized in Figure 3. Moreover they once more illustrate that it is unlikely that patenting behavior by firms is only driven by changes in local regulation. The designation of the Japanese patents towards the signatory countries is another case in point. We conclude that the negotiations on the inclusion of BAT-obligations into the Annex of the Oslo protocol and the incentives for as much emission reduction as possible due to the U.S. CAA regulation in 1995 seem to have been sufficiently promising for (Japanese) firms to take in their strategic positions by patenting their inventions abroad.

Because the main inventing activity in FGD control technology gradually shifted from German to Japanese firms after Helsinki was signed, the relative impact of the event variable on mother (family) patents is likely to decline (rise) in the signatory countries. And this is exactly what we observe. The gradual relocation of patenting activity also accounts for the apparently anomalous results for Oslo. The negative sign for mother patents as well as for the U.S. policy dummy just illustrates that a lot more activity was going on *outside* both the signatory country and the only country that imposed stricter regulations around that time. The reason we no longer find a significant effect for family patenting in the specification that accounts for ratification is likely to be explained by a so called 'movement to universality' (Eaton et al., 2004) at the end of our sample and we discuss its likely impact on our estimations in more detail in the next subsection.

We believe that it is unlikely that the same amount and distribution of innovation would have occurred were the Helsinki and Oslo protocols never adopted. For new inventions the Helsinki protocol provided an excellent opportunity for Germany to built somewhat longer on its knowledge stock to reap potential benefits at the time of the actual signing of the protocol. Also an additional effect on family patents seems hard to deny such as the remarkable difference in the value of the mother patents (measured by the number of families for a given mother patent) before and after the negotiations started to sign a binding protocol. And finally, Japan could benefit from the opportunity provided by the Oslo protocol to designate their newly acquired knowledge not only to the U.S., but to the participating countries in the IEA as well.

8 Robustness and further discussion

Obviously a number of problems, such as the construction of the event dummy, institutional differences in the propensity to patent and alternative controls, could affect our results. Given the panel data structure of our sample we can easily check a number of time and/or cross-section related robustness issues of our estimation strategy.

8.1 Construction of the length of the event variable

The first issue is the choice of the length of the event dummy. The choice of a two year lag seems somewhat arbitrary because we do not exactly know how and when policy signals affect inventors. Therefore we ran several alternative specifications using longer or shorter lag lengths, i.e., three years and one year, respectively. This hardly affects our main findings [32] Results for the three year lag for our main specification are presented in Table 6 (columns 1 and 2). This somewhat longer window of anticipation produces fairly similar results. The expected increase in the number of filed patents for the signatory countries in anticipation to Helsinki declines slightly for mother patents and is still negative for Oslo, but hardly significant.[33] We conclude for mother patents that a significant effect exists on the expected number of filed patents for the signatory countries in anticipation of Helsinki, but not of Oslo. This effect becomes stronger when the protocol date comes closer. For family patents no remarkable changes can be observed either. The weak evidence for a higher number of filed family patents for Helsinki even disappears completely and the effect for Oslo becomes somewhat smaller with a longer anticipation period. For the one year lag model nothing of importance changes either whether or not we test with or without the inclusion of Germany. Hence there is systematic evidence that firms file new inventions in signatory countries up to three years in advance of Helsinki, but not for Oslo.

[32] In the three (one) year lag model we set our event dummy equal to one in 1982-1985 (1984-1985) and 1991-1994 (1993-1995) for all countries that signed the Helsinki and Oslo protocol.

[33] Further experimentation with the cross-section without Germany confirms our previous conclusion that the negative effect is entirely due to the observed (lack of) filing of mother patents in Germany in this period. The negative effect simply resolves in this case. Results are available on request.

Table 7: Robustness analysis

	(1)	(2)
Dependent Variable	Mother Patents	Family Patents
	Lag 3	Lag 3
Protsig_Helsinki	1.35 (0.15)***	0.13 (0.13)
Protsig_Oslo	- 0.33 (0.19)*	0.64 (0.07)***
Coal share	- 0.77 (1.78)	0.95 (0.63)
Total patents	- 0.00 (0.01)	- 0.05 (0.02)***
Trend	0.07 (0.05)	0.11 (0.02)***
Log likelihood	-609	-919
Number of obs	420	405
Groups	15	15

8.2 Differences in institutional rules in patent protection

The second major issue are institutional differences in the legal protection of ideas across countries. Japan differs substantially from other countries in our sample. In Japan every claim needs to be filed as a separate patent, whereas in other countries a single patent can hold several claims. This institutional difference might give rise to a disproportionally large number of Japanese patents and cause biased results. Eaton and Kortum (1999, p.542) estimate that the filing of patents in Japan is 5 times as large as elsewhere. If we divide the number of Japanese mother patents by 5 and re-estimate our basic specification we only observe minor changes in our results (see Table 7 column 1).[34]

Another concern relates to our family counts. The overall number of counts might be affected by the growing importance of so called European (EPs) and international patents (WOs). As explained before, an EP or WO is a bundle of exactly the same national patents granted in several countries after applying for a patent at a single patent office. For example, an EP patent granted by the Dutch patent office guarantees protection in a number of selected member states (i.e., indicated/selected by the inventor) of the European Patent Convention (EPC) or Patent Cooperation Treaty (PCT) within Europe. Due to these treaties, seeking protection in multiple countries has become cheaper. For instance, the European Patent Office provides a simplified, and less costly, means of seeking patent protection in the majority of

[34]The problem only exists for mother patents because foreign countries that designate Japan to protect their invention do so for each original invention (mother patent) separately.

Table 8: Robustness analysis

	(1)	(2)	(3)	(4)
Dependent Variable	Mother Patents	Family Patents	Mother Patents	Family Patents
	Scaling Japan	Excl DK/FIN	R&D expenditures	R&D expenditures
Protsig_Helsinki	1.35 (0.17)***	0.28 (0.13)**	0.90 (0.15)***	0.34 (0.10)***
Protsig_Oslo	- 0.32 (0.21)	0.67 (0.14)***	- 0.30 (0.17)*	0.67 (0.06)***
Coal share	- 2.06 (1.75)	0.97 (0.66)	- 3.62 (2.36)	- 1.01 (0.93)
Research			107.03 (67.03)	86.90 (39.31)**
Total patents	0.01 (0.02)	- 0.05 (0.02)***	0.01 (0.03)	- 0.07 (0.02)***
Trend	0.03 (0.03)	0.10 (0.02)***	- 0.00 (0.03)	0.08 (0.01)***
Log likelihood	-528	-792	-295	-461
Number of obs	420	351	200	206

Standard errors within parenthesis. ***[**](*) denotes significance at the 1[5](10) percent level.

The Poisson model is estimated by quasi-maxiumum likelihood (see text).

All regressions include a full set of year dummies.

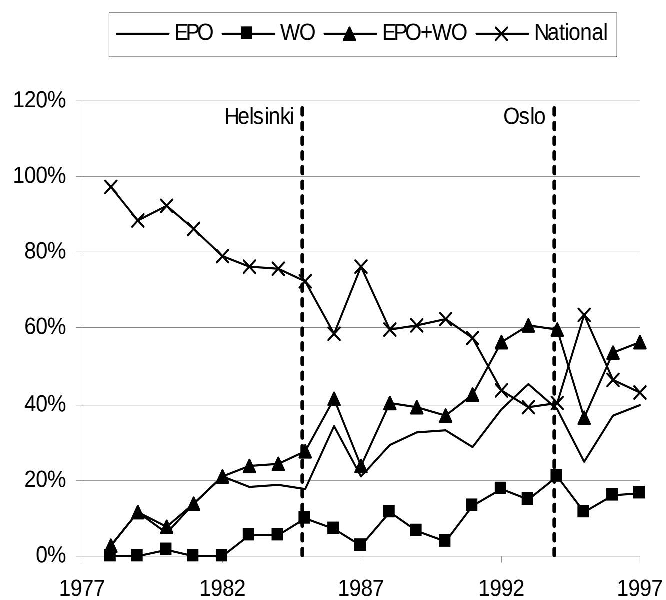
European countries. According to Eaton et al. (2004) EPs publications grew with 70% between 1991 and 2000, whereas also the number of destinations designated for protection in a typical EP ('family size') has grown substantially in this period.

Because we treat the family members of an EP as separate counts and all of our sample signatory countries except one (Canada) are located in Europe, we face two potential biases. First, EP and WO patents may have replaced family members filed at the national patenting offices over time. Accordingly, geography is less likely to play a role in the destination of knowledge transfers as a result of the reduction in costs of filing additional family members (Eaton et al., 2004). Second, if more countries join the patent treaties (EPC and PCT) one expects an increase in the average size of patent families due to the reduction in marginal protection costs and not because of the incentives provided by our main events. For instance, Denmark and Finland signed the EPC respectively in 1990 and 1996 and both countries show a strong increase in filed family members afterwards.

To put this problem into perspective, the filing of EP and WO patents has already been possible since the late seventies. We indeed observe the first EP and WO patents in our data base in 1978. Since the number of EPs and WOs has increased steadily but only until the mid 1990s (see Figure 5). Even at the end of our sample period the share of EP and WO never went beyond 60% of all of our family counts. In total 287 EPs and 97 WOs have been filed up to 1997, whereas we found 756 family patents filed at national offices. Given that our overall number of family counts is 3,123 simple arithmetics learns that these 384 EP and WO patents account in total for 2,367 family members or 6 designated countries on average. Even in 1997 still 26 of an overall number of 60 abatement technology family patents were just filed at the national offices, whereas only 24 were EPs and 10 WOs. Moreover, the share of non-EP&WO family members in non-European countries like the U.S., Canada and Japan fluctuates around 60% since the early 1980s. These observations support the Eaton et al. (2004) findings that the growth in EP publications was not at the expense of patents sought directly through national patent offices.

Figure 6: Share of EPO and WO patents in overall counts
4 - EPWO patent

shares



6.*pdf*

Furthermore, the increase in the share of the overall number of EP and WO patents is quite strong in the periods 1981-1986 and 1991-1994 followed by steep declines in both cases. These periods coincide with the advent to Helsinki in 1985 and Oslo in 1994. Moreover, this development is in stark contrast with the much more gradual penetration pattern for all EP patenting as described by Eaton et al. (2004). Hence, the protocols may have acted as an additional trigger for EP in this specific technology subfield which also makes perfect sense. If firms seek protection for their inventions in foreign countries, they are likely to exploit opportunities to reduce their cost of protection. And this is precisely what EPs offer. Moreover, most European countries cooperating through the protocols also participated in the EPC treaty.

Even if EPs and WOs have not entirely substituted for national patent offices filings, their likely effect on family size of a given invention may still give rise to some concern. To the end of the 1990s a number of factors induced the 'movement to universality' in Europe (Eaton et al., 2004). By 2000 most EPs designated all EPO members for protection. Fees for a given EP fell dramatically in 1997 with 33% reduction for a single EP and a 50% for the cost of each additional country designated for protection. Moreover, since 1999 no additional fees are levied for EPs designated for over seven EPO members. So it is hardly surprising that Eaton et al. (2004) find evidence that the tendency to universality can be explained by these price changes. With our sample period ending in 1997, these factors are unlikely to have biased our results. Indeed, only at the end of our sample period (1995-1997) we find some evidence of a co-movement of European family patents. Even then important differences in the number of family patents applied in different EPO member states remained.

As a final check we also estimated our basic specification without countries where this propensity to designate effect is large, such as Denmark and Finland.[35] The likelihood of increased patenting in the pre-Oslo period is only slightly lower, whereas both the effect and its significance is considerably larger for the Helsinki protocol.

8.3 The role of R&D expenditures

An often exploited variable to explain variation in patenting activity is R&D expenditure. With higher (contemporaneous) expenditures on R&D it is more likely to expect more R&D output for which patents act as an indicator. Unfortunately, data on R&D expenditures are not available for our entire sample, in particular not in the pre-protocol period. Therefore we created an unbalanced subsample including country-specific overall expenditure on R&D, i.e., including business enterprise and government funds, and used this for robustness purposes only.[36] With the R&D expenditures as a percentage of GDP as an explanatory variable, we obtain strongly robust results for our event variables (see Table 7 columns (3) and (4)). Again

[35] Results are available upon request.

[36] For a detailed explanation of the research data used see http://www.uis.unesco.org/ev.php?ID=5127_201&ID2=DO_TOPIC Data on R&D expenditures for Luxemburg are not available, for Poland only since 1990, for Sweden only biannually, and for Switzerland we have only 6 observations.

Helsinki is associated with a positive impact on anticipatory behavior for mother patents, but now also on the decision to get protection in other countries. The expected number of family patents is 37% higher in signatory countries compared to non-signatory countries. Moreover, this effect is strongly significant. We also find evidence for additional explanatory power of research efforts as measured by these R&D expenditures. Higher effort positively affects the likelihood of both mother and family patenting, although this effect is significant only for families. One could argue that higher R&D activities in a country signal a higher likelihood of copying inventions, implying a greater propensity for foreign inventors to protect their invention in that country.

9 Conclusion

Our results provide clear indications in favor of a separate role of protocols in the strategic decisions of firms to invest in new knowledge as well as to transfer and protect their knowledge abroad. This result contrasts with the currently dominant view that IEAs have added little on their own in reducing emissions like those of SO_2. It also sheds new light on international knowledge transfers and what incites them. Our analysis supports the idea that international negotiations provide an important signal for firms to invest in new technologies as well as to protect their inventions abroad assuming market size is likely to expand in the nearby future. Firms anticipate the potential benefit of such international agreements and exploit the advantages of the protocols for their market expansion through the designation of their family patents. Negotiations cast their shadows even before they become successful and lead to more stringent measures. The Helsinki protocol provided German inventors with an opportunity to expand their output market and in the same way Japanese and to a smaller extent U.S. inventors exploited similar opportunities around the Oslo protocol together with the options provided by the renewal of the U.S. CAA.

Although our main result differs from Popp (2006), the two studies also complement each other. First of all, our unique set of patent counts confirms the inventive dominance of the three major countries in FGD technology —the U.S., Japan and Germany— because they cover most of the mother patents. Second, our broader set of countries shows how countries that do not host major inventive industries benefit from knowledge transfers through international cooperation. In addition, however, we observe that these transfers flow around the world in anticipation not only of local but also international signals. Knowledge transfers *through* international markets are very likely to happen if opportunities for new markets open up soon. Responsiveness of firms to such signals in other countries is a major factor in driving such transfers.

Whether or not the trigger provided by the SO_2 protocols on the transfer of knowledge on new inventions within signatory countries also had an impact on emission reduction cannot be concluded from our analysis, however. Our data only show that protocols, or at least the expectation that an IEA will come into existence and is likely to spur more stringent local regulation, incite inventive activities and transfer of knowledge as embedded in these new technologies. Accordingly, the benefit from protocols seems to be the international diffusion of new knowledge in the first place. This is not only in the interest of the countries that lack such innovative firms, but also in the interest of these innovative firms themselves (and their hosting countries). In this sense the protocols do have an impact on emissions reduction. Signing of a protocol is a signal that the country will enact more stringent domestic environmental policy, whether or not it leads to more reductions than prescribed in the treaty.

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Appendix A SO_2 protocols and local regulation

Table A.1 summarizes the countries' emission reduction commitments under the Helsinki and Oslo protocols, as well as the year of ratification. Countries without any form of commitment under Helsinki were Japan, United States, United Kingdom and Poland. The latter two committed to emissions reduction under the Oslo protocol up to 50% and 37%, respectively. Whereas the Helsinki protocol implied a uniform emission reduction of 30 percent, the Oslo protocol allowed for differentiated reduction targets. Germany committed itself to the biggest reduction (83%). Other countries with relatively high commitment levels under the Oslo protocol are Austria and the Scandinavian countries Denmark, Finland, Sweden (all 80%), closely followed by the Netherlands (77%) and France (74%).

Table A.1: International SO2 emission reduction cooperation

	1985 Helsinki Protocol		1994 Oslo Protocol	
	Ratification	Commitment[a)]	Ratification	Commitment[b)]
Austria	1987	-30%	1998	-80%
Canada	1985	-30%	1997	-30%
Denmark	1986	-30%	1997*	-80%
Finland	1986	-30%	1998**	-80%
France	1986*	-30%	1997*	-74%
Germany	1987	-30%	1998	-83%
Italy	1990	-30%	1998	-65%
Japan	No	No	No	No
Luxemburg	1987	-30%	1996	-58%
Netherlands	1986**	-30%	1995**	-77%
Poland	No	No	No***	-37%
Sweden	1986	-30%	1995	-80%
Switzerland	1987	-30%	1998	-52%
United Kingdom	No	No	1996	-50%
U.S.	No	No	No	No

[a)] Uniform 30% emission reduction targets from 1980 SO_X levels by 1993

[b)] Differentiated emission reduction targets from 1980 SO_X levels by 2000

* No ratification, but approval; ** No ratification, but acceptance;

*** Signing but no ratification (yet)

Source: UNECE (http://www.unece.org/env/lrtap/)

For each country a systematic overview of the various local policies is given below. Data have been obtained from Placet et al. (1988), Vernon (1988) and Sloss (2003). All measures are in mg/Nm3, except noted otherwise. The various regulations were mainly targeted at power plants. Regulatory data for Germany, Japan and the U.S. are checked with Popp (2006). For additional regulatory information on these latter countries see also appendix A of his study.

- Austria
  - 1986: 3000 for 50-100 MW; 2000 for 100-200 MW; 90% desulfurisation for >200 MW
  - 1987: 400 for >400 M
  - 1989: 400 for lignite >10 MW; 400 for hard coal 10-50 MW; 200 for >50 MW
- Canada
  - 1986: 740 for all new boilers
- Denmark
  - 1986: 860 for >100 MW new
  - 1987: 860 for >50 MW new
  - 1990: 700 for >100 MW new
  - 1991: 400 for new utilities >500 MW/therm
- Finland
  - 1987: 600 for 50-150 MW new; 370 for >150 MW new; 600 for >200 MW existing
  - 1988: 400 for >150 MW new
- France
  - 1986: 72% of sulfur in coal
  - 1988: 683 for Paris
- Germany

- 1983: 400 for new plants; 2000 for existing plants
- 1993: 400 for existing plants

- Italy
  - 1986: no statutory limits
  - 1987: 1200 for >100 MW; 400 after 2-3 years
  - 1990: 1200 for 100-500 MW; 400 for >500 MW
  - 1991: sliding scale 1700-400 for 100-500 MW
  - 2000: 2000 for 50 – 100 MW; sliding scale 2000-400 for 100-500 MW
- Japan
  - 1968: SO_2 regulations vary by plant according to formula based on region's environmental quality and plant's effective stack height[37]
- Netherlands
  - 1986: 700 for <300 MW new and existing; 400 for >300 MW new
  - 1991: 200 for >300 MW new
  - 1992: 700 for <300 MW existing
  - 1994: 400/200 for >300 MW existing
- Sweden
  - 1986: 572-972 for plants emitting <800 tons sulfur; 286-572 for plants emitt >800 tons sulfur
  - 1987: 100-170 gram sulfur/GJ fuel input average for plants emitting <400 tons sulfur/year; 50-100 g sulfur/GJ fuel input average for plants emitting >400 tons sulfur/year
  - 1990: 190 gram sulfur/GJ fuel input yearly average for existing plant; 50 g sulfur/GJ fuel input yearly average for new plants
  - 1995: 30 gram sulfur/GJ fuel input yearly average for plant >500 MW
- Switzerland

[37] See p.A3 of appendix in Popp (2006) for an overview of Japanese air pollution regulations.

- 1986: 2000 for all
- 1987: 2000 for 1-300 MW; 400 for > 300 MW
- 1995: 2000 for 1-100 MW; 400 for > 100 MW

- United Kingdom
  - 1991: 2000 for 50-100 MW; 400 for >500 MW

- United States
  - 1970: Passage of 1970 Clean Air Act setting 1480 for new plants
  - 1977: Passage of 1977 CAA setting 1480 plus an additional 90% SO_2 removal for new plants
  - 1990: Passage of 1990 CAA setting goals for reducing SO_2 emissions through permit trading in two phases applied to power plants[38]
  - 1995: Phase I emissions trading, covering the 263 dirtiest, large generating existing power plants in the country
  - 2000: Phase II emissions trading, covering virtually all (new as well as existing) power plants in the country

[38] See, for instance, Joskow et al. (1998).

Appendix B Patent data description

We use patent data obtained from the European Patent Office (EPO), based in The Hague, the Netherlands. The EPO identifies patents around the world by using both the International Patent Classification (IPC) and the more detailed European Classification System (ECLA). EPO's database can be accessed in different ways. The common approach is to use the online database *esp@cenet*.[39] This classification scheme has a nested structure and allows for searches for specific technologies, such as sulfur dioxide abatement technologies. Also Popp (2006) follows this procedure as explained in his detailed Appendix. Given the search outcomes, some individual patent documents are subsequently screened to tally frequently occurring ECLA classes, where the classes were assessed on their relevance for pollution control technologies (see p.B2 of appendix Popp, 2006). In this way Popp obtains four classes that he considers representative for sulfur dioxide control technologies: B01D53/14H8, B01D53/50, B01D53/86B4 and F23C10. For instance, class B01D53/50 refers to the class of performing operations that aim at separation of gases or vapors, in particular those that purify waste gases, and specifically those targeted at the removal of defined structure like sulfur compounds.

In constructing our patent data set we followed a different approach. In close cooperation with EPO experts we also first constructed a base set by means of keywords but now in order to identify all relevant *individual* patents, not classes. So we fed the entire *esp@cenet* database with keywords. We first used general keywords (step 1) and then imposed combined group-related keywords (step 2). Step 1 and step 2 yielded a set of potentially relevant patents, which were then screened individually on the basis of patent abstracts (step 3) to determine whether the patent was explicitly related to SO_2 abatement or not. If not, the patent was eliminated from the set; it remained in the set otherwise. This third step in the patent retrieval procedure is a distinctive feature of our database. The final step in the procedure (step 4) implied 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 document(s), which means that these are patents that comprise exactly the same claim. This information is particularly relevant because of our focus on international technology diffusion. In the final step 5, we checked the overall set for a language bias. That is, in evaluating the patent abstracts we sometimes encountered patents that were described in a national language, for instance in French or German. We now discuss each step in

[39] http://www.espacenet.com/

more detail.

Step 1: Confining the base set by general keywords

We first constructed a base set by using general keywords. Since the focal point of our analysis is sulfur abatement technologies, 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+. A "+" put in front of or after a keyword guarantees that the search engine yields patents that also contain these original words. For example, "+sulfur+" also yields patents that include the word "desulfurization". The result is a base set that identifies all those patents related to "sulfur". At the date of the first search (26 September 2003), the generated base set contained a total number of 121,913 patents.

Step 2: Restricting the base set by technology-specific keywords

As the next step, we further restricted the patent set to SO_2 abatement technology categories. One well-known technique with a long history in SO_2 reduction is scrubbing, which is typically an of end-of-pipe technology. This category is representative for much of the technologies patented in the 1970s and 1980s. However, scrubbing is not the only technique to deal with SO_2 emissions. Given the range of technical options, we followed the technological distinctions that are included in the RAINS model, developed at the International Institute for Applied Systems Analysis (see http://www.iiasa.ac.at/). The RAINS model classifies the following SO_2 abatement categories (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.

We used this subclassification to define new keywords for subsearches within our initial set of patents. In particular, we used the group-related keywords represented in Table A2. 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. Subsearch 2 focused on in-furnace control of SO_2 emissions by imposing the keywords COMBUST, BURN, INCINER, LIME, LIMESTONE, CA and CALCIUM. In subsearch 3 we combined classes 3 and 4 of the RAINS classification by simultaneously employing the keywords FLUE and GAS. Note that category 5, with measures to control process emissions, may comprise various techniques. Therefore, we did not specify this class in detail but used expert opinion from the Eindhoven University of Technology, The Netherlands, on relevant characteristics of the newest technologies instead. In this respect, oxidative desulfurization was recognized as a relatively new process to cut back SO_2 emissions. We included "oxidative desulfurization" by using the keywords OXIDATIVE and DESUL in subsearch 4. The subsearches of step 2 reduced the set of potentially relevant patents to 4,243.

Table A.2: Keywords (in caps) in subsearches

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: Individual patent screening

The four subsearches outlined above led to a pool of potentially relevant patents. In step 3 all these 4,243 patents were individually screened in order to assess the explicit relationship to SO_2 abatement. If no relationship was found, the patent was removed from the set. It remained in the set otherwise. The total number of rejected patents, including double counts, was 1,741 (41%). Thus, the adjusted patent yield was 2,502.

Step 4: Retrieval of patent families

The final step in the data acquisition procedure required the identification and retrieval of the mother patents and their family members using the clean set of 2,502 patents as obtained in the previous step. Information on the filing procedure is required for labeling a patent as a mother patent or as family member.

The patent office at which a patent is filed assigns an application number and an application date (filing date) to the patent. The application number is unique for each patent filed. The inventor must request a 'novelty search', which is conducted by experts at the patent office. During this search process the experts examine the national patent database and go through international literature to identify the current state of the specific technology (i.e. previous claims that have been made and patents that have been filed).[40] The findings are summarized in a report, after which the inventor may rewrite the application within a given time frame. Essential is that on the basis of the 'novelty search', the actual novelty of the claim made by the inventor is identified. The novelty of the claim is therefore intrinsically linked to the application number. If the technology uses existing knowledge from other patent applications or publications, as identified by the novelty search, these are registered in the patent through patent citations.

Once an inventor files its patent application for the first time (the application date) in a certain country, it has a maximum of one year to also file the same application in other countries. This is the so-called priority year. Important is that the application date in the country of first filing serves as the reference date (priority date) for the novelty search in the additional countries. Only technological developments prior to this date are considered while examining the patent application. In order to make use of this priority right, the inventor needs to add the application number of the initial filing to the list of priority documents (or numbers). This list contains references to previous patent applications done by the inventor over the same technology. By linking the current application to previous patent applications the list of priority documents provides information on how the technology developed over time and space. If the protected technology is completely new the list of priority numbers only contains the application number.[41]

Formally, we have identified the mother patent as the patent for which the application number and date are equivalent to the priority number and date. Since the filing of a family member is a request for protection of the technology in another country, it also receives a unique application number and application date in that country. The protected technology, however, is exactly the same as the mother patent. Therefore the same list of priority numbers is assigned to the family member as to the mother patent. Family members can thus be defined as patents that have exactly the same priority number(s) as the mother patent, but which are filed in another country and therefore have a different application number. Hereby we follow the definition of the European Patent Office (EPO).

The priority and application numbers of the 2,502 clean patents served as the

[40] For European and international patents a global search in patent databases is required.

[41] Note that the list of priority numbers is different from a patent citing, which refers to a previously filed patent from which (some of) the essentials are used in a new, but potentially different, type of technology. Hence the former refers to the development of a single technology, while the latter refers to knowledge spillovers in general.

basis to identify the mother and family patents. Using the priority numbers, a search in EPO's online database *esp@cenet* identified 2,271 mother patents filed between 1970 and 2000. As explained above, multiple patents can be found by entering a priority number due to the existence of family patents and technological improvements over time. If additional priority numbers were encountered during this search process, they were added to the search procedure. To maintain the cleanness of the database all patents were again tested on relevance by screening the patent text based on the keywords mentioned in Table A.2.

Step 4a: European patents and World patents

European patents (EP) and international patents (WO) are special patents, because each such patent grants protection in multiple countries. The inventor can opt to file a European or international patent application in one patent office instead of filing several patents at the national offices of those countries. The inventor can choose in which participating countries of the patent treaties (European Patent Convention or the Patent Cooperation Treaty) patent protection is requested. If during our search a European or international patent was encountered, the countries in which protection was requested were registered using the official document (in pdf-format). If the new technology was directly filed as a European or international patent, the priority document(s) therefore include the EP#### or WO#### reference. The mother country was identified by means of this official document in which the filing office was mentioned. If the filing office was lacking, the mother patent was assigned to the country of origin of the inventor. The countries mentioned in the document, excluding the mother country, were identified as countries holding a family member. If the new technology was first filed at a national patent office and then internationally protected by means of European and international patents, the mother patents were assigned to a country on the basis of the priority number, i.e., DE#### belonged to Germany, U.S.#### to the U.S., etcetera. During the 1970-1997 period, 287 EPs and 97 WOs were filed respectively.

Example In the following case the European patent serves both as mother patent and as family member.

- Priority #: EP19970114906 - priority date: 28 August 1997
- Mother patent: EP0899001 - filed by a German inventor at the European Patent Office. Therefore it is assigned to Germany.

Besides the national family members in the U.S., Japan and Canada, the original document shows that additional protection is requested in Austria, Switzerland, Denmark, Finland, France, UK, Italy, Luxemburg, Netherlands, Sweden and more European countries. In the next case the European patent serves only as family member.

- Priority #: DE19782839541 - priority date: 12 September 1978
- Mother patent: DE2839541 - Germany
- European patent: EP0008770 - filed on 29 August 1979, entails Belgium, Switzerland, France, UK, Luxemburg, Netherlands and Sweden as a family member.

If the mother country is also included in the pdf it is not registered to prevent double counting. Other family members are JP55039298 and DK150704.

For certain European and international patents the family members showed an overlap for the countries in which the technology was protected with patents filed at national offices. For instance, if an EP patent was part of the WO patent or the EP patent had a national equivalent. To prevent double counting we have ranked the family members in the order from national to international patent. Thus if there was already a national family member it was not registered anymore as part of the EP and/or WO patent. The countries protected by the EP patent were not listed anymore as part of the WO patent.

Once a WO patent is filed all nationally registered family members receive the application number (WO####) of the international patent as additional priority number. Due to the strict definition of patent families these family members should be treated as members of a different (new) family for which no mother patent exists, as illustrated by the following example.

Example

- Priority #: DE19971053191 - priority date: 21 November 1997
- Mother patent: DE19753191 - Germany
- Family members: PL340564, WO9926713, EP1039964 and AU751684B

The Australian patent (AU751684B) is discarded because is does not belong to the countries researched. All three other family members are filed on 18 November

1997. For the Polish (PL340564) and EP patent (EP1039964) one can see the added WO1998EP07368 in the priority number row. In addition, this example illustrates the issue of double counting. By looking at the original document of the international patent, we can see that it offers protection in multiple countries. One of these countries is Poland, which is already registered by the national patent. Furthermore, a reference is made to the EP patent, which was also already registered. To prevent double counting we have not registered these patents again as family members. For this particular WO patent it turned out, that it did not provide us with additional family members within our group of countries.

A final remark on the registration of patent family members concerns the registration of Canadian patents. The online database *esp@cenet* had some trouble in retrieving the priority and filing documents of Canadian patents and represented them as CAD000000.[42] To obtain the correct information for these patents, we have used the database of the Canadian Intellectual Property Office and the information from family members. By searching for the specific patent numbers, which were correctly reported in *esp@cenet*, the required information was obtained.

Step 5: Testing for language bias

In evaluating the individual patent abstracts we sometimes encountered patents (title and/or abstract) that were described in a national language, for instance in French or in German. In most cases an English abstract was available as well, but not for all. This brought up the issue of a potential language bias in our database. In order to check for this language bias, and to identify the relevance of these patents, we translated the keywords. Table A.2 contains the used keywords in the respective languages.

Within *esp@cenet* it is possible to search within a limited number of national databases and within the worldwide database. The worldwide database includes patents from over 70 countries and regions and also covers the publications from the national databases. Within the national databases one can search using national languages, while in the worldwide database only the English language is allowed. To retrieve patents written in a national language from the worldwide database English keywords are sufficient according to the *esp@cenet* help file. Although titles are indexed with English keywords, there still may be some patents that have abstracts written in another language, such as German.

[42] See http://v3.espacenet.com/textdoc?DB=EPODOC&IDX=CA1022728&F=0&QPN=CA1022728 for an example.

Table A.3: Keywords in different languages

English	**German**	**French**	**Dutch**
SO_2	SO_2	SO_2	SO_2
SO_x	SO_x	SO_x	SO_x
Sulfur/sulphur	Schwefel	Soufre	Zwavel
Fuel	Brennstoff, brandstoff, benzin	Combustible	Brandstof
Combust	(ver)brennbar	Combustible	Brandbaar
Lime	Kalk	Platre, Mortier	Kalk/calcium
Gas	Vergasen	Gaz, gazifier	Vergassen
Oxidation	Oxydation	Oxydation	Oxidatie
Flue	Schornstein, Abzurgsrohr	Carneau	Schoorsteen, rookkanaal
Desulfurization	Entschwefelung		Ontzwaveling

To test for a language bias, we used different translations of the word 'sulfur'. Using the German translation of sulfur into the worldwide database provides zero hits. The Dutch translation also generates zero hits, since the patents filed in the national database can be retrieved in the worldwide database having English titles and/or abstracts. Only one French patent from 1903 was found by using "soufre" as a keyword. However, 54 Canadian patents were retrieved by this search of which 24 also have English abstracts and family members. None of them passed the selection criteria described in step 2. Out of the 54 Canadian patents 12 were filed outside of the period covered by this research. For the remaining 18 patents *esp@cenet* did not provide the priority number and date (see step 4; CAD000000). As a final remark regarding the testing of the language bias, note that the power of the search engine used by *esp@cenet* is smaller than the one used by the patent experts of EPO. For instance, it does not allow for subsearches as described in step 2.

Help-files on the sites of the Canadian Intellectual Property Office and *esp@cenet* make clear that for most Canadian patents granted before 15 August 1978 abstracts and claims were unavailable.[43] For this reason priority dates and numbers cannot

[43] The text of the abstracts and claims is not available for patents that were granted prior to August 15, 1978. These patents can only be searched by their patent number, titles, owner or inventor names, or classification. Canadian patent applications can be filed in either English or French. All patent documents on this site have both English and French titles. However, between 1960 and 1978, titles are available only in the language used at the time of filing. http://patents1.ic.gc.ca/content-e.html. Abstracts where published systematically from 1978 onwards, although there are some earlier Abstracts, if provided by the applicant, mostly in English. http://patentinfo.european-patent-office.org/_resources/data/pdf/canada.pdf

be retrieved in the *esp@cenet* database and we might have missed several patents filed in French. The 18 remaining patents were all granted between 1970 and 1978 and were filed only in French. Language barriers and the absense of an abstract prevent a full screening of those patents and we therefore exclude them from the database. Despite this potential language bias we decided to maintain the other Canadian observations for this period within our database. First, the Canadian family members from this period were detected by our described search process in *esp@cenet*. Second, the fact that the referred period falls outside of the influence of the protocols, the limited share of Canada in the number of patent filings and the small language bias for other countries provide enough confidence in the quality of our database.

Appendix C Data sources and definitions of variables

- *MOTHER AND FAMILY PATENTS:* See Appendix B for a detailed explanation of our counts, including the distinction between EP/WO and national counts. Source: European Patent Office in The Hague, The Netherlands
- *COAL SHARE*: Defined as total production of electricity generated from coal inputs relative to total electricity produced. Source: Energy Balances, Statistical Compendium, ed. 01, CD-ROM, Paris: OECD.
- *TOTAL PATENTS:* Overall number of claimed patents for all types of technologies filed in each country, i.e., all mother patents that have been claimed in at least one other country (so having at least one family member). Source: OECD
- *RESEARCH*: Gross Domestic Expenditures on R&D as a percentage of GDP. For explanation of R&D epxenditures see http://www.uis.unesco.org/ev.php?ID=5127_201&I Source: Main Science and Technology Indicators OECD
- *EVENT DUMMY* Own construction with dummy equal to 1 if country is signatory country of a specific protocol. See table 3 in main text.