

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

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Abstract

This article uses the EPO Worldwide Patent Statistical Database (PATSTAT) to examine the geographic distribution and global diffusion of inventions in thirteen climate mitigation technologies since 1978. The data suggest that until 1990 innovation was driven mostly by energy prices. Since then, environmental policies, and, more recently, climate policies, have accelerated the pace of innovation.

The data also indicate that innovation is highly concentrated in three countries—Japan, Germany and the USA—which together account for 60% of total inventions. Surprisingly, the contribution of emerging economies is far from negligible, as China and South Korea together account for about 15% of total inventions. However, inventions from emerging economies are less likely to find markets beyond their borders, suggesting that inventions from emerging economies have less value. More generally, international transfers occur mostly between developed countries (73% of all exported inventions). Exports from developed countries to emerging economies are still limited (22%), but are growing rapidly, especially to China.

Key words: Climate change, innovation, international technology diffusion

JEL classification numbers: O33, O34, Q54, Q55

Introduction

Accelerating the development of new low-carbon technologies and promoting their global application is a key challenge 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 Map¹ 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, environment-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 of 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 countries² have argued for the creation of a different IPR regime for climate-friendly technologies in order to encourage diffusion, whereas industrialized countries claim that the incentives provided by

¹ Participants at the 2007 United Nations Climate Change Conference in Bali set out a road map for negotiating a new climate agreement by the end of 2009, referred to as the Bali Road Map.

² The countries referred to as « developing countries » are in fact quite heterogenous. We will thus distinguish between emerging economies and less developed countries when required.

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 seeks to inform the debate with factual evidence on the geographic distribution and global diffusion of climate mitigation inventions. Using data from the European Patent Office (EPO) Worldwide Patent Statistical Database (PATSTAT), we examine patented inventions in 13 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 areas⁴. 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 84 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

³ See Maskus (2010) for a discussion.

⁴ Throughout the paper, we use the terms innovation and invention interchangeably.

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 USA and fourteen developing countries, is the most closely related study to our work. The authors identify the leaders in environmental patenting and find that significant transfers occur to developing countries. However, our analysis focuses more specifically on climate change mitigation, uses more recent data, and covers more countries.

The key questions we seek to answer include: 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. 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 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 documents provide information not only the countries where these new technologies are developed, but also where they are used.⁵

⁵ It is these unique features of patent data that make our study climate mitigation technologies possible.

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 USA. For example, Popp (2006) uses patent data from Japan, the US, and Germany to examine the invention and diffusion of air pollution control devices for coal-fired power plants. Johnstone et al. (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 a 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.⁶

Patent Indicators and their Limitations

⁶ Accordingly, the first patent is called the priority application and the first patent office is referred to as the priority office.

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; Thompson and Fox-Kean, 2005; Peri, 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 et al. 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 *et al.* 2001).

Second, the propensity to patent differs between sectors, depending on the nature of the technology (Cohen et al. 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 intellectual property rights. This means that greater patenting activity could reflect greater inventive activity or greater propensity to file patents. Our methodology, which measures patenting activity in various countries in 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.⁷ 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 and 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, its distribution is skewed. That is, because many patents have very low value, and as a consequence the absolute number of patents

⁷ See Helfgott (1993) and Berger (2005) for information about the cost of applications at the EPO.

does not perfectly reflect the value of technological innovation. Methods have been developed to address this issue (see Lanjouw et al. 1998), such as using weights based on the number of times a given patent is cited in 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

Efforts to develop a large patent database that would be suitable for statistical analysis were first undertaken by the OECD Directorate for Science, Technology and Industry, in cooperation with other members of the OECD Patent Statistics Taskforce.⁸ Further efforts were then directed towards developing a worldwide patent database. The European Patent Office (EPO) took over responsibility for development and production of the database, with the first version distributed in April 2006. It has since become known as the EPO Worldwide Patent Statistical Database or PATSTAT.

PATSTAT is unique in that it covers more than 80 patent offices and contains over 60 million patent documents. It is updated bi-annually. 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

⁸ The other Taskforce members include European Patent Office (EPO), Japan Patent Office (JPO), United States Patent and Trademark Office (USPTO), World Intellectual Property Organisation (WIPO), National Science Foundation (NSF), Eurostat, and DG Research.

database also includes patent descriptions (i.e., abstracts) and citation data for some offices.

Technologies and Patent Applications

We considered fourteen climate mitigation technologies: 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, energy-efficient lighting, and carbon capture and storage (CCS).^{9,10} 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% of all GHG abatement opportunities (excluding forestry) beyond business as usual until 2030, as identified by Enkvist et al. (2007).

To build the data set, we extracted all patent applications filed from 1978 to 2005 in the 13 climate-mitigation technology fields. Patent applications related to these fields were identified using International Patent Classification (IPC) codes¹¹. The IPC codes corresponding to the climate mitigation technologies were

⁹ A more detailed description of the technology fields covered by the study can be found in Appendix 1.

¹⁰ CCS technology is not yet accounted for in international patent classifications. We have used a specific search algorithm to identify CCS patent applications. For this reason, results on this technology are presented separately in Appendix 2.

¹¹ Some previous studies have related patent classes to industrial sectors using a concordance table matching IPC classes with the International Standard Industrial Classification (ISIC) 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

identified in two ways. First, we searched the descriptions of the IPC codes online to identify those relevant to our study¹². Second, using ESP@CENET, an on-line patent search engine maintained by the EPO¹³, we reviewed patent titles and abstracts for 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.¹⁴

The resulting data set contains 285,770 patent applications filed in 76 countries. On average, the climate-related patents included in our data set represent 1% of the total number of patents filed annually worldwide. The number of patent applications in each technology field is presented in the on-line supplementary materials for this article. The PATSTAT database 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.¹⁵

Data Issues

Two types of error may arise when building this type of data set: 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

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.

¹² The IPC system can be searched at <http://www.wipo.int/tacsy/>

¹³ Available at <http://ep.espacenet.com/>

¹⁴ The descriptions of the IPC codes used to build the data set can be found in the on-line supplementary materials for this article.

¹⁵ 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.

order to avoid this problem, we carefully examined a sample of patent titles for every IPC code considered for inclusion in the data set, 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 data set 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 data sets in each technology field are unlikely to be equally inclusive. Therefore estimates of the absolute volume of innovative activity may be less reliable than differences in temporal trends. For this reason, cross-technology comparisons throughout the paper 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 in order 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 data set. That is, we examined all international patent families in the PATSTAT database and then calculated how

many patents protect the same invention across the countries in the data set. 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 information to calculate country-specific patent breadth coefficients. For example, we found that, on average, seven patents filed at the Japanese Patent Office (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.¹⁶ 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.¹⁷ 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 US, 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

¹⁶ Note that is a much lower ratio than others have obtained using ‘claims’ rather than patents as the unit of analysis.

¹⁷ The EPO-equivalent country weights (coefficients) for various patent offices are presented in Appendix 3.

applications. A more detailed description of these two issues and how we addressed them is presented in the on-line supplementary materials.

4 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?¹⁸ As shown in Table 1 innovation appears to be highly concentrated: The top twelve countries account for nearly 90% of all inventions between 2000 and 2005. Japan, the USA and Germany are the three top inventor countries for most technologies. With 37% 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% of the world's inventions in electric & hybrid, waste, and lighting.¹⁹

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 US (\$US 70 million) and the EU15²⁰ (\$US 50 million) combined (Lazarus & Kartha 2007).

¹⁸ Recall that in this study an invention corresponds to a patent family. Hence a patent filed in several countries is only counted once.

¹⁹ 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.

²⁰ EU15 countries were the European Union members 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 12 inventor countries (2000 - 2005)

| Country | Rank | Average % of world inventions | Average % of world's high-value inventions | Country's top 3 technology fields (decreasing order) |
|--------------|------|-------------------------------|--|--|
| Japan | 1 | 37.1 % | 17.4 % (2) | All technologies |
| USA | 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 & hybrid, insulation |
| UK† | 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 |
| Netherlands† | 12 | 1.1 % | 2.1 % (12) | Lighting, geothermal, marine |
| Total | - | 87.2 % | 77.2 % | |

† Note: Together, the 27 countries of the European Union (EU27) represent 24% of the world's inventions.

* High-value inventions are inventions patented in at least two countries.

Source: Authors' calculations, based on PATSTAT data

Interestingly, the world's three top inventor countries are followed by three emerging economies: 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 12 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. For example, Guellec and van Pottelsberghe (2000) find that the value of patents filed in several countries (known as “claimed priorities”) is higher than the value of patents filed in only one country (“singulars”). 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.²¹ Using this indicator significantly changes the rankings. With 22.2% of the world’s high-value inventions, Germany becomes the leader, while Japan falls to third place, with about 17%. Moreover, the performance of the emerging economies – in particular China and Russia – becomes far less impressive. They innovate, but their inventions are of relatively minor economic value²². This is consistent with previous findings by Lanjouw and Mody (1996).

²¹ 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.

²² This also suggests that emerging economies do not export many inventions. We discuss diffusion issues in the next section.

The evolution of climate-mitigation innovation

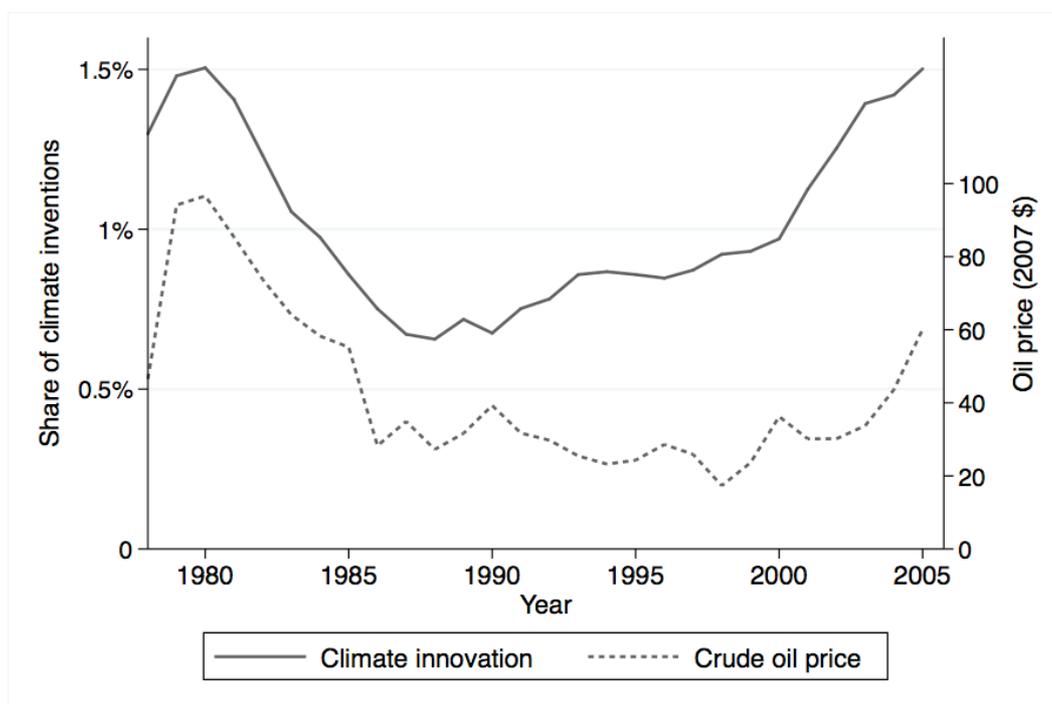
Figure 1 presents the evolution of climate-mitigation innovation worldwide since 1978. Because the growth of innovation in environmental technologies could reflect a general growth of innovation in all technologies (including non-environmental ones), Figure 1 indicates climate-mitigation inventions as 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 reveal 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 apparent rapid response has been well documented in previous research (e.g., Newell et al., 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 prices²³. While innovation steadily increases during the 1990s, oil prices remain relatively stable until 2003. Innovation rises sharply after 2000, at an average annual growth rate of nine 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.

Figure 1: Climate-mitigation innovation and oil prices



²³ While the correlation coefficient between innovation and oil prices is 0.87 from 1978 to 1990, it is only 0.61 after 1990.

Source: Authors' calculations based on PATSTAT data and BP Statistical Review of World Energy June 2009

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.

Table 2: Average annual growth rates of innovation for different technologies

| Technology | 1990-99 | 2000-05 |
|------------------------------|----------------|----------------|
| <i>Lighting</i> | 7.6% | 15.9% |
| <i>Renewable energy</i> | 1.8% | 8.0% |
| <i>Heating</i> | 1.0% | 7.7% |
| <i>Cement</i> | -1.3% | 5.2% |
| <i>Electric & hybrid</i> | 13.9% | 7.8% |
| <i>Methane</i> | 4.0% | 1.7% |
| <i>Waste</i> | 13.8% | -7.3% |
| <i>Insulation</i> | 6.4% | -1.0% |

Source: Authors' calculations, based on PATSTAT data

Recall that there has been an increasing trend in innovation which accelerates in 2000. This trend is driven by the sub-set 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 & 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 countries²⁴). 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 (METI) 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 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

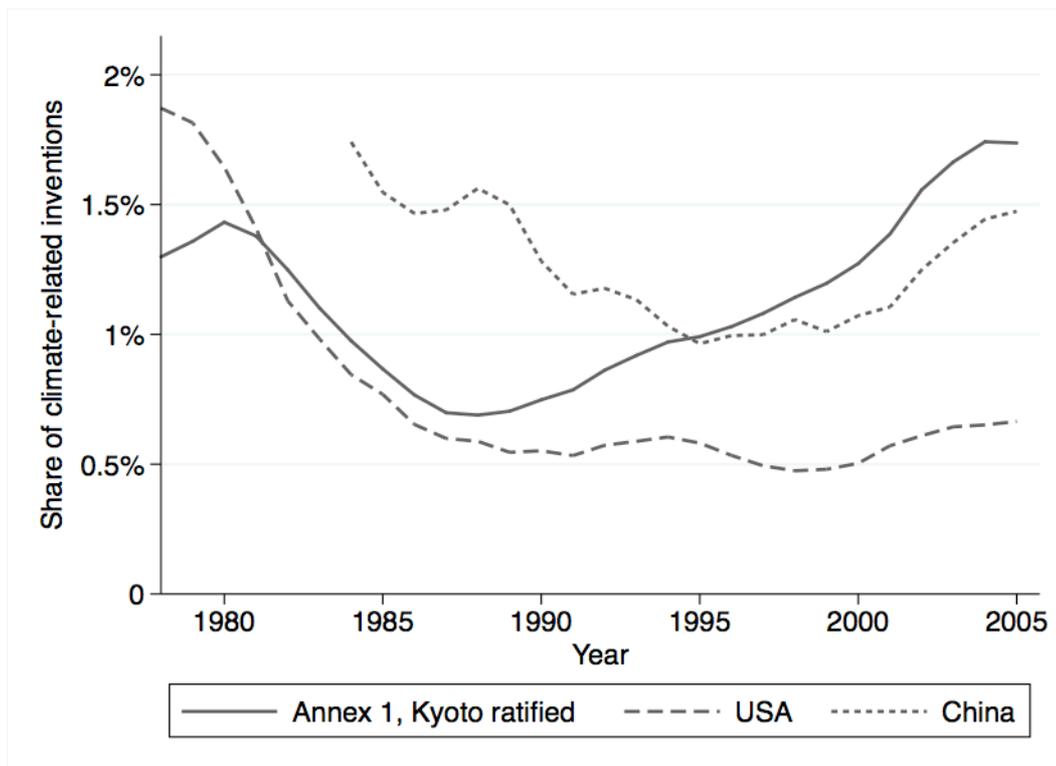
An examination of individual countries also provides some interesting insights about the evolution of climate-mitigation technological innovation, and

²⁴ Industrialized countries and economies in transition are listed in Annex I of the United Nations Framework Convention on Climate Change (UNFCCC). Annex I countries which have ratified the Kyoto Protocol (to this date, all Annex I countries but the USA) have committed to reduce their greenhouse gas emissions.

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 USA, 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 emissions reductions, rates of innovation in the United States have remained relatively stable since the late 1980s. Climate-mitigation innovation trends in the US 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 environmental protection agency (SEPA) to ministerial status.

Figure 2: Climate-mitigation innovation (as a share of total innovation) in Kyoto-ratifying countries, USA and China



Source: Authors' calculations, based on PATSTAT data.

Note: Chinese patent data not available before 1985.

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 technology. China is now the industry leader in this area, with 27% 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 et al. (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 on 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 et al. (1997) find that the share of machinery and equipment imports in GDP 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 et al., 2006). International companies might also generate local spillovers through labor turnover if local employees of the subsidiary move to domestic firms (see Fosfuri et al. 2001). Local firms may also increase their productivity by observing nearby foreign firms or becoming their suppliers or customers (see, for example, Ivarsson and Alvstam 2005; Girma et al., 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 et al., 2006).

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

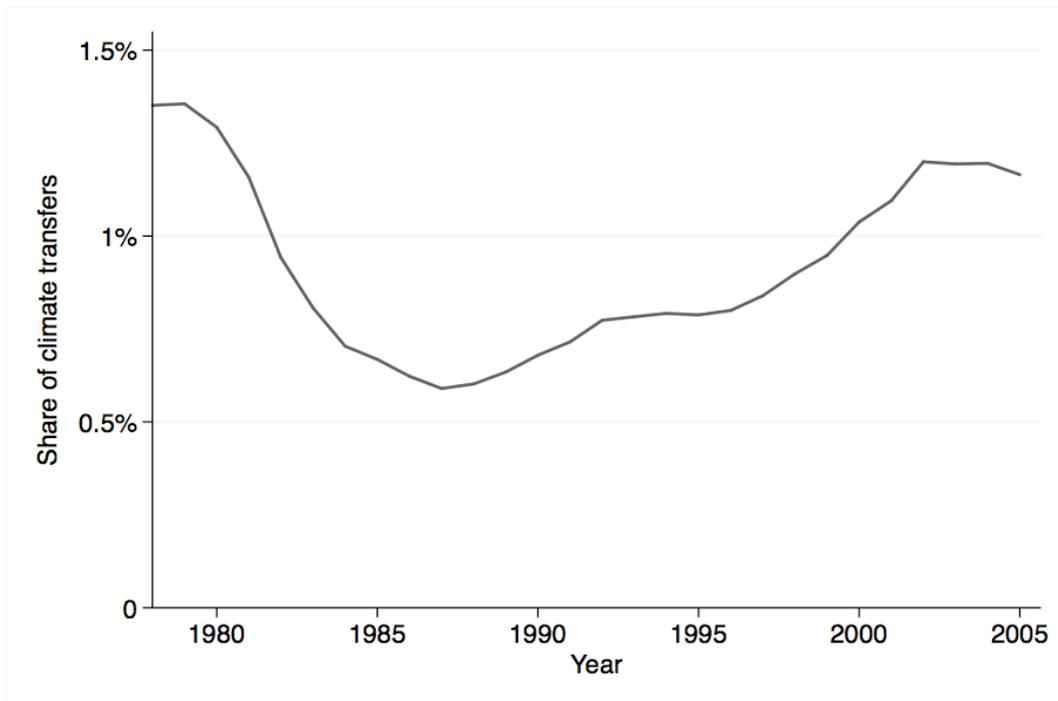
sought (e.g., a patent filed in the US by an inventor working in Germany²⁵). This indicates a transfer because patenting provides the exclusive right to commercially exploit the technology in the country where the patent is filed. As patenting is costly, the inventor requests protection because s/he 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).²⁶

The data indicate that during the 1990s, the number of climate-mitigation patents filed abroad increased at an average annual rate of 8%. 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.

Figure 3: Transfers of climate-mitigation technologies as a share of total transfers

²⁵ We use information on the inventor's country of residence, irrespective of his nationality, to determine where inventions are developed.

²⁶ Another strand of the literature relies on patents as an indicator for international technology *spillovers*, that is, diffusion that occurs outside of 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 et al. (1993).



Source: Authors' calculations, based on PATSTAT data

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 industrialized countries (about 77% of total transfers), while transfers between developing countries are almost non-existent (1% of total transfers).

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

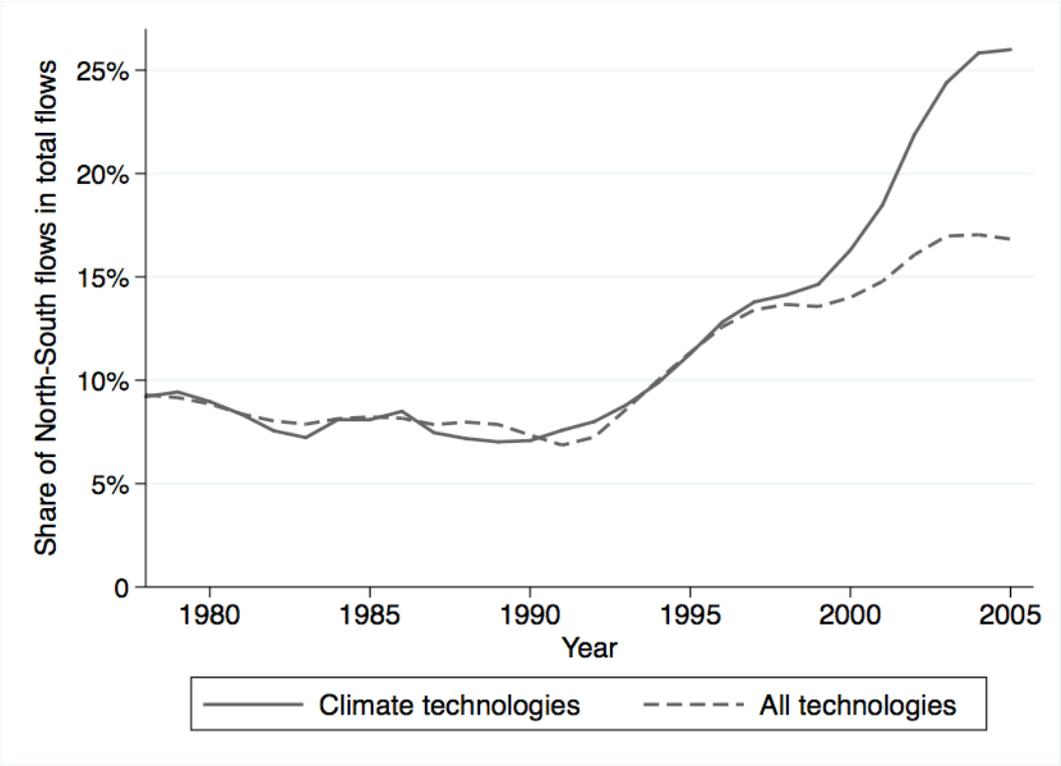
Note: Results for "all technologies" appear in parentheses

Technology flows from OECD to non-OECD economies account for only 22 % of all climate-mitigation transfers. This is, however, slightly higher than the share (16%) 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 induced domestic demand for climate-friendly technologies.

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

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% for all technologies and slightly lower (15%) for climate-mitigation technologies. However, there are significant differences at the country level.

Table 4 presents the export performance for the top 12 inventor countries. Countries in Europe and North America are the world leaders in technology exports, with export rates ranging from 40% to 90%. This strong performance likely reflects the success of economic integration in the European Union and North American Free Trade Association (NAFTA) 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 (Table 5). The most widely-diffused technologies are lighting, wind power, and electric and hybrid vehicles, with more than 30% of inventions transferred. In contrast, waste, biomass, and hydro are more localized, with less than 20% of inventions transferred. Interestingly, the propensity of a technology to be exported does not appear to be correlated with the share of inventions related to that technology that is developed by emerging economies, suggesting that technology-specific characteristics are the determining factor.

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

| Inventor country | Rate of export of inventions |
|------------------|------------------------------|
| Netherlands | 89.9% |
| UK | 60.3% |
| France | 46.1% |
| Germany | 56.1% |
| Canada | 56.9% |
| USA | 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 5: Rate of export of inventions by technology (2000-2005)

| Technology | Export rate |
|-------------------|-------------|
| Lighting | 36.3% |
| Wind | 30.7% |
| Electric & 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

Summary and Conclusions

This article has used the PATSTAT database to examine the dynamics, distribution, and international transfer of patented inventions in 13 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% of total climate-mitigation innovations in our data set), but that the innovation performance of certain emerging economies, particularly China, South Korea, and Russia, is far from being negligible. The data also suggest that innovation was mostly driven 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.

How can this diffusion be further 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 (Less & McMillan, 2005). 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 emissions regulations in the US led to the transfer of technology from Japan and Germany to the US (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 US inventors in these countries (Popp et al., 2007). Our data suggest that more recently, domestic regulation in China may have spurred technology flows into this 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 intellectual property rights (IPR) system, and local absorptive capacities (e.g., human capital) also help to 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 et al. 2005). Lowering barriers to trade and FDI is thus a way to foster technology transfers. Duke et al. (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 in developing countries is a controversial issue²⁷. As IPRs 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 biofuels 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 (IGCC)—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 towards developing countries when foreign technology providers face the threat of imitation by local

²⁷ The controversy has mainly revolved around the Agreement on Trade Related Aspects of Intellectual Property Right (TRIPS) that was negotiated at the end of the Uruguay Round of the General Agreement on Tariffs and Trade (GATT) in 1994. The TRIPS agreement sets down minimum standards for intellectual property, leading developing countries to strengthen their IPR regimes.

competitors (Maskus, 2000; Smith, 2001; Hoekman et al. 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 et al., 1998). By contrast, low absorptive capacities mean shortages of skilled technical personnel, a lack of information on available technologies, and high transaction costs (Metz et al., 2000; Worrell et al., 1997). This highlights the importance of long term education and capacity building policies and programs in promoting North-South technology transfer.

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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Appendix 1. Description of technology fields included in the study

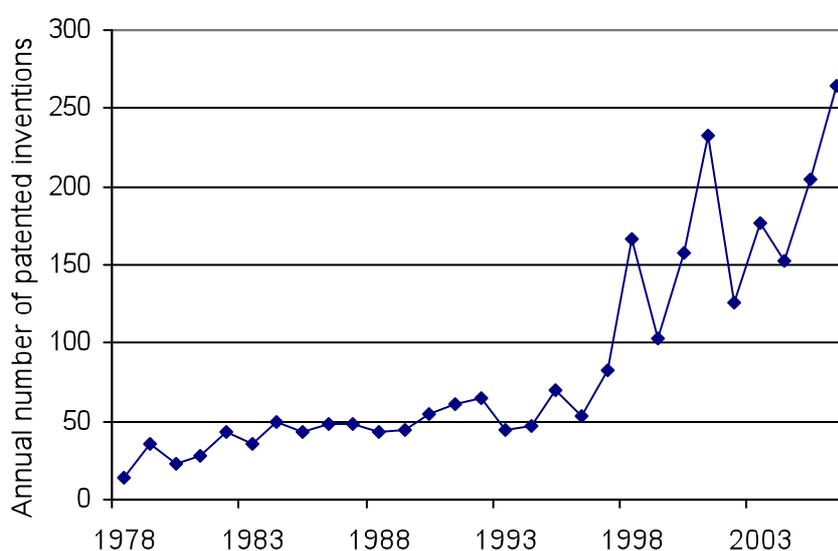
| Technology field | Description |
|-------------------|---|
| Biomass | Solid fuels based on materials of non-mineral origin (i.e. animal or plant); engines operating on such fuels (e.g. wood). |
| Insulation | Elements or materials used for heat insulation; double-glazed windows |
| Heating | Heat 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 | Hydro power stations; hydraulic turbines; submerged units incorporating electric generators; devices for controlling hydraulic turbines. |
| Lighting | Compact Fluorescent Lamps; Electroluminescent light sources (LED) |
| Methane | Equipment for anaerobic treatment of sludge; biological treatment of waste water 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), incl. solar panels; concentrating solar power (solar heat collectors having lenses or reflectors as concentrating elements); solar heat (use of solar heat for heating & cooling). |
| Waste | Solid fuels based on industrial residues or waste materials; recovery of heat from waste incineration; production of energy from waste or waste gasses; recovery of waste heat from exhaust gases. |
| Wind | Wind motors; devices aimed at controlling such motors. |

Appendix 2. Invention and diffusion of carbon capture and storage technologies

We have decided to present the CCS data in a separate appendix because the data set was constructed in a different way from the others. More specifically it was implemented with the help of patent examiners from the European Patent Office through a search of their in-house DOCDB database²⁸ using keyword searches and a variety of different patent classification systems. While this creates a bias towards the inclusion of English-language patents, reliance upon IPC searches in PATSTAT was not sufficient to identify the relevant documents reliably.

The CCS technology is still at an early stage of development.²⁹ Thus the volume of patenting activity in this field is quite low compared to other climate-mitigation technologies. As shown in Figure 3, between 1978 and 1996 less than 100 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 around 15%, twice the rate of the 1978-1996 period.

Figure 5: Patented CCS inventions worldwide (1978-2006)



Source: Authors' calculations, based on PATSTAT data

²⁸ See : <http://www.epo.org/patents/patent-information/raw-data/test/product-14-7.html>

²⁹ CCS technology is not easily identifiable using the IPC scheme. The data in this Appendix is based upon work done in collaboration with patent examiners at the EPO (see Hašiči et al. 2010). Note that no effort has been made to correct for differences in patent breadth and other patent office-specific factors, as discussed in the data section of this article.

The average export rate of CCS inventions was 20.5% from 2000 to 2006, significantly above the rate for other climate-mitigation technologies (15%), 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%), Germany (6%), the Netherlands and France (5% each). With 4% of total CCS inventions, China's share is roughly equivalent to that of a large European country.

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 |
| UK | 0.94 |
| USA | 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

Supplementary materials

Number of patent applications and priorities included in the data set

| Technology field | Number of priorities | Number of claimed priorities | Total number of patents |
|-------------------|----------------------|------------------------------|-------------------------|
| Biomass | 1853 | 182 | 2541 |
| Cement | 4470 | 462 | 6595 |
| Electric vehicles | 29217 | 5166 | 43271 |
| Geothermal | 1706 | 162 | 2230 |
| Heating | 12527.5 | 1682.5 | 17348.5 |
| Hydro | 8892 | 574 | 10847 |
| Insulation | 17542 | 2330 | 26041 |
| Lighting | 60231.5 | 9154.5 | 86207.5 |
| Marine | 4454 | 496 | 6640 |
| Methane | 7938 | 1032 | 11911 |
| Solar | 31186 | 3816 | 44011 |
| Waste | 4993 | 614 | 7358 |
| Wind | 13368 | 1804 | 20769 |
| TOTAL | 198378 | 27475 | 285770 |

Source: Authors' calculations, based on PATSTAT data

Note: "Claimed priorities" refers to patents first filed in a country and then filed in another country (where the priority is claimed)

