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Cerna, Centre d'économie industrielle
MINES ParisTech
60, boulevard Saint Michel
75272 Paris Cedex 06 – France
Tél. : 33 (1) 40 51 90 00

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Invention and Transfer of Climate Change Mitigation Technologies on a Global Scale: A Study Drawing on Patent Data

Antoine Dechezleprêtre[†], Matthieu Glachant[+], Ivan Hascic[*],
Nick Johnstone*, Yann Ménière[+]

Correspondence to:

Matthieu Glachant
CERNA, Mines ParisTech
60, Boulevard Saint Michel
75272 Paris Cedex 06, France
Tel: + 33 1 40 51 92 29
Fax: + 33 1 40 51 91 45
E-mail address: glachant@mines-paristech.fr

[†] Grantham Research Institute on Climate Change and the Environment, London School of Economics and Political Science
[+] MINES ParisTech, CERNA
[*] Empirical Policy Analysis Unit, OECD Environment Directorate

Abstract

This paper uses the EPO/OECD World Patent Statistical Database (PATSTAT) to provide a quantitative description of the geographic distribution of inventions in thirteen climate mitigation technologies since 1978 and their international diffusion on a global scale.

Statistics suggest that innovation has mostly been driven by energy prices until 1990. Since then, environmental policies, and climate policies more recently, have accelerated the pace of innovation.

Innovation is highly concentrated in three countries—Japan, Germany and the USA—which account for 60% of total innovations. Surprisingly, the innovation performance of emerging economies is far from being negligible as China and South Korea together represent about 15% of total inventions. However, they export much less inventions than industrialized countries, suggesting their inventions have less value. More generally, international transfers mostly occur between developed countries (73% of exported inventions). Exports from developed countries to emerging economies are still limited (22%) but are growing rapidly, especially to China.

1 Introduction

Accelerating the development of new low-carbon technologies and promoting their global application is a key challenge in stabilizing atmospheric GHG emissions. Consequently, technology is at the core of current discussions surrounding the post-Kyoto climate regime. The 2007 Bali Road Map cites technology development and diffusion as strategic objectives, thereby inciting a debate on appropriate policies.

This debate is complicated by a number of factors. To begin with, environment-friendly technologies have been developed primarily in industrialized countries, but are urgently required to mitigate GHG emissions in fast-growing emerging economies. Ensuring their global diffusion thus entails considerable policy and economic challenges because developing countries are reluctant to bear the financial costs of catching up alone, while firms in industrialized countries are wary about giving away strategic intellectual assets. The role of intellectual property rights is particularly controversial. Developing countries have argued for the creation of a differentiated regime for climate-friendly technologies in order to encourage diffusion, whereas industrialized countries claim that the incentives provided by existing IP regimes reinforce diffusion incentives by securing patent holders' benefits.

The problem is compounded by the lack of information. There is no clear, widespread understanding of what constitutes a 'climate change mitigation technology', and of how such technologies are diffused in the world.

Using a worldwide patent database, this paper seeks to foster this debate with factual evidence on the geographic distribution of climate mitigation inventions and their international diffusion on a global scale. We address questions such as: In which countries does climate-friendly innovation take place? More particularly, what is the contribution of innovators located in emerging economies? To what extent is technology being transferred to developing countries? Is climate innovation special as compared to other technology areas? Whenever possible, we also try to characterize the impact on innovation and technology diffusion of climate and environmental policies which have already been implemented in certain countries.

We identify 13 different classes of technologies with significant global GHG emission abatement potentials, and analyze inventive activities and their international transfer between 1978 and 2005. More precisely, we consider seven renewable energy technologies (wind, solar, geothermal, marine energy, biomass, hydropower, and waste-to-energy), methane destruction, climate-friendly cement, thermal insulation in buildings, heating, electric and hybrid vehicles, and energy-efficient lighting. We also present data on carbon capture & storage (CCS). Although we cover a wide range of climate-friendly technologies, note that a number of other important technologies have not been included 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 beyond business as usual until 2030 – excluding forestry – identified by Enkvist et al. (2007).

As a measure of innovation in the different domains we use counts of patent applications. Although patents do not provide a measure of all innovation, they offer a good indication of the results of innovative activity and allow for interesting cross-country comparisons. Moreover, the database contains information from a large number of patent offices, and thus enables us to draw insights about international technology transfer.

In recent years, an increasing number of studies have used patent data to analyze innovation and international technology diffusion, in particular in the environmental field. They usually rely 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 innovation and diffusion of air pollution control devices for coal-fired power plants. Johnstone et al. (2009) analyze the effects of policy and market factors on innovation with respect to renewable energy technologies in IEA countries. Dekker et al. (2009) constructed a dataset of patents for SO_2 abatement technologies for fifteen countries over the period 1970-1997. They find that innovating firms file patent applications before the relevant international sulfur protocols were implemented. Moreover, the filing of patents abroad (‘families’) is particularly strong in the countries that are signatories to the protocols.

The data used in this paper go well beyond that of previous work. We use the EPO/OECD World Patent Statistical Database (PATSTAT) which includes patents from 84 national and international patent offices. This allows us – contrary to most studies focusing on a few patent offices – to conduct a global analysis of innovative activity, including patents filed in developing countries. Moreover, it is the first time that indicators are constructed such that absolute cross-country comparisons can be made. We present the methodology that we implemented to limit biases stemming from the differences in propensity to patent across countries.

To the best of our knowledge, this work is the first study using patent data to quantitatively describe the geographical and temporal trend of innovation and diffusion of climate change mitigation technologies at global level. A paper by Lanjouw and Mody (1996) is the most closely related to our work but it does not focus on climate change mitigation. The authors focus on patents for environmentally responsive technology in Japan, Europe, the USA and fourteen developing countries. They identify the leaders in environmental patenting and find that significant transfers occur to developing countries. Our focus is more specifically on climate change mitigation, the data is more recent, and it covers more countries.

This paper is also related to a different body of literature which examines how patenting influences innovation and diffusion in an international context. In particular, this literature seeks to analyze the impacts of the TRIPS agreement, which has reinforced intellectual property rights regimes (see Maskus 2000;

Maskus 2004; Smith 2001; Hoekman et al. 2004). More generally, Barton (2007) discusses from a legal perspective whether strong intellectual property rights in emerging economies would hinder or promote the transfer of "green" technology. Among other results, these studies highlight the fact that effective patent protection is a means to promote technology transfer towards developing countries that already have a certain level of technological capability. However, contrary to this literature, our paper is mostly descriptive, although we try wherever possible to identify what drives our observations.

The paper is organized as follows. Section 2 introduces the key concepts and discusses the use of patents as indicators of innovation and technology transfer. The dataset is presented in Section 3 along with data issues. In Section 4 we describe innovative activity in the world between 1978 and 2005, across different countries and technologies. Section 5 analyzes the international transfer of technologies. A final section summarizes the main results.

2 Patents as indicators of innovation and technology transfer

There are a number of possibilities for the measurement of innovation (see OECD *Main Science and Technology Indicators* 2008). Most commonly, R&D expenditures or the number of scientific personnel in different sectors are used. Although such indicators reflect an important element of the innovation system, there are a number of disadvantages associated with their use. For example, data on private R&D expenditures are incomplete. Furthermore, the data are only available at an aggregate level. Importantly, they are measures of inputs to the innovation process, whereas an "output" measure of innovation is broadly preferable.

By contrast, patent data focus on outputs of the inventive process (Griliches 1990). They provide a wealth of information on the nature of the invention and the applicant. Most importantly, they can be disaggregated to specific technological areas. Finally, they indicate not only the countries where inventions are made, but also where these new technologies are used. These features make our study of climate mitigation technologies possible. Of course they present drawbacks which are discussed below.

In order to provide an accurate explanation of the indicators presented, it is necessary to briefly recall how the patent system works. Consider a simplified innovative process. In the first stage, an inventor from country 0 discovers a new technology. He then decides to patent the new technology in certain countries. A patent in country *i* grants him the exclusive right to commercially exploit the invention in that country. Accordingly, the inventor patents his invention in a country *i* if s/he plans to use 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 that 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.[1] In this paper, patents are sorted by priority year.

In this paper we use the number of families as an indicator of the number of inventions and the number of patents invented in country 0 and filed in country

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

i as an indicator of the number of innovations transferred from country 0 to country *i*. This approach has also been used by Lanjouw and Mody (1996) and Eaton and Kortum (1999). Other studies use a slightly different indicator based on patent citations (for instance, see Jaffe, Tratjenberg and Henderson, 1993; Thompson and Fox-Kean, 2005; Peri, 2005). More specifically, they count the number of citations of the patented invention from country 0 in subsequent patents filed in country i. This measures knowledge *externalities* – that is, knowledge that spills over to other inventors. Our indicator differs in that it measures *market-driven* technology transfer.

These patent-based indicators are only imperfect proxies. The first limitation is that patents are only one of the means of protecting innovations, along with lead time, industrial secrecy or purposefully complex specifications (Cohen et al. 2000; Frietsch and Schmoch 2006). In particular, 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 which have not been patented (Dernis and Guellec 2001).

Importantly, 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 the country. Accordingly, patenting is more likely to concern countries with technological capabilities and a strict enforcement of intellectual property rights. In this study we have developed a method which partly controls for this problem.

A further limitation is that a patent grants only the exclusive right to use the technology in a given country. It does not mean that the patent owner will actually do so. This could significantly bias our results if applying for protection does not cost anything, so that inventors might patent widely and indiscriminately. But this is not the case in practice. Patenting is costly – in terms of both the costs of preparation of the application, and the administrative costs and fees associated with the approval procedure (see Helfgott 1993 and Berger 2005 for EPO applications). In addition, possessing a patent in a country is not always in the inventor's interest if that country's enforcement is weak, since the publication of the patent in the local language can increase vulnerability to imitation (see Eaton and Kortum, 1996 and 1999). Finally, infringement litigations usually take place in the country where the technology is commercialized, for this where the alleged damage occurs. Inventors are thus unlikely to incur the cost of patent protection in a country unless they expect a potential market for the technology covered.

However, the fact remains that the value of individual patents is heterogeneous. Moreover, its distribution is skewed: as many patents have very little value, the number of patents does not perfectly reflect the value of innovations. Methods have been developed to mitigate this problem (see Lanjouw et al. 1998), for instance, the use of weights based on the number of times a given patent is cited in subsequent ones. Unfortunately our data do not allow us to implement these methods. Instead, in addition to presenting data on the number of inventions, we also construct statistics for 'high-value inventions' by utilizing data on international patent families (claimed priorities).

3 Data

Over the past several years, the European Patent Office (EPO) along with the OECD's Directorate for Science, Technology and Industry have developed a worldwide patent database – the EPO/OECD World Patent Statistical Database (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) and some national classification systems. In addition to the basic bibliometric and legal data, the database also includes patent descriptions (abstracts) and citation data for some offices. The PATSTAT database has not been exploited much until now for it has become available only recently. Our study is the first to use PATSTAT data pertaining to climate change mitigation.

We have extracted all patent applications filed from 1978 to 2005 in 13 climate-mitigation fields[2]: 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. We also present data on carbon capture & storage (CCS). The precise description of the fields covered by the study can be found in Annex 1. This represents 285,770 patent applications

[2] Applications for utility models are excluded from our search. Utility models are of shorter duration than regular patents and do not require the same inventive step.

filed in 76 countries. On average, climate-related patents included in our data set represent 1% of the total annual number of patents filed worldwide. The number of patent applications by technology field can be found in the Supplementary materials.

Patent applications related to climate change are identified using the International Patent Classification (IPC) codes, developed at the World Intellectual Property Organization (WIPO)[3]. The IPC classes corresponding to the climate mitigation technologies are identified in two alternative ways. First, we search the descriptions of the classes online to find those which are appropriate[4]. Second, using the online international patent database maintained by the European Patent Office[5], we search patent titles and abstracts for relevant keywords. The IPC classes corresponding to the patents that come up are included, provided their description confirms their relevancy. The definitions of the IPC codes used to build the datasets can be found in the Supplementary materials.

When building the data sets, two possible types of error may arise: irrelevant patents may be included or relevant ones left out. The first error happens if an IPC class includes patents that bear no relation to climate

[3] Some previous studies have related patent classes to industrial sectors using concordances (e.g. Jaffe and Palmer 1997). The weaknesses of such an approach are twofold: 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 in the analysis; and, second,, the use of sectoral classifications (and commodity classifications) will result in a bias toward the inclusion of patent applications from sectors that produce explicitly ‘environmental’ goods and services, rather than more integrated innovations. (See OECD 2008 for a full discussion of the relative merits of the approach adopted in this paper.)

[4] The International Patent Classification can be searched for keywords at http://www.wipo.int/tacsy/

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

mitigation. In order to avoid this problem, we carefully examine a sample of patent titles for every IPC class considered for inclusion, and exclude those classes that do not consist only of patents related to climate change mitigation. This is why some key technologies in terms of carbon reduction potential are outside the scope of this study. Important missing technologies include energy efficient technologies in industry, aspects of 'clean' coal technologies, and energy storage.

The second error – relevant inventions are left out – is less problematic. We can reasonably assume that all innovation in a given field behaves in a similar way and hence our datasets can be seen at worst as good proxies of innovative activity in the field considered. However, overall innovative activity may be underestimated and the data sets are very unlikely to be equally inclusive. Therefore totals may be less reliable than trends and cross-technology comparisons throughout the paper are only based on trends.

It is well known among experts in intellectual property rights that the number of patents that is granted for a given innovation varies significantly across countries. A usual illustration is Japan where patent breadth is said to be particularly low. Therefore comparing innovation activity across countries based on crude patent counts can be problematic. This paper offers a unique methodology to address this problem. We examine all international patent families in the PATSTAT database and calculate how many patents correspond to the same invention in every country. Recall that each family corresponds to a particular invention. The examination of international families yields information on the number of patents in the countries where the invention is patented. We use this information to calculate country weights. As an illustration, we find that, on average, seven Japanese patents result in approximately five European patents when filed at the EPO. This means that one EPO patent is equivalent, on average, to 1.4 Japanese patents. We set the weight of applications at the EPO to unity, meaning that the statistics presented below yield the number of 'EPO-equivalent' inventions. The EPO-equivalent country weights for various patent offices are available in Annex 2. The shortcoming of this approach is that while – by definition – we rely on international families to determine the patent breadth coefficients, we use these coefficients to weight both international patent applications and patents filed in only one country. Yet it is possible that these two kinds of patents are designed differently. For example, a Japanese inventor who expects to file a patent both in Japan and abroad may design a "larger" patent that will be readily transferable to foreign patent offices. Our method may thus underestimate the actual patent breadth.

A specific problem concerns patents filed in the US, where until 2000 published data concerned only *granted* patents, while other offices provide data on *applications*. In addition, the inventor's country of residence is not available for some patent applications. An appendix in the Supplementary materials presents details on how we address these problems.

4 Innovation

The geography of innovation

In this section we discuss the level of innovation across countries, and the time trend over the period 1978-2005. Recall that, in our study, an invention corresponds to a patent family. Hence a patent filed in several countries is only counted once.

Where does innovation take place? The PATSTAT database includes information on the country of residence of the inventors for the technologies for which patent protection is sought, independently of the country where applications are filed. We use this indicator to measure country performance.[6] Table 1 displays the main inventor countries between 2000 and 2005. Innovation appears highly concentrated: the top twelve countries account for nearly 90% of the world inventions. Japan, the USA and Germany are the three main inventor countries for most technologies. With 37% of the world's inventions on average, the performance of Japan is particularly impressive. It ranks first in all fields, except in *marine* where it is second. Japan accounts for over 50% of the world's inventions in *electric & hybrid*, *waste,* and *lighting*.[7]

This is consistent with available evidence on R&D activity. In the absence of detailed data on private R&D, available figures on public R&D for low-carbon

[6] 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.

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

technologies[8] confirm the strong leadership of Japan: with $US 220 million spent in 2004, Japan alone outweighs the sum of US and EU15 public R&D spending (respectively $US 70 million and $US 50 million in 2004).

Table 1: Top 12 inventors, with average % of total inventions (2000 - 2005)

Country	Rank	Average % of world's inventions	Average % of world's high-value inventions	Top 3 technologies (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, EU27 countries represent 24% of the world's inventions.
Source: Authors' calculations, based on PATSTAT data

[8] Nuclear not included. Source: Lazarus & Kartha (2007)

Interestingly, the three world's leaders 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). Brazil also figures among the top 12 countries. Other emerging economies lag far behind: Taiwan, India, and Mexico, respectively rank 21, 27 and 29.

This ranking is based on patent counts which do not take into account the quality of the individual innovations generated in the different countries. This might pose a problem as it is well-established that the economic value of individual patents varies greatly. In particular Guellec and van Pottelsberghe (2000) find a significant difference between the value of patents filed in one country ("singulars") and that of patents filed in several countries ("claimed priorities"). We refer to the latter as high-value inventions.

As a way to roughly adjust indicators according to innovation quality, column 4 of Table 1 displays the share of inventions developed by each inventor country that are patented internationally[9]. This significantly changes the overall picture. Germany becomes the world leader (22.2% of world's high-value inventions) while Japan falls dramatically to about 17%. Most importantly, the performance of the emerging economies – in particular China and Russia – becomes far less impressive. They innovate, but their inventions are of relatively

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

minor economic value[10]. This is in line with previous findings by Lanjouw and Mody (1996).

The time trend

Figure 1 presents the evolution of world innovation since 1978. Since the growth of innovation in environmental technologies could reflect a general growth of innovation in all technologies (including non-environmental ones), the graph presents the *share* of climate-related inventions in the number of inventions in all technology areas. The graph also displays the evolution of the price of oil since incentives for innovation related to climate change mitigation are likely to be influenced by energy prices.

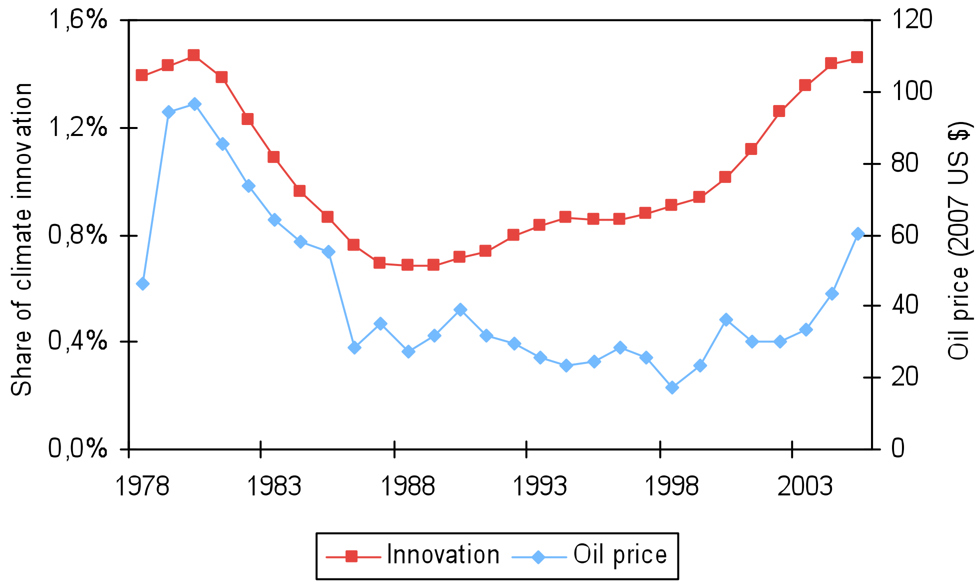
Figure 1 confirms this expectation. Examining carefully the graph, it is nonetheless possible to distinguish two distinct time periods. Until 1990, innovation and the oil price closely mirror each other: in particular, the 1980 innovation peak coincides with the second oil shock. Then, innovation and oil price simultaneously fall before stagnating until 1990. That innovators respond so quickly to changes in energy prices may be surprising, but this has already been well documented in previous research (e.g., Newell et al., 1999; Popp, 2002). One explanation is that many patents cover innovations that have already been developed (and are available "on the shelves") but are not yet profitable. The new market conditions simply make it worthwhile to legally protect them.

[10] This also suggests that they do not export many inventions. We will return to diffusion issues in the next section.

The second period starts in 1990 and is characterized by a decoupling between innovation and oil prices. While innovation steadily increases during the 1990s, oil prices remain relatively stable until 2003. Innovation then rises sharply after 2000 at an average annual growth rate of nine percent during the last five years. This suggests a significant influence of environmental policies and climate policies since the beginning of the 1990s. The post-2000 acceleration could presumably 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: Share of climate-related innovation in total innovation in comparison with oil prices

Source: Authors' calculations, based on PATSTAT data



It is however difficult to derive firm conclusions on the role of policy drivers after 1990 by considering solely aggregate statistics. In order to assess further the role of policy, Table 2 presents the annual growth rate of innovation for different technologies. We distinguish two periods: before and after the acceleration of the pace of innovation observed around 2000. Moreover, we aggregate renewable technologies, assuming they are driven by the same policy regimes.

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

Source: Authors' calculations, based on PATSTAT data

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

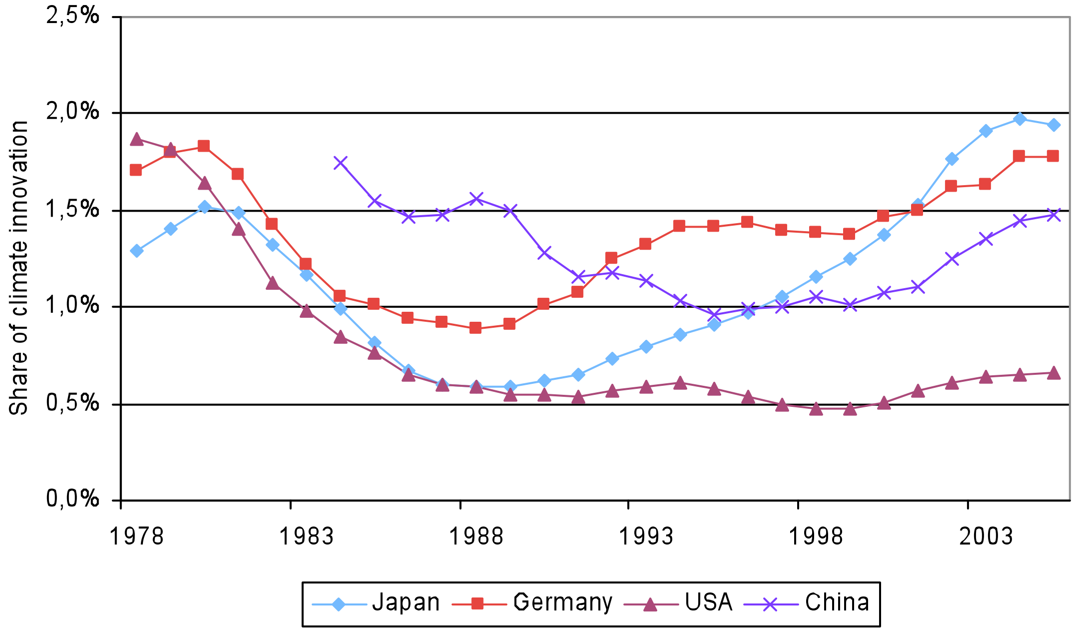
Recall that the overall trend is an increase of innovation which accelerates further in 2000. This trend is driven by a specific sub-set of technologies that are presented in the upper part of the table: *lighting, renewable energy, heating and cement.* In the bottom part, we identify four technologies – *electric & hybrid*, *methane, insulation* and *waste* – which are not in line with the general pattern since the increase mainly occurs before 2000, before the introduction of significant climate policies in certain Kyoto Protocol's Annex I countries. This is probably a consequence of the introduction of other environmental policies previously. For instance, the beginning of the 1990s is marked in the European Union and in Japan by new waste policies, reinforcing regulatory standards for waste disposal. As a result, many new incinerators were built to replace obsolete ones and many landfills were retrofitted. This probably explains the surge of innovation in technologies to produce heat from waste or to collect methane. Similarly, an aggressive market expansion plan for electric and hybrid vehicles was issued by the Japanese METI in 1991. The program is further reinforced in 1997 (Ahman, 2006). In California, the ZEV Mandate is also created in 1991 to increase the percentage of Zero-Emission Vehicles ("ZEV") to be sold in California. This is in line with the impressive growth rate of *electric & hybrid* innovation observed in the 1990s.

Examining individual countries also provides interesting insights. Figure 2 displays the evolution of the top 4 innovating countries. Differences are striking: while Germany and Japan follow the general trend described previously; US innovation efforts have remained stable since the end of the 1980s. The trend of innovation in the US seems to closely follow oil prices, which suggests a limited influence of environmental and climate policies.

China is also a very interesting case. Environmental innovation decreases until the mid-1990s, suggesting that priority was given to non-environmental innovation to foster economic growth at that time. The regime shifts around the year 2000, which could be explained by the emergence of domestic policies to deal with increasing environmental problems. In particular, an important reform of government administration is conducted by the Ninth National People's Congress in 1998 when the environmental protection agency SEPA is upgraded to ministerial status.

Figure 2: Share of climate-related innovation in the top 4 inventing countries

Source: Authors' calculations, based on PATSTAT data. Chinese patent data is not available before 1985.



However, Chinese innovators could also have responded to Kyoto Protocol's Annex I countries' environmental and climate policies. Consider the case of the photovoltaic technology. In this area, China is now the industry leader with 27% of the world production of cells and modules in 2007 (Jäger-Waldau, 2008). This production is almost entirely exported to industrialized countries where the introduction of feed-in tariffs and other support measures have boosted the demand for solar energy (e.g., Germany, Japan, and Spain). These policies are likely to have induced more innovation by Chinese firms

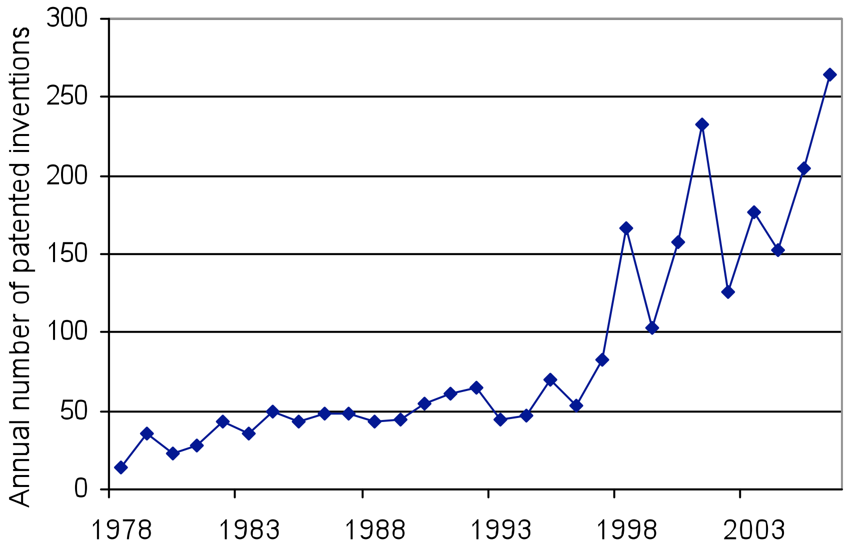
A few studies have provided evidence that environmental regulation might promote innovation both domestically and abroad. Lanjouw and Mody (1996) find evidence that strict vehicles emissions regulations in the US spurred innovation in Japan and Germany, and those foreign inventors responded more to these regulations than US inventors. Popp et al. (2007) find that inventors of chlorine-free technology in the pulp and paper industry respond both to domestic and foreign environmental regulatory pressure.

Box: Innovation and diffusion in Carbon Capture and Storage

Carbon capture and storage (CCS) technology is still at an early development stage[11], and the volume of patenting activity in this field is quite low as compared with other climate friendly technologies. As shown in Figure 3, less than 100 inventions where patented annually at the global scale between 1978 and 1996. The innovation trend however sharply accelerated in 1997, denoting a new interest for this technology. Since then, the average growth rate of innovation has been around 15%, twice as much as in the previous period.

Figure 3: Patented inventions in CCS (1978-2006)

Source: Authors' calculations, based on PATSTAT data



The average export rate of CCS inventions is 20.5% in 2000-2006, significantly above the other climate technologies (15%). This denotes a higher quality of patented inventions, which is consistent with an early stage of technology development.

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

[11] CCS technology is not yet accounted for in international patent classifications. We have therefore used a specific search algorithm to identify CCS patent applications.

5 International technology transfer

The channels of technology diffusion

Before presenting statistics on the diffusion of climate technologies, it is worth explaining briefly how technology moves from one country to another. This question is central to the general economic literature on technology diffusion which identifies three channels (for a good survey, see Keller, 2004).

A first channel 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 this 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. Coe et al. (1997) show that the share of machinery and equipment imports in GDP has a positive effect on total factor productivity of developing countries. In their descriptive paper, Lanjouw and Mody (1996) show that imported equipment is a major source of environmental technology for some countries.

A second channel of international technology diffusion is foreign direct investment. Several papers find evidence that multinational enterprises transfer firm-specific technology to their foreign affiliates (for example, Lee and Mansfield, 1996; Branstetter et al., 2006). A first reason why international companies might generate local spillovers is through labor turnover, if local employees of the subsidiary take up employment in domestic firms, as confirmed empirically by 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 last market channel of technology diffusion—and the most self-evident—is licensing. A firm may license its technology to a company abroad that uses it to upgrade its own production. Data on royalty payments have been mostly used to analyze the impact of stricter patent protection on technology transfer (Smith, 2001; Yang and Maskus, 2001; Branstetter et al., 2006).

Empirical studies suggest that patent protection is relied upon for technology transfers along all three channels—trade, FDI, and licensing—as such transfers raise a risk of leakage and imitation in recipient countries. For this reason, patents can be used to measure direct international technology diffusion.

In our study, we define a transfer as a patent granted to an inventor from a country different from that in which protection is sought, e.g. a patent filed in the US by a German inventor. This indicates a transfer because patenting gives the exclusive right to exploit commercially the technology in the country where the patent is filed. As patenting is costly, the inventor requests protection because s/he has plans to use the technology locally. This approach has been used inter alia by Eaton and Kortum (1996, 1999) and Lanjouw and Mody (1996).[12]

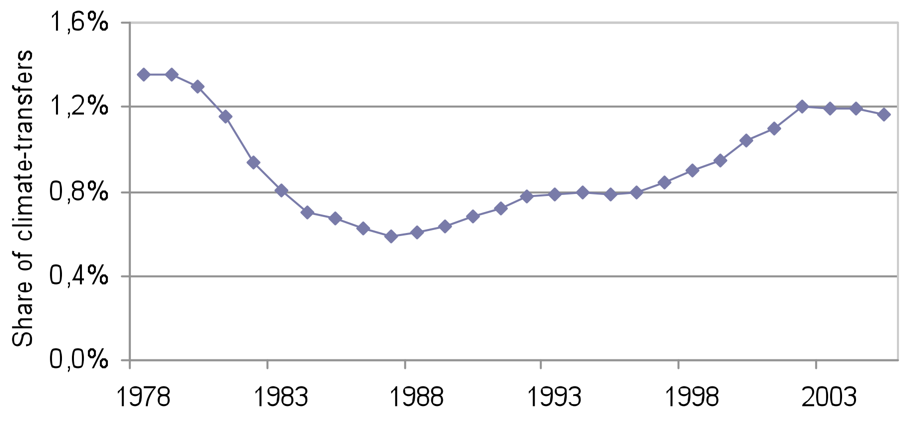
[12] Like ours, these studies use patents to measure *direct* technology diffusion. Another stand of the literature relies on patents as an indicator for international technology *spillovers*. That is, diffusion that occurs out of the market. To do so, they exploit the fact that, when a patent is filed, it must include citations to earlier patents that helped the inventor develop his own invention. Since patents include information about the location of the inventor, patent citations can shed light on the international diffusion of technical knowledge. See the seminal paper by Jaffe et al., 1993.

Empirical evidence

During the 1990's, the number of climate-related patents filed abroad has increased at the average annual rate of 8%. This rapid growth is however not specific to climate-related technology, and rather corresponds to a general increase of international technology transfers over the same period. Considering the share of climate-related transfers in total patent transfers between 1978 and 2005, Figure 10 makes possible to highlight the specific drivers of climate-related technology diffusion. The similarity with Figure 4 on innovation is striking, suggesting that innovation and diffusion are driven by the same factors: energy prices and regulation.

Figure 4: Share of transfers of climate technologies in total tranfers

Source: Authors' calculations, based on PATSTAT data



What are the origins and destinations of these transfers? Table 3 gives the distribution of technology flows between OECD and Non-OECD countries in the period 2000-2005. As a benchmark, the table displays in brackets the same information for all technologies. In both cases, technology is mostly exchanged between industrialized countries (about 75% of total transfer). By contrast, transfers among developing countries are almost non-existent.

Table 3: Origin-Destination matrix giving the distribution of exported climate inventions from 2000 to 2005 (all technologies in brackets)

Source: Authors' calculations, based on PATSTAT data

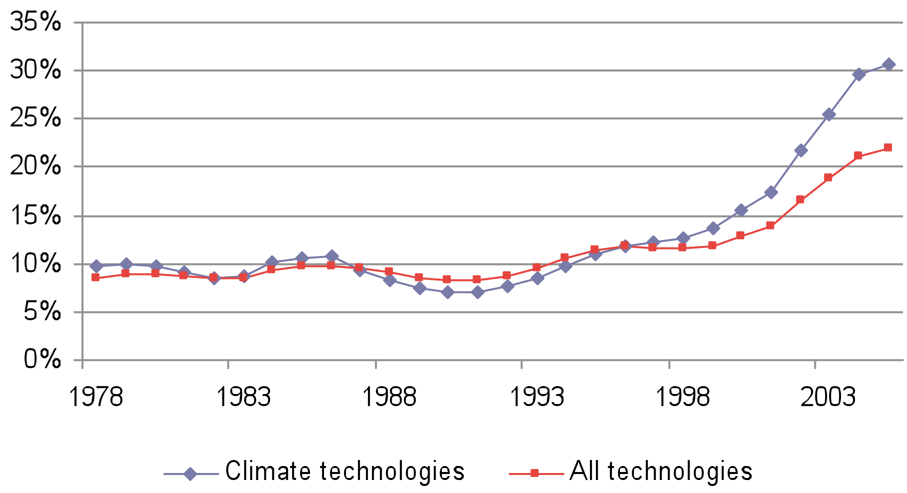
Destination / Origin	OECD	Non-OECD
OECD	73 % (77 %)	22 % (16 %)
Non-OECD	4 % (6 %)	1 % (1 %)

Technology flows from industrialized to emerging economies only represent 22 % of all climate-related transfers. This is however slightly higher than the share (16%) for non-climate technologies. These flows mostly concern fast-growing economies. In particular, China alone attracts about three quarter of the transfers.

Interestingly, this pattern is relatively new. In Figure 5, we depict the share of North-South transfers in total transfers for climate and non-climate technologies. This shows a decoupling around 1998. It is interesting to relate this pattern with that of Figure 2 which shows that innovation in China also started to increase around 1998. This lends support to our claim that Chinese environmental policies have already created a domestic demand for climate-friendly technologies.

Figure 5: Share of technology flows from OECD to non-OECD countries in total flows, 1978-2005.

Source: Authors' calculations, based on PATSTAT data



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. At 15% for the 2000-2005 period, this rate is slightly lower in climate-related technologies than in other technologies (17%). Calculated at the country level, it reveals significant differences.

Table 4 displays the export performance of the 12 main inventor countries. With export rates ranging between 40% and 90%, countries in Europe and North America are the world leaders in technology exports. This probably reflects the success of economic integration in the EU and ALENA areas as many of these transfers occur between their member countries. By contrast, Korea, Japan and Australia have poor performances in terms of exports. This is especially striking in the case of Japan, which is the leader in climate-related innovation but fails to diffuse its technology abroad.

Table 4 also indicates that the good innovation performance of China, Russia and Brazil is not reflected in their export rates. The average value of inventions in emerging countries is probably low, a point previously made.

Note that the export rate of patents also varies across technologies. With more than 30% of inventions transferred, the most international technologies are *lighting*, *wind power*, and *electric and hybrid vehicles*. To the contrary, *waste*, *biomass* and *hydro* are more localized. Interestingly, the propensity of technologies to be exported is not correlated with the share of inventions developed by emerging countries in each technology, suggesting that technology-specific factors are determinant.

Table 4: Export rate of inventions by inventor country (2000-2005)

Source: Authors' calculations, based on PATSTAT data

Inventor country	Export rate 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%

Policy discussion

Evidence suggests that transfer of climate-related innovation to emerging countries has increased in recent years. How can we further accelerate this diffusion? Our data do not allow us to investigate the potential of different policy tools to do so. But interesting insights are available in the economic literature on technology diffusion.

Regulation is a first obvious factor that fosters the creation of markets for environmentally-sound technologies and provides an incentive for firms to acquire new technologies (Less & McMillan, 2005). Since industrialized countries have more advanced environmental and climate regulations, it should thus be no surprise that they also attract more technology transfer. In this respect, our data already suggests that domestic regulation may have spurred inward technology flows in China in the recent period. In other works, it has been established that strict vehicle emissions regulations in the US led for example to the transfer of up-to-date technology from Japan and Germany into the US (Lanjouw and Mody, 1996). The adoption of tighter regulations in the pulp and paper industry in Finland and Sweden has similarly triggered an increase in patent applications on chlorine-free technology filed by US inventors in these countries (Popp et al., 2007).

But the lack of strict environmental and climate legislation in developing countries is clearly not the only explaining factor as our data indicate a similar pattern of low diffusion to the South for all technologies. Therefore, general factors such as trade openness, the IPR system and local absorptive capacities also explain why technology diffusion in concentrated in industrialized countries.

Since technology transfers take place through market channels such as trade, FDI or licenses, they are more frequent 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 responds in turn to an adequate business environment, including governance and economic institutions (Maskus, 2004).

Whether stronger IPR can foster the transfer of climate technology in developing countries is a controversial issue. As IPRs confer legal exclusivity, they may reduce competition and raise price barriers to technology transfer in developing countries. Several case studies however 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.

To 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 competitors (Maskus, 2000; Smith, 2001; Hoekman et al. 2005; Mancusi, 2008; Parello, 2008). For the same reason, stronger protection encourages the use of FDI and licenses, which induce more technology transfer than the mere export of equipment goods (Smith, 2001).

Since the positive effect of IPR depends on the threat of local imitation, it mostly concerns 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 level of domestic human capital increases 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 encompass shortage of skilled technical personnel, 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 in promoting North-South technology transfer.

7 Conclusion

In this paper we use the PATSTAT database to identify and analyze patented inventions in 13 climate-related technology classes between 1978 and 2005. This allows us to draw conclusions concerning the dynamics and distribution of innovation, and the international transfer of technology.

We show that innovation in climate change technologies is highly concentrated in three countries, namely Japan, Germany and the USA, which accounts for 60 % of total climate innovations in our data set. The performance of Japan is particularly impressive as it ranks first in twelve technology fields out of 13. On average it accounts for 37 % of worldwide patented inventions.

Surprisingly, the innovation performance of certain emerging economies is far from being negligible as China, South Korea and Russia are respectively the fourth, fifth and sixth largest innovators. Together, they represent about 17 % of global inventions. However, their inventions are probably of relatively minor economic value as suggested by the low percentage of inventions patented abroad.

Statistics suggest that innovation was mostly driven by energy prices until 1990. Since then, environmental policies and climate policies have seemingly induced more innovation. The pace of innovation has accelerated since 2000 with an average annual growth rate of nine percent. Differences between countries are however striking. US innovation has been stable since the end of the 1980s and seems almost exclusively driven by energy prices. In contrast, Germany or Japan exhibits a very significant influence of public policies since the beginning of the 1990s.

The issue of international technology transfer is currently high on the political agenda. Our statistics show little specificities of climate-related technologies as compared to others: export rates—measured by the share of inventions that are patented in at least two countries—are similar. International transfers mostly occur between developed countries (73% of exported inventions). Exports from developed countries to emerging economies are still limited (22%). The only detectable specificity is that north-south transfers of climate technologies are growing more rapidly.

This suggests a huge potential for the development of North-South transfers. Moreover, although China, Russia and South Korea are major innovators, flows between emerging economies are almost non-existent. Accordingly, there also exists a huge potential for South-South exchanges—particularly given that these countries may have developed technologies that are better tailored to the needs of developing countries. In this regards, the economic literature suggests different policy tools: the development of environmental regulation in the South, removing trade barriers and relaxing constraints on foreign direct investments. It also stresses the positive role of Intellectual Property Rights in countries where sufficient technological capabilities create a risk of imitation.

In conclusion, it is useful to recall certain limitations of our analysis. The main shortcoming is probably that, although they are the only data available on a global scale, patents are imperfect proxies of innovation and technology transfer. Furthermore, the work is mostly descriptive in that it does not seek to explain the drivers of innovation and technology transfer. In this regards, it would be very relevant to complement this study with econometric analyses. This is left for future research.

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Annex 1. Description of the technology fields covered

Technology field	Description of aspects covered
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 CO2.
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.

Annex 2. 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 of priorities included in each 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

IPC Codes for Selected Climate Change Mitigation Technologies

Renewable energy technologies

WIND POWER	
Wind motors	F03D
SOLAR ENERGY	
Devices for producing mechanical power from solar energy	F03G6
Use of solar heat, e.g. solar heat collectors	F24J2
Drying solid materials or objects by processes involving the application of heat by radiation - e.g. from the sun	F26B3/28
Devices consisting of a plurality of semiconductor components sensitive to infra-red radiation, light – specially adapted for the conversion of the energy of such radiation into electrical energy	H01L27/142
Semiconductor devices sensitive to infra-red radiation, light, electromagnetic radiation of shorter wavelength, or corpuscular radiation, specially adapted as devices for the conversion of the energy of such radiation into electrical energy, including a panel or array of photoelectric cells, e.g. solar cells	H01L31/042-058
Generators in which light radiation is directly converted into electrical energy	H02N6
GEOTHERMAL ENERGY	
Devices for producing mechanical power from geothermal energy	F03G4
Production or use of heat, not derived from combustion – using geothermal heat	F24J3/08
MARINE ENERGY	
Tide or wave power plants	E02B9/08
Submerged units incorporating electric generators or motors characterized by using wave or tide energy	F03B13/10-26
Ocean thermal energy conversion	F03G7/05
HYDRO POWER	
Water-power plants; Layout, construction or equipment, methods of, or apparatus for AND NOT Tide or wave power plants	E02B9 and not E02B9/08
Machines or engines for liquids of reaction type; Water wheels; Power stations or aggregates of water-storage type; Machine or engine aggregates in dams or the like; Controlling machines or engines for liquids; AND NOT Submerged units incorporating electric generators or motors characterized by using wave or tide energy	[F03B3 or F03B7 or F03B13/06-08 or F03B15] and not F03B13/10-26
BIOMASS ENERGY	
Solid fuels based on materials of non-mineral origin - animal or vegetable substances	C10L5/42-44
Engines or plants operating on gaseous fuels from solid fuel - e.g. wood	F02B43/08
WASTE-TO-ENERGY	
Solid fuels based on materials of non-material origin - sewage, town, or house refuse; industrial residues or waste materials	C10L5/46-48

Incineration of waste - recuperation of heat	F23G5/46
Incinerators or other apparatus consuming waste - field organic waste	F23G7/10
Liquid carbonaceous fuels; Gaseous fuels; Solid fuels; AND Dumping solid waste; Destroying solid waste or transforming solid waste into something useful or harmless; Incineration of waste; Incinerator constructions; Incinerators or other apparatus specially adapted for consuming specific waste or low grade fuels, e.g. chemicals.	[C10L1 or C10L3 or C10L5] and [B09B1 or B09B3 or F23G5 or F23G7]
Plants for converting heat or fluid energy into mechanical energy – use of waste heat; Profiting from waste heat of combustion engines; Machines, plant, or systems, using particular sources of energy – using waste heat. AND Incineration of waste; Incinerator constructions; Incinerators or other apparatus specially adapted for consuming specific waste or low grade fuels.	[F01K27 or F02G5 or F25B27/02] and [F23G5 or F23G7]

Motor vehicle technologies

ELECTRIC & HYBRID VEHICLES	
Dynamic electric regenerative braking for vehicles	B60L7/10-20
Electric propulsion with power supply from force of nature, e.g. sun, wind	B60L8
Electric propulsion with power supplied within the vehicle	B60L11
Methods, circuits, or devices for controlling the traction- motor speed of electrically-propelled vehicles	B60L15
Arrangement or mounting of electrical propulsion units	B60K1
Arrangement or mounting of plural diverse prime-movers for mutual or common propulsion, e.g. hybrid propulsion systems comprising electric motors and internal combustion engines	B60K6
Arrangements in connection with power supply from force of nature, e.g. sun, wind	B60K16
Electric circuits for supply of electrical power to vehicle subsystems characterized by the use of electrical cells or batteries	B60R16/033
Arrangement of batteries in vehicles	B60R16/04
Supplying batteries to, or removing batteries from, vehicles	B60S5/06
Conjoint control of vehicle sub-units of different type or different function; including control of energy storage means for electrical energy, e.g. batteries or capacitors	B60W10/26
Conjoint control of vehicle sub-units of different type or different function; including control of fuel cells	B60W10/28
Control systems specially adapted for hybrid vehicles, i.e. vehicles having two or more prime movers of more than one type, e.g. electrical and internal combustion motors, all used for propulsion of the vehicle	B60W20

Energy efficiency in the residential, commercial, and industrial sectors (selected aspects)

INSULATION	
Insulation or other protection; Elements or use of specified material for that purpose	E04B1/62
Heat, sound or noise insulation, absorption, or reflection; Other building methods affording favorable thermal or acoustical conditions, e.g. accumulating of heat within walls	E04B1/74-78
Insulating elements for both heat and sound	E04B1/88
Units comprising two or more parallel glass or like panes in spaced relationship, the panes being permanently secured together	E06B3/66-677
Wing frames not characterized by the manner of movement, specially adapted for double glazing	E06B3/24
HEATING	

Hot-water central heating systems - in combination with systems for domestic hot-water supply	F24D3/08
Hot-water central heating systems **-** using heat pumps	F24D3/18
Hot-air central heating systems **-** using heat pumps	F24D5/12
Central heating systems using heat accumulated in storage masses - using heat pumps	F24D11/02
Other domestic- or space-heating systems - using heat pumps	F24D15/04
Domestic hot-water supply systems - using heat pumps	F24D17/02
Use of energy recovery systems in air conditioning, ventilation or screening	F24F12
Combined heating and refrigeration systems, e.g. operating alternately or simultaneously	F25B29
Heat pumps	F25B30
LIGHTING	
Gas- or vapor-discharge lamps (Compact Fluorescent Lamp)	H01J61
Electroluminescent light sources (LED)	H05B33
CEMENT MANUFACTURING	
Natural pozzuolana cements	C04B7/12-13
Cements containing slag	C04B7/14-21
Iron ore cements	C04B7/22
Cements from oil shales, residues or waste other than slag	C04B7/24-30
Calcium sulfate cements	C04B11

Other climate-change relevant technologies

METHANE CAPTURE	
Anaerobic treatment of sludge ; Production of methane by such processes	C02F 11/04
Biological treatment of water, waste water, or sewage: Anaerobic digestion processes	C02F 3/28
Apparatus with means for collecting fermentation gases, e.g. methane	C12M 1/107

Miscellaneous data issues

USPTO grants

Up until 2000, the data published by the US Patent and Trademark Office (USPTO) included only those patent applications that were eventually granted, whereas all other offices provide data on applications as well. Therefore, the number of applications filed at the USPTO prior to 2001 needs to be extrapolated, based on other available information. Specifically, the number of US singulars and the share of international families including a US member are multiplied by the yearly ratio of applications filed at the USPTO over granted patents (the inverse of the approval rate of applications). These figures are provided online by the USPTO[13]. For example, 65% of applications were granted in 1978. Consequently, the number of singular US applications and the share of international families including a US member were multiplied by 1.52 for the year 1978.

Missing inventor countries

For 35% of the patent applications included in our data set, the inventor's country of residence is not available. Since the filing of a patent in multiple offices raises the probability of this information being available, this problem almost only concerns patents filed in a single patent office[14]. Yet, patents filed in a single office are usually filed by local inventors. This is the so-called "home-bias" in patent applications. Therefore we simply assume that the inventor country corresponds to the priority office when the information is missing.

Since this methodology may underestimate filings by foreign inventors, we tried another methodology as a robustness check. Assuming that the sub-sample of patents with no information on the inventor's country is randomly drawn from the overall sample of priorities filed in the same patent office, we attribute these patents proportionally to inventor countries on the basis of the average proportion for the same technology field in the same patent office. This average is calculated on the basis of the actual distribution of

[13] http://www.uspto.gov/go/taf/us_stat.htm
[14] 99% of missing inventor countries concern patents filed in a single patent office

inventor countries for priority applications between 1978 and 2005[15]. For example, the distribution of the main inventor countries for wind power priority applications filed at the German Patent Office is the following:

Inventor country	**Share of patents**
Germany	92.2 %
USA	1.6 %
Denmark	1.5 %
Others	4.7 %

This distribution was used to attribute inventor countries to wind power patents filed at the German patent office when this information was missing.

Because of the home bias, this second methodology affects only priority applications first filed in a different country from that of the inventor's, which represent 1.9% of the patents in the data set. Therefore both methodologies yields very similar results. We adopt the first methodology in the paper for the sake of simplicity.

[15] Due to the small size of some samples, calculating the *annual* average distribution of inventor countries would introduce a bigger bias than calculating the 1978-2005 average.