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Invention and Transfer of Climate Change–Mitigation Technologies: A Global Analysis

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Introduction

Accelerating the development of new low-carbon technologies and promoting their global application are key challenges for stabilizing atmospheric greenhouse gas (GHG) emissions. Consequently, technology is at the core of current discussions surrounding the post-Kyoto climate regime. The 2007 Bali Road Map[1] cites technology development and diffusion as strategic objectives, which has triggered a debate about appropriate policies.

This debate is complicated by a number of factors. In particular, environmentally friendly technologies have been developed primarily in industrialized countries but are urgently required to mitigate GHG emissions in fast-growing emerging economies. Ensuring the global diffusion of these technologies thus entails considerable policy and economic challenges because developing countries are reluctant to bear all the financial costs associated with their adoption, while firms in industrialized countries are reluctant to give away strategic intellectual assets. The role of intellectual property rights (IPR) is particularly controversial. Developing countries[2] have argued for the creation of a different IPR regime for climate-

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[1] Participants at the 2007 United Nations Climate Change Conference in Bali developed a road map, known as the Bali Road Map, for negotiating a new climate agreement by the end of 2009.

[2] The countries referred to as "developing countries" are in fact quite heterogeneous. Thus, when appropriate, we will distinguish between emerging economies (e.g., China, Brazil, Indonesia) and less-developed countries.

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friendly technologies in order to encourage diffusion, whereas industrialized countries claim that the incentives provided by existing IPR regimes reinforce diffusion incentives by ensuring patent holders the benefits that result from their inventions.[3]

The challenge of technology diffusion on a global scale is also compounded by a lack of information. There is neither a clear and widely accepted definition of what constitutes a "climate change–mitigation technology" nor a widespread understanding of how such technologies are diffused globally.

This article, which is part of a two-article symposium on Technology Transfer and Climate Policy, seeks to inform the debate with factual evidence on the geographic distribution and global diffusion of climate-mitigation inventions.[4] Using data from the European Patent Office (EPO) Worldwide Patent Statistical Database (PATSTAT), we examine patented inventions in thirteen technology areas with significant global GHG emission abatement potential and analyze their international transfer between 1978 and 2005. We use counts of patent applications to measure technological innovation in the different areas.[5] Although patents do not provide a measure of all innovation, they are a good proxy for innovative activity and allow us to make cross-country comparisons.

Most previous studies have used data from a small number of patent offices (usually one). The data and analysis presented here go well beyond these studies because the PATSTAT data contain patents from eighty-four national and international patent offices, including patents filed in developing countries. This allows us to conduct a global analysis of innovative activity and to gain insights about international technology transfer. Moreover, we have developed a methodology that makes it possible to construct indicators that can be used to make absolute cross-country comparisons.

To the best of our knowledge, this is the first study that uses patent data to quantitatively describe the geographic distribution and temporal trend of invention and diffusion of climate change–mitigation technologies at the global level. Lanjouw and Mody (1996), which focuses on patents for environmentally-responsive technology in Japan, Europe, the United States, and fourteen developing countries, is the study most closely related to our work. These authors identify the leaders in environmental patenting and find that significant transfers to developing countries occur. However, our analysis focuses more specifically on climate-change mitigation, uses more recent data, and covers more countries.

We seek to address the following key questions. In which countries does climate-friendly innovation take place? What is the specific contribution of innovators located in emerging economies? To what extent is technology being transferred to developing countries? Is climate-mitigation innovation different from other technology areas? Whenever possible, we also try to assess the impact of climate and environmental policies on invention and technology diffusion.

The remainder of this article is organized as follows. The next section introduces key concepts and discusses the use of patents as indicators of technological innovation and technology transfer. This is followed by a description of our dataset and a discussion of data issues.

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[3] See Maskus (2010) for a discussion.

[4] The other article, Popp (2011), reviews the economics literature concerning the transfer of environmentally friendly technologies and discusses the implications for climate policy, focusing in particular on the Clean Development Mechanism.

[5] Throughout the article, the terms *innovation* and *invention* are used interchangeably.

We present our analytical results in the next two sections. We first use the data to examine global innovative activity in the thirteen climate-mitigation fields and across countries between 1978 and 2005. We then analyze the international transfer of these inventions and relate our findings to the general literature on patents and technology diffusion. The final section summarizes the findings and presents some conclusions.

Patents as Indicators of Innovation and Technology Transfer

There are a number of ways to measure technological innovation (see Organization for Economic Cooperation and Development [OECD] 2008a). Research and development (R&D) expenditures or the number of scientific personnel in different sectors are the most commonly used measures. Although such indicators reflect important elements of the innovation system, they have a number of disadvantages. For example, data on private R&D expenditures are generally incomplete and available only at an aggregate level. Moreover, these data measure inputs to the innovation process, whereas an "output" measure is generally preferable.

Patent data have several advantages over R&D expenditures and numbers of scientific personnel. First, patent data focus on outputs of the innovation process (Griliches 1990) and provide a wealth of information on both the nature of the invention and the applicant. More importantly, patent data can be disaggregated into specific technological areas. Finally, patent data provide information about not only the countries where these new technologies are developed but also where they are used.[6]

In recent years, an increasing number of studies have used patent data to analyze innovation and international technology diffusion, particularly in the environmental field. These studies have usually relied on patent data from OECD countries, especially the United States. For example, Popp (2006) uses patent data from Japan, the United States, and Germany to examine the invention and diffusion of air pollution control devices for coal-fired power plants. Johnstone, Haščič, and Popp (2010) analyze the effects of policy and market factors on the development of renewable energy technologies in OECD member countries.

The Patent System

Before describing the indicators used in this and other studies, we briefly review how the patent system works. Consider a simplified innovation process. In the first stage, an inventor from a particular country discovers a new technology. He then decides where to market his invention and how to protect the intellectual property associated with the invention. A patent in country *i* grants him the exclusive right to commercially exploit the invention in that country. Accordingly, he will patent his invention in country *i* if he plans to market it there. The set of patents related to the same invention is called a patent family. The vast majority of families include only one country (often the home country of the inventor, particularly for large countries). When a patent is filed in several countries, the first filing date worldwide is called the priority date.[7]

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[6] It is these unique features of patent data that make our study climate-mitigation technologies possible.

[7] Accordingly, the first patent is called the priority application and the first patent office is referred to as the priority office.

Patent Indicators and Their Limitations

In this study, patents are sorted by priority year. We use the number of families as an indicator of the number of inventions. The number of technologies invented in country A and patented in country B is used as an indicator of the number of inventions transferred from country A to country B. This approach has also been used by Lanjouw and Mody (1996) and Eaton and Kortum (1999). Other studies have used a slightly different indicator based on patent citations (e.g., see Jaffe, Trajtenberg, and Henderson 1993; Peri 2005; Thompson and Fox-Kean 2005). More specifically, these studies count the number of citations of the patented invention from country A in subsequent patents filed in country B. This approach measures knowledge *externalities*—that is, knowledge that spills over to other inventors. Our indicator differs in that it measures *market-driven* technology transfer.

Patent-based indicators are imperfect proxies for technological innovation and technology transfer and have several limitations. First, patents are only one of the means of protecting inventions, along with lead time, industrial secrecy, or purposely complex specifications (Cohen, Nelson, and Walsh 2000; Frietsch and Schmoch 2006). In particular, some inventors may prefer secrecy to prevent public disclosure of the invention imposed by patent law or to save the significant fees attached to patent filing. However, there are very few examples of economically significant inventions that have not been patented (Dernis, Guellec, and van Pottelsberghe de la Potterie 2001).

Second, the propensity to patent differs between sectors, depending on the nature of the technology (Cohen, Nelson, and Walsh 2000). It also depends on the risk of imitation in a country. Accordingly, inventions are more likely to be patented in countries with technological capabilities and a strict enforcement of IPR. This means that greater patenting activity could reflect either greater inventive activity or a greater propensity to file patents. Our methodology, which measures patenting activity in various countries using a common unit, partly controls for this problem.

Another limitation is that while a patent grants the exclusive right to use a technology in a given country, it does not mean that the patent owner will actually exercise this right. This could significantly bias the results if applying for patent protection is free, as this might encourage inventors to patent widely and indiscriminately. However, patenting is costly—in terms of both the costs of preparing the application and the administrative costs and fees associated with the approval procedure.[8] In addition, possessing a patent in a country may not be in the inventor's interest if that country's enforcement of intellectual property is weak, since publication of the patent can increase the risk of imitation (see Eaton and Kortum 1996, 1999). Finally, patent infringement litigation usually takes place in the country where the technology is commercialized (as this is where the alleged infringement occurs). Thus, inventors are unlikely to be willing to incur the cost of patent protection in a country unless they expect there to be a market for the technology concerned.

However, the fact remains that the value of individual patents is heterogeneous. Moreover, because many patents have very low value, the distribution is skewed, and as a consequence, the absolute number of patents does not perfectly reflect the value of technological innovation. Methods have been developed to address this issue (see Lanjouw, Pakes, and Putnam 1998), such as using weights based on the number of times a given patent is cited in

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[8] See Helfgott (1993) and Roland (2005) for information about the cost of applications at the EPO.

subsequent patents. Unfortunately, our data do not allow us to implement these methods. Instead, in addition to presenting data on the number of inventions, we use data on international patent families to construct statistics for "high-value inventions."

The Data

The first efforts to develop a large patent database that would be suitable for statistical analysis were initiated by the OECD Directorate for Science, Technology, and Industry in cooperation with other members of the OECD Patent Statistics Taskforce.[9] Subsequent efforts were directed toward developing a worldwide patent database. The EPO took over responsibility for the development and production of the database, with the first version distributed in April 2006. The database has since become known as the EPO PATSTAT.

PATSTAT is unique in that it covers more than eighty patent offices and contains over sixty million patent documents. It is updated biannually. Patent documents are categorized using the international patent classification (IPC) codes, developed by the World Intellectual Property Organization (WIPO), and some national classification systems. In addition to basic bibliometric and legal data, the database also includes patent descriptions (i.e., abstracts) and citation data for some offices.

Technologies and Patent Applications

We considered thirteen climate-mitigation technologies[10]: seven renewable energy technologies (wind, solar, geothermal, marine energy, hydropower, biomass, and waste to energy), methane destruction, climate-friendly cement, thermal insulation in buildings, heating, electric and hybrid vehicles, and energy-efficient lighting.[11] Although we include a wide range of climate-mitigation technologies, a number of important technologies have been omitted due to data constraints. These include energy efficiency improvements in industry, aspects of "clean" coal technologies, and energy storage. Nevertheless, the technologies included in our dataset represent nearly 50 percent of all GHG abatement opportunities (excluding forestry) beyond business as usual until 2030, as identified by Enkvist, Nauclér, and Rosander (2007).

To build the dataset, we extracted all patent applications filed from 1978 to 2005 in the thirteen climate-mitigation technology fields. Patent applications related to these fields were identified using IPC codes.[12] The IPC codes corresponding to the climate-mitigation

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[9] The other taskforce members include the EPO, the Japan Patent Office (JPO), the United States Patent and Trademark Office, the WIPO, the National Science Foundation, Eurostat, and the European Commission Directorate-General for Research.

[10] A more detailed description of the technology fields covered by the study can be found in Appendix 1.

[11] We also considered a fourteenth technology, carbon capture and storage (CCS). However, the CCS technology is not yet included in the international patent classifications system. Thus, we have used a specific search algorithm to identify CCS patent applications. The results for CCS are presented separately in Appendix 2.

[12] Some previous studies have related patent classes to industrial sectors using a concordance table matching IPC classes with the International Standard Industrial Classification system. This approach has two weaknesses. First, if the industry of origin of a patent differs from the industry of use, then it is not clear to which industrial sector a patent should be attributed. Second, the use of sectoral classifications (and commodity classifications) will result in a bias toward including patent applications from sectors that produce explicitly "environmental" goods and services rather than more integrated innovations. See OECD (2008b) for a full discussion of the relative merits of the approach adopted in the current study.

technologies were identified in two ways. First, we searched the descriptions of the IPC codes online to identify those relevant to our study.[13] Second, using ESP@CENET, an online patent search engine maintained by the EPO,[14] we reviewed patent titles and abstracts to identify relevant keywords. The IPC codes corresponding to the patents that resulted from our search were included, provided that the definition of an IPC code confirmed its relevance.[15]

The resulting dataset contains 285,770 patent applications filed in seventy-six countries. On average, the climate-related patents included in our dataset represent 1 percent of the total number of patents filed annually worldwide. The number of patent applications in each technology field is presented in the online supplementary materials for this article. The PATSTAT includes the country of residence of the inventors of those technologies for which patent protection is sought (independent of the country in which the applications are actually filed). This information is used to measure a country's innovation performance.[16]

Data Issues

Two types of error may arise when building this type of dataset: Irrelevant patents may be included or relevant ones left out. The first error occurs if a selected IPC code covers patents that are not related to climate mitigation. In order to avoid this problem, we carefully examined a sample of patent titles for every IPC code considered for inclusion in the dataset and excluded those codes that contain patents not related to climate mitigation. This is why some key technologies with carbon reduction potential were excluded from the study (e.g., energy-efficient technologies in industry, certain "clean" coal technologies, energy storage).

The second potential error—exclusion of relevant inventions—is less problematic. We can reasonably assume that all innovation in a given field follows a similar trend. Hence, at the worst, our dataset can be seen as being a good proxy of innovative activity in the technology fields considered. However, because of the conservative approach we adopted when constructing the data, overall innovative activity may be underestimated, and the datasets in each technology field are unlikely to be equally inclusive. Therefore, estimates of the absolute volume of innovative activity may be less reliable than estimated differences in temporal trends. For this reason, cross-technology comparisons throughout the article are based only on trends.

Another data issue is that the number of patents granted for a given invention (known as patent breadth) varies significantly across countries, making it problematic to rely on crude patent counts to compare innovation activity across countries. A commonly cited example is Japan, where patent breadth is particularly low. To address this problem, we developed patent breadth coefficients for the countries in our dataset. That is, we examined all international patent families in the PATSTAT and then calculated how many patents protect the same invention across the countries in the dataset. Recall that each patent family corresponds to a particular invention. Thus, the examination of international families yields information on the number of patents in those countries where the invention is patented. We used this

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[13] The IPC system can be searched at http://www.wipo.int/tacsy/.

[14] Available at http://ep.espacenet.com/.

[15] The descriptions of the IPC codes used to build the dataset can be found in the online supplementary materials for this article. See http://www.reep.oxfordjournals.org.

[16] Patents with multiple inventors are counted fractionally. For example, if two inventor countries are involved in an invention, then each country is counted as one-half.

information to calculate country-specific patent breadth coefficients. For example, we found that, on average, seven patents filed at the JPO result in approximately five patents filed at the EPO. This means that one EPO patent is equivalent, on average, to 1.4 JPO patents.[17] We set the coefficient for applications at the EPO to unity. This means that the results presented in the next section indicate the number of "EPO-equivalent" inventions.[18] The drawback of this approach is that although we use international families to calculate the patent breadth coefficients, these coefficients are used to weight both international patent applications and patents filed in only one country, and it is possible that the two kinds of patents have different breadth. For example, a Japanese inventor who expects to file a patent both in Japan and abroad may design a "broader" patent that will be readily transferable to foreign patent offices. Thus, our method for calculating the coefficients may underestimate the actual patent breadth.

One data issue specifically concerns patents filed in the United States, where until 2000 published data concerned only *granted* patents, while offices in other countries have consistently provided data on *applications*. A final data issue is that the inventor's country of residence is not available for some patent applications. A more detailed description of these two issues and how we addressed them is presented in the online supplementary materials.

Innovation Activity Worldwide

This section discusses the level of innovation across countries and the evolution of innovation over the period 1978–2005.

The Geography of Innovation

Where does innovation take place?[19] As shown in Table 1, innovation appears to be highly concentrated: The top twelve countries account for nearly 90 percent of all inventions between 2000 and 2005. Japan, the United States, and Germany are the three top inventor countries for most technologies. With 37 percent of the world's inventions, Japan's performance is particularly impressive. Japan ranks first in all technology fields, except for marine energy, where it is second, and accounts for over 50 percent of the world's inventions in electric and hybrid, waste, and lighting.[20]

These findings are consistent with the available evidence on R&D activity. Although detailed data on private R&D are not available, the data on public R&D for low-carbon technologies confirm the strong leadership of Japan, which in 2004 spent $US 220 million, significantly more than public R&D spending in the same year by the United States ($US 70 million) and the EU15[21] ($US 50 million) combined (Lazarus and Kartha 2007).

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[17] Note that this is a much lower ratio than others have obtained using "claims" rather than patents as the unit of analysis.

[18] The EPO-equivalent country weights (coefficients) for various patent offices are presented in Appendix 3.

[19] Recall that in this study an invention corresponds to a patent family. Hence, a patent filed in several countries is counted only once.

[20] The aggregate country shares were calculated as the mean of the percentage shares for the individual technological fields. The number of patent applications identified in each of the fields is affected by the exhaustiveness of the patent search strategy, which varies across the different technologies. The intention of this approach is to avoid aggregation across a possibly heterogeneous set of climate change–mitigation technologies.

[21] The EU15 consisted of those countries that were members of the European Union as of 2004: Austria, Belgium, Denmark, Finland, France, Germany, Greece, Ireland, Italy, Luxembourg, the Netherlands, Portugal, Spain, Sweden, and the United Kingdom.

Table 1 Top twelve inventor countries (2000–2005)

Country	Rank	Average % of world inventions	Average % of world's high-value inventions	Country's top three technology fields (decreasing order)
Japan	1	37.1	17.4 (2)	All technologies
United States	2	11.8	13.1 (3)	Biomass, insulation, solar
Germany[†]	3	10.0	22.2 (1)	Wind, solar, geothermal
China	4	8.1	2.3 (10)	Cement, geothermal, solar
South Korea	5	6.4	4.4 (6)	Lighting, heating, waste
Russia	6	2.8	0.3 (26)	Cement, hydro, wind
Australia	7	2.5	0.9 (19)	Marine, insulation, hydro
France[†]	8	2.5	5.8 (4)	Cement, electric and hybrid, insulation
United Kingdom[†]	9	2.0	5.2 (5)	Marine, hydro, wind
Canada	10	1.7	3.3 (8)	Hydro, biomass, wind
Brazil	11	1.2	0.2 (31)	Biomass, hydro, marine
The Netherlands[†]	12	1.1	2.1 (12)	Lighting, geothermal, marine
Total	—	87.2	77.2	

Source: Authors' calculations, based on PATSTAT data.

[a] Together, the twenty-seven countries of the European Union (EU27) represent 24% of the world's inventions.

[b] High-value inventions are defined as inventions that have been patented in at least two countries.

Interestingly, the world's top three inventor countries are followed by China, South Korea, and Russia. These countries are important sources of innovation in fields such as *cement* (China and Russia), *geothermal* (China), and *lighting* (South Korea). Another emerging economy, Brazil, also ranks among the top twelve countries. However, other emerging economies lag far behind, with Taiwan, India, and Mexico ranked 21, 27, and 29, respectively.

The Quality of Innovation

The rankings in Table 1 are based on patent counts, which do not take into account the *quality* of the individual inventions generated in different countries. This could pose a problem, as it is well established that the economic value of individual patents varies greatly. In particular, it has been demonstrated that the value of a patent is correlated with the number of countries in which it is filed (Lanjouw, Pakes, and Putnam 1998; Harhoff, Scherer, and Vopel 2003). Thus, we refer to those inventions with patents filed in several countries as high-value inventions.

The fourth column of Table 1 presents each country's share of the world's high-value inventions (i.e., those that are patented internationally) and thus offers a rough indicator of innovation quality.[22] Using this indicator changes the rankings significantly. With 22.2 percent of the world's high-value inventions, Germany becomes the leader, while Japan falls to third place, with about 17 percent. Moreover, the performance of the emerging economies—in particular China and Russia—becomes far less impressive. They innovate,

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[22] Patent citations are used extensively in the existing literature as a measure of patent quality (see Popp 2002). Unfortunately, there is no suitable source of citation data that can be used in conjunction with PATSTAT for the wide cross-section of countries in our study.

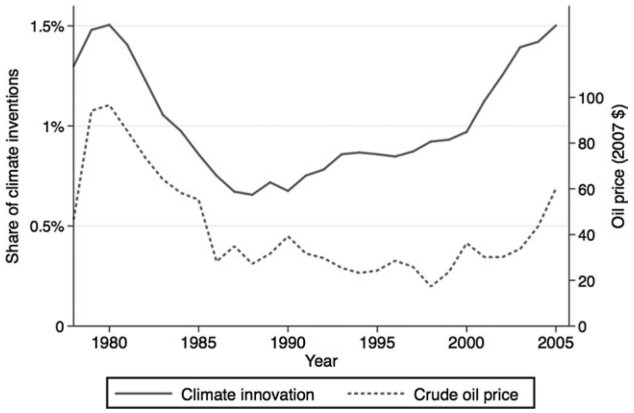

Figure 1 Climate-mitigation innovation and oil prices.
Source: Authors' calculations, based on PATSTAT data, and BP Statistical Review of World Energy June 2009.

but their inventions are of relatively minor economic value.[23] This is consistent with previous findings by Lanjouw and Mody (1996).

The Evolution of Climate-mitigation Innovation

Figure 1 presents the evolution of climate-mitigation innovation worldwide since 1978. Because the growth of innovation in environmental technologies could reflect a general growth of innovation in all technologies (including nonenvironmental ones), Figure 1 indicates climate-mitigation inventions as a share of inventions in all technology areas. The evolution of the price of oil over the same time period is also presented, since the incentives for innovation related to climate-change mitigation are likely to be influenced by energy prices.

Oil Prices and Innovation

Figure 1 appears to indicate that trends in climate-mitigation innovation follow oil price trends. However, a close examination of the data and the figure reveals two distinct time periods. Until 1990, innovation and oil prices closely mirror each other: In particular, the 1980 peak in innovation coincides with the second oil price shock. After 1980, innovation and oil prices both decline and then stagnate until 1990. It may be surprising that innovators respond so quickly to changes in energy prices, but this apparently rapid response has been well documented in previous research (e.g., Newell, Jaffe, and Stavins 1999; Popp 2002). One explanation for this phenomenon is that many patents cover inventions that have already been developed (and are "on the shelf") but are not yet profitable. The new, more profitable market conditions simply make it worthwhile to legally protect them.

The second distinct time period starts in 1990 and is characterized by an apparent decoupling of innovation and oil prices.[24] While innovation steadily increases during the 1990s, oil prices remain relatively stable until 2003. Innovation rises sharply after 2000, at an average

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[23] This also suggests that emerging economies do not export many inventions. We discuss diffusion issues in the next section.

[24] While the correlation coefficient between innovation and oil prices is 0.87 from 1978 to 1990, it is only 0.61 after 1990.

Table 2 Average annual growth rates of innovation for different technologies

Technology	1990–1999 (%)	2000–2005 (%)
Lighting	7.6	15.9
Renewable energy	1.8	8.0
Heating	1.0	7.7
Cement	−1.3	5.2
Electric and hybrid	13.9	7.8
Methane	4.0	1.7
Waste	13.8	−7.3
Insulation	6.4	−1.0

Source: Authors' calculations, based on PATSTAT data.

annual growth rate of 9 percent between 2000 and 2005. This suggests that environmental policies and climate policies have had a significant impact on climate-mitigation innovation since the beginning of the 1990s. The post-2000 acceleration could be interpreted as the innovators' response to the signing of the Kyoto Protocol in 1997 and the subsequent implementation of climate policies in ratifying countries.

Policy Impacts

It is difficult to draw firm conclusions about the role of policy drivers after 1990 based solely on aggregate statistics. To further assess the role of policy drivers, Table 2 presents the annual growth rate of innovation for different climate change–mitigation technologies in two time periods: before and after the acceleration in the pace of innovation observed around 2000. We have aggregated renewable energy technologies, as we assume they are driven by the same policy regimes.

Recall that there has been an increasing trend in innovation that accelerates in 2000. This trend is driven by the subset of technologies in the top part of the table: lighting, renewable energy, heating, and cement. The bottom part of the table identifies four technologies—electric and hybrid, methane, waste, and insulation—which do not follow the general trend, as the growth in innovation concerning these technologies occurs mainly before 2000 (i.e., before the implementation of significant climate policies in certain Kyoto Protocol Annex I countries[25]). The growth in innovation before 2000 is likely a consequence of other, earlier environmental policies. For instance, at the beginning of the 1990s, the European Union and Japan implemented new waste policies, which reinforced regulatory standards for waste disposal. As a result, many new incinerators replaced those that were obsolete and many landfills were retrofitted. This probably explains the surge of innovation in the 1990s in technologies to produce heat from waste or to collect methane. Similarly, in 1991, Japan's Ministry of Economy, Trade, and Industry issued an aggressive market expansion plan for electric and hybrid vehicles, which was further reinforced in 1997 (Ahman 2006). In California, the Zero-Emission Vehicle ("ZEV") Mandate was passed in 1991, with the objective of increasing

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[25] Industrialized countries and economies in transition are listed in Annex I of the United Nations Framework Convention on Climate Change. Annex I countries that have ratified the Kyoto Protocol (to this date, all Annex I countries except the United States) have committed to reducing their GHG emissions.

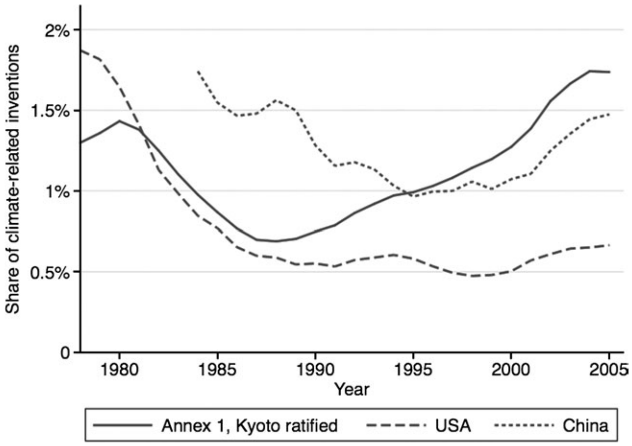

Figure 2 Climate-mitigation innovation (as a share of total innovation) in Kyoto-ratifying countries, United States, and China.
Source: Authors' calculations, based on PATSTAT data.
Note: Chinese patent data not available before 1985.

the percentage of ZEVs sold in California. These policies help explain the strong growth in electric and hybrid vehicle innovation observed in the 1990s.

Country-specific Trends and Policies

An examination of individual countries also provides some interesting insights about the evolution of climate-mitigation technological innovation and the role of public policy. Figure 2 presents the evolution of climate-mitigation inventions in Annex I countries that have ratified the Kyoto Protocol, the United States, and China. The differences across countries are striking: While climate-mitigation technological innovation has steadily increased since the beginning of the 1990s in countries that have committed themselves to carbon emission reductions, rates of innovation in the United States have remained relatively stable since the late 1980s. Climate-mitigation innovation trends in the United States seem to more closely follow oil prices, suggesting that environmental and climate policies have had a limited impact.

China also offers a very interesting case. Climate-mitigation innovation decreases until the mid-1990s, suggesting that during that time period priority was not given to climate-mitigation innovation. Climate-mitigation innovation begins to increase around the year 2000, which may reflect the implementation of domestic policies to address the country's worsening environmental problems. In particular, in 1998 the Ninth National People's Congress implemented an important reform of government administration, which included upgrading the State Environmental Protection Agency (SEPA) to ministerial status.

However, it is also possible that the increase in climate-mitigation innovation in China since 2000 has been a response to environmental and climate policies in Annex I countries. Consider, for example, the case of solar photovoltaic (PV) technology. China is now the industry leader in this area, with 27 percent of the world's production of cells and modules in 2007 (Jäger-Waldau 2008). This production is exported almost entirely to industrialized countries (e.g., Germany, Japan, and Spain) where various policies (such as feed-in tariffs, tax rebates, or investment subsidies) have boosted the demand for solar energy technologies.

A few other studies provide evidence that environmental regulation promotes innovation both domestically and abroad. For example, Lanjouw and Mody (1996) find evidence that strict U.S. regulations on vehicle emissions spurred innovation in Japan and Germany and that inventors in these countries responded more than inventors in the United States. Popp, Hafner, and Johnstone (2007) find that inventors of chlorine-free technology for the pulp and paper industry respond to both domestic and foreign environmental regulatory pressures.

International Technology Transfer

This section reviews evidence concerning how technologies are diffused between countries and discusses trends in the international diffusion of climate-mitigation technologies.

Technology Diffusion Channels

Before presenting statistics on the diffusion of climate-mitigation technologies, we briefly review how technology moves from one country to another. This is a central concept in the more general literature on the economics of technology diffusion, which identifies three channels of diffusion (see Keller 2004 for a good survey).

The first channel for diffusing technology is trade in goods. The idea that international trade is a significant channel for knowledge flows and R&D spillovers was first developed by Rivera-Batiz and Romer (1991). In their model, foreign R&D creates new intermediate goods with embodied technology that the home country can access through imports. There is empirical evidence that the importation of capital goods, such as machines and equipment, improves productivity. For example, Coe, Helpman, and Hoffmaister (1997) find that the share of machinery and equipment imports in Gross Domestic Product has a positive effect on the total factor productivity of developing countries. In their descriptive study, Lanjouw and Mody (1996) show that imported equipment is a major source of environmental technology for some countries.

The second channel of international technology diffusion is foreign direct investment (FDI). Several studies find evidence that multinational enterprises transfer firm-specific technology to their foreign affiliates (e.g., Lee and Mansfield 1996; Branstetter, Fisman, and Foley 2006). International companies might also generate local spillovers through labor turnover if local employees of the subsidiary move to domestic firms (see Fosfuri, Motta, and Rønde 2001). Local firms may also increase their productivity by observing nearby foreign firms or becoming their suppliers or customers (see, e.g., Ivarsson and Alvstam 2005; Girma, Gong, and Gorg 2009). Overall, the literature finds strong evidence that FDI is an important channel for technology diffusion.

The third channel of technology diffusion—and the most direct—is licensing. That is, a firm may license its technology to a company abroad that uses it to upgrade its own production. Data on royalty payments have been used mostly to analyze the impact of stricter patent protection on technology transfer (Smith 2001; Yang and Maskus 2001; Branstetter, Fisman, and Foley 2006).

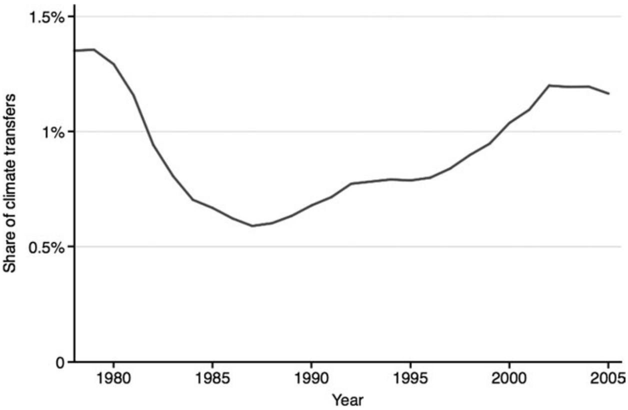

Figure 3 Transfers of climate-mitigation technologies as a share of total transfers.
Source: Authors' calculations, based on PATSTAT data.

Empirical Evidence

Empirical studies suggest that firms rely on patent protection for technology transfer along all three channels discussed above—trade, FDI, and licensing—as such transfers raise a risk of leakage and imitation in recipient countries. Thus, patents can be used to measure direct international technology diffusion.

In our analysis, we define a transfer as a patent application filed by an inventor residing in a country that is different from the one in which protection is sought (e.g., a patent filed in the United States by an inventor working in Germany[26]). This indicates a transfer because patenting provides the exclusive right to commercially exploit the technology in the country where the patent is filed. As patenting is costly, the inventor requests protection because he/she plans to use the technology locally. This approach (i.e., using patents to measure *direct* technology diffusion) has also been used by Eaton and Kortum (1996, 1999) and Lanjouw and Mody (1996).[27]

The data indicate that during the 1990s, the number of climate-mitigation patents filed abroad increased at an average annual rate of 8 percent. However, this rapid growth is not unique to climate-mitigation technology; rather, it corresponds to a general increase in international technology transfers over the same period. Figure 3 shows the share of climate-mitigation transfers in total patent transfers between 1978 and 2005.

Technology Flows between OECD and Non-OECD Countries

What are the origins and destinations of these transfers? Table 3 presents the distribution of climate-mitigation technology flows between OECD and non-OECD countries from 2000 to 2005. As a benchmark, the table also displays (in parentheses) the origin and destination data for technology transfers overall. In both cases, technology is exchanged mostly between

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[26] We use information on the inventor's country of residence, irrespective of his nationality, to determine where inventions are developed.

[27] Another strand of the literature relies on patents as an indicator for international technology *spillovers*, that is, diffusion that occurs outside the market. This literature uses patent citations (which include information about the location of the inventor) to shed light on the international diffusion of technical knowledge. See the seminal paper by Jaffe, Trajtenberg, and Henderson (1993).

Table 3 Origin–destination matrix: distribution of exported climate-mitigation inventions from 2000 to 2005

	Destination	
Origin	**OECD**	**Non-OECD**
OECD	73% (77%)	22% (16%)
Non-OECD	4% (6%)	1% (1%)

Source: Authors' calculations, based on PATSTAT data.
Note: Results for "all technologies" appear in parentheses.

industrialized countries (about 77 percent of total transfers), while transfers between developing countries are almost nonexistent (1 percent of total transfers).

Technology flows from OECD to non-OECD economies account for only 22 percent of all climate-mitigation transfers. This is, however, slightly higher than the share (16 percent) for all technologies. Climate-mitigation technology flows to non-OECD countries mostly concern fast-growing economies. In particular, China accounts for about three-quarters of the climate-mitigation transfers from OECD to non-OECD countries.

Our data show that the flows of climate-mitigation inventions from OECD to non-OECD economies have increased recently. Figure 4 indicates technology flows from OECD to non-OECD countries as a share of total transfers for climate and all technologies. There appears to be a decoupling of climate and all technologies around 1998. This mirrors the pattern in Figure 2, which shows that innovation in China also started to increase around 1998 and perhaps provides support for the argument that China's environmental policies had already encouraged domestic demand for climate-friendly technologies.

Rate of Export of Inventions

We use the export rate, defined as the share of inventions that are patented in more than one country, as an indicator of the level of international technology diffusion. For the 2000–2005 period, this rate is 17 percent for all technologies and slightly lower (15 percent) for climate-mitigation technologies. However, there are significant differences at the country level.

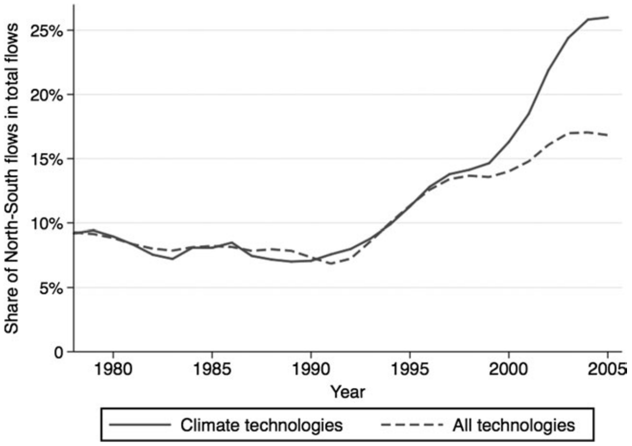

Figure 4. Technology flows from OECD to non-OECD countries (as a share of total flows), 1978–2005.
Source: Authors' calculations, based on PATSTAT data.

Table 4 Rate of export of inventions by inventor country (2000–2005)

Inventor country	Rate of export of inventions (%)
The Netherlands	89.9
United Kingdom	60.3
France	46.1
Germany	56.1
Canada	56.9
United States	42.3
Korea	24.5
Japan	21.7
Australia	15.8
China	6.8
Brazil	6.9

Source: Authors' calculations, based on PATSTAT data.

Table 4 presents the export performance for the top twelve inventor countries. Countries in Europe and North America are the world leaders in technology exports, with export rates ranging from 40 to 90 percent. This strong performance likely reflects the success of economic integration in the European Union and North American Free Trade Association areas, as many of the transfers occur between their member countries. In contrast, Korea, Japan, and Australia have had relatively poor export performance. This is especially striking in the case of Japan, which is the leader in climate-mitigation innovation but fails to diffuse its technology abroad. Similarly, Table 4 indicates that the strong innovation performance of China, Russia, and Brazil is not reflected in their export rates, again suggesting that the average value of inventions in emerging economies is low.

The data reveal that the export rate of patents also varies across technologies (see Table 5). The most widely diffused technologies are lighting, wind power, and electric and hybrid vehicles, with more than 30 percent of inventions transferred. In contrast, waste, biomass, and hydro are more localized, with less than 20 percent of inventions transferred. Interestingly, the propensity of a technology to be exported does not appear to be correlated

Table 5 Rate of export of inventions by technology (2000–2005)

Technology	Export rate (%)
Lighting	36.3
Wind	30.7
Electric and hybrid	29.8
Insulation	26.8
Heating	25.4
Solar	25.2
Marine	24.8
Cement	24.0
Geothermal	22.2
Hydro	19.9
Methane	18.9
Biomass	18.7
Waste	15.6

Source: Authors' calculations, based on PATSTAT data.

with the share of inventions related to that technology that is developed by emerging economies, suggesting that technology-specific characteristics are the determining factor.

Conclusions

We conclude with a summary of our findings and discussions of policy options for accelerating the transfer of climate-mitigation technologies to developing countries and directions for future research.

Summary of Findings

This article has used the PATSTAT to examine the dynamics, distribution, and international transfer of patented inventions in thirteen climate-mitigation technology classes between 1978 and 2005. We find that innovation in climate change technologies is highly concentrated in Japan, Germany, and the United States (together accounting for 60 percent of total climate-mitigation innovations in our dataset) but that the innovation performance of certain emerging economies, particularly China and Russia, as well as South Korea, is far from being negligible. The data also suggest that innovation was driven mostly by energy prices until 1990. Since then, environmental policies and climate policies appear to have induced more innovation, with the pace of innovation accelerating since 2000.

The issue of international technology transfer is currently high on the political agenda. Our data indicate that historically international transfers of climate-mitigation technologies have occurred mostly between developed countries. However, there appears to be tremendous potential for North–South transfers, as well as South–South exchanges—particularly since these countries may have developed inventions that are better tailored to the needs of developing countries.

Policies to Accelerate Technology Diffusion

How can the diffusion of climate-mitigation technologies to developing countries be encouraged and accelerated? Our data do not allow us to assess the potential impact of different policy tools. However, the more general literature on the economics of technology diffusion offers some interesting insights.

Regulation is one obvious policy instrument that can be used to foster the creation of markets for environmentally sound technologies and provide an incentive for firms to acquire new technologies. Since historically industrialized countries have more advanced environmental and climate regulations, it is not surprising that they have also attracted more technology transfer. It has been established, for example, that strict vehicle emission regulations in the United States led to the transfer of technology from Japan and Germany to the United States (Lanjouw and Mody 1996) and, similarly, that the adoption of tighter regulations in the pulp and paper industry in Finland and Sweden triggered an increase in patent applications on chlorine-free technology filed by U.S. inventors in these countries (Popp, Hafner, and Johnstone 2007). Our data suggest that more recently, domestic regulation in China may have spurred technology flows into the country.

However, the lack of strict environmental and climate legislation in developing countries is clearly not the only explanation for the lower rates of climate-mitigation technology transfer to these countries, as our data indicate a similar pattern of low diffusion for all technologies.

More general factors such as trade openness, the IPR system, and local absorptive capacities (e.g., human capital) also help explain why technology diffusion is concentrated in industrialized countries.

Since technology transfers take place through market channels such as trade, FDI, or licenses, they occur more frequently in open economies (Saggi 2002; Hoekman, Maskus, and Saggi 2005). Lowering barriers to trade and FDI is thus a way to foster technology transfers. Duke, Jacobson, and Kammen (2002) show, for example, that the reduction of tariffs on solar modules in Kenya increased imports of PV systems. Foreign investment also responds to a healthy business environment that includes adequate governance and economic institutions (Maskus 2004).

Whether a stronger IPR regime can foster the transfer of climate-mitigation technology to developing countries is a controversial issue.[28] As IPR confer legal exclusivity, they may reduce competition and raise price barriers to technology transfer in developing countries. However, several case studies suggest that IPR does not eliminate competition in markets for environmental technologies. Barton (2007) finds that patent issues are unlikely to be a barrier for the transfer of solar PV, wind power, and biofuel technologies in emerging economies. Similarly, Ockwell et al. (2008) show that IPR is not the main barrier to the transfer of integrated gasification combined cycle—the most efficient coal power technology—to India.

On the contrary, empirical evidence suggests that effective patent protection is a means to promote technology transfer toward developing countries when foreign technology providers face the threat of imitation by local competitors (Maskus 2000; Smith 2001; Hoekman, Maskus, and Saggi 2005; Mancusi 2008; Parello 2008). Along the same lines, stronger patent protection encourages the use of FDI and licenses, which induces technology transfer that goes beyond the mere export of equipment or goods (Smith 2001).

Since the positive effect of IPR depends on the threat of local imitation, it mostly concerns those recipient countries that already have technology capabilities, such as emerging economies. More generally, there is strong evidence that countries need absorptive capacities in order to successfully adopt foreign technology (Keller 1996). The higher the level of domestic human capital, the higher the level of foreign technology transfer (Eaton and Kortum 1996), as well as local spillovers from trade and FDI (Borensztein, De Gregório, and Lee 1998). By contrast, low absorptive capacities mean shortages of skilled technical personnel, a lack of information on available technologies, and high transaction costs (Worrell et al. 1997; Metz et al. 2000). This highlights the importance of long-term education and capacity building policies and programs in promoting North–South technology transfer.

Directions for Future Research

The research presented in this article has been mostly descriptive and does not examine in detail or seek to explain the drivers of innovation and technology transfer. Clearly an important area for future research would be to complement this descriptive study with econometric analyses of climate-mitigation technology innovation and diffusion worldwide.

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[28] The controversy has mainly revolved around the agreement on trade-related aspects of intellectual property right (TRIPS) that was negotiated in 1994, at the end of the Uruguay Round of the General Agreement on Tariffs and Trade. The TRIPS agreement establishes minimum standards for intellectual property and is aimed at encouraging developing countries to strengthen their IPR regimes.

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Appendix 1. Description of technology fields included in the study

Technology field	Description
Biomass	Solid fuels based on materials of nonmineral origin (i.e., animal or plant); engines operating on such fuels (e.g., wood)
Insulation	Elements or materials used for heat insulation; double-glazed windows
Heating	Heat pumps, central heating systems using heat pumps; energy recovery systems in air conditioning
CCS	Extraction, transportation, storage, and sequestration of CO_2
Cement	Natural pozzuolana cements; cements containing slag; iron ore cements; cements from oil shales, residues, or waste; calcium sulfate cements
Electric vehicles	Electric propulsion of vehicles; regenerative braking; batteries; control systems specially adapted for hybrid vehicles
Geothermal	Use of geothermal heat; devices for producing mechanical power from geothermal energy
Hydro	Hydropower stations; hydraulic turbines; submerged units incorporating electric generators; devices for controlling hydraulic turbines
Lighting	Compact fluorescent lamps; electroluminescent light sources
Methane	Equipment for anaerobic treatment of sludge; biological treatment of wastewater or sewage; anaerobic digestion processes; apparatus aiming at collecting fermentation gases
Marine	Tide or wave power plants; mechanisms using ocean thermal energy conversion; water wheels
Solar	Solar photovoltaic (conversion of light radiation into electrical energy), including solar panels; concentrating solar power (solar heat collectors having lenses or reflectors as concentrating elements); solar heat (use of solar heat for heating and cooling)
Waste	Solid fuels based on industrial residues or waste materials; recovery of heat from waste incineration; production of energy from waste or waste gases; recovery of waste heat from exhaust gases
Wind	Wind motors; devices aimed at controlling such motors

Appendix 2. Invention and diffusion of CCS technologies

The CCS data are presented in this appendix because this dataset was constructed in a different way than the other datasets. More specifically, in collaboration with patent examiners from the EPO, the CCS data were assembled through a search of the EPO's DOCDB database using keyword searches and a variety of different internal patent classification systems (see Haščič et al. 2010). While this creates a language bias, IPC searches in PATSTAT could not reliably identify the relevant documents.[29]

The CCS technology is still at an early stage of development. Thus, the volume of patenting activity in this field is quite low compared to other climate-mitigation technologies. As shown in Figure 5, between 1978 and 1996 less than one hundred CCS inventions were patented worldwide annually. However, the innovation trend accelerated sharply in 1997, reflecting a new interest in this technology. Since then, the average annual growth rate of innovation has been about 20 percent, twice the rate of the 1978–1996 period.

The average export rate of CCS inventions was 20.5 percent from 2000 to 2006, significantly above the rate for other climate-mitigation technologies (15 percent), suggesting a higher quality of patented inventions, which is consistent with an early stage of technology development.

The United States is by far the leading CCS inventor country, with about half of global inventions between 2000 and 2005 and one-third of exported inventions. Japan is second, with 11% of global inventions, followed closely by Canada (7 percent), Germany (6 percent), and the Netherlands and France (5 percent each). With 4 percent of total CCS inventions, China's share is roughly equivalent to that of a large European country.

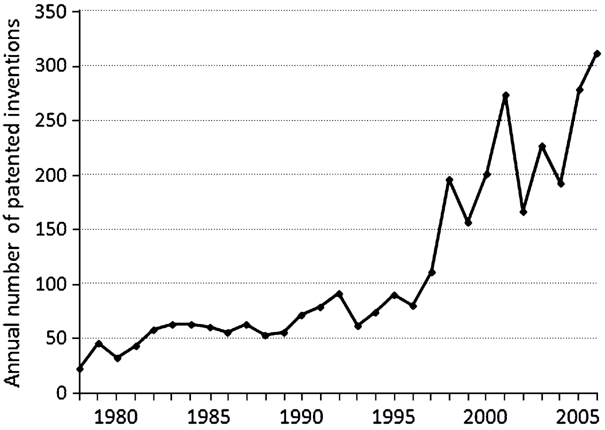

Figure 5 Patented CCS inventions worldwide (1978–2006).
Source: Authors' calculations, based on PATSTAT data.

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[29] This is because CCS technology is not easily identifiable using the IPC scheme. As discussed in the data section of this article, in preparing this dataset no effort has been made to correct for differences in patent breadth and other patent office-specific factors.

Appendix 3. Main patent offices and patent breadth coefficients

Patent office	Patent breadth coefficient
Japan	0.72
Taiwan	0.74
Australia	0.80
South Korea	0.82
Russia	0.90
China	0.91
India	0.93
Mexico	0.93
Canada	0.94
Denmark	0.94
United Kingdom	0.94
United States	0.97
Switzerland	0.98
Austria	0.99
France	0.99
EPO	1
Belgium	1.02
Italy	1.08
Luxembourg	1.14
Germany	1.15

Source: Authors' calculations, based on PATSTAT data.

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