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Invention and International Diffusion of Climate Change Mitigation Technologies: An Empirical Approach

par

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Thèse

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Contents

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Preface

This dissertation deals with innovation activities in climate change mitigation technologies and their international diffusion. In order to contribute to the literature on this subject, we construct and analyze two unique data sets. We present five empirical papers based on these data sets for this dissertation:

- **Research paper 1: Invention and Transfer of Climate Change Mitigation Technologies on a Global Scale: A Study Drawing on Patent Data**, 2009. Commissioned by the *Review of Environmental Economics and Policy* (joint with Matthieu Glachant, Nick Johnstone, Ivan Hascic and Yann Ménière)
- **Research paper 2: What Drives the International Transfer of Climate Change Mitigation Technologies? Empirical Evidence from Patent Data**, 2009. Submitted to the *Journal of Environmental Economics and Management* (joint with Matthieu Glachant and Yann Ménière).
- **Research paper 3: Does foreign regulation influence domestic inventors? The case of renewable energy innovation**, 2009. CERNA Working Paper
- **Research paper 4: The Clean Development Mechanism and the international diffusion of technologies: an empirical study**, 2008. *Energy Policy* 36, 1273–1283 (joint with Matthieu Glachant and Yann Ménière).
- **Research paper 5: Technology transfer by CDM projects: a comparison of Brazil, China, India and Mexico**, 2009. *Energy Policy* 37, 703-711 (joint with Matthieu Glachant and Yann Ménière).

These papers deal with the same research topic and share a common methodological approach. However, each paper puts forward distinct research questions and can be read on its own.

We start this dissertation with a short preliminary chapter that outlines the research topic and the general methodology. The structure of the document is presented in more detail in the third section of this introduction. The five following chapters are based on the research papers presented above.

Introduction

1 Policy context and research question

According to the IEA Energy Technology Perspectives 2008, global greenhouse gas (GHG) emissions under a business as usual scenario are expected to increase by 130% between 2008 and 2050, from 27 Gt CO_2-eq to 62 Gt CO_2-eq. A rise of such magnitude could raise global average temperatures by 6°C in 2100 relative to pre-industrial levels, far above the commonly accepted level of "tolerable" warming of 2°C. The Intergovernmental Panel on Climate Change (IPCC) recommends that carbon emissions be reduced by 50% to 85% by 2050 from current levels in order to limit the rise in temperatures between 2°C and 2.4°C.

Reaching this objective requires a massive deployment of low carbon technologies, including renewable energies, nuclear power, energy efficiency technologies and carbon capture and sequestration (CCS). According to the IEA's scenario, achieving a 50% cut in CO_2 emissions in 2050 with respect to current level would require the *annual* deployment of—among other—32 nuclear power plants, 14,000 wind turbines, 215 million m^2 solar panels and 35 coal-fired power plants with carbon capture. By comparison, only 2 nuclear power plants were constructed in 2006 (while 8 plants were dismantled) and there is currently no commercial plant with CCS operating at all. Under this scenario, additional investment amounts for $1,100 billion every year, while around $100 billion only were invested in clean energy projects in 2007 (World Economic Forum, 2009). The development and deployment of climate-related technologies are therefore a priority for climate change mitigation policies.

In addition, achieving global emission reductions will not be possible if large emitters from the developing world are not involved in the process. Indeed, more than 75% of the growth in CO_2 emissions until 2050 is expected to come from developing countries, with India and China alone accounting for 50%. Yet, most low-carbon technologies have so far been developed and used in the North. OECD countries represent 82% of global R&D expenditures in 2000, with the US and Japan alone accounting for 50% (National Science Board, 2006). An examination of patents filed in 13 climate-related technologies shows that Japan, Germany and the USA represent two thirds of worldwide innovation (Dechezleprêtre *et al.*, 2009). For this reason, technology transfer to developing countries is at the heart of current discussions about the post-Kyoto agreement.

Against this background, the first objective of this dissertation is to provide an accurate and up-to-date description of innovation in low carbon technologies and of their international diffusion at a global scale. The debates surrounding future climate policy usually presuppose the need to accelerate technology transfer. Yet, little is known about the actual extent of diffusion as well as about the geography of innovation. We seek to shed light on these issues. In a context of growing tension between Northern and Southern countries on future GHG abatement commitments, providing the climate community with objective data is of great importance.

The second objective of this dissertation is to analyze the factors that promote or hinder the international diffusion of climate-friendly technologies. Our descriptive work shows that some countries benefit more from technology transfers than others. Do these countries have higher technology absorptive capacities? Do they suffer from weak patent protection? We provide answers to these questions. This allows us to determine how national and international policy measures can enhance technology diffusion, especially towards developing countries. In particular, we discuss the implications of these findings for the next international climate agreement.

The third research direction—tackled in the third paper presented in this dissertation—investigates the links between international technology diffusion and innovation. There is empirical evidence in the literature that inventors respond to stricter regulation by increasing their innovation effort. However, previous studies only link innovation with *domestic* regulation. Given the degree of technology diffusion between countries, an interesting question is whether they also respond to stricter foreign regulation. If the answer is in the affirmative, overlooking this important aspect of the data might have led previous empirical studies to overestimate the effect of regulation on domestic innovative activities.

2 Methodological approach

In this dissertation, we adopt an empirical approach to address these questions. We construct to unique data sets, which we analyze in turn. The first includes about 300,000 patents protecting climate-related technologies. The second consists in about 650 GHG abatement projects set up under the Clean Development Mechanism.

In order to build the first data set, we use the World Patent Statistical Database (PATSTAT), recently developed by the European Patent Office (EPO) along with the OECD. PATSTAT is unique in that it covers more than 80 patent offices and contains over 70 million patent documents. It is updated bi-annually. PATSTAT data have not been exploited much until now for they became available only recently and require processing of the raw data before analysis can be carried out.

Patent documents are categorized using the international patent classification (IPC) system. We have identified the IPC classes pertaining to 13 climate mitigation technologies, allowing us to extract patents in these fields from the database. These technologies include seven renewable energy technologies (wind, solar, geothermal, ocean energy, biomass, waste-to-energy, and hydropower), methane destruction, climate-friendly cement, energy conservation in buildings, motor vehicle fuel injection, energy-efficient lighting and carbon capture & storage (CCS). These technologies were selected based on their mitigation potential. Together they represent nearly 50% of all GHG abatement opportunities beyond business as usual until 2030—excluding forestry—identified by McKinsey & Co (see Enkvist et al., 2007).

We have extracted all patents filed worldwide in these 13 climate change mitigation technologies since 1978. Because patents are granted by national patent offices, inventors must file a patent in each country in which they seek protection. Using an international patent database allows us to identify all countries in which a single innovation is patented[1]. Therefore our data set

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[1] Least developed countries are not included in the database, but their patenting activity is very limited.

provides an extensive picture of innovation activities in these technologies and of the market-driven technology flows between countries.

We use this data set to provide descriptive statistics about the geographic distribution of climate mitigation inventions on a global scale. We complement this data with country level data and use panel data analysis to analyze the determinants of cross-border diffusion of climate-friendly technologies. We use similar econometric techniques to look for evidence of cross-border induced innovation.

Patent data have a number of limitations. First, not all inventions are patented. In particular, certain forms of knowledge, such as know-how or learning-by-doing, are not patentable. Secondly, patenting is more likely in countries that have strong technological capabilities and that strictly enforce intellectual property rights. For these reasons, patent data might overlook some important aspects of international technology diffusion, especially North-South transfer. The analysis of CDM projects overcomes some of these limitations.

The second data set consists of 644 GHG abatement projects set up under the Kyoto protocol's Clean Development Mechanism (CDM) up until May 2007. The CDM allows industrialized countries which have ratified the Kyoto Protocol to develop and implement projects that reduce GHG emissions in non-Annex I countries in exchange for emission reduction credits.[2] For anyone who is interested in technology transfer in the context of climate change mitigation, the Clean Development Mechanism is a naturally attractive research area. First, the

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[2] Non-Annex I countries have also ratified the Kyoto Protocol but do not have any emissions reduction targets. This group has 148 members and is mainly comprised of developing countries. Large GHG emitters such as China, India, Brazil or Mexico belong to this group.

CDM is explicitly expected to promote North-South technology transfer (UNFCCC 2001). Indeed, if the technology used in a project is not available in the host country but must be imported, the project leads, de facto, to a technology transfer. Secondly, the CDM involves a large number of projects (for which most of the data is easily available) aiming at reducing GHG emissions, using a large array of technologies in various sectors and countries. For this reason, the CDM lends itself very well to empirical analysis.

Information about the CDM projects can be found in Project Design Documents (PDD), available online. They are mandatory standardized documents of about 50 pages submitted to the Executive Board by the project developers for registration. The Guidelines for completing the PDD indicate that the document "should include a description of how environmentally safe and sound technology, and know-how to be used, is transferred to the host Party(ies)." However, this is not a compulsory requirement, and no section is specifically devoted to technology transfer. Therefore, we have read carefully all the PDDs in order to get relevant information about technology transfer.

We use this unique data set to examine whether the CDM encourages technology transfer. We complement project-level data with country-level data and use discrete choice models to analyze the factors promoting technology transfer in CDM projects.

3 Structure of the document

The dissertation has two parts and five chapters. We use the patent data set in the first part (chapters 1, 2 and 3) and the CDM projects data set in the second part (chapters 4 and 5).

The first three papers are based on our data set including all patents filed worldwide between 1978 and 2006 in 13 climate change mitigation technologies.

Research paper 1

This paper gives a quantitative description of the geographic distribution of inventions and of their international diffusion on a global scale. The data suggest that the Kyoto Protocol has induced more innovation in low carbon technologies. However, there is no visible effect of the protocol on international technology transfer. We show that innovation is highly concentrated in three countries—Japan, Germany and the USA—which account for two thirds of total innovations. The innovation performance of emerging economies is very significant as China, South Korea and Russia globally represent about 15% of total inventions. However, they export much less than industrialized countries. International technology transfers mostly occur between developed countries (75% of exported inventions). Exports from developed countries to emerging economies are still limited (18%) but are growing rapidly.

Research paper 2

In this paper, we develop a structural model of technology diffusion and use patent data from 66 countries for the period 1990-2003 in order to characterize the factors that promote or hinder the international diffusion of climate-friendly technologies. To the best of our knowledge, this work is the first econometric study using patent data to analyze specifically the diffusion of climate change mitigation technologies at a global level. Regression results show that the domestic knowledge stock of the recipient countries is a determinant factor. In contrast, the general level of education is less important. We also show that restrictions to international trade—e.g., high tariff rates—and lax intellectual property regimes negatively influence the international diffusion of patented knowledge. Surprisingly, we find that barriers to foreign direct investment can promote technology transfer. We discuss different possible interpretations.

Research paper 3

This paper focuses on the consequences of technology diffusion on innovation. We examine the influence of domestic and foreign regulation on innovation activity in four renewable energy technologies, using patent data from 72 countries from 1990 to 2005. We use data on the growth of installed power capacities to measure the level of pro-renewable regulations in a country. There is empirical evidence that inventors respond to domestic environmental regulation by increasing their innovation effort. We confirm this finding and find strong evidence that innovation also responds to foreign regulation. This work reports evidence of cross-border induced innovation and shows that previous literature on induced innovation might have overstated the influence of domestic regulation on innovation. This result also has important implications for global climate policies.

Research paper 4

In this paper, we use our data set including all CDM projects registered up to May 2007 to provide an assessment of the technology transfers that take place through the CDM. We show that North-South transfers of climate-friendly technologies take place in 43% of CDM projects. Technology transfers mainly concern the end-of-pipe destruction of non-CO_2 greenhouse gas (such as HFCs, CH_4 and N_2O) and wind turbines. Most projects include the transfer of knowledge and operating skills, allowing project implementers to appropriate the technology. We use econometric analysis in order to characterize the drivers of technology transfer. We show that transfer likeliness increases with the size of the projects. The transfer probability is 50% higher if the project is implemented in a subsidiary of a company located in an Annex 1 country while credit buyers also have a positive impact. The analysis also yields interesting results on how technological capabilities of the host country influence technology diffusion in the CDM.

Research paper 5

In the last paper, we use the same data and similar econometric models to explain inter-country differences. We focus on Brazil, China, India, and Mexico. Together, these countries gather about 75% of the CDM projects. 68% of Mexican projects include an international transfer of technology. The rates are, respectively, 12%, 40% and 59% for India, Brazil and China. Our results show that transfers to Mexico and Brazil are mainly related to the strong involvement of foreign partners and good technological capabilities. In contrast, the lower rate of international transfer in India may be due to a better capability to diffuse domestic technologies.

We conclude this dissertation by summarizing the results of the five papers and discussing some implications of these findings for policy makers.

Part 1

Empirical analyses based on patent data

Research paper 1

Invention and Transfer of Climate Change Mitigation Technologies on a Global Scale: A Study Drawing on Patent Data[3]

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 agreement. The 2007 Bali Road Map cites technology development and diffusion as strategic objectives, thereby inciting a debate on appropriate policies.

This debate is difficult in various respects. Environment-friendly technologies have been developed mostly in industrialized countries, but are urgently required to mitigate GHG emissions in fast-growing emerging economies. Ensuring their

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[3] This chapter is based on the following article: Dechezleprêtre, A., Glachant, M., Hascic, I., Johnstone, N., Ménière, Y. (2009). Invention and Transfer of Climate Change Mitigation Technologies on a Global Scale: A Study Drawing on Patent Data, commissioned by the *Review of Environmental Economics and Policy.*

global diffusion thus implies considerable policy and economic challenges because developing countries are reluctant to bear the financial costs of catching up alone, while firms in industrialized countries refuse to give away strategic intellectual assets. The problem is compounded by the lack of information. In the absence of a clear, widespread understanding of what constitutes a 'climate change mitigation technology', and also of how such technologies are diffused in the world, reaching consensus is a daunting task.

Against this background, the purpose of this paper is to shed light on the geographic distribution of climate mitigation inventions on a global scale. Using a worldwide patent database, 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 2003. More precisely, we consider seven renewable energy technologies (wind, solar, geothermal, ocean energy, biomass, waste-to-energy, and hydropower), methane destruction, climate-friendly cement, energy conservation in buildings, motor vehicle fuel injection, energy-efficient lighting and 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 such as clean coal technologies or electric vehicles due to data constraints. The technologies included in our data set 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.

The literature on the development and transfer of non-environmental technologies is extensive. They usually rely on patent data from OECD countries, especially from the USA. Eaton and Kortum (1996, 1999) use patent data from five leading economies to estimate the effect of international technology flows on domestic productivity. They find that research performed in the US and Japan together account for two thirds of the growth in Germany, France and the UK. Co (2002) studies the evolution of innovative activity across US States in 42 industrial sectors between 1963 and 1997. She finds that patent-lagging regions catch up with patent leaders and that knowledge diffusion between States is a significant determinant of patent growth. Note that whereas few studies use patents to measure direct technology diffusion, many papers use patent citations as an indicator for international technology spillovers (see for example Peri, 2005).

A different line of research investigates how patenting influences innovation and diffusion in an international context. In particular, it seeks to analyze the impacts of the TRIPS agreement which has reinforced intellectual property rights. Among other results, this literature highlights 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 (Maskus, 2000; Smith, 2001; Maskus et al., 2004; Mancusi, 2008; Parello, 2008). Barton

(2007) discusses from a legal perspective whether strong intellectual property rights in emerging economies would hinder or promote the transfer of renewable energy technology. He finds that patent issues could be a barrier for the transfer of solar PV technologies, but not for wind power and biofuels, because production is less concentrated in these two sectors.

As compared to the literature dealing with non-environmental technologies, the number of studies focusing on environmental technologies is much more limited. A few papers focus on the role of environmental regulation in the development and diffusion of climate-related technologies (see for example Popp, 2006; Popp et al., 2007). Johnstone et al. (2008) analyze the effects of policy and market factors on innovation with respect to renewable energy technologies in IEA countries. In a recent paper, Verdolini and Gazeotti (2009) analyze international knowledge flows and foreign R&D spillovers in energy-efficient technologies.

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-mitigation technologies at global level. A paper by Lanjouw and Mody (1996) is the most closely related to our work. These authors analyze patents protecting environmentally responsive technologies 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. However, they do not focus on climate change mitigation technologies. Moreover, the data in this paper are more recent and cover more countries.

In this paper we advance well beyond this work. We use the EPO/OECD World Patent Statistical Database (PATSTAT) which includes patents from 81 national and international patent offices. This allows us—contrary to most studies focusing on a single patent office—to conduct a global analysis of innovative activity, including patents filed in developing countries. Moreover, it is the first time that indicators are constructed so 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.

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 2003, across different countries and technologies. Section 5 analyzes the international transfer of technologies. A final section summarizes the main results.

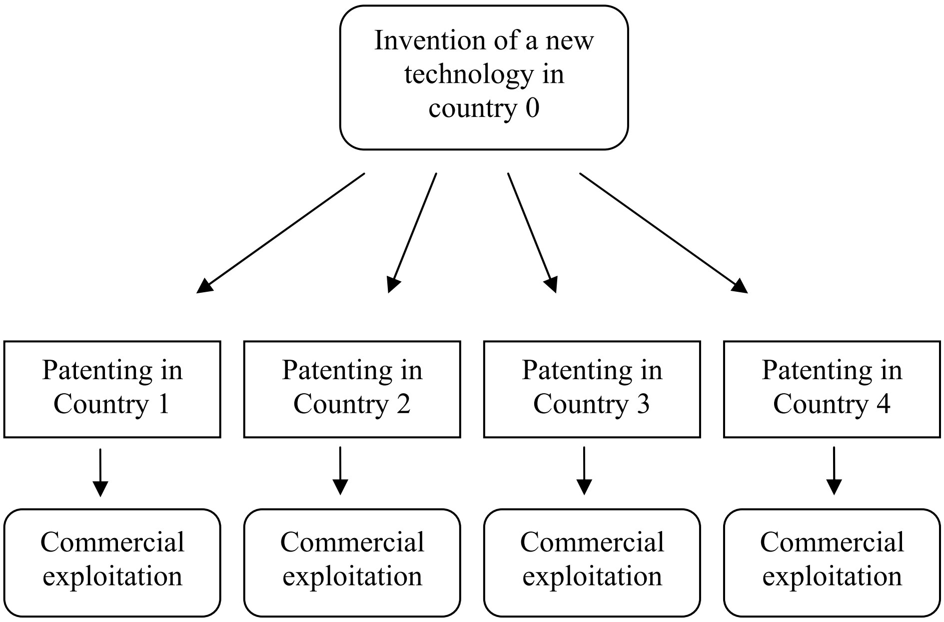
2 Patents as indicators of innovation and technology transfer

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. Figure 1 depicts 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 innovation in that country. Accordingly, the inventor patents his invention in a country i if 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).

Figure 1. The innovative process



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 *i* as an indicator of the number of innovations transferred from country 0 to country *i*.

These 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). Moreover, if enforcement is weak, the publication of the patent in the local language can increase vulnerability to imitation (see Eaton and Kortum, 1995 and 1999). Therefore, inventors are unlikely to apply for patent protection in a country unless they are relatively certain of the 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.

3 Data description

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 70 million patent documents. It is updated bi-annually. Patent documents are categorized using the international patent classification (IPC) and national classification systems. In addition to the basic bibliometric and legal data, the database also includes patent descriptions (abstracts) and harmonized citation data. PATSTAT data have not been exploited much until now for they became available only recently. Our study is the first to use PATSTAT data pertaining to climate change mitigation.

We have extracted all the patents filed from 1978 to 2003 in 13 climate-mitigation fields[4]: 6 renewable energy technologies (wind, solar, geothermal, ocean energy, biomass and hydropower), waste use and recovery, methane destruction, climate-friendly cement, energy conservation in buildings, motor vehicle fuel injection, energy-efficient lighting and carbon capture & storage (CCS). The

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[4] Two types of patent are excluded from our search: utility models and design applications. Utility models are of shorter duration than regular patents and do not require the same inventive step. Registered designs protect only the appearance of products, for example the look of a computer monitor.

precise description of the fields covered by the study can be found in Table 1. This represents 273,900 patent applications 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.

Patent applications related to climate change are identified using the International Patent Classification (IPC) codes, developed at the World Intellectual Property Organization (WIPO)[5]. 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[6]. Second, using the online international patent database maintained by the European Patent Office[7], 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.

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[5] 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. This is important when studying specifically "environmental" technology because in this case the demand (users of technology) and supply (inventors of technology) of environmental innovation may involve different entities. Often, "environmental" innovations originate in industries which are not specifically environmental in their focus. On the other hand, some "environmental" industries invent technologies which are widely applicable in non-environmental sectors (e.g. processes for separation of waste; separation of vapors and gases). More fundamentally, the use of sectoral classifications (and commodity classifications) will result in a bias toward the inclusion of patent applications from sectors that produce environmental goods and services. By contrast, the application-based nature of the patent classification systems allows for a richer characterization of relevant technologies. (See OECD 2008 for a full discussion of the relative merits of the approach adopted for this report.)

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

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

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 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 key technologies in terms of carbon reduction potential are outside the scope of this study. Important missing technologies include electric vehicles, energy efficient technologies in industry, or clean coal technologies.

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 totals may be less reliable than trends.

The definitions of the IPC codes used to build the datasets can be found in Annex 1. The number of applications by technology field can be found in Annex 2.

We also deal with the issue of patent breadth. 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. We address this problem by examining international patent families. Recall that each family corresponds to a particular innovation. The study of international families yields information on the number of patents in the countries where the innovation is patented. We use this information to calculate country weights. As an illustration, we found 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 3.

Other specific problems concern patents in the US, where until 2000 published data concerned only *granted* patents, while other offices provide data on *applications*. Patent counts in Europe also involve specific difficulties because of the procedural specificities of the European Patent System. Finally, the inventor's country of residence is not available for some patent applications. Annex 4 presents details on how we treat these problems.

Table 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).
Buildings	Elements or materials used for heat insulation; double-glazed windows; energy recovery systems in air conditioning or ventilation.
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.
Fuel injection	Motor fuel-injection apparatus (allowing reduced fuel consumption)

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.
Ocean	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 waste; 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.

4 Descriptive statistics on innovation

In this section we discuss the level of innovation outputs across technologies and countries, and the time trend over the period 1978-2003.

4.1 General figures

The average number of inventions is about 7,300 per year in the last 6 years of our dataset (1998-2003). The innovation trend since 1978 is depicted in Figure 2. As a benchmark, we also represent the evolution of the annual number of inventions in all sectors. The graph clearly shows that while the trend for climate-friendly technologies was little different than that for technologies overall until the end of the nineties, the growth rate after this point is much higher than the rate for technologies overall. This suggests a significant influence of climate change policies since the signing of the Kyoto protocol in 1997.

The fact that the protocol seems to have affected innovation so rapidly, although it was ratified as recently as 2002 by the European Union and its Member States, is not that surprising. First, it is well documented that innovators react swiftly to policy changes and the adoption of the protocol clearly sent a strong signal to the private sector. Secondly, many countries took early action, passing laws and adopting regulations as if Kyoto was already ratified, well before it actually was. For example, climate policies had already been implemented in the European Union in the early 1990s.

Figure 2: Innovation trend in climate technologies* compared to all sectors

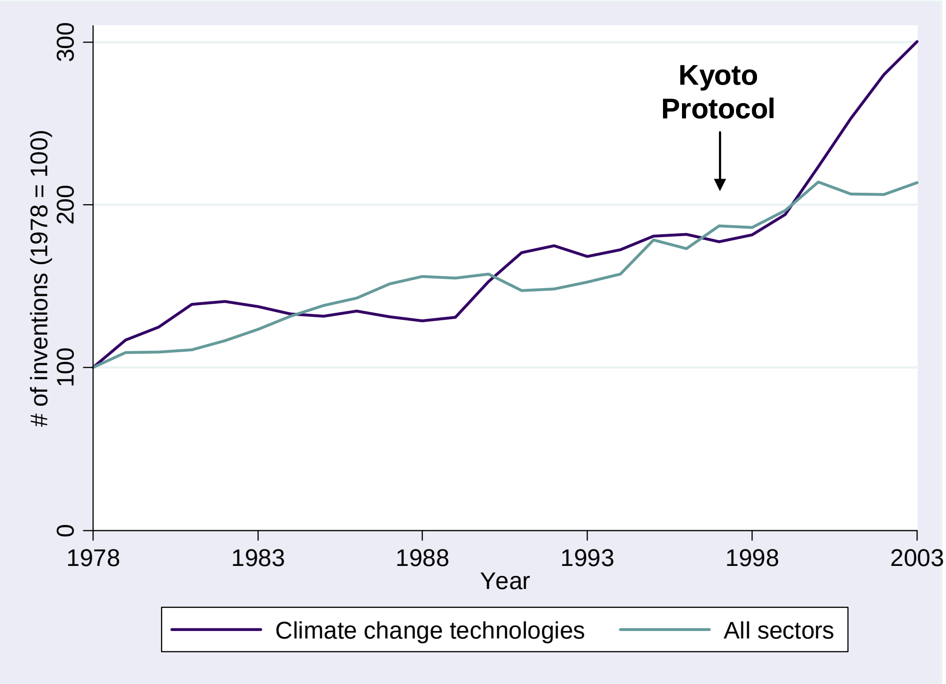
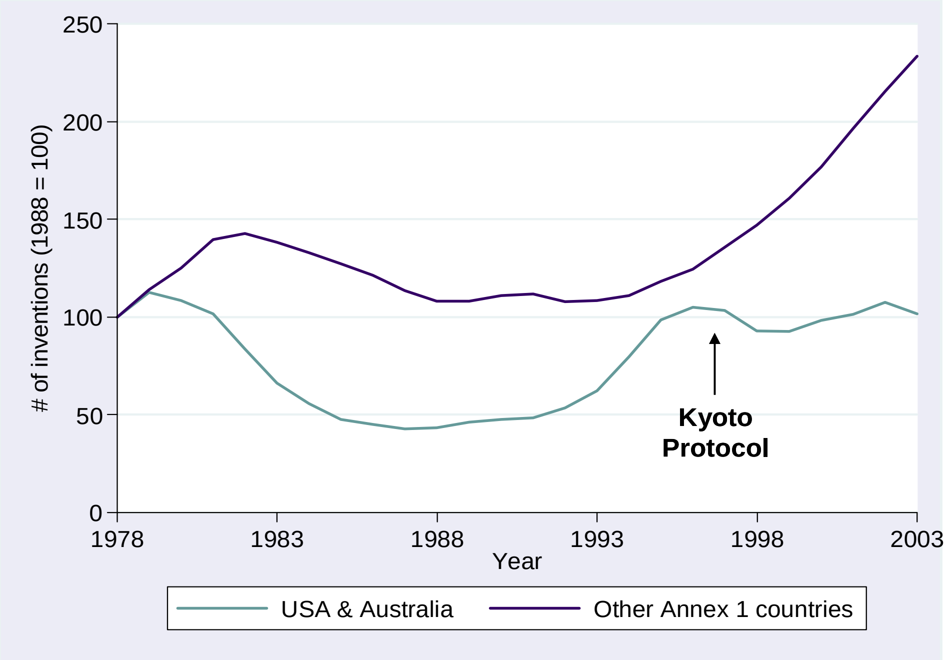
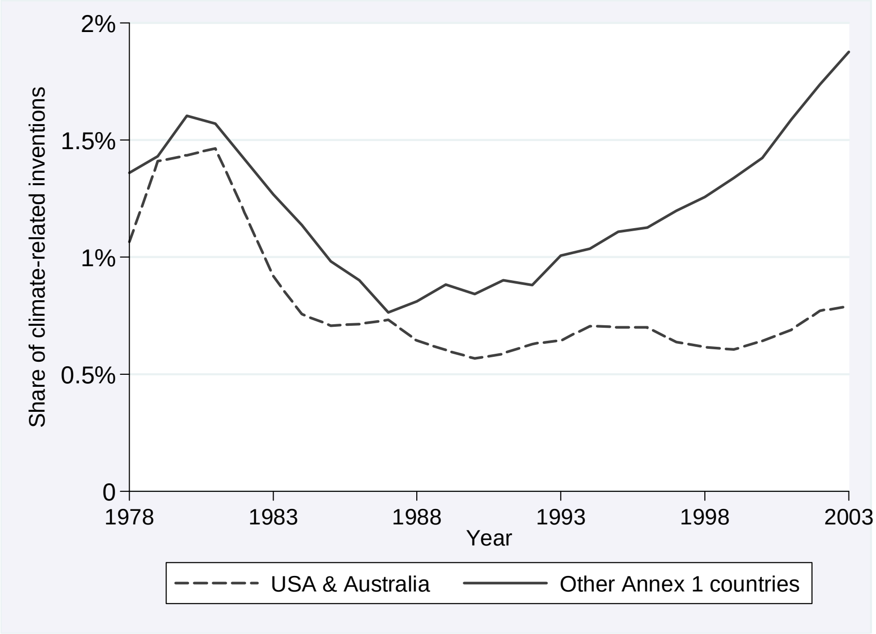


Figure 3: Innovation trend in Annex 1 countries



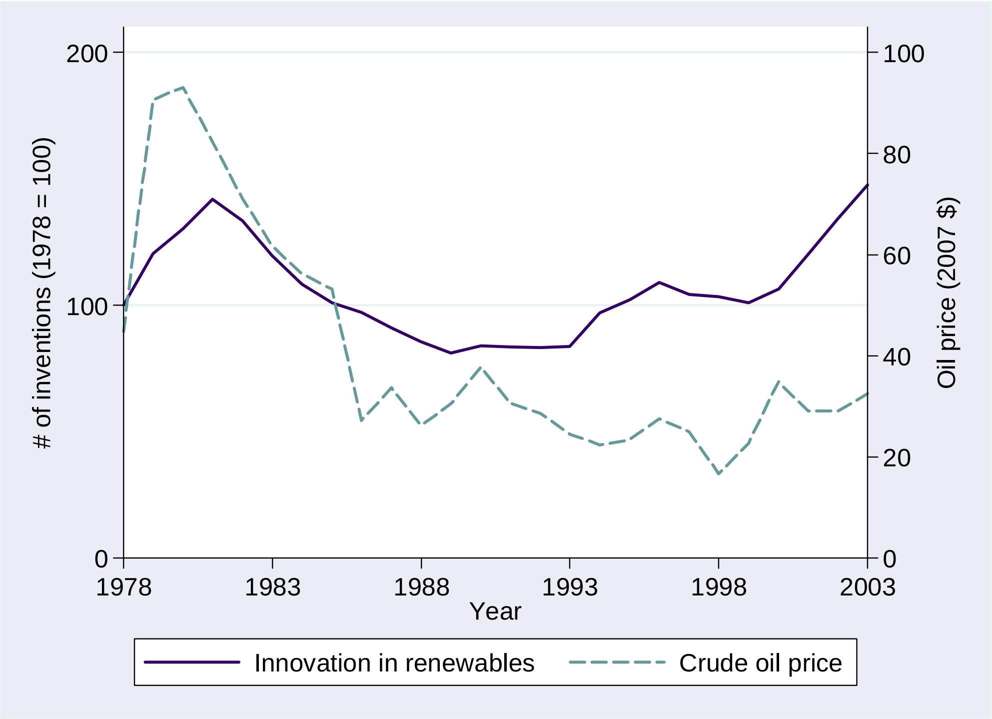
This influence of the protocol is also suggested by Figure 3 which compares innovation performance of Annex 1 countries, which have ratified the Kyoto protocol, with the USA and Australia, which have not (until very recently as regards Australia). On this graph, each patent is counted according to the inventor's country of residence. The good performance of Annex 1 Kyoto signatories could reflect a general growth of innovation in all technologies (including non-environmental ones) driven by other factors. However, Figure 4 invalidates this hypothesis: the graph presents the share of climate-related patents in the total number of inventions patented by inventors from the USA and Australia on the one hand and from other Annex 1 countries on the other hand and it shows the same difference between the two sets of countries. The Kyoto protocol seemingly increased innovation activities in the countries that ratified it.

Figure 4: Share of climate-related inventions in Annex 1 countries



In specific areas, the evolution of oil prices seems to have had a significant influence. As shown in Figure 5, this is the case of renewable energies. Note that the level of innovation in 2003 just equals the early 1980s record high in this area.

Figure 5: Innovation in renewable energy technologies between 1978 and 2003, in comparison with oil prices

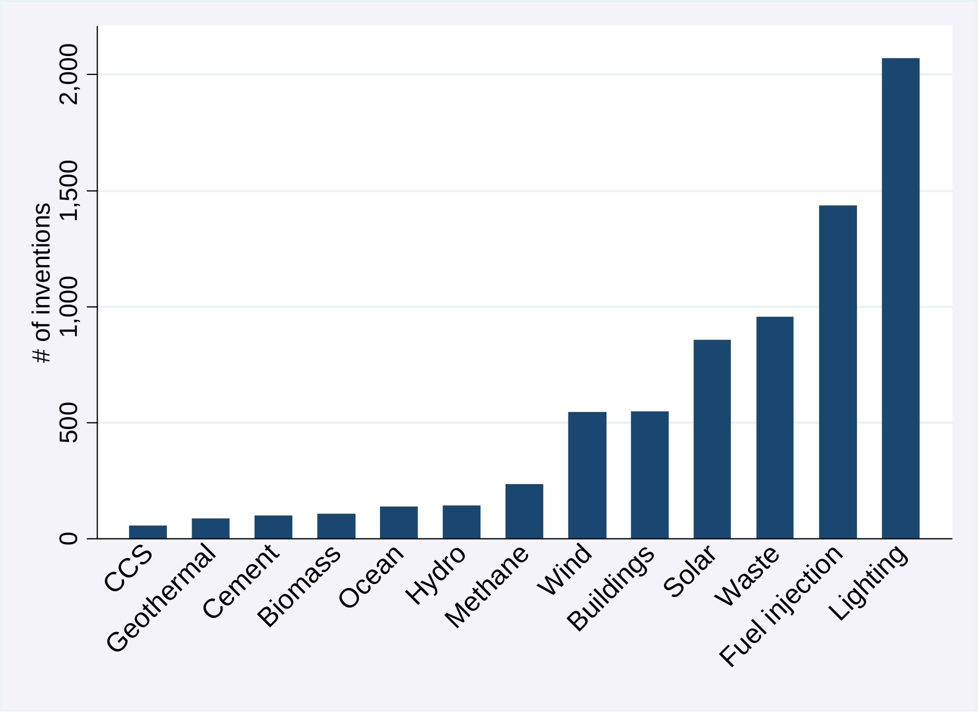


4.2 Innovation by technology

We now consider the different technology classes. Recall that patent breadth varies across sectors and that we have controlled only for cross-country heterogeneity. As a result, observed differences between technologies may reflect differences either in patent breadth or in innovation outputs.

Keeping this important limitation in mind, Figure 6 below shows that the recent level of innovation output differs widely across technologies. *Lighting* and *fuel injection* are clearly dominant, with about 2,000 and 1,500 inventions per year, respectively. This corresponds to large R&D-intensive industries where patents are perceived as an efficient means of protection (Cohen et al. 2000). By contrast, *CCS*, *geothermal*, *cement*, *biomass*, *ocean*, *hydro* and *methane* have fewer than 500 inventions per year over the same period. This group is heterogeneous. *Biomass*, *hydropower* and *geothermal energy* have already reached maturity whereas *ocean energy* and *CCS* are currently in the early development stages.

Figure 6: Average number of annual patented inventions 1998-2003, by technology



What about trends since 1978? To answer the question, we have used as a benchmark the growth of inventions that are technologically similar to the technology classes of interest, without necessarily being related to the environment. The sectoral benchmarks reflect the growth of patenting activity in electricity production, motor vehicles, buildings, cement and lighting. The IPC codes that we used for these benchmarks can be found in Annex 5.

Table 2 shows the difference between the growth rate of innovation for each technology between 1978 and 2003, and the growth rate in the sectoral benchmarks. Carbon capture and storage is a new field with very few inventions and is treated separately.

Innovative activity in climate-change related technologies increased faster than in the corresponding benchmark in 5 fields out of 12. The growth of innovation is particularly strong in *lighting*, *waste*, *wind*, *biomass* and *methane*, whereas it is weak in the *ocean*, *solar*, *hydro* and *geothermal* classes. This result could be expected in the case of mature technologies such as *hydro* and *geothermal,* but is more surprising in the case of *solar* and *ocean.* Interestingly, the growth of innovation in *fuel injection* systems is also lower than that of the motor vehicle sector as a whole.

The evolution of all technology fields between 1978 and 2003 is shown in Annex 6.

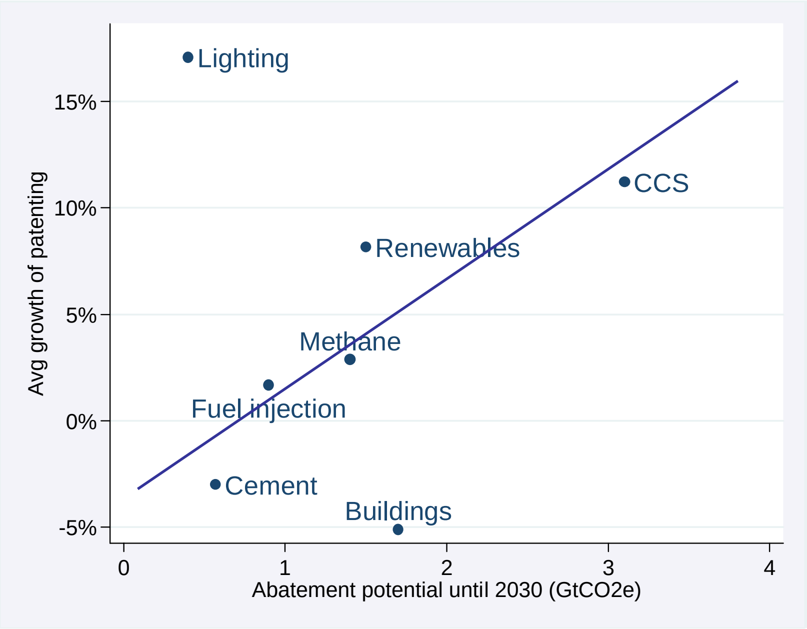
Table 2: Growth of innovation by technology between 1978 and 2003, in comparison with relevant benchmarks

Technology	Growth 1978-2003	Growth of associated benchmark 1978-2003	Difference in growth rates (percentage pts)
Biomass	+ 134%	+40%	+94
Buildings	+50%	+77%	-27
Cement	-14%	+46%	-60
Fuel injection	+174%	+226%	-52
Geothermal	+32%	+40%	-8
Hydro	-5%	+40%	-45
Lighting	+609%	+283%	+326
Methane	+253%	+114%	+139
Ocean	-29%	+40%	-69
Solar	-25%	+40%	-65
Waste	+760%	+114%	+646
Wind	+231%	+40%	+190

Are these innovation efforts in line with future needs? Figures 7 relates the average level of patenting in the recent period to the potential of abatement by 2030, i.e. the quantity of GHG emissions that can be avoided at the global level at a cost below 40 €/tCO2e. This graph suggests that innovation is in line with future abatement potential However, the graph highlights the specificity of *lighting* on the one hand and of *buildings* on the other. It suggests that innovation would be too limited in the *buildings insulation* sector.

Figure 7: Average annual growth rate of patenting 1998-2003

and global GHG abatement opportunities up to 2030



Note: abatement potential until 2030 with a cost below 40 €/ton of avoided CO2e emissions

Source: McKinsey / Vattenfall analysis & authors' calculations

4.3 Leading inventor countries

Where do innovations take place? The PATSTAT database includes information on the country of residence of patent applicants, independently of the country where applications are filed. We use this indicator to measure the performance of inventor countries.[8]

Table 3 displays the main inventor countries between 1998 and 2003. Japan, the USA and Germany are the three main inventors in most technologies (details

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[8] 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.

on the top 3 inventors for each technology can be found in Annex 7). With more than 40% of the world's inventions on average, the performance of Japan is particularly impressive. It ranks first in all fields, except in *biomass* where it is second. In terms of percentage, Japan accounts for over 50% of the world's innovations in *methane*, *waste* and *lighting*.

Table 3: Top 10 inventors, with average % of total inventions (1998 - 2003)

Country	**Rank**	**Average % of world inventions**	**Most important technology classes (decreasing order)**
Japan	1	40.8 %	All technologies
USA	2	12.8 %	Wind, solar, hydro, methane, buildings
Germany	3	12.7 %	Biomass, Ocean, Waste, CCS, wind, solar
China	4	5.8 %	Cement, geothermal, solar, hydro, methane
South Korea	5	4.6 %	Lighting, ocean, hydro, biomass, cement
Russia	6	4.2 %	Geothermal, cement, hydro, CCS, ocean
France	7	2.4 %	Cement, CCS, buildings, biomass, hydro
UK	8	1.9 %	Ocean, biomass, wind, methane
Canada	9	1.5 %	Hydro, wind, CCS, ocean
Brazil	10	1.1 %	Ocean, building

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 technologies[9] 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).

Interestingly, the three world's leaders are followed by China, South Korea and Russia. Surprisingly, some emerging countries are already major innovators. As shown in Annex 7, these countries have strong positions in particular fields, namely *geothermal* and *cement* (China and Russia), *biomass* (South Korea) and *CCS* (Russia).

Together, EU27 countries represent 24% of innovation.

Table 3 suggests that the production of innovation in climate-related technologies is strongly concentrated in a limited number of inventor countries. For a more synthetic view, we calculate an index based on the countries' shares in the world patented inventions. The index is equal to:

$$H = \sum_{i=1}^{n} s_i^2$$

where s_i is the share of inventions patented by country i, and n is the number of countries. This index is directly adapted from the so-called Herfindahl-Hirschman Index (HHI) which is commonly used by antitrust authorities to measure the concentration in markets. Above 0.2, it characterizes a strong concentration; below 0.1, it denotes a weak concentration.

Table 4 presents this index for each technology. We have used the standard threshold of 0.2 to sort out the technology classes for which innovation is highly

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

concentrated. This approach highlights contrasting degrees of concentration across technologies.

Table 4: Spatial concentration of innovation for each technology (1998 - 2003)

Strong concentration	**Index**	**Mild concentration**	**Index**
Lighting	0.437	Cement	0.198
Waste	0.428	Hydro	0.170
Methane	0.303	Geothermal	0.164
CCS	0.294	Biomass	0.148
Fuel injection	0.285	Wind	0.137
Buildings	0.260	Ocean	0.085
Solar	0.228		

Interestingly, technology classes exhibiting a high concentration index also seem to be those with the highest innovation outputs. Figure 8 represents the concentration index as a function of the volume of innovation and confirms this positive correlation. This suggests the existence of specialization gains which enable certain countries to benefit from comparative advantages in certain technology fields.

4.4 A focus on Carbon Capture and Storage

Given the potentially huge importance of CCS in the medium term, we consider it relevant to dedicate a specific subsection to these technologies. Identifying patent applications related to carbon capture and storage is difficult since there is no IPC code corresponding precisely to CCS inventions. However, IPC class B01D53 includes inventions relative to "chemical or biological purification of waste gases". We extracted all patents belonging to the

B01D53/62 sub-class which concerns carbon oxides, and identified patents dealing specifically with carbon dioxide. To this data set we added patents found through a keyword search on titles—thus biased towards patents published in English. We searched for titles mentioning "capture", "storage" or "sequestration" together with "CO_2" or "carbon dioxide". This dataset is a good proxy of innovative activity in CCS.

Figure 8: Concentration indices as a function of the annual innovation flow by technology

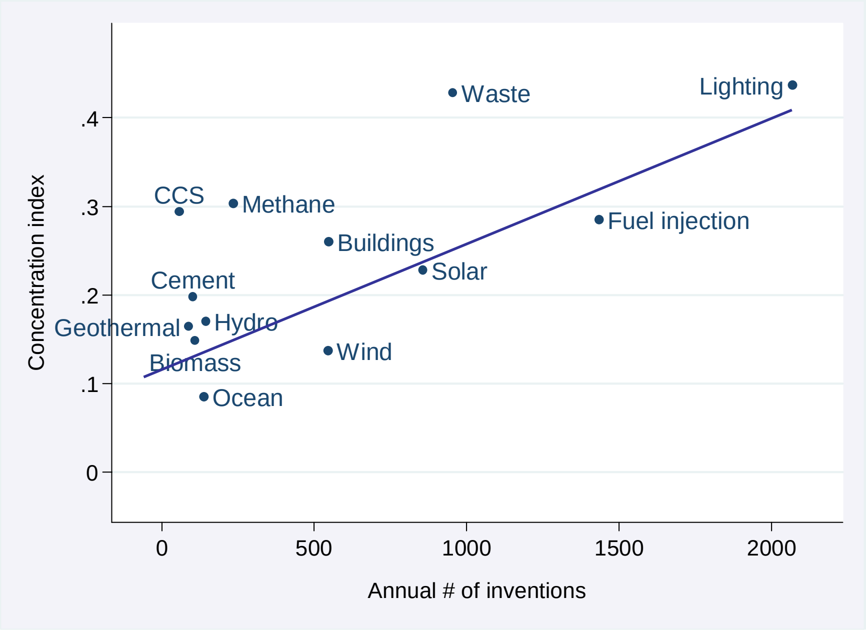
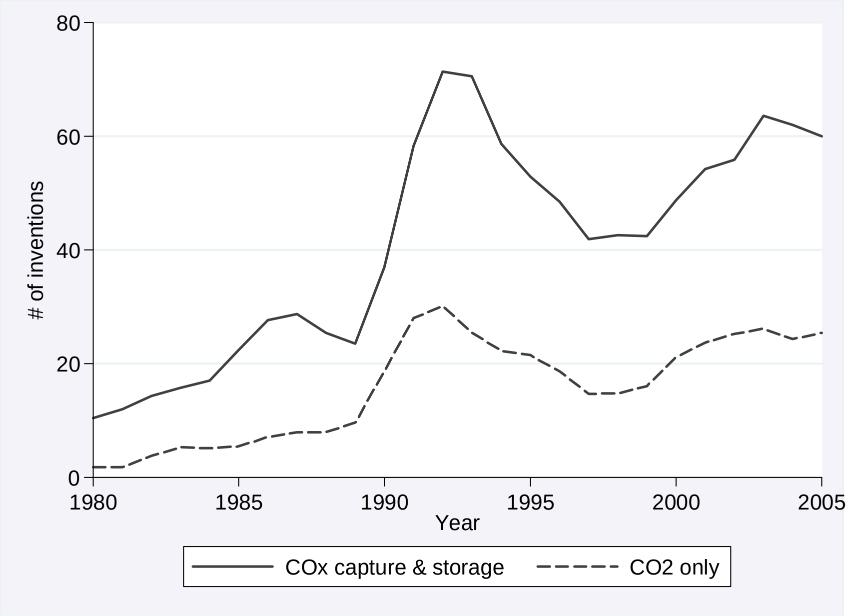


Figure 9 displays the number of yearly inventions in CCS technologies from 1980 to 2005. The solid line includes all patents in the data set and the dashed line includes only patents specifically dealing with CO2. Surprisingly, the annual number of inventions increased steeply in the late 1980s, reaching a peak in 1992, before falling for about 5 years. Since 1997 the level of innovation has been increasing gradually, but in 2005 it was still below the 1992 record high. According to our data set, between only 25 and 60 inventions sought legal protection in 2005.

Figure 9. Patented innovation in carbon capture & storage, 1980-2005



Note that we probably underestimate the actual rate of innovation, since many inventions designed to isolate, transport and store gases are likely to have potential applications for CO_2. However, our data shows that there are still very few inventions with specific CO_2 capture & storage applications.

Between 2000 and 2005, Japan accounted for over half of these inventions, followed by the US, which has been particularly active in the late 1990s and early 2000s. Other countries such as France, Russia and UK are also starting to emerge as significant sources of invention.

4.5 A focus on emerging economies

We have already seen that certain emerging countries—China, Russia, and South Korea in particular—are performing well in certain areas (*geothermal*, *cement*, *biomass*). Apart from these countries, what is the overall picture? Table 5 displays statistics on selected emerging countries.[10] It clearly shows that China, South Korea and Russia are the only significant innovators in this group of countries.

Table 5: Averages of the share of world innovations in each technology field for selected emerging economies (1998-2003)

	World rank	**Average % of world inventions.**	**Most important technology classes (decreasing order)**
China	4	5.8 %	Cement, geothermal, solar, hydro, methane
South Korea	5	4.6 %	Lighting, ocean, hydro, biomass, cement
Russia	6	4.2 %	Geothermal, cement, hydro, CCS, ocean
Brazil	10	1.1 %	Ocean, building
Taiwan	18	0.6 %	Ocean, lighting
India	30	0.2 %	Cement
Mexico	34	0.1%	Ocean
South Africa	53	0.03%	

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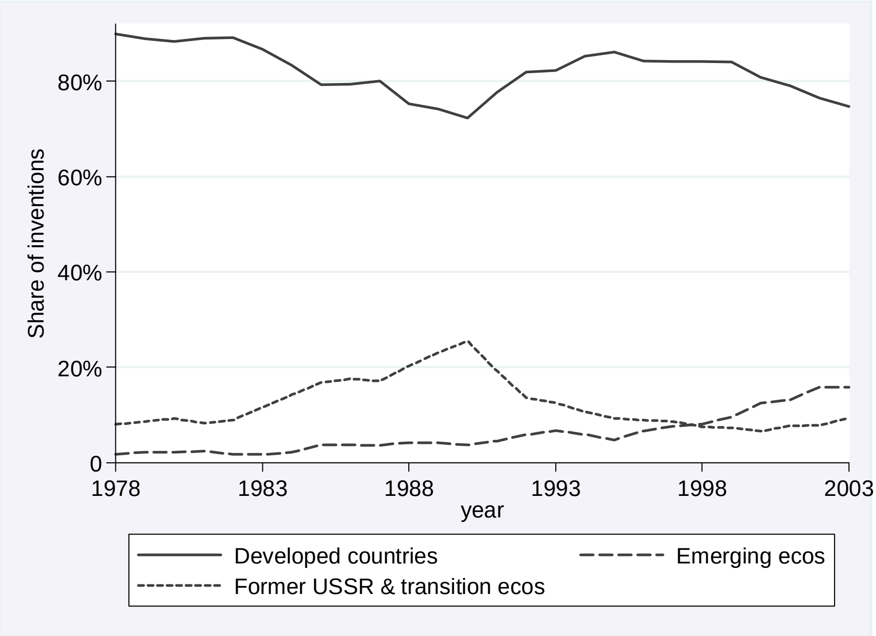
[10] Note that Least Developed Countries are not present in our dataset, for two related reasons: their patenting activity is extremely limited, and available statistics are not reliable.

Emerging countries accounted for 16.3% of patented climate-friendly innovations in 2003. As shown in Figure 10, this is the result of a continuous increase which accelerated in the mid-nineties. Between 1997 and 2003, the share of inventions patented by emerging countries grew at an average annual rate of 18%. Additional figures on the growth of innovation in emerging countries for each technology field can be found in Annex 9.

The case of the former USSR and the transition economies is also very interesting. Before 1990, the Soviet Union and its satellite countries were steadily catching up with developed countries. Their innovative output then fell dramatically after the collapse of the Soviet Union.

Figure 10: Share of inventions by inventor country groups (1978 - 2003)



The list of countries included in each group can be found in Annex 8.

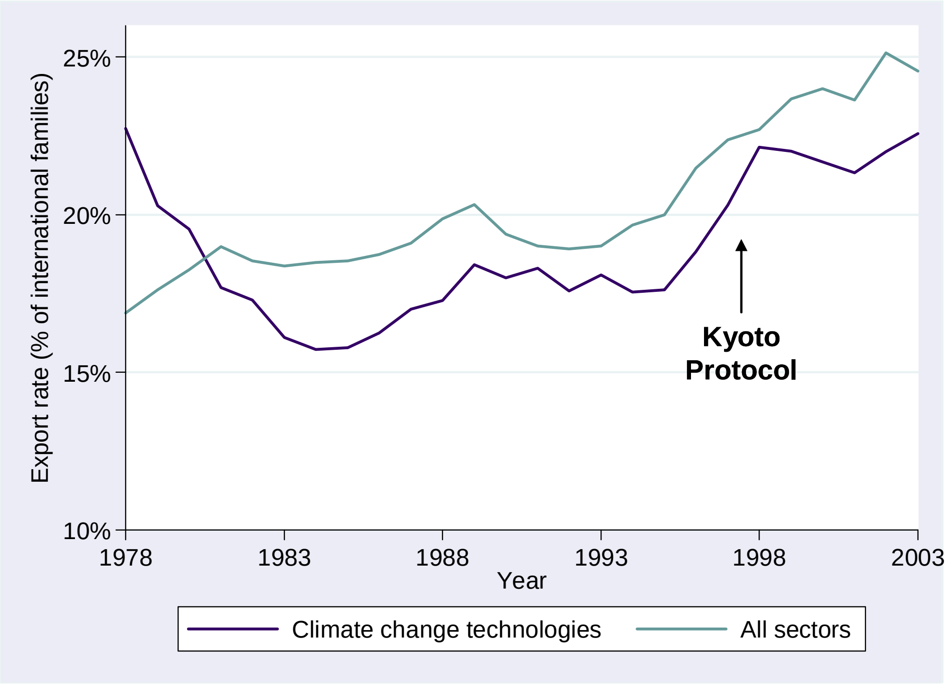
5 International technology transfer

We now study where inventions are used and in particular whether they cross national borders. International patent families provide interesting indicators of the international transfer of technologies. Inventors who want to enter markets in foreign countries usually seek patent protection in these countries for their most valuable innovations. We use the proportion of international families—the share of inventions that are patented in at least two countries—to measure the degree of internalization of markets for technology. At the country level, a large share of international families among inventions developed by domestic inventors denotes a good performance in terms of technology exports.

Figure 11 shows the export rate of climate change technologies between 1978 and 2003. As a benchmark we report in the same graph the evolution for all technologies. The export rate varied significantly over the period. It decreased sharply between 1978 and 1984—possibly after a peak due to the 1979 oil crisis which temporarily increased the international demand for energy-efficient technologies—and then increased until 2003.

Although this trend marks a real progression of technology internationalization since 1983—from 16% of inventions to 23% in 2003—, the export rate in 2003 only equals its 1978 value. This sounds very modest. However, the graph shows that it is not that much lower than the rate for all technologies. Furthermore, unlike the case of innovation, the signature of the Kyoto Protocol does not seem to have had a significant impact on the international diffusion of climate mitigation technologies as compared to the overall trend in all sectors.

Figure 11: Percentage of international families, 1978-2003.



5.1 The geography of international technology flows

The PATSTAT database identifies the inventor countries—the countries of residence of the inventors—and the recipient countries—the countries where the invention is patented. We define an exported invention 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.

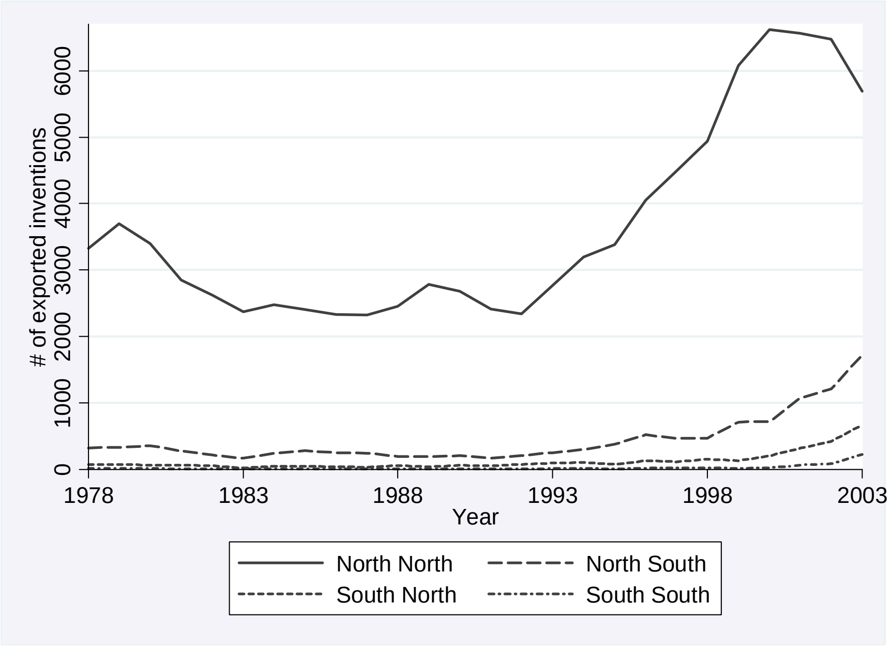
Table 6 gives the origin and destination of the inventions exported in the period 1998-2003. Clearly, international transfer essentially concerns the developed countries. North-South transfer accounts for less than 20 % of all exported inventions. South-South transfers are almost non-existent. Nevertheless,

Figure 12 shows that this has been evolving very quickly since the end of the nineties.

Table 6: Origin-Destination matrix giving the average annual number of exported inventions from 1998 to 2003 (% in brackets)

Destination / Origin	Developed countries	Emerging & transition economies
Developed	5812 (75.9 %)	1360 (17.8 %)
Emerging & transition economies	377 (4.9 %)	112 (1.5 %)

Figure 12: International trends in technology flows, 1978-2003.



In this graph, "North" countries are Annex 1 countries and "South" countries are non-Annex 1

5.2 International transfer by technology

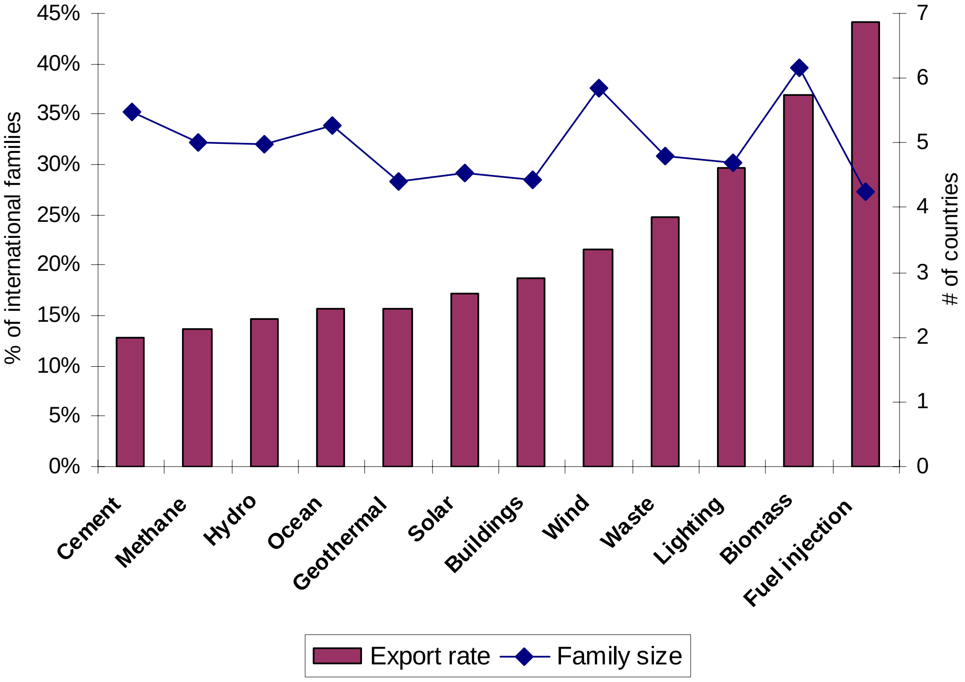
Figure 13 below displays the export rate, as measured by the percentage of international families, by technology. It differs substantially between technology classes (from 13% to 45%) and tends to reflect the level of maturity of each class.

The most internationalized technology classes are *fuel injection* (45%), *biomass* (37%) and *lighting* (30%). The *fuel injection* and *lighting* classes correspond to internationalized industries that invest heavily in R&D (as shown in Figure 6). The case of *biomass* is different, since the global number of patented innovations is much lower in this mature renewable energy technology class. This suggests an original pattern of modest but strongly internationalized innovation.

The less internationalized technologies (*cement*, *methane*, *hydro*, *ocean*, *geothermal*) are also those with the lowest numbers of inventions. These features denote limited inventive activity taking place mainly on a local scale. Besides *cement*, they concern either mature (except, again, biomass) or emerging renewable energy technologies.

The average size of international families, as measured by the number of countries where patent protection is asked for, provides information on the size of the markets targeted by patent owners. In contrast to export rates, the size of international families is relatively constant among technology fields: on average, exported inventions are patented in about 5 countries, with peaks at 6 for *wind* and *biomass*. This suggests that the size of the international market for technology (as measured by the number of countries where patent protection is sought) does not vary significantly across technology fields. The most frequent family members are the US, Germany, Japan, Austria and Spain.

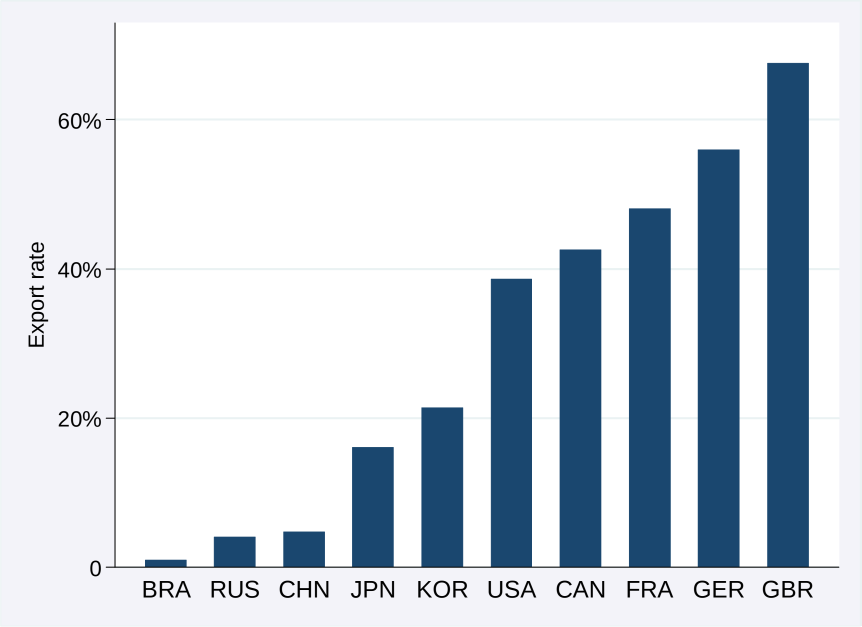
Figure 13: Export rate and size of international families by technology(1998-2003)



5.3 Exporting countries

Figure 14 shows the rate of export for the 10 main inventor countries presented in Table 3. Interestingly, export rates vary widely across countries and the main innovators are not necessarily the best exporters. More than half of German inventions are exported. But the export rate is below 20% for Japan. More generally, Figure 14 shows very good performances of western countries (Germany, France, the USA, Canada and the UK). By contrast, emerging economies—with the exception of South Korea—export much less.

Figure 14: rate of exports for the 10 main inventor countries (1998-2003)



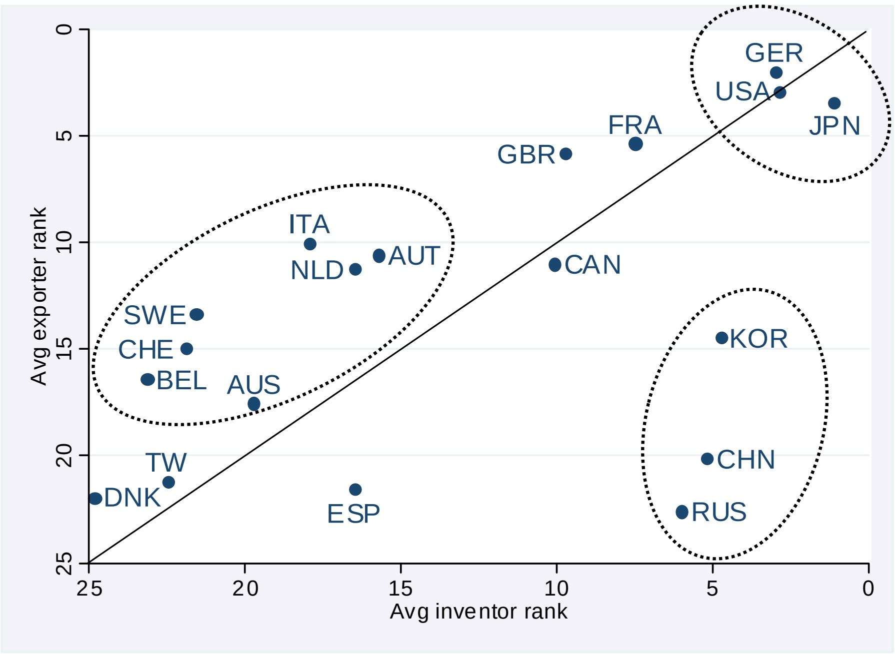
Note: the export rate of inventions is the percentage of inventions that have been patented in at least one country other than the inventor's country

In Figure 15, we seek to compare the countries' performances in terms of innovation and technology exports countries. The graph represents each according to their average ranking as inventor and as technology exporter in each technology field. The observations suggest a positive link between invention and exports, but also highlight important differences between three categories of countries.

In the top right corner, Japan, the USA and Germany stand out as world leaders in both innovation and exports. On the left-hand side, a group of medium-sized European economies have excellent performances in terms of technology exports, given their limited contributions to world inventions. This suggests that inventors in these countries are strongly oriented towards international markets.

By contrast, emerging economies such as China, South Korea and Russia have good innovative performances in some technologies (especially in *geothermal*, *cement* and *lighting*), but scarcely export their inventions. Inventors in these countries seem to focus primarily on local markets, either because their inventions mostly address local needs or because they lack the resources to export their technologies.

Figure 15: Countries' performances in invention and technology exports (1998-2003)



Note: the country codes are available in Annex 10.

5.4 Importing or innovating?

We define technology imports in a country as the foreign inventions that are patented in that country. As regards imports, a key question is whether they crowd out local innovations. Figures 16 and 17 allow us to answer that question. They unambiguously show that the volume of imports is positively correlated with the volume of local innovations. But they also show a negative correlation between the volume of local innovations and the *share* of imports

How can we reconcile these two statements? In fact, Figure 17 suggests that there is a “crowding out effect”. But Figure 16 shows that this effect is compensated by demand factors: when demand for climate change technologies increases in a country, this boosts both local innovations and imports.

Figure 16: Number of local inventions and number of imported inventions (logs) for selected countries (1998-2003)

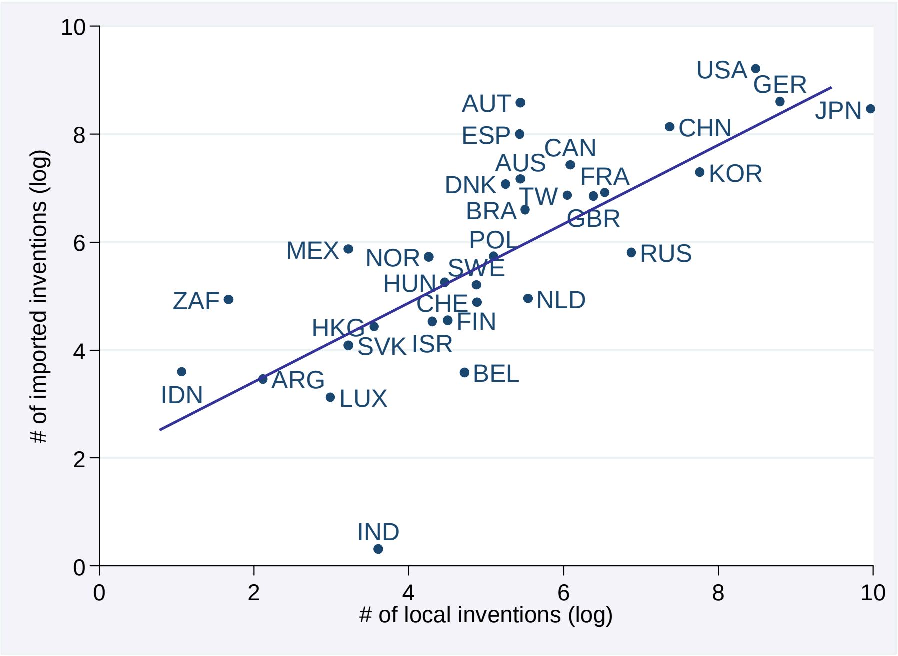
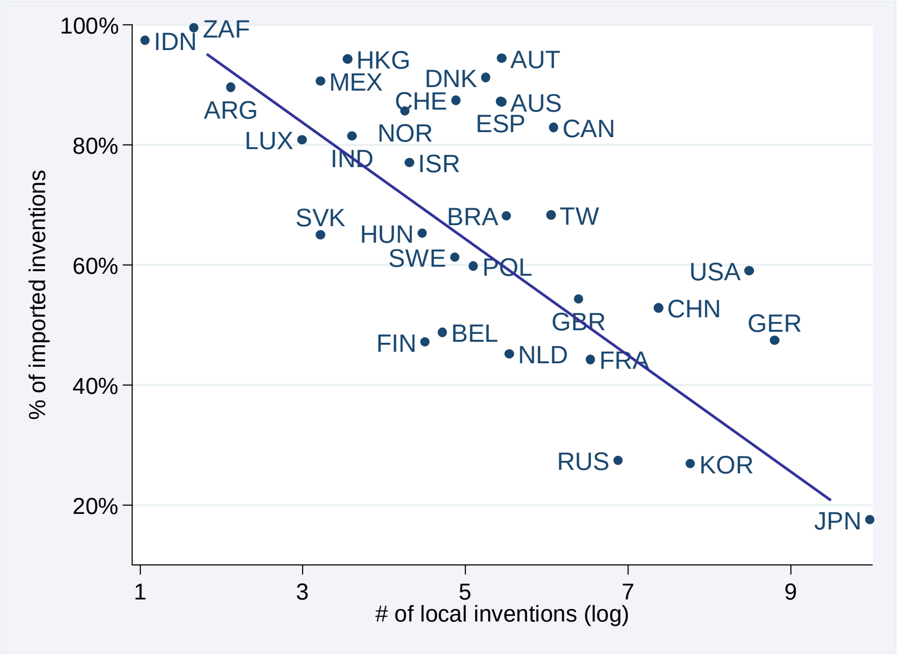


Figure 17: Number of inventions (log) and share of imported inventions for selected countries (1998-2003)



6 Conclusion

In this paper we use the PATSTAT database to identify and analyze patented inventions in 13 climate-related technology classes between 1978 and 2003. This allows us to draw major conclusions concerning the dynamics and distribution of innovation, and the international transfer of technology.

A first set of results concern the impact of the Kyoto Protocol. Statistics suggest the protocol has induced more innovation in the recent period. While innovation in climate change technologies and innovation in all technologies were growing at the same pace until the mid-nineties, the former is now developing much faster. Between 1998 and 2003, innovation in climate mitigation technologies has been growing at the average annual rate of 9%. This increase has only taken place in Annex 1 countries which have ratified the Kyoto Protocol—as opposed to Australia and the USA.

In contrast, there is no visible effect of the Kyoto protocol on technology transfer: international technology flows have actually been increasing in the recent period, but the growth rate is the same as the average.

Our study also yields information on who are the major inventor countries. We show that innovation in climate change technologies is highly concentrated in three countries, namely Japan, Germany and the USA, which accounts for two thirds of total climate innovations in our thirteen technologies. The performance of Japan is particularly impressive as it ranks first in twelve technology fields out of 13. In average it accounts for 42 percent of worldwide innovation.

Surprisingly, the innovation performance of 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 15% of global inventions.

Do these new technologies cross national borders? The export rate—measured by the share of inventions that are patented in at least two countries—is around 25%. This sounds small, but it is only a few percents below the rate for all technologies. International transfers mostly occur between developed countries (75% of exported inventions). Exports from developed countries to emerging economies are still limited (18%) but are growing rapidly. This suggests a huge potential for the development of North-South transfers. 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 conclusion, it is useful to recall the limits of our analysis. Its main shortcoming is probably that patents are imperfect proxies of innovation and technology transfer, and we have explained why in the paper. But they are currently the only data available to investigate climate change technologies world wide.

Appendix

Annex 1. Definition of IPC codes

Description	Class
Buildings	
Insulation or other protection; Elements or use of specified material for that purpose.	E04B 1/62
Heat, sound or noise insulation, absorption, or reflection; Other building methods affording favorable thermal or acoustical conditions, e.g. accumulating of heat within walls	E04B 1/74–78
Insulating elements for both heat and sound	E04B 1/88
Units comprising two or more parallel glass or like panes in spaced relationship, the panes being permanently secured together	E06B 3/66–67
Wing frames not characterized by the manner of movement, specially adapted for double glazing	E06B3/24
Use of energy recovery systems in air conditioning, ventilation or screening.	F24F 12/00
Biomass	
Solid fuels based on materials of non-mineral origin—animal or plant	C10L 5/42-44
Engines operating on gaseous fuels from solid fuel—e.g. wood	F02B 43/08
Liquid carbonaceous fuels - organic compounds	C10L 1/14
Anion exchange - use of materials, cellulose or wood	B01J 41/16
Carbon capture & storage	
Chemical or biological purification of waste gases—carbon oxides	B01D 53/62

Fuel injection	
Arrangements of fuel-injection apparatus with respect to engines; Pump drives adapted top such arrangements	F02M 39/00
Fuel-injection apparatus with two or more injectors fed from a common pressure-source sequentially by means of a distributor	F02M 41/00
Fuel-injection apparatus operating simultaneously on two or more fuels or on a liquid fuel and another liquid, e.g. the other liquid being an anti-knock additive	F02M 43/00
Fuel-injection apparatus characterized by a cyclic delivery of specific time/pressure or time/quantity relationship	F02M 45/00
Fuel-injection apparatus operated cyclically with fuel-injection valves actuated by fluid pressure	F02M 47/00
Fuel-injection apparatus in which injection pumps are driven, or injectors are actuated, by the pressure in engine working cylinders, or by impact of engine working piston	F02M 49/00
Fuel injection apparatus characterized by being operated electrically.	F02M 51/00
Fuel-injection apparatus characterized by heating, cooling, or thermally-insulating means	F02M 53/00
Fuel-injection apparatus characterized by their fuel conduits or their venting means	F02M 55/00
Fuel injectors combined or associated with other devices	F02M 57/00
Pumps specially adapted for fuel-injection and not provided for in groups F02M 39/00 to F02M 57/00	F02M 59/00
Fuel injection not provided for in groups F02M 39/00 to F02M 57/00	F02M 61/00
Other fuel-injection apparatus, parts, or accessories having pertinent characteristics not provided for	F02M 63/00
Testing fuel-injection apparatus, e.g. testing injection timing	F02M 65/00
Low-pressure fuel-injection apparatus	F02M 69/00
Combinations of carburetors and low-pressure fuel-injection apparatus	F02M 71/00

Cement	
Natural pozzuolana cements	C04B 7/12–13
Cements containing slag	C04B 7/14–21
Iron ore cements	C04B 7/22
Cements from oil shales, residues or waste other than slag	C04B 7/24-30
Calcium sulfate cements	C04B 11/00
Geothermal	
Other production or use of heat, not derived from combustion—using natural or geothermal heat	F24J 3/00-08
Devices for producing mechanical power from geothermal energy	F03G 4/00-06
Hydro power	
Machines or engines of reaction type (i.e. hydraulic turbines)	F03B 3/00
Water wheels	F03B 7/00
Adaptations of machines or engines for liquids for special use; Power stations or aggregates; Stations or aggregates of water-storage type; Machine or engine aggregates in dams or the like; Submerged units incorporating electric generators	F03B 13/06-10
Controlling machines or engines for liquids	F03B15/00
Lighting	
Gas- or vapor-discharge lamps (Compact Fluorescent Lamp)	H01J 61/00
Electroluminescent light sources (LED)	H05B 33/00
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

Ocean power	
Tide or wave power plants	E02B 9/08
Adaptations of machines or engines for special use—characterized by using wave or tide energy	F03B 13/12-26
Mechanical-power-producing mechanisms—using pressure differences or thermal differences occurring in nature; ocean thermal energy conversion	F03G 7/04-05
Water wheels	F03B 7/00
Solar power	
Semiconductor devices sensitive to infra-red radiation, light, electromagnetic radiation of shorter wavelength, or corpuscular radiation and specially adapted either for the conversion of the energy of such radiation into electrical energy or for the control of electrical energy by such radiation—adapted as conversion devices, including a panel or array of photoelectric cells, e.g. solar cells	H01L 31/042-058
Generators in which light radiation is directly converted into electrical energy	H02N 6/00
Aspects of roofing for energy collecting devices—e.g. including solar panels	E04D 13/18
Use of solar heat, e.g. solar heat collectors; Receivers working at high temperature, e.g. solar power plants; having lenses or reflectors as concentrating elements	F24J 2/06-18
Devices for producing mechanical power from solar energy	F03G 6/00-06
Use of solar heat; Solar heat collectors with support for article heated, e.g. stoves, ranges, crucibles, furnaces or ovens using solar heat	F24J 2/02
Use of solar heat; solar heat collectors	F24J 2/20-54
Drying solid materials or objects by processes involving the application of heat by radiation—e.g. from the sun	F26B 3/28

Waste	
Solid fuels based on materials of non-material origin—refuse or waste	C10L 5/46-48
Machine plant or systems using particular sources of energy—waste	F25B 27/02
Hot gas or combustion—Profiting from waste heat of exhaust gases	F02G 5/00-04
Incineration of waste—recuperation of heat	F23G 5/46
Plants or engines characterized by use of industrial or other waste gases	F01K 25/14
Prod. of combustible gases—combined with waste heat boilers	C10J 3/86
Incinerators or other apparatus consuming waste—field organic waste	F23G 7/10
Manufacture of fuel cells—combined with treatment of residues	H01M 8/06
Wind power	
Wind motors with rotation axis substantially in wind direction	F03D 1/00-06
Wind motors with rotation axis substantially at right angle to wind direction	F03D 3/00-06
Other wind motors	F03D 5/00-06
Controlling wind motors	F03D 7/00-06
Adaptations of wind motors for special use	F03D 9/00-02
Details, component parts, or accessories not provided for in, or of interest apart from, the other groups of this subclass	F03D 11/00-04

Annex 2. Number of patent applications and of priorities included in each data set

Technology field	**# patent applications**	**# priorities**
Biomass	7,667	2,798
Buildings	20,852	13,366
CCS	954	548
Cement	5,612	3,698
Fuel injection	62,687	32,654
Geothermal	4,120	2,782
Hydro	6,604	5,106
Lighting	71,530	43,351
Methane	9,634	6,235
Ocean	6,235	4,430
Solar	35,342	24,620
Waste	26,354	16,729
Wind	16,309	10,689
Total	**273,900**	**167,006**

Annex 3. Main patent offices and patent breadth coefficients

Patent office	Patent breadth coefficient
Japan	0.71
Taiwan	0.74
Australia	0.79
South Korea	0.81
Russia	0.88
India	0.89
China	0.90
Mexico	0.90
Canada	0.93
Denmark	0.93
UK	0.93
USA	0.96
Switzerland	0.98
Austria	0.99
France	0.99
EPO	1
Belgium	1.01
Italy	1.07
Germany	1.12
Luxembourg	1.13

Annex 4. 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[11]. 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 mainly concerns patents filed in a single patent office. Assuming that the sub-sample of patents with no information on the inventor's country is randomly drawn from the overall sample of patents, 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 inventor countries for priority applications between 1978 and 2003[12]. For example, the distribution of the main inventor countries for wind power priority applications filed at the US Patent Office is the following:

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[11] http://www.uspto.gov/go/taf/us_stat.htm

[12] Due to the small size of samples, calculating the *annual* average distribution of inventor countries would introduce a bigger bias than calculating the 1978-2003 average.

Inventor country	**Share of patents**
USA	82.5%
Canada	5.8%
Taiwan	2.9%
Germany	1.6%
UK	1.2%
Japan	1.1%
Denmark	0.9%
Sweden	0.7%
Others	3.3%

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

EPO applications

Patent counts in Europe involve specific difficulties because of the existence of the European Patent System. Inventors have two possibilities to file national patents. They can make applications either at the national patent offices, or at the European Patent Office and then obtain national patents through designation afterwards, if their application is approved. As a consequence, European patent families often include EPO and subsequent national patent applications, the latter corresponding to the designations. Recall that a successful examination at the EPO allows the inventor to obtain patents in all countries of the European Patent System without further examination. Hence, the observed designations correspond to all the countries in which the inventor was seeking patent protection, although there may have been some discrepancy in the past. If a patent was filed first at the EPO, and then at the national office of at least one EPO member state, we considered only the subsequent national applications.

We also observe some EPO applications for which there are no national applications in PATSTAT. It is very likely that such applications have in fact been withdrawn or rejected by the EPO. Since we are interested in all countries in which the inventor was seeking patent protection, we need to take into account these observations. We therefore attribute these patents on the basis of the designations of an average granted EPO patent. More precisely, the attributed designations reflect the average distribution of designated countries of all EPO patents that have one or more designations. This average is calculated on the basis of the actual designations of EPO applications for all IPC classes, for every year. For example, in 1978, EPO patents that have subsequent national designations were eventually filed in an average of 3 countries, the distribution of which is the following:

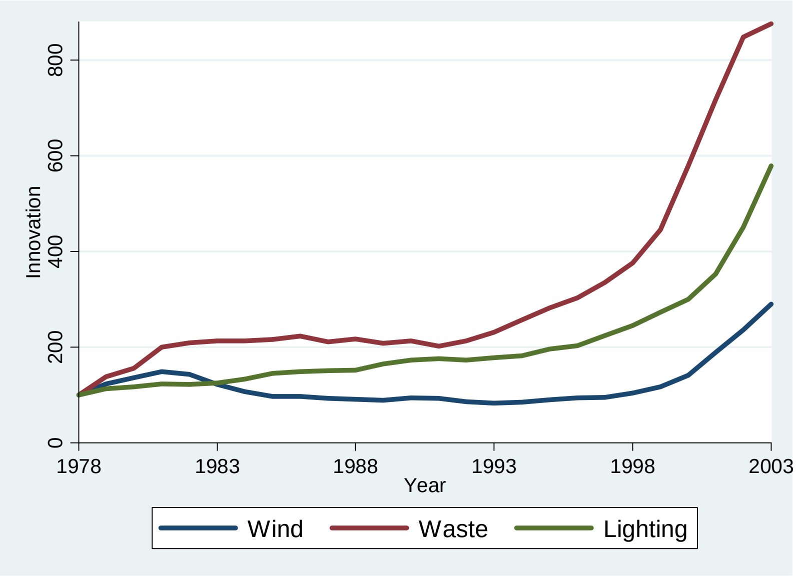
Country	Share of EPO patents filed in that country
Austria	7.8%
Belgium	16.5%
Switzerland	18.0%
Germany	95.0%
France	37.8%
Great-Britain	48.1%
Greece	0.1%
Italy	18.7%
Luxembourg	7.8%
Netherlands	21.7%
Sweden	11.2%

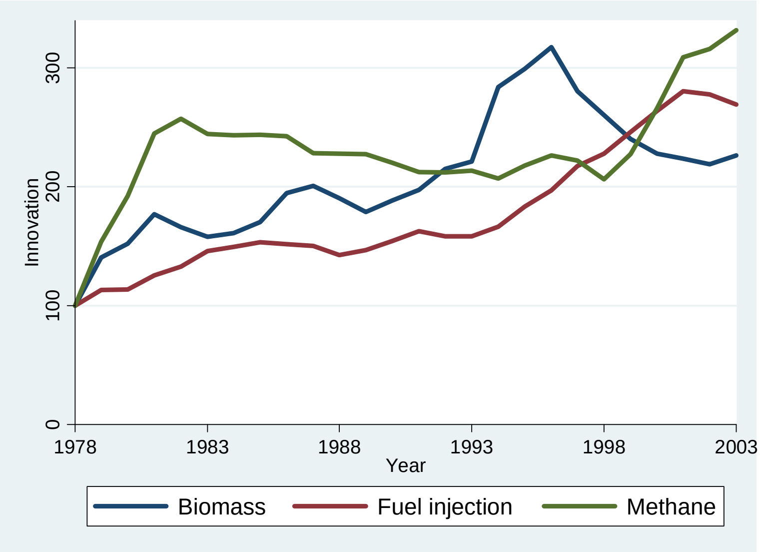
NB: the total is over 100% since EPO patents are usually claimed in several countries, with an average of 3 as noted above.

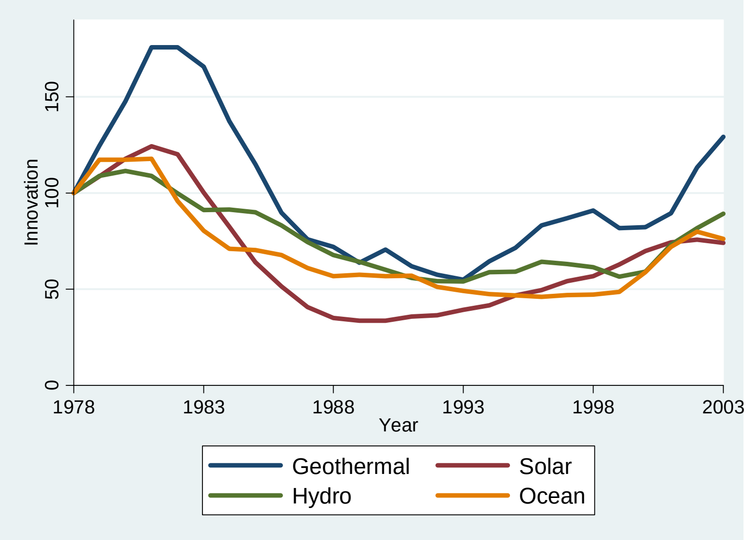
Annex 5. Definition of IPC codes used for benchmarking

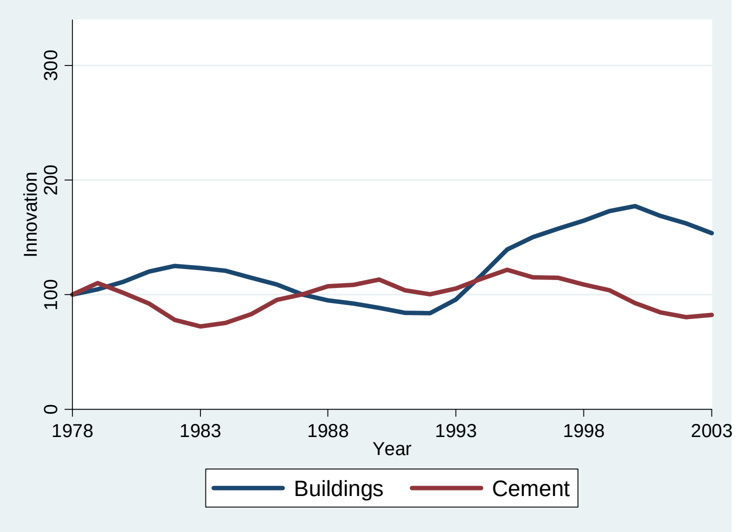
Sector	IPC code	Description
Electricity	H02	Generation, conversion, or distribution of electric power
Vehicles	B62D	Motor vehicles
Buildings	E04	Buildings
	E06	Doors, windows, shutters, or roller blinds
Cement	C04	Cements, concrete, artificial stone, ceramics, refractories
Lighting	F21	Lighting

Annex 6. Pace of innovation in climate change mitigation technologies 1978-2003 (for comparison purposes, the data are normalized to equal 100 in 1978)




Innovation
0
100
200
300
1978
1983
1988
1993
1998
2003
Year
Biomass
Fuel injection
Methane


Innovation
0
50
100
150
1978
1983
1988
1993
1998
2003
Year
Geothermal
Solar
Hydro
Ocean


Innovation
0
100
200
300
1978
1983
1988
1993
1998
2003
Year
Buildings
Cement

Annex 7: Top 3 inventors for each technology, with % of total inventions (1998 - 2003)

Technology field	First	Second	Third
Biomass	USA (25.8%)	Japan (20.3%)	Germany (16.8%)
Buildings	Japan (47.0%)	Germany (14.4%)	USA (10.8%)
CCS	Japan (45.9%)	USA (27.6%)	Russia (4.8%)
Cement	Japan (38.7%)	China (17.3%)	Russia (7.5%)
Fuel injection	Japan (40.2%)	Germany (32.3%)	USA (13.1%)
Geothermal	Japan (33.1%)	China (12.7%)	Russia (12.2%)
Hydro	Japan (37.1%)	Germany (9.5%)	USA (8.7%)
Lighting	Japan (64.2%)	S. Korea (10.3%)	USA (9.9%)
Methane	Japan (52.5%)	Germany (10.7%)	USA (9.7%)
Ocean	Japan (19.9%)	USA (11.4%)	Germany (10.0%)
Solar	Japan (42.0%)	Germany (17.2%)	USA (11.4%)
Waste	Japan (63.1%)	USA (12.3%)	Germany (11.3%)
Wind	Japan (26.3%)	Germany (22.2%)	USA (7.8%)

Annex 8. List of countries by group (developed, emerging & transition)

Developed countries	**Transition economies**	**Emerging countries**
Australia	Armenia	Argentina
Austria	Azerbaijan	Brazil
Belgium	Belarus	China
Canada	Bosnia and Herzegovina	Colombia
Denmark	Bulgaria	Egypt
Finland	Croatia	India
France	Czech Republic	Indonesia
Germany	Czechoslovakia	Malaysia
Greece	Estonia	Mexico
Hong Kong	German Democratic Republic	Morocco
Iceland	Hungary	Peru
Ireland	Kazakhstan	Philippines
Israel	Kyrgyzstan	South Korea
Italy	Latvia	South Africa
Japan	Lithuania	Taiwan
Luxembourg	Macedonia	Thailand
Netherlands	Moldova	Turkey
New Zealand	Poland	
Norway	Romania	
Portugal	Russia	
Singapore	Serbia	
Spain	Slovakia	
Sweden	Slovenia	
Switzerland	Soviet Union	
UK	Tajikistan	
USA	Turkmenistan	
	Ukraine	
	Uzbekistan	
	Yugoslavia	

Annex 9. Share of innovation by emerging countries for each technology (average 1978-1983 and average 1998 - 2003)

Technology field	(A) 1978-1983	(B) 1998-2003	(B)/(A)
Biomass	8.7 %	10.9 %	1.3
Buildings	0.9 %	10.7 %	11.9
CCS	0 %	4.8 %	-
Cement	1.4 %	24.7 %	17.6
Fuel injection	1.2 %	3.9 %	3.3
Geothermal	2.0 %	17.4 %	8.7
Hydro	2.8 %	15.5 %	5.5
Lighting	0.7 %	13.6 %	19.4
Methane	1.5 %	12.0 %	8.0
Ocean	2.5 %	21.2 %	8.5
Solar	0.3 %	13.4 %	44.7
Waste	0.1 %	4.3 %	43.0
Wind	3.0 %	9.7 %	3.2

Annex 10. Country codes used for figures 14 to 16

Argentina	ARG	Japan	JPN
Australia	AUS	Mexico	MEX
Austria	AUT	Netherlands	NLD
Belgium	BEL	Poland	POL
Brazil	BRA	Russia	RUS
Canada	CAN	South Africa	ZAF
China	CHN	South Korea	KOR
Denmark	DNK	Spain	ESP
France	FRA	Sweden	SWE
Germany	GER	Switzerland	CHE
Hong Kong	HKG	Taiwan	TW
India	IND	Ukraine	UKR
Indonesia	IDN	United Kingdom	GBR
Israel	ISR	United States	USA
Italy	ITA		

Research paper 2

What Drives the International Transfer of Climate Change Mitigation Technologies? Empirical Evidence from Patent Data[13]

1 Introduction

The international diffusion of technologies for mitigating climate change is at the core of current discussions surrounding the post-Kyoto agreement. Technology development and diffusion are considered strategic objectives in the 2007 Bali Road Map. North-to-south technology transfer is of particular interest since technologies have been developed mostly in industrialized countries and that technologies are urgently required to mitigate GHG emissions in fast-growing emerging economies. As shown in paper 1, two-thirds of the inventions patented worldwide between 1998 and 2003 in thirteen climate change mitigation technologies have been developed in only three countries: Japan, the USA, and Germany.

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[13] This chapter is based on the following article: Dechezleprêtre, A., Glachant, M., Ménière, Y. (2009). What Drives the International Transfer of Climate Change Mitigation Technologies? Empirical Evidence from Patent Data, submitted at the *Journal of Environmental Economics and Management.*

However, enhancing technology transfer involves considerable policy and economic challenges because developing countries are reluctant to bear the financial costs of catching up alone, while firms in industrialized countries refuse to give away strategic intellectual assets. This has led to an intense debate on policies that affect technology diffusion, with a particular focus on the role of intellectual property rights (IPRs) that developing countries view as barriers to technology diffusion. By contrast, industrialized countries advocate that IPRs provide innovators with incentives to disseminate their inventions through market channels, such as foreign direct investment and the international trade of equipment goods. In their view, every developing country could actually promote transfers by developing its capability to absorb new technologies.

This paper examines these issues by identifying the factors that promote or hinder the international diffusion of climate-friendly technologies. We focus the analysis on the most relevant questions in current policy discussions. First, is the capacity of countries to absorb foreign technologies important? If the answer is in the affirmative, this implies that capacity building is a powerful lever to technology transfer. Do strict IPRs induce more transfers? Do barriers to trade or to foreign direct investment significantly reduce the import of technologies? Has the Kyoto Protocol—and the related domestic policies—accelerated technology diffusion?

We address these questions using a data set of climate-related patents filed in 66 countries from 1990 to 2003. The data come from the World Patent Statistical Database (PATSTAT). We focus the analysis on twelve technologies: six renewable energy technologies (wind, solar, geothermal, ocean energy, biomass, and hydropower), waste-to-energy, methane destruction, energy conservation in buildings, climate-friendly cement, motor vehicle fuel injection, and energy-efficient lighting. Compared to the data set used in paper 1, we have excluded patents related to carbon capture and sequestration (CCS), for which there are too few observations. Consequently, the technologies covered represent around 33% of all GHG abatement opportunities up to 2030, excluding forestry (McKinsey and Vattenfall, 2007). However, they concern very diverse sectors such as electricity and heat production, the manufacturing industry, and the residential sector.

The literature dealing with the international diffusion of environment-related technology is limited but is growing rapidly[14]. Unlike the present work, this literature is mostly descriptive. Lanjouw and Mody (1996) presented the first patent-based empirical evidence for the international diffusion of environmentally responsive technology. Based on data from Japan, Germany, the USA, and fourteen developing countries, the paper identifies the leaders in environmental patenting and finds that significant transfers occur to developing countries. Focusing on chlorine-free technology in the pulp and paper industry, Popp et *al.* (2007) provide evidence that environmental regulation may promote international technology transfer. They observe for instance an increase in the number of patents filed by US inventors in Finland and Sweden after passage of tighter regulations in these countries. Several case studies discuss whether stricter patent protection promotes or hinders the transfer of climate-related technology to

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[14] In contrast, the general empirical literature on international technology diffusion is well developed (for a good survey, see Keller, 2004).

developing countries (see, for example, Barton, 2007; Ockwell et al., 2008). Finally, we recently used PATSTAT data to describe the geography of innovation and international technology diffusion (Dechezleprêtre et al., 2009).

To the best of our knowledge, our work is one of the first econometric studies in this area. Another very recent work is by Dekker et al. (2009) who study how sulfur protocols trigger invention and diffusion of technologies for reducing SO2 emissions. A paper by Hascic and Johnstone (2009) is the most closely related to our work. They use the same data to study the impact of the Kyoto protocol. Our focus is different since we deal with a broader set of policy variables (including trade barriers, FDI control, etc.). Moreover, we develop a theoretical model to cope with simultaneity problems neglected in the other papers.

As a measure of diffusion, our approach is similar to that of Lanjouw and Mody (1996), Eaton and Kortum (1999), or Hascic and Johnstone (2009). We count the number of patent applications in recipient countries for technologies invented abroad. Because patent data include the inventor's country of residence, we know precisely the geography of technology flows and we can run regressions to understand what drives cross-border technology exchanges. This indicator is a proxy of technology transfer because holding a patent in a country gives the holder the exclusive right in that country to exploit the technology commercially. This does not necessarily mean that the inventor will actually use the technology there. Yet, as patenting is both costly and risky, it implies that the inventor definitely plans to do so.

This approach appears similar to the method based on patent citation analysis used in many studies seeking to measure the extent of international knowledge flows (see Jaffe et al., 1993; Peri, 2005). But there is an important difference. Inventors obviously patent abroad to reap private benefits. Therefore, while citations made by inventors to previous patents are an indicator of *knowledge spillovers*, our indicator is a proxy for *market-driven knowledge flows*.

The study is organized as follows: Section 2 discusses the use of patents as indicators of technology transfer. The data set is presented in Section 3 along with data issues. In Section 4 we develop a theoretical model that describes the diffusion of inventions between countries. The model is estimated in Section 5. A final section summarizes the main results.

2 Patents as indicators of technology transfer

In the empirical literature, scholars have proposed a number of solutions for the measurement of international technology transfers. Because major transmission channels of knowledge across countries include international trade and foreign direct investments (FDI), many studies use the import flows of intermediate goods or FDI as a proxy variable for international transfer (for example, Coe and Helpman, 1995; Lichtenberg and van Pottelsberghe de la Potterie, 2001). Data on trade and FDI are easily available from a large number of countries, thereby allowing a very broad geographical coverage. However, such data are highly aggregated, which prevents their use in measuring the flows of climate-friendly technologies. More generally, that data are only indirect vehicles of knowledge transfer.

This is why more recent papers tend to rely on patent data.[15] 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 important, 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 change mitigation technologies possible. Of course, patent data also present drawbacks, which will be discussed below.

To accurately explain how we use patent data in this paper, we must briefly recall how the patent system works. Consider a simplified innovative process. In the first stage, an inventor from country i develops a new technology. He then decides to patent the new technology in certain countries. A patent in country j grants him the exclusive right to commercially exploit the innovation in that country. Accordingly, the inventor patents his invention in country j if he plans to use it there. The set of patents protecting the same invention in several countries is called a patent family.

In this paper we use the number of patents invented in country i and filed in country j as an indicator of the number of innovations transferred from country i to country j. As mentioned in the introduction, this indicator has already been used in previous work (see, for instance, Lanjouw and Mody, 1996; Eaton and Kortum, 1999). It differs, however, from those indicators that are based on

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[15] Alternatively Branstetter, Fisman and Foley (2006) or Smith (2001) use royalty payments and licenses. Such data provide an accurate view of the commercial value of technology transfers through a particular channel, namely IP licensing, but those data are available only for the U.S.A. Therefore it is not appropriate to assess global technology transfers through various channels.

backward patent citation and are used in the literature measuring knowledge spillovers (see Jaffe et al., 1993).[16]

Our approach is obviously imperfect. The first limitation is that for protecting innovations, patents are only one of several means, along with lead time, industrial secrecy, or purposefully complex specifications (Cohen et al., 2000; Frietsch and Schmoch, 2006). In fact, inventors may prefer secrecy to avoid the 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 and Guellec, 2001), although the propensity to patent differs between sectors, depending on the nature of the technology (Cohen et al., 2000) and the risk of imitation in a country. These factors behind the propensity to patent have a significant effect on our data, because patenting is more likely in countries that have strong technological capabilities and that strictly enforce intellectual property rights. However, we will see that the econometric models developed below partly control for this problem.

More generally, certain forms of knowledge are not patentable. Know-how or learning-by-doing, for example, cannot be easily codified, particularly because these are skills incorporated in individuals. The nature of such knowledge limits the accuracy of our data. Nevertheless, research shows that flows of patented

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[16] It is argued that the count of forward citations reflects the value of individual patents. This has been exploited in the literature to compute weighting coefficients. We could have done the same to control for the heterogeneity of patents' value. However, citations data are not available for most countries (with the exceptions of the U.S.A. and the European Union).

knowledge and of tacit knowledge are positively correlated (Cohen et al., 2000; Arora et al., 2008).

A further limitation is that a patent grants the exclusive right to use the technology only 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 did not cost anything, so that inventors might patent widely and indiscriminately. But this is not the case in practice. In paper 1, we show that the average invention is patented in two countries.[17] Patenting is costly, in both the preparation of the application and the administration 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). Therefore, inventors are unlikely to apply for patent protection in a country unless they are relatively certain of the potential market for the technology covered. Finally, because patenting protects an invention only in the country where the patent is filed, inventors are less likely to engage in strategic behavior to protect their inventions abroad and prevent the use of their technology in the production of goods imported by foreign competitors in their domestic markets.

In addition to the above limitations, the value of individual patents is heterogeneous and its distribution is skewed: Since many patents have very little value, the number of patents does not perfectly reflect the value of innovations.

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[17] In fact, about 75% of the inventions are patented in only one country.

This problem is probably less acute in this paper than in other works, as we focus on international diffusion. Exported technologies are of the highest value and make up only about a quarter of all inventions (Lanjouw et al., 1998).

3 Data description

In this paper, we use the same data set as in paper 1. The details on data construction can be found in paper 1. The definitions of the IPC codes used to build the data sets can be found in the Annex 1 of paper 1.

We extracted all the patents filed from 1990 to 2003 in 12 climate-mitigation fields: six renewable energy technologies (wind, solar, geothermal, ocean energy, biomass, and hydropower), waste use and recovery, methane destruction, climate-friendly cement, energy conservation in buildings, motor vehicle fuel injection, and energy-efficient lighting. The precise description of the fields covered by the study can be found in paper 1. This represents 186,660 patent applications filed in 76 countries.[18] On average, climate-related patents included in our data set represent 1% of the total annual number of patents filed worldwide. Since our interest is on technology diffusion, we only consider inventions that are patented in several countries, leaving us with 110,170 patents.

In addition to climate-friendly patents, other data are also used, in particular in order to describe the demand for technology. These data are described in section 5.

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[18] Note that Least Developed Countries are not present in our dataset, for two related reasons: Their patenting activity is extremely limited, and available statistics are not reliable.

4 Theoretical framework

We now present a model that we use to specify estimation equations in the next section. We seek to explain cross-border knowledge flows. The ideal structural model would therefore account for the interplay between inventors and technology adopters as well as for the dynamics of innovation and diffusion, since inventors arguably anticipate diffusion outcomes when they define their innovation strategy. The model could then simultaneously determine innovation and diffusion outcomes. Such a comprehensive approach was developed, for instance, by Eaton and Kortum (1999). But econometric estimation requires much data—for instance, on R&D expenditures—that are not available in our case given the broad geographical scope of our study and its focus on climate technologies.

Alternatively, we could estimate gravity-like models such as those frequently used in the literature about knowledge spillovers. The micro-foundations of this approach are weak, however. This is probably not a serious limitation when dealing with the spillover type of knowledge flows: The mechanisms through which diffusion occurs—e.g., labour mobility—are not driven by the market for technologies, and inventors who own the technologies do not play an active role, as they derive no profits from diffusion. But using a gravity model is more problematic in our case because we seek to explain *intentional* technology transfer through the market.

Based on these arguments, we have opted for an intermediate solution: a model of diffusion that ignores the innovation stage. The model characterizes the flows of technology between M countries. The ultimate goal of our study is to explain n_{ijt}, which denotes the number of inventions invented in country i and adopted in another country j ($i \neq j$) in year t. The problem is that competition between technologies in the recipient country j implies that n_{ijt} is influenced by inventions provided by local inventors, n_{jjt}, and by inventions imported from other foreign countries n_{kjt} ($k \neq i, j$). As a result, the n_{ijt}, n_{jjt} and n_{kjt} are jointly determined. Our model aims to solve this simultaneity problem.

Consider first the adopters. Let U_{jt} be the aggregate utility of all adopters located in country j. We adopt a Cobb-Douglas functional form[19]:

$$U_{jt}\left(n_{1jt}..n_{ijt},..n_{njt}\right) = (n_{jjt})^{a_1}\left(\prod_{i \neq j} n_{ijt}\right)^{a_2} K_{jt}^{\;a_3} D_{jt}^{\;a_4} \quad \text{for} \quad j = 1,...M \; (1)$$

The utility depends on the number of technologies transferred from the different foreign countries and on the number of technologies locally invented. Note that we make the simplifying assumption that all foreign inventions exhibit the same elasticity. K_{jt} is the stock of knowledge accumulated in the recipient country. This captures the usual view in the literature on technology diffusion that accumulated knowledge increases the ability to exploit new technologies. D_{jt} is a variable capturing factors affecting the demand for technology in the recipient country. Finally, a_i, with $i = 1,..4$ are coefficients that do not vary over time and across countries. Furthermore, we impose $0 < a_i < 1$ so that U increases with the demand factors while marginal utility is decreasing.

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[19] A Cobb Douglas specification is restrictive in that the (partial) elasticity of substitution is constant and equal to unity, but it is sufficiently flexible in our case as we impose limited restrictions on the coefficients ($0 < a_i < 1$). More generally, a Cobb Douglas functional form, say $x^{\alpha} y^{\beta}$, is an intermediate case between $\alpha x+\beta y$ where the demand factors x and y are perfect substitutes and min{ $\alpha x,\beta y$ } where they are perfect complements.

Turning next to the supply side, innovators of country *i* can commercially exploit their technologies in country *j* at unit cost C_{ijt}. This is an implementation cost which captures factors that are specific to the recipient country, such as the strictness of the intellectual property regime and transfer costs hindering the international trade of technology (such as tariffs when the technology is embodied in an intermediate good, geographical distance, or linguistic barrier).

For the sake of simplicity, we assume away any inefficiency in the market for technology. Such an assumption can be justified with the argument that the inventor of a particular technology is a monopolist who can perfectly discriminate technology adopters.[20] This assumption implies that the overall allocation of technologies is socially efficient.[21] It simplifies the analysis by allowing us to focus on the social welfare maximization program:

$$\max \quad W_t = \sum_{j=1}^{M} U_{jt}\left(n_{1jt}..n_{ijt},..n_{njt}\right) - \sum_{i=1}^{M}\sum_{j=1}^{M}\left(n_{ijt}C_{ijt}\right) \qquad (1)$$

We solve this program in Annex 1, leading to

Proposition The number of technologies invented in country i and subsequently transferred in country j at time t is given by:

$$n_{ijt} = \alpha_0 K_{jt}^{\alpha_1} C_{ijt}^{\alpha_2} C_{jjt}^{\alpha_3} \left(\prod_{k\neq i,j} C_{kjt}\right)^{\alpha_4} D_{jt}^{\alpha_5} \quad (2)$$

where

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[20] Note that the equilibrium allocation would be the same if we have assumed a perfectly competitive technology market.

[21] Or the technology market is perfectly competitive.

$$\alpha_0 = \left(a_2 a_1^{\frac{a_1}{1-a_1}} \right)^{\frac{1-a_1}{a_2(M-1)-(2-a_2)(1-a_1)}}$$

$$\alpha_1 = \frac{a_3}{a_2(M-1)-(2-a_2)(1-a_1)}$$

$$\alpha_2 = -\frac{(M-1)a_2 - 2(1-a_1) - a_1 a_2}{\left[a_2(M-1)-(2-a_2)(1-a_1)\right](2-a_2)}$$

$$\alpha_3 = \frac{a_1}{a_2(M-1)-(2-a_2)(1-a_1)}$$

$$\alpha_4 = \frac{a_2}{\left[a_2(M-1)-(2-a_2)(1-a_1)\right](2-a_2)}$$

$$\alpha_5 = \frac{a_4}{a_2(M-1)-(2-a_2)(1-a_1)}$$

Proof. See Annex 1.

The reduced-form equation (2) will serve as a basis for our econometric equation. It gives an expression of the flow of inventions between country i and country j as a function of the exogenous variables. The LHS does not include the endogenous variables n_{jjt} and Πn_{kjt} that are simultaneously determined with n_{ijt} through competition on the technology market. In fact, the potential for substitution between technologies imported from country i and the domestic inventions of country j is captured by the variable C_{jjt}: as α_3 is positive, the higher the implementation cost of local technologies, the greater the number of technologies imported from country $i \neq j$. The variable ΠC_{kjt} plays a similar role and controls for the substitutability with technologies from countries $k \neq i, j$.

5 Empirical issues

We have constructed a panel data set for each of the 12 technology fields described in Section 3. This is a strong point of our study: Estimating the model on each field allows us to control for technology-specific factors. The panels extend over 14 years, from 1990 to 2003. The final samples include between 2,176 and 3,181 country pairs over that period.

5.1 Estimation equations

A practical problem in estimating equation (2) is that we do not observe the number of inventions transferred but rather the patent flow between country i and country j. There are differences between these variables for the two reasons mentioned earlier. First, the number of patents that are granted for a given innovation varies significantly across countries. A common illustration is Japan, where the "amount" of technology covered by a patent—referred to by IPR experts as the patent breadth—is said to be particularly low. For example, the same wind turbine covered by one patent in Germany may require three patents in Japan. Second, patenting is not the only way to protect innovation, and the propensity to patent varies across sectors and countries.

To tackle these problems, we follow Peri (2005) and Branstetter (2001) by assuming that the patent flow P_{ijt} is such that:

$$P_{ijt} = n_{ijt}\Phi_j e^{\gamma_{jt}} \quad (3)$$

In this expression, Φ_j is an observed fixed factor which measures patent breadth in country *j*. We will explain later how this variable is constructed. In contrast, $e^{\gamma_{jt}}$ is an unobserved random term reflecting the propensity to patent inventions in country *j* at time *t*.

We then substitute (2) in (3), take the logs on both sides, adopt new notations, and add time dummies to control for potential endogeneity due to transitory shocks. This leads to the model we will estimate:

$$p_{ijt} = \beta_0 + \beta_1 k_{jt} + \beta_2 c_{ijt} + \beta_3 c_{jjt} + \beta_4 \sum_{k \neq i,j} c_{kjt} + \beta_5 d_{jt} + \delta t + \eta \varphi_{jt} + u_{ijt} \quad (4)$$

where lower case letters denote the logs of the initial variables. We allow the error term in (4) to contain γ_{jt}, the random term capturing the unobserved propensity to patent, a country-pair specific component and random time-varying effects such that

$$u_{ijt} = \gamma_{jt} + \nu_{ij} + \varepsilon_{ijt} \qquad (5)$$

where the latter term is assumed to be a normal iid disturbance.

5.2 Variable description

PATSTAT only yields information on P_{ijt}. We do not have readily available data on absorptive capacities k_{jt}, the implementation costs c_{ijt} with $i,j = 1,..M$, the demand variable d_{jt}, and the patent-breadth variable $\varphi_j = \ln \Phi_j$. For these variables, we will use a linear combination of different proxies, which we now describe in turn.

The recipient country's absorptive capability k_{jt}:

We seek to understand whether transferring a technology requires generic skills and/or technology-specific knowledge. This leads us to use two different proxy variables to describe local technological knowledge. The first variable is S_{jt-1}, the discounted stock of previously filed patents in the technology at date t–1 by local inventors in the recipient country j. This is an indicator of the local absorptive capabilities that are specific to each technology. Following Peri (2005), the patent stock is calculated using the perpetual inventory method. We initialize patent stocks for the year 1978 and use the recursive formula

$$S_{jt-1} = (1-\delta)S_{jt-2} + P_{jjt-1}$$

where P_{jjt} is the number of patented technologies invented by domestic inventors in year t. The value chosen for δ, the depreciation of R&D capital, is 10%, a value commonly used in most of the literature (see Keller, 2002).[22] Note that using S_{jt-1}—i.e., lagging the variable by one year to predict transfers in year t given the stocks in year t-1—eliminates the potential problem of endogeneity.

The second proxy variable is edu_{jt}, the tertiary gross enrollment ratio, which is the average percentage of the population of official school age for tertiary education actually enrolled in this level over the previous 10 years.

The implementation cost c_{ijt}, **with** $i, j = 1,..M$

Note that we describe here not only the cost c_{ijt}, but also c_{jjt} and c_{kjt}, with $k \neq i$ j. We use five variables to measure the cost of adopting a patented invention. A country-specific index built by Park and Lippoldt (2008), ipr_{jt}, measures the strictness of intellectual property rights in the recipient country. A lax patent

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[22] A problem is that we do not have patent data from before 1978. In order to take inventions patented prior to this year into account, we set the initial value of knowledge stock at $S_{j1978} = P_{ini}/(\delta + g)$ where g is the average worldwide growth rate of patenting activity in the technology for the period 1978–1983 and P_{ini} is the average annual number of patents filed between 1978 and 1980. Note that the influence of the calculated initial stocks is greatly diminished as we perform regressions on the 1990–2003 period.

system can deter the import of foreign technologies, because of the fear of counterfeiting (see, for example, Maskus, 2000; Smith, 2001; and Barton, 2007). This issue is hotly debated in the political arena.

Note that ipr_{jt} likely affects the propensity to patent in country j, which may make our results more difficult to interpret. McCalman (2001) shows that the value of patent rights significantly increased in those countries that had signed the TRIPS agreement in 1994. That increase in value may have two consequences. First, the increase in the payoff associated with patenting may result in more transfers of patented technologies, which is what we want to measure. However, it may also result in additional patent applications for technologies that would have been transferred anyway through trade or FDI. Consequently, we can overestimate the effect of ipr_{jt} on technology transfer.

The variables $tariff_{jt}$ and $trade\_bloc_{ijt}$ capture the existence of potential barriers to international trade. More precisely, $tariff_{jt}$ is the recipient country's mean of tariff rates based on data from the World Trade Organization and the World Bank. Meanwhile, $trade\_bloc_{ijt}$ is a dummy variable indicating whether the countries are part of the same trade bloc. Arguably, restrictions to trade may hinder the transfer of technologies embodied in capital equipment goods.

As is usual in the trade literature, we also include the log of the geographic distance[23] between country i and country j, called $distance_{ij}$. This distance variable is generally viewed as a proxy for transportation costs. Empirical

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[23] Distances between countries were taken from the online CEPII data sets available at http://www.cepii.fr/anglaisgraph/bdd/distances.htm.

evidence shows that knowledge flows are affected by distance (Peri, 2005), though less than trade flows.[24]

Foreign direct investments are another well-known channel of technology diffusion. Accordingly, we include the variable $fdi\_control_{jt}$, which is an index of international capital market control based on data from the World Economic Forum and the International Monetary Fund.[25]

Finally, one can reasonably assume that filing a patent in a country where the same language is spoken reduces transaction costs. Indeed, the applicant saves translation costs, and national legal systems are likely to be closer. Therefore, $language_{ij}$ is a dummy variable which equals 1 if both countries share a common official language and 0 otherwise.

The demand for climate change technologies d_{jt}

We use three variables that are common to all technologies: $gdp\_per\_capita_{jt}$, $pop_{jt,}$[26] and $kyoto_{jt.}$[27] The first one describes country j's per capita GDP in PPP USD, the second one is the log of its population, and the last one is a dummy variable equal to one if $t > 1997$ and if country j is an Annex 1 country that has ratified the Kyoto Protocol. We also use technology-specific demand variables, which are listed in Table 2.

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[24] Obviously, $distance_{jjt} = 0$.

[25] The average tariff rate and the index of international capital market controls are from the Economic Freedom of the World 2008 Annual Report. Missing years were filled by interpolation.

[26] Data on population were obtained from the World Bank's World Development Indicators 2008.

[27] In a first specification, we also included the GDP growth of the recipient country but the variable turned out to be statistically insignificant in all regressions.

Table 2. Description of demand variables, by technology

Technology field	Variable	Definition and sources
Biomass	$elec\_biomass_{jt}$	Energy production from biomass (Mtoe)
Buildings	$urban_{jt}$ $construction_{jt}$ $winter\_temp_{j}$	Urban population (million inhabitants) Construction sector (bn USD) Average winter temperature 1991-2000 (°C)
Cement	$construction_{jt}$	Construction sector (bn USD)
Fuel injection	$cars_{jt}$ gas_price_{jt}	# of passenger cars per 1,000 people Gasoline price (USD per liter)
Geothermal	$elec\_renew_{jt}$	Production of renewable energy (Mtoe)
Hydro	$elec\_hydro_{jt}$	Production of hydro electricity (Mtoe)
Lighting	$urban_{jt}$ $construction_{jt}$	Urban population (million inhabitants) Construction sector (bn USD)
Methane	$agriculture_{jt}$	Agriculture sector (bn USD)
Ocean	$elec\_renew_{jt}$ $coast\_length_{j}$	Production of renewable energy (Mtoe) Coast length (1,000 km)
Solar	$elec\_renew_{jt}$ $cloud\_cover_{j}$ $latitude_{j}$	Production of renewable energy (Mtoe) Average cloud cover (%) Latitude of main city (absolute value)
Waste	$elec\_renew_{jt}$	Production of renewable energy (Mtoe)
Wind	$elec\_renew_{jt}$ $coast\_length_{j}$	Production of renewable energy (Mtoe) Coast length (1,000 km)

Sources: International Energy Agency, World Bank 2008, Tyndall Center, World resources Institute, CEPII, United Nations Statistics Division

Table 3. Descriptive statistics for independent variables

Variable	Observations	Mean	Std deviation
P_{ij},	Depending on the technology		
S_{jt-1}	Depending on the technology		
edu_{jt}	59150	33.64	20.35
ipr_{jt}	60060	3.261	0.998
$tariff_{jt}$	55315	12.17	11.29
$trade\_bloc_{jt}$	60060	0.064	0.245
$fdi\_control_{jt}$	58240	4.311	2.907
$distance_{ijt}$	60060	8.586	0.945
$language_{ijt}$	60060	0.094	0.292
$\sum_{k\neq i,j} trade\_bloc_{kjt}$	60060	4.16	6.05
$\sum_{k\neq i,j} distance_{kjt}$	60060	558.1	29.55
$\sum_{k\neq i,j} language_{kjt}$	60060	6.121	5.814
$kyoto_{jt}$	60060	0.201	0.401
pop_{jt}	60060	9.907	1.576
$elec\_renew_{it}$	58240	14.855	36.065
$elec\_biomass_{it}$	58240	10983	32185
$elec\_hydro_{it}$	58240	2988.5	5931.8
$urban_{jt}$	59150	34.766	64.811
$agriculture_{jt}$	57070	1.5885	2.7058
$construction_{jt}$	57070	0.0233	0.0609
gas_price_{jt}	58240	0.6922	0.3869
$cars_{jt}$	57330	217.8	181.5
$coast\_length_{j}$	60060	19.039	40.391
$cloud\_cover_{j}$	59150	58.64	14.19
$latitude_{j}$	60060	35.32	16.65
$GDP\_percapita_{jt}$	59605	12953.1	9107.0
$winter\_temp_{j}$	59150	7.355	11.20

The patent breadth variable φ_j

We computed patent breadth coefficients in a previous study (Dechezleprêtre et al., 2009). That strategy consists in analyzing so-called international patent families that include patents protecting a given technology in several countries. By doing so, we found, for instance, that on average, one patent filed at the European Patent Office (EPO) translates up to 1.4 patent when the same technology is patented at the Japanese patent office. Setting the weight of applications at the EPO to unity, we calculated patent breadth coefficients Φ_j for every patent office included in the PATSTAT database. These coefficients are available in Dechezleprêtre et al. (2009). We use $\varphi_j = \log \Phi_j$ in this study.

5.3 Other econometric issues

A notable feature of our data is that most patents are only filed in one country (usually, the inventor's country), implying that the patent flow between two countries in a given year frequently equals zero. As shown in Table 4, the proportion of zeros in the data sets ranges from 68% to 81%, depending on the technology. Therefore, the use of OLS may generate inefficient estimates. The Poisson distribution would be too restrictive, as it imposes a mean that is equal to the variance. In our case, the data are highly over dispersed with a sample variance that is on average 10 times greater than the mean. For this reason, we use a negative binomial regression model, which tests and corrects for over-dispersion. Following Branstetter (2001), we run the regressions with the number of patents P_{ijt} as the dependent variable.

Table 4. Descriptive statistics for the dependent variable, by technology

Technology	Obs	Mean	Std. Dev.	Frequency of 0
Biomass	23205	0.152	1.018	72.0%
Buildings	30615	0.167	1.014	73.4%
Cement	17875	0.064	0.352	79.9%
Fuel injection	33020	0.682	8.243	81.9%
Geothermal	17225	0.048	0.736	67.4%
Hydro	20930	0.044	0.299	76.0%
Lighting	31525	0.725	10.279	68.5%
Methane	25415	0.082	0.501	78.3%
Ocean	28080	0.039	0.273	68.9%
Solar	39975	0.162	1.638	71.5%
Waste	27365	0.316	3.289	69.8%
Wind	37440	0.118	1.197	79.0%

A further difficulty is that the propensity to patent is just partly controlled by the variable ipr_{jt}, which only reflects cross-border heterogeneity. Yet we know that patenting propensity also varies much across sectors and technologies. We mitigate this problem by running sector-specific regressions. The remaining unobserved part is captured by the random term γ_{jt} in (5). If γ_{jt} is uncorrelated with the regressors on the right-hand side, then this effect can be estimated using a random-effects model. But if the random term is correlated, then estimates are biased. A fixed effect estimator cannot totally fix this problem, since this effect varies over time.

For our estimations, we opted for a random-effects model for the following reasons. First, key variables such as ipr_{jt} or $trade\_bloc_{ijt}$ do not vary much across time. They are thus highly correlated with country-pair specific effects, which leads to inefficient estimates of their coefficients when using a fixed effect model. Second, fixed effect estimation causes all groups with zero patent transferred during the 1990–2003 period to be dropped from the regression, including many potential technology suppliers, which induces a selection bias. For that same reason, we cannot perform the standard Hausman test of the random versus fixed effects specification as the models are ran on different samples.

6 Results

We report the results in Tables 3a and 3b. Estimates across technologies are relatively stable, although there are some differences, which we will discuss below. We focus the interpretation on six policy-relevant questions.

1) Does accumulated knowledge facilitate the import of technology? The local stock of technology-specific knowledge S_{jt-1} has a positive impact on the flows of patents in 11 regressions out of 12. The coefficient is statistically significant at the 0.1% level. There is no doubt that patent transfers increase if the recipient country is actively involved in R&D in the same technology field.

In contrast, the recipient country's level of education is statistically significant and has a positive impact only in five regressions. This suggests that generic absorptive capabilities are less important than technology-specific knowledge.

Counter to an intuitive assessment of the situation, the impact of higher technology-specific knowledge stock is negative in buildings insulation technologies. A possible explanation is that high technological capabilities imply strong imitation capacities, which lead some innovators to refrain from introducing new technologies in the recipient country.

2) Do strict intellectual property rights promote technology transfer? As mentioned earlier, this issue is very high in the political agenda. Our results suggest a positive influence of strict IP rights on technology transfer. More precisely, this result holds in 7 regressions out of 12. Exceptions are three renewable energy technologies (ocean energy, hydro power, and geothermal energy), as well as methane destruction and cement, on which IP rights have no statistically significant impacts.

When IPR strictness has a significant positive effect, part of the induced patenting could also reflect a substitution between patented and non-patented knowledge flows, rather than additional technology flows.

3) Do restrictions on international trade hinder technology transfer? Restrictions to trade seem to be more important than IPR strictness: Higher tariff rates have a statistically significant negative impact on patent flows in 11 regressions. This result is confirmed by the fact that being part of the same trade bloc significantly increases patent flows in seven regressions. This suggests that transferred technologies are frequently incorporated in equipment goods.

4) Do restrictions on foreign direct investments hinder technology transfer? Stricter international capital control has a statistically significant positive effect in seven regressions. This is clearly counter-intuitive. Several factors may explain this result, involving either a real effect on technology transfers or simply an increased use of patents as a means to secure these transfers. We do not know the precise contents of FDI regulations in the different countries, since we use a synthetic index developed by the World Economic Forum, but in some cases FDI control may directly aim at promoting the transfer of technology through foreign investments. More generally, it is likely that regulations increase the risk of losing control of transferred technology,[28] thus pushing foreign investors to rely more heavily on patents as a way to secure their intellectual assets. A final interpretation could be that restrictions on FDI tend to shift technology transfer to other channels—such as licensing to local users—that are more patent-intensive than FDI.

5) Has the Kyoto Protocol accelerated the diffusion of climate-related technology? The variable *kyoto* has a statistically significant positive impact on patent flows in 4 regressions over 12. This suggests that the impact of domestic policy measures related to the protocol is differentiated across technologies.

Consider first the renewable energy technologies. It appears that the protocol has had an impact on three technologies—ocean, solar and geothermal technologies—that have a large potential for energy generation but that are still at an early stage of their technology development and commercial deployment. The potential for further development of these technologies contrasts with more mature technologies, such as hydropower, wind power, biomass energy, for which the *kyoto* dummy is not statistically significant.

The *kyoto* variable also has a statistically significant positive impact on the diffusion of motor vehicle fuel injection, which suggests that the transfer of this technology is particularly responsive to public policies.

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[28] China, for instance, is notorious for usually requiring foreign companies to create joint ventures with local partners, so that control of transferred technologies has to be shared.

Other variables

Demand variables are either not significant or exhibit the expected signs. For instance, the cloud coverage in the recipient country reduces the number of solar technologies that are imported. The transfer of fuel-injection technologies increases with gasoline prices and with number of cars. The production of renewable electricity promotes the import of renewable energy technologies (see *elec_renew*, *elec_biomass, elec_hydro*), etc.

As expected, technology flows fall as geographic distance increases and rise if both countries speak the same language. The recipient country's size (*pop*) and economic wealth (*GDP_percapita*) also promote the importation of technologies.

Finally, the control variable Σ*distance* has the expected positive impact in many regressions: the longer the geographical distance between the recipient country j and the technology providers from countries $k \neq i, j$, the larger the transfer from country i. Similarly, the higher the number of countries speaking the same language among countries $k \neq i, j$ (captured by Σ*language*), the less the transfer from country i. The only potential problem concerns Σ*trade_bloc*, which should have a negative impact but is actually statistically positive in eight regressions. A likely explanation is that Σ*trade_bloc* is a proxy variable for the overall trade openness of the recipient country.

7 Conclusions

In this paper we use the PATSTAT database to analyze the international diffusion of patented inventions in twelve climate-related technologies between

1990 and 2003. This allows us to draw conclusions about those factors which promote or hinder international technology transfer.

Regressions show that absorptive capacities of recipient countries are determinant factors. This is particularly true for technology-specific knowledge, whereas the general level of education exerts less influence.

We are also able to assess the impacts of different policy barriers. The results stress that restrictions to international trade—e.g., high tariff rates—and lax intellectual property regimes negatively influence the international diffusion of patented knowledge. In addition, results suggest that, unexpectedly, barriers to Foreign Direct Investments promote technology transfer in those cases where the coefficients are significant. This puzzle can have different interpretations. Perhaps strict FDI regulations include requirements of technology transfers. Another interpretation is that restrictions on FDI lead foreign technology owners to rely more systematically on patents, either to secure their FDI or as an alternative to it.

In conclusion, it is crucial to recall that patents are imperfect proxies of technology transfer for reasons explained in the paper. This should be kept in mind when interpreting the results. If the transfer of patented technologies is positively correlated with non-patented knowledge flows (e.g., know-how), our work gives a general view of the international diffusion of knowledge. Alternatively, if they are negatively correlated, because they are substitutes, our results only give a partial view of the overall picture. Further work is clearly necessary to clarify these points.

Table 3a. Results for wind, ocean, solar, hydro, biomass, and geothermal.

Variable	Wind	Ocean	Solar	Hydro	biomass	Geothermal
S_{jt-1}	0.0698** (0.0157)	0.2345** (0.0427)	0.3561** (0.0363)	0.2292** (0.0383)	0.0824** (0.0247)	0.1611** (0.0447)
edu_{jt}	0.0093* (0.0041)	0.0059 (0.0051)	-0.0044 (0.0034)	-0.0023 (0.0048)	0.008* (0.0038)	0.0209** (0.0052)
ipr_{jt}	0.3126** (0.0948)	-0.0261 (0.1266)	0.1586* (0.0791)	0.1309 (0.1371)	0.2192* (0.0905)	-0.2499 (0.1576)
$tariff_{jt}$	-0.0505** (0.0097)	-0.0464** (0.0122)	-0.0122 (0.0067)	-0.0252* (0.0127)	-0.0288** (0.0084)	-0.0434** (0.014)
$trade\_bloc_{jt}$	0.2676 (0.1494)	1.27** (0.1863)	-0.2135 (0.112)	0.4898** (0.1788)	0.0431 (0.1295)	0.4656* (0.2108)
$fdi\_control_{jt}$	0.0892** (0.0288)	0.086* (0.0395)	0.0558* (0.0224)	0.0084 (0.0452)	-0.0032 (0.027)	0.0272 (0.0468)
$language_{ijt}$	0.1908 (0.1809)	0.9381** (0.187)	0.7667** (0.189)	0.6429** (0.2196)	1.228** (0.2283)	0.8953** (0.2335)
$distance_{ijt}$	-0.3455** (0.0696)	0.0137 (0.0829)	-0.318** (0.063)	-0.2179* (0.0853)	-0.2501** (0.085)	-0.0284 (0.0869)
$\sum_{k\neq i,j} distance_{kjt}$	0.007* (0.0028)	0.0178** (0.0036)	0.0087** (0.0032)	0.0136** (0.0043)	-0.0008 (0.0034)	-0.0004 (0.0042)
$\sum_{k\neq i,j} trade\_bloc_{kjt}$	0.0481** (0.0112)	0.0343* (0.0153)	0.0485** (0.0089)	0.0351* (0.0147)	0.0016 (0.0107)	0.0349* (0.0148)
$\sum_{k\neq i,j} language_{kjt}$	-0.0235* (0.0118)	-0.0222 (0.0142)	-0.0209 (0.0121)	-0.025 (0.0158)	-0.0484** (0.0139)	-0.0372* (0.0154)
$kyoto_{jt}$	0.0134 (0.1004)	0.3717** (0.1291)	0.1769** (0.0684)	-0.1844 (0.1495)	0.0472 (0.093)	0.4816** (0.1802)
$patent\_breadth$	-1.04** (0.499)	-0.6256 (0.6698)	-0.4808 (0.5557)	0.6719 (0.8799)	-0.4496 (0.6132)	-2.001** (0.6582)
$GDP\_percapita_{jt}$	0.039** (0.0098)	0.044** (0.012)	0.055** (0.0093)	0.043** (0.012)	0.057** (0.01)	0.032* (0.014)
pop_{jt}	0.3087** (0.0549)	0.2039** (0.0705)	0.2559** (0.0592)	0.2812** (0.0722)	0.4035** (0.0681)	0.1882* (0.0751)
$elec\_renew_{it}$	0.0067** (0.0015)	0.0075** (0.0017)	0.0031 (0.0016)			0.0087** (0.0021)
$coast\_length_{j}$	0.0001 (0.0013)	0.0009 (0.0017)				

Variable (continued)	Wind	Ocean	Solar	Hydro	biomass	Geothermal
$cloud\_cover_j$			-0.0267** (0.005)			
$latitude_j$			0.0051 (0.0069)			
$elec\_hydro_{jt}$				0.0415** (0.0092)		
$elec\_biomass_{jt}$					0.0048* (0.0021)	
constant	-6.276** 1.595	-1.513 265.9	-5.59** 1.924	-8.485** 2.476	-4.202** 1.814	-3.818 2.373
Log-likelihood	-5809	-3045	-7187	-2384	-4442	-1861
Observations	32973	24795	35179	18562	20500	15271
Notes: Standard error in parentheses; * denotes significance at 5% level, ** denotes significance at 1% level. Time dummies included in each regression (not reported for brevity)						

Table 3b. Results for waste, cement, lighting, building, methane, and fuel injection

Variable	Waste	Cement	light	Building	Methane	fuel injection
S_{jt-1}	0.1472** (0.0181)	0.1202** (0.0308)	0.0818** (0.0187)	-0.0314** (0.0104)	0.243** (0.0392)	0.0515** (0.0161)
edu_{jt}	0.0002 (0.0033)	0.0086 (0.0048)	0.0161** (0.0034)	0.0099* (0.0039)	0.0036 (0.004)	-0.0013 (0.0035)
ipr_{jt}	0.1566* (0.0799)	0.182 (0.1117)	0.2096* (0.0837)	0.439** (0.0796)	0.1583 (0.0974)	0.352** (0.079)
$tariff_{jt}$	-0.0434** (0.0078)	-0.0487** (0.0109)	-0.0228** (0.0075)	-0.049** (0.0081)	-0.0476** (0.0091)	-0.0156* (0.0067)
$trade\_bloc_{jt}$	0.3826** (0.1264)	0.3091* (0.1575)	0.6033** (0.1346)	-0.1511 (0.086)	0.3754** (0.1284)	0.1052 (0.1028)
$fdi\_control_{jt}$	0.045 (0.025)	0.087* (0.0339)	0.0667** (0.0235)	0.0565* (0.0227)	0.0879** (0.0283)	0.0244 (0.0205)
$language_{ijt}$	1.033** (0.185)	0.8077** (0.2411)	0.642** (0.1728)	0.9239** (0.1969)	0.4591* (0.2052)	0.2313 (0.1609)
$distance_{ijt}$	-0.0651 (0.0643)	-0.204* (0.0814)	0.104 (0.0541)	-0.3648** (0.0617)	-0.3799** (0.0731)	-0.1903** (0.0573)

Variable (continued)	**Waste**	**Cement**	**light**	**Building**	**Methane**	**fuel injection**
$\sum_{k\neq i,j} distance_{kjt}$	-0.0018 (0.0027)	0.0045 (0.004)	-0.0146** (0.0025)	-0.0026 (0.0031)	0.0061 (0.0034)	0.0017 (0.0027)
$\sum_{k\neq i,j} trade\_bloc_{kjt}$	0.0276** (0.009)	-0.0358** (0.0127)	0.0427** (0.0085)	0.0056 (0.0086)	-0.0073 (0.011)	0.0417** (0.0084)
$\sum_{k\neq i,j} language_{kjt}$	-0.0441** (0.0114)	-0.0349* (0.0156)	-0.0553** (0.0103)	-0.0573** (0.0118)	-0.0127 (0.0138)	-0.0683** (0.0108)
$kyoto_{jt}$	0.0898 (0.0786)	0.1046 (0.1453)	0.1228 (0.0779)	0.0509 (0.0863)	0.1964 (0.1088)	0.2488** (0.0794)
$patent\_breadth$	-1.027** (0.4981)	-0.9939 (0.6586)	-1.901** (0.4766)	-1.36** (0.5018)	-0.3084 (0.614)	-0.1145 (0.5145)
$GDP\_percapita_{jt}$	0.037** (0.0089)	0.059** (0.013)	0.043** (0.0087)	0.072** (0.0085)	0.029* (0.012)	0.044** (0.009)
pop_{jt}	0.295** (0.0496)	0.3954** (0.0869)	0.1481* (0.0607)	0.538** (0.0581)	0.3275** (0.0747)	0.5123** (0.0459)
$elec\_renew_{it}$	0.0055** (0.0015)					
$construction_{jt}$		-1.214 (0.8201)	-0.168 (0.2509)	0.0424 (0.3522)		
$urban_{jt}$		0.0009 (0.0013)	0.0045** (0.0008)	0.0026* (0.001)		
$winter\_temp_{j}$				-0.0192* (0.0075)		
$agriculture_{jt}$					0.0364 (0.0238)	
gas_price_{jt}						0.3557** (0.0956)
$cars_{jt}$						0.0015** (0.0005)
$constant$	-2.677 1.479	3.8 532.5	3.201* 1.424	-4.273* 1.722	-4.772* 1.892	-7.415** 1.396
Log-likelihood	-6861	-2611	-8386	-6700	-4002	-8103
Observations	24148	15644	27688	26799	22288	29580

Annex 1. Proof of Proposition 1

By differentiating (1) with respect to n_{jjt}, we obtain the following M first-order conditions:

$$\frac{\partial W_t}{\partial n_{jjt}} = a_1 \left(n_{jjt}\right)^{a_1 - 1} \left(\prod_{k \neq j} n_{kjt} \right)^{a_2} K_{jt}{}^{a_3} D_{jt}{}^{a_4} - C_{jjt} = 0, \quad \text{for } j = 1,..M$$

Rearranging this expression, we obtain an expression of n_{jjt} which we will use in the following:

$$n_{jjt} = \left(\frac{C_{jjt}}{a_1 K_{jt}{}^{a_3} D_{jt}{}^{a_4}} \right)^{-\frac{1}{1-a_1}} \left(\prod_{k \neq j} n_{kjt} \right)^{\frac{a_2}{1-a_1}}, \quad \text{for } j = 1,..M \qquad \text{(A.1)}$$

Then the differentiation of (1) with respect to n_{ij} with $i \neq j$ yields the M (M-1) conditions

$$\frac{\partial W_t}{\partial n_{ijt}} = a_2 \left(n_{jjt}\right)^{a_1} \left(\prod_{k \neq j} n_{kjt} \right)^{a_2} (n_{ijt})^{a_2 - 2} K_{jt}{}^{a_3} D_{jt}{}^{a_4}$$

$$- C_{ijt} = 0, \quad \text{for } i, j = 1,..M \text{ and } i \neq j$$

Substituting (2) in each of these conditions and rearranging, we obtain

$$a_2 \left[a_1{}^{a_1} \left(C_{jjt}\right)^{-a_1} \left(\prod_{k \neq j} n_{kjt} \right)^{a_2} K_{jt}{}^{a_3} D_{jt}{}^{a_4} \right]^{\frac{1}{1-a_1}} (n_{ijt})^{a_2 - 2} = C_{ijt} \quad \text{for } i, j = 1,..M \text{ and } i \neq j$$

(A2)

Then, we multiply for each j the M-1 conditions (A2). This leads to

$$\prod_{k \neq j} n_{kjt} = \left[\prod_{k \neq j} c_{kjt} \right]^{1/Z} \left[a_2 \left(\frac{a_1^{\,a_1} K_{jt}^{\,a_3} D_{jt}^{\,a_4}}{C_{jjt}^{\,a_1}} \right)^{\frac{1}{1-a_1}} \right]^{\frac{1-M}{Z}} \qquad \text{for } j = 1,..M$$

where

$$Z = \frac{(M-1)a_2 + (a_2 - 2)(1-a_1)}{(1-a_1)}$$

We substitute this expression in (A2) and solve for n_{ijt}. This leads to

$$n_{ijt} = \alpha_0 K_{jt}^{\,\alpha_1} C_{ijt}^{\,\alpha_2} C_{jjt}^{\,\alpha_3} \left(\prod_{k \neq i,j} C_{kjt} \right)^{\alpha_4} D_{jt}^{\,\alpha_5}$$

where

$$\alpha_0 = \left(a_2 a_1^{\frac{a_1}{1-a_1}} \right)^{\frac{1-a_1}{a_2(M-1)-(2-a_2)(1-a_1)}}$$

$$\alpha_1 = \frac{a_3}{a_2(M-1)-(2-a_2)(1-a_1)}$$

$$\alpha_2 = -\frac{(M-1)a_2 - 2(1-a_1) - a_1 a_2}{\left[a_2(M-1)-(2-a_2)(1-a_1) \right](2-a_2)}$$

$$\alpha_3 = \frac{a_1}{a_2(M-1)-(2-a_2)(1-a_1)}$$

$$\alpha_4 = \frac{a_2}{\left[a_2(M-1)-(2-a_2)(1-a_1) \right](2-a_2)}$$

$$\alpha_5 = \frac{a_4}{a_2(M-1)-(2-a_2)(1-a_1)}$$

Research paper 3

Does foreign regulation influence domestic inventors? The case of renewable energy innovation

1 Introduction

The growing amount of data available to economists—especially patent data—has made it possible in recent years to empirically examine whether environmental regulation fosters innovation in environment-friendly technologies. The empirical literature in this field can be categorized in two groups. A first range of studies measures the level of regulation with pollution abatement and control expenditures (PACE). Jaffe and Palmer (1997) and Brunnermeier and Cohen (2003) show that stricter environmental regulation has a positive effect on the number of environment-related patents. In addition, Brunnermeier and Cohen (2003) find that government monitoring activities positively influence innovation. The other branch of the literature analyzes the impact of higher energy prices on innovation. Newell *et al.* (1999) find that increased energy prices in the US led to significant technological improvements in the energy efficiency of air conditioners and water heaters. Stricter energy efficiency standards play in the same direction.

Popp (2002) shows that higher energy prices in the US are associated with more innovations in energy-efficient technologies patented by US inventors in their country. Although energy prices are not a direct measure of environmental stringency, these results suggest that market-based instruments such as taxes or cap-and-trade systems can be expected to encourage innovative activity.

These studies only link innovation with *domestic* pollution control expenditures or energy prices. Yet, the market for technologies is increasingly global. In a recent study based on international patent data (Dechezleprêtre *et al.*, 2009), we found that around 25% of patented inventions are filed in several countries and that this share has been constantly growing since the end of the 1970s. Given that technologies are increasingly exported, an interesting question is whether, for example, an increase in energy prices in Europe would lead to more energy-efficient innovations in the US. Similarly, does stricter regulation in one country lead inventors from a second country to develop new technologies, with the aim to exporting them? Do inventors react more to factors affecting their domestic market than to those affecting their foreign markets? We attempt to answer these questions in this paper.

A few studies have started to explore the effect of stricter domestic and foreign regulation on the number of environment-friendly innovations. However, they come to diverging conclusions. Lanjouw and Mody (1996) find evidence that strict vehicles emissions regulations in the US spurred innovation in Japan and Germany, and that foreign inventors responded more to these regulations than US inventors. Popp (2006) finds that inventors of air pollution control devices for coal-fired power plants respond to environmental regulatory pressure in their own country, but not to foreign environmental regulation. Popp *et al.* (2007) examine the case of chlorine-free technology in the pulp and paper industry and find that both domestic and foreign regulation seem to influence innovation. In these three papers, however, the conclusions are based on correlation analysis, which may not provide sufficient evidence of causality. Whether these results can be supported by econometric evidence remains an open question.

This paper develops a methodology for empirically testing the effect of foreign regulation on domestic innovation in 30 OECD countries from 1990 to 2005. We focus our investigation on four renewable energy technologies: solar power, wind power, hydro, and geothermal energy. We use patent data from the World Patent Statistical Database (PATSTAT) to measure the development and the international diffusion of new inventions in each of these technologies. This method, used for example by Eaton and Kortum (1996, 1999), is made possible by the fact that a single invention may be patented in several countries.

The primary innovation of this paper is to construct a measure of the foreign regulatory level that potentially influences domestic inventors. Analyzing the effect of domestic and of foreign regulation on innovation requires both variables to be expressed in the same unit. PACE data are collected through surveys, which make them unsuitable for cross-country comparisons. Data on energy prices are a better candidate. However, in order to control for other factors affecting innovation, they must be complemented with regulatory data such as energy-efficiency standards, which are not always comparable across countries. In this paper, we use data on the amount of additional power capacity installed in a country in a given year to measure the level of pro-renewables regulations in that country. Since data on installed capacities are expressed in megawatts (MW), they allow for cross-country comparisons. This methodology allows us to jointly analyze the effect of domestic and foreign regulations on companies' innovation efforts.

The effect of foreign regulatory pressures on domestic innovation has important policy implications. To the extent that PACE or energy prices in different countries are positively correlated, overlooking this important aspect of the data might have led previous empirical studies to overstate the effect of domestic regulation on innovative activities.

The remainder of the paper is organized as follows. Section 2 describes the basic framework of our analysis. Section 3 presents the data and discusses the use of patents as indicators of innovation and technology diffusion. In section 4, we highlight some features of the data and present evidence of the importance of foreign markets for innovation. Our empirical findings are discussed in Section 5. A final section concludes.

2 Modeling framework

Our objective is to analyze the effect of a change in domestic or in foreign regulation on the innovation output of a country. We measure country i's innovation output by the number of inventions for which inventors from country i have sought patent protection. To avoid any double counting, inventions patented in several countries are only counted once. The number of inventions patented by inventors from country i in year t, N_{it}, is our dependent variable. We explain N_{it} as a function of domestic and foreign regulation and a number of control variables.

In line with previous studies on the determinants of innovation (e.g., Jaffe and Palmer, 1997; Newell, 1999; Popp, 2002) we use a log-log regression framework. Our basic specification is as follows:

$$\log(N_{i,t}) = \alpha_0 + \alpha_1 \log(R_{it}^d) + \alpha_2 \log(R_{it}^f) + \alpha_n X_{it} + \varepsilon_{it}$$

where R_{it}^d is the expected regulatory level in country i, R_{it}^f is the expected regulatory level in foreign countries, X_{it} is a vector of control variables and ε_{it} is the error term. The objective of our analysis is to estimate the elasticities α_1 and α_2.

2.1. Measuring domestic and foreign regulation

A practical challenge is to construct a measure of R_{it}^d and R_{it}^f, the expected domestic and foreign regulatory levels. In our estimations, we will use the amount of additional power capacity installed in country i in year t to measure the level of regulations promoting renewable energy that are in place in that country. We now explain why this variable can be used as a measure of regulation.

To be concrete, consider a wind turbine producer—call it WindCorp—that performs R&D activities. Assume for simplicity that it is the only wind company in country i, so that the number of inventions developed by WindCorp in year t is equal to N_{it}. The firm has to make a decision on (1) how many inventions to develop, and (2) in which countries to patent (and use) these inventions. When a single invention is patented in several countries, the international patent system makes it compulsory to file all patent applications within 18 months. Because this time period is relatively short, we can reasonably assume that WindCorp anticipates in which countries it will protect its technologies when deciding how many inventions to develop. Therefore WindCorp jointly makes the two decisions above: the company forms expectations about future demand for wind technology both in its own country *and* abroad and decides how many inventions to develop.

How can we measure the demand for new wind power technologies in country i? Wind power technologies are embodied in various components of wind turbines, such as rotors, blades, or electrical generators. Consequently, the demand for new technologies is directly related to the number of turbines to be installed in the next future. Although we do not have information on the number of wind turbines installed every year, the International Energy Agency provides data on added wind power capacity by country, measured in MW. We use annual added capacities—respectively in wind, solar, hydro, and geothermal power—to proxy the demand for new technologies. For any country i, we note $AddedCap_{it}$ the capacity added in year t.[29]

Importantly, WindCorp's decision depends on its *expectations* about future installations. We assume that these expectations are based on observations at year t.[30] This assumption is in line with previous studies. Newell et al. (1999) and Popp (2002) use past prices to proxy expected future prices[31]. Brunnermeier and Cohen (2003) use current PACE to measure perceived regulatory stringency, while Jaffe and Palmer (1997) use lagged values of PACE.

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[29] Denoting $Capacity_{it}$ the installed capacity at year t, $AddedCap_{it} = Capacity_{it} - Capacity_{it-1}$.

[30] We use several lagged specification to test the robustness of this assumption.

[31] Newell et al. (1999) use a three-year lag of energy prices. Popp (2002) uses an average of past prices weighted by an adjustement coefficient which is endogeneously determined in the model. He finds an average lag of about 4 years between a change in price and a change in innovation activity.

Our use of current demand as a measure of producers' expectations about future demand may lead to a bias in our estimates (see Newell et al., 1999, for a discussion on this issue). The reason is that annual added capacities are likely to exhibit greater variation than the true expectations of added capacities for which they are used as a proxy. However, this can only bias the coefficient downward. As a result, our results may underestimate the effect of new domestic and foreign power capacities[32].

Another possibility would be to assume that producers form rational expectations about future demand and to use the discounted sum of real future added capacities as a measure of producers' expectations. However, this solution has two major weaknesses. First, assuming rational expectations is likely to prove unrealistic given the uncertainty about future regulation and long-term fossil fuel prices. Secondly, using future added capacities introduces a causality problem in the estimation, because innovations patented in year t may reduce the cost of producing wind turbines, which would in turn induce new power capacities[33]. Using added capacities in year t eliminates this problem since inventions patented in year t cannot have an influence on installations built the same year.

Since the deployment of renewable energies is largely attributable to government regulation, installations of new power capacities are also a proxy for the level of pro-renewables policies in place in each country. Using added

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[32] Moreover, the IEA only provides data on net added capacity. If some power plants are dismantled and others are constructed, we underestimate the actual amount of new capacities. Again, this can only lead to downwardly biasing our estimates.

[33] Many inventions in the field of renewable energy are developed in order to cut production costs. For example, the primary aim of research on thin films is to reduce the production cost of solar panels.

capacities as a proxy for pro-renewables policies is similar to using PACE as a proxy for environmental regulation. Pro-environment regulation leads to investments in pollution abatement devices, which are measured by PACE. Similarly, national energy policies induce investments in renewable energy, which are reflected by added power capacities. The difference is that PACE are expressed in monetary units whereas added power capacities are expressed in MW.

The advantage of focusing on renewable energy is that we can directly observe the output of the policy process. Many policies, such as feed-in tariffs, tax rebates, or investment subsidies, support the deployment of renewable energy worldwide. An overview of these measures is available from the Global Renewable Energy Policies and Measures database[34] maintained by the International Energy Agency. The number of policies that are in place at the same time makes it difficult to analyze the specific impact of each of them. It is however possible to analyze their joint effect by focusing directly on the result of these policies.

Neither wind nor solar power offer a competitive alternative to conventional sources of electricity on the power grid during the time-period covered by our analysis (see Lorenz et al., 2008, for an economic analysis of solar power). Added power capacities are therefore a good measure for the level of regulation promoting these energies. We recognize, however, that mature technologies such as hydro power may be less dependent upon government regulation. In this technology, our study nonetheless provides an interesting insight into the cross-border determinants of innovation.

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[34] http://www.iea.org/textbase/pm/grindex.aspx

There are many reasons to suspect that the market in country *j* actually taken into consideration by innovators from country *i*—referred to as the *accessible* market—is smaller than the total market in country *j*. Barriers due to geographical distance or language may even prevent inventors from country *i* to consider the market in country *j* at all. For this reason, we do not measure country *i*'s accessible foreign market simply as the sum of the capacities added in the rest of the world in year *t*.

To construct a measure of the accessible foreign market, we adapt the methodology used by Coe and Helpman (1995). The objective of Coe and Helpman (1995) is totally different from this paper's. They study the extent to which a country's total factor productivity depends not only on domestic R&D capital but also on foreign R&D capital. Coe and Helpman (1995) define country *i*'s foreign R&D capital as the sum of the R&D stock of its trade partners, weighted by bilateral import shares.

Similarly, we measure the market in country *j* accessible to inventors from country *i* as the amount of capacities added in country *j* weighted by the share of patents filed by inventors from country *i* in country *j*, noted s_{ijt}. More precisely:

$$s_{ijt} = \frac{n_{ijt}}{\sum_i n_{ijt}}$$

where n_{ijt} is the number of technologies patented in country *j* by inventors from country *i* in year *t*, and $\sum_i n_{ijt}$ is the total number of patents filed in country *j* in year *t*. Following Lichtenberg and van Pottelsberghe de la Potterie (2001), we use a three-year moving average of market shares, in order to mitigate the effect of annual fluctuations.

For example, in 2005, US inventors represented 54% of all wind power patents filed in the US, 22% in Canada, 12% in Taiwan, 2% in Germany and 1% in Japan. We use these figures to measure the share of each market accessible to US inventors – including, as a matter of consistency, the US market. It is important to keep in mind that s_{ijt} represents country *i*'s share on the innovation market and is only an imperfect proxy for the market share on the product market. In the model, we use these market shares to measure the domestic and foreign regulatory level that potentially influences inventors from country *i*:

$$R_{it}^{d} = s_{iit}.AddedCap_{it}$$

$$R_{it}^{f} = \sum_{j \neq i} s_{ijt}.AddedCap_{jt}$$

where $AddedCap_{jt}$ is the capacity added in year *t* in country *j*.

A simpler alternative method would be to define R_{it}^{f} as the sum of the capacities added in the rest of the world in year *t*. With respect to this method, the main advantage of the weighting strategy is that the weights take into account all factors other than market size that are difficult to observe but affect the diffusion of technologies. These include geographical factors—such as distance, language, trade blocks, and cultural differences—and institutional factors—e.g., tariffs, the quality of the patent system—that have been shown to influence the market diffusion of technology (see Keller, 2004, for a review of these factors). Moreover, we partly control for the effects of competition on technology diffusion: A high degree of competition in country *i* negatively affects the expected profitability of patented technologies, which provides a disincentive for firms to patent in country *i*.

2.2 Control variables

Empirical evidence shows that the level of innovation depends on previously accumulated knowledge stock (Popp 2002, 2006). We include the local knowledge stock available to inventors as a control variable for technological opportunity. Following Peri (2005), the knowledge stock is calculated using the perpetual inventory method. Let Kn_Stock_{it-1} be the discounted stock of previously filed patents in the technology in country *i* at date t–1. We initialize patent stocks for the year 1977 and use the recursive formula:

$$Kn\_Stock_{it-1} = (1-\delta)Kn\_Stock_{i,t-2} + P_{it-1}$$

where P_{it-1} is the number of patents filed in country *i* in year *t-1*. The value chosen for δ, the depreciation of R&D capital, is 10%, a value commonly used in most of the literature (see Keller, 2002). Our patent data go back to 1978 so we set the initial value of knowledge stock at $Kn\_Stock_{i,1977} = 0$. Setting the initial value of knowledge at 0 has an insignificant influence on the results since we only start the regression analysis in 1990. Note that using S_{jt-1}—i.e., lagging the variable by one year to predict transfers in year *t* given the stocks in year *t*-1—eliminates the potential problem of endogeneity.

Finally, country fixed-effects control for any time-invariant differences in inventor countries' characteristics that may influence their innovation performance and for cross-country differences in the propensity to use patents as a means of protecting new inventions. Year dummies account for time-specific events, such as economic downturns, that could have OECD-wide effects on the pace of innovation.[35]

3 Data

3.1 Patent data

Our data set includes all patents filed worldwide from 1990 to 2005 in four renewable energy technologies: wind, solar, geothermal, and hydropower. The description of the technologies covered as well as the IPC classes can be found in paper 1. Our dataset includes 49,601 patent applications filed in 72 countries[36].

Patent data have been extensively used as a measure of innovation, and more recently as a measure of technology diffusion. The advantages and the limitation of this indicator have been discussed in the previous papers (for a good overview, see OECD 2009). For this paper, the main advantage of patent data is that they indicate not only the countries where inventions are made, but also where these new technologies are used. These features make our study possible.

A patent gives an inventor the exclusive right to use an innovation in a country. Because patents are granted by national patent offices, inventors must file a patent in each country in which they seek protection. The first patent application of an invention is called the priority. The set of patents protecting the

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[35] 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*. To ensure that this asymmetry between US and non-US data does not affect our results, we include a pre-2001 US dummy variable in our regressions.

[36] Note that Least Developed Countries are not present in our dataset, for two related reasons: their patenting activity is extremely limited, and available statistics are not reliable.

same invention in several countries is called a patent family. A remarkable advantage of using an international patent database is that it includes every patent family. For every patented innovation in the world, we know where it was invented and the set of countries where it is used.

In this study, patents are dated by their priority year. For innovations patented in several countries, this corresponds to the earliest application year. Once patent protection has been asked for in a country, inventors must file subsequent patents in other countries within 18 months. Patents filed in 2006 but pertaining to inventions first filed in 2005 in another country are thus included in the data set. This way our data cover the comprehensive diffusion of all inventions developed worldwide between 1990 and 2005.

3.2 Data on installed power capacity

Data on installed capacities for renewable energy production are taken from the International Energy Agency (IEA) Renewables information database[37]. They are available for all OECD countries from 1990 onwards. For non-OECD countries, the IEA only provides data on energy production by technology. For each technology, we have run a pooled linear regression of energy capacities on energy production, using the data from OECD countries from 1990 to 2006. We use these models to make out-of-the-sample predictions of capacities in non-OECD countries based on their production. This allows us to proxy the demand in non-OECD countries, which might influence inventors located in OECD countries. The results of these regressions are shown in Table 2. The quality of

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[37] Available at http://data.iea.org/

the estimations is very good (with R-squared between 0.83 and 0.96), except for solar power.[38]

Table 2. Regression results of capacities on production

Variable	Hydro	Solar	Wind	Geothermal
Production	2.962** (0.0519)	6.107** (0.4087)	6.795** (0.0619)	0.2016** (0.0019)
Constant	2936** (392.6)	488.2** (103.5)	-15.44 (19.45)	-25.26** (5.143)
R-squared	0.87	0.31	0.96	0.96

Notes: Standard error in parentheses; ** denotes significance at 1% level.

4 Descriptive statistics

In this section we highlight some features of the data and provide some evidence on the influence of foreign markets on innovators.

4.1. Innovation activity and power capacity at the global level

Figure 1 shows the trend in innovation activity and installed capacity between 1990 and 2006 for each technology. With around 400 GW of capacity worldwide and a low growth rate, hydro power is a very mature technology. The growth rate in geothermal capacity is also very low, although this technology is still marginal. Solar and wind power are growing rapidly.

The number of yearly inventions across the world has increased in all technologies. In wind and solar power, the total number of inventions per year has more than tripled since 1990, whereas the increase in much smaller in hydro

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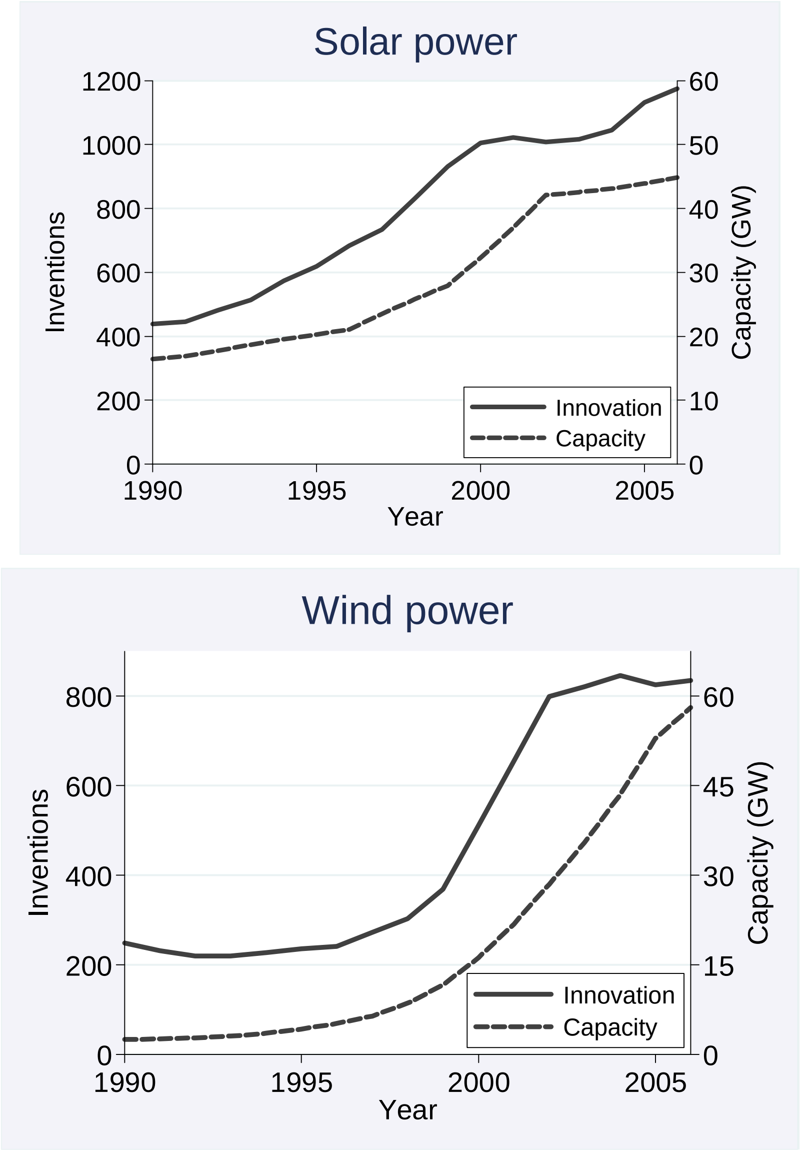
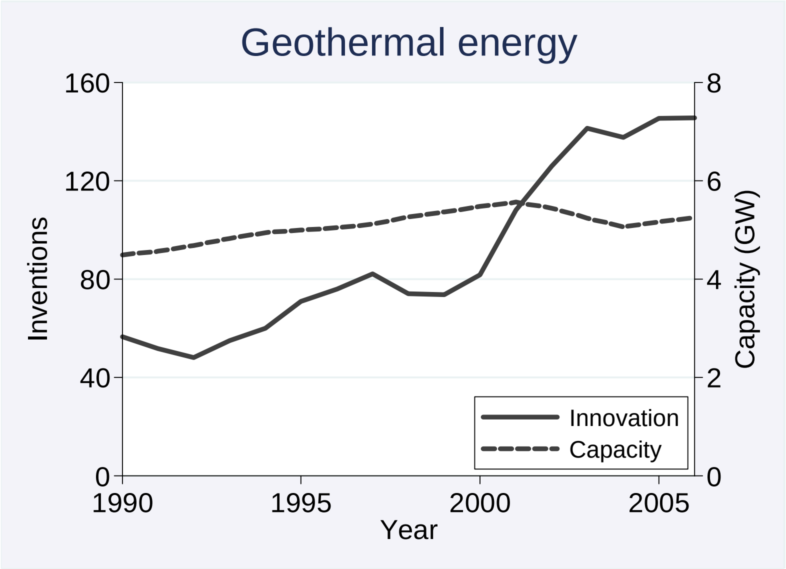
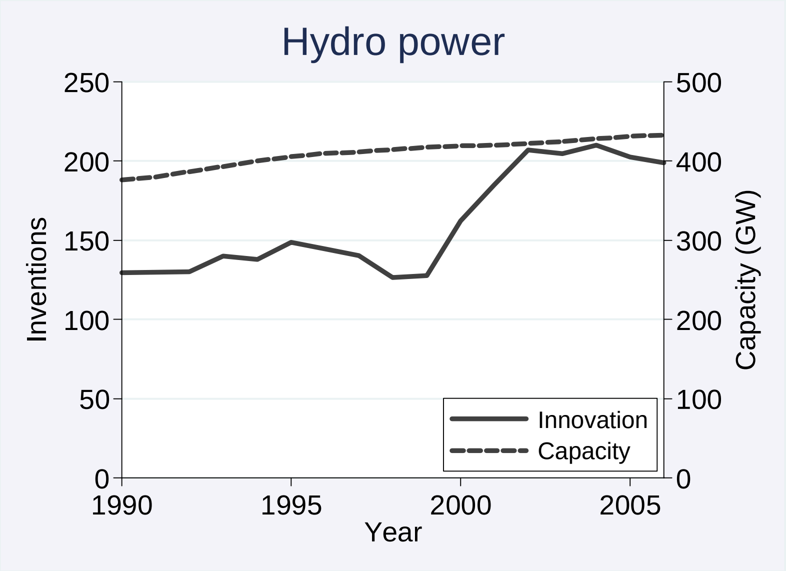
[38] The reason is that data on solar capacity include all individual solar panels for which there is no corresponding data on production.

power. Interestingly, there has been a temporary acceleration in innovation activity at the end of the nineties and the beginning of the years 2000 across all sectors. This suggests that the signing of the Kyoto protocol in 1997 may have rapidly induced more innovation in low carbon technologies.

Figure 1. Worldwide innovation activity and installed capacities







From Figure 1, we can see that innovation is correlated with installed power capacity. At the global level, the deployment of new power capacity corresponds to increases in the number of inventions. The correlation is almost perfect in solar and wind power but is lower in geothermal and hydro power. This suggests that the determinants of innovation may be different between mature technologies and technologies undergoing rapid deployment. In these fields, the data show that innovators keep patenting new inventions, even when installed capacities are stable (hydro) or decrease (geothermal). The rise in innovative activity around the year 2000 in geothermal and hydro power did not correspond to a comparable increase in installed capacities.

4.2. The importance of foreign patenting

Table 3 presents information about international technology flows. Overall, 41% of the patents in the data set are filed by foreign inventors (see column 2). The proportion of patents filed by a foreign inventor ranges from 28% to 42% depending on the technology. These figures are suggestive of a clearly global market for renewable energy technologies.

What is the proportion of inventions that cross borders? As shown in table 3 (column 3), the majority of patents seem to be designed for local markets. International patent families—invention filed in two or more countries—represent 17% of inventions on average between 1990 and 2005. The percentage ranges from 11% (hydro) to 20% (geothermal). This share is relatively constant over time, except wind power for which there has been a significant increase in technology exports since 2000. Table 4 shows the rate of export for the 10 main inventor countries within OECD. Interestingly, export rates vary widely across countries. Around 30% of US and German inventions are exported, but the export rate is below 10% for Japan and South Korea.

Although exported inventions make up only 17% of all inventions, they are patented in around four countries on average (including the country of origin). Table 5 presents the distribution of the size of patent families over all technologies. This distribution is much skewed. The largest patent family in our data set includes 26 countries. Around 1% of inventions are patented in 10 countries or more. These figures show that foreign markets clearly matter for inventors.

Table 3. Export rate of inventions, international patent family size and proportion of foreign patents

Technology	Share of foreign patents	Export rate of inventions	Average number of countries
Geothermal	34.8 %	20 %	3.9
Hydro	28.3 %	11 %	4.4
Wind	41.9 %	16 %	4.7
Solar	33.2 %	17 %	4.0
All technologies	35.8 %	17 %	4.2

Table 4. Export rate for the 10 main OECD inventor countries

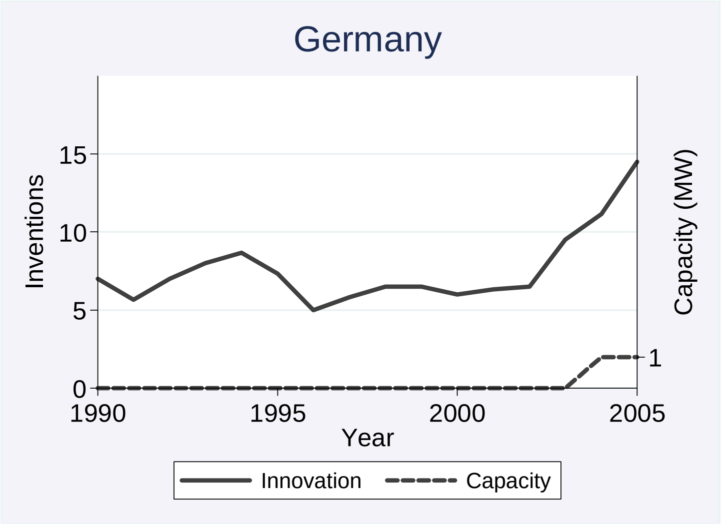
Country	Export rate
Canada	31.4 %
France	33.8 %
Germany	33.7 %
Japan	9.1 %
Netherlands	41.2 %
S Korea	7.6 %
Spain	34.7 %
Sweden	89.2 %
UK	38.9 %
USA	28.3%

Table 5. Frequency distribution of the size of patent families (all technologies)

Family size	Frequency distribution (%)
1	83.5
2	6.3
3	3.2
4	2.2
5	1.5
6	0.9
7	0.7
8	0.4
9	0.4
10+	0.9

Figure 2 illustrates the importance of foreign markets for innovators. Looking at geothermal energy, we find that one of the main innovators in this field is Germany. As shown in Figure 2, German inventors patented between 5 and 15 inventions annually between 1990 and 2005. However, there was no geothermal power plant operating in Germany until the first opened in November 2003, and in 2005 the geothermal power capacity in Germany only amounts to 1 MW. All German inventions between 1990 and 2005 were developed for foreign markets. For example, 13 German patents were filed in the US.

Figure 2. Innovation and domestic capacity in geothermal energy



5 Estimation and results

5.1 Econometric issues

Recall that our dependent variable is N_{it}, the number of inventions patented by inventors from country i in year t.[39] We explain N_{it} as a function of domestic and foreign market demand, fixed-effects for each inventor country, year dummies, and a control variable for technological opportunity. We estimate the following equation[40]:

$$\begin{aligned}\log(1+N_{it}) = \alpha_0 + \alpha_1 \log(R_{it}^{d}) + \alpha_2 \log(R_{it}^{f}) \\ + \alpha_3 \log(Kn\_Stock_{it\text{-}1}) + \beta_i + \gamma_t + \varepsilon_{it}\end{aligned} \qquad (1)$$

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[39] Almost all patents are first filed in the home country of the inventor. This characteristic of the patent system is known as the home-bias. Therefore we do not add up patents filed in various patent offices to construct the dependent variable. This would cause a serious problem because of the heterogeneity of national patent systems.

[40] Since the number of patents filed in a given year frequently equals 0, we use log(1+ N_{it}) as the dependent variable.

where i indexes country and t indexes time. R_{it}^{d} is the expected regulatory level in country i, R_{it}^{f} is the expected regulatory level in foreign countries, Kn_Stock_{it-1} is a control variable for technological opportunity, β_i is a vector of fixed-effects for each inventor country, γ_t is a vector of year dummies and ε_{it} is the error term. The vectors of coefficients α_i, β_i and γ_t are specific to each technology.

In the basic specification, we do not impose any lag structure. Although patents are filed early in the R&D process (Griliches, 1990), the decision to perform R&D activity is taken prior to the patent filing. Therefore we use different lags of R_{it}^{d} and R_{it}^{f} as robustness checks.

We have constructed a panel data set for each of the five technologies. This is a strong point of our study: estimating the model on each technology allows us to control for technology-specific factors. The panels extend over 16 years, from 1990 to 2005 and cover the 30 OECD countries. Descriptive statistics for the variables used in the analysis are shown in tables 6 to 9.

Table 6—Descriptive statistics: wind power

	Obs.	Mean	Std. Dev.	Min	Max
$\ln(1+N_{it})$	480	1.49	1.47	0.00	6.37
$\ln(R_{it}^{d})$	480	1.46	1.82	0.00	7.93
$\ln(R_{it}^{f})$	480	2.00	1.88	0.00	7.01
$\ln(Kn\_Stock_{i,t-1})$	480	4.01	1.68	0.00	8.35

Table 7—Descriptive statistics: solar power

	Obs.	Mean	Std. Dev.	Min	Max
$\ln(1+N_{it})$	480	0.49	0.86	0.00	4.18

$\ln(R_{it}^{d})$	480	0.13	0.62	0.00	4.43
$\ln(R_{it}^{f})$	480	0.21	0.62	0.00	3.56
$\ln(Kn\_Stock_{i,t-1})$	480	2.36	1.26	0.00	6.13

Table 8—Descriptive statistics: hydro power

	Obs.	Mean	Std. Dev.	Min	Max
$\ln(1+N_{it})$	480	0.71	1.03	0.00	4.68
$\ln(R_{it}^{d})$	480	1.70	2.08	0.00	7.27
$\ln(R_{it}^{f})$	476	2.05	2.72	0.00	8.11
$\ln(Kn\_Stock_{i,t-1})$	480	2.43	1.42	0.00	6.81

Table 9—Descriptive statistics: geothermal

	Obs.	Mean	Std. Dev.	Min	Max
$\ln(1+N_{it})$	480	1.32	1.29	0.00	5.73
$\ln(R_{it}^{d})$	480	1.62	1.98	0.00	7.78
$\ln(R_{it}^{f})$	480	1.72	1.82	0.00	6.97
$\ln(Kn\_Stock_{i,t-1})$	480	3.45	1.50	0.00	7.42

Recall that for we do not have data on installed power capacities in non-OECD countries. In order to limit this problem, we focus our analysis on innovations made by inventors located in OECD countries only. However, inventors from OECD countries may hold patents in non-OECD countries[41]. In this case, we calculate power capacities in non-OECD countries using the model presented in section 3. Note that across the four technologies only 6.5% of inventions made in OECD countries between 1990 and 2005 have been patented in non-OECD countries. Thus the fitted values used in the analysis represent a

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[41] In other words, we may have $s_{ijt}>0$, with i indexing OECD countries and j indexing non-OECD countries.

small part of the sum of foreign capacities weighted by market shares and this should not affect our estimations much.

We estimate equation (1) using linear fixed effects model. We also used a random effects model, but in all regressions, a Hausman test rejects the hypothesis that unobserved heterogeneity is uncorrelated with the explanatory variables. This supports the inclusion of country fixed-effects.

5.2 Estimation results

Estimation results of equation (1) are shown in table 8.

Table 8—Estimation results

Variable	Solar	Geothermal	Hydro	Wind
R_{it}^{d}	0.062*** (0.0189)	0.0371 (0.039)	0.0551*** (0.0155)	0.1285** (0.0279)
R_{it}^{f}	0.2174*** (0.0254)	0.1235*** (0.0396)	0.1155*** (0.0139)	0.2056*** (0.0261)
$Kn\_Stock_{i,t\text{-}1}$	0.0586 (0.0552)	0.2034*** (0.0568)	-0.0484 (0.067)	0.0517 (0.056)
Constant	1.067*** (0.2465)	0.2023 (0.1564)	0.697*** (0.1962)	0.5226* (0.2681)
Observations	480	480	476	480

Notes: Standard error in parentheses; * denotes significance at 10% level, ** denotes significance at 5% level, *** denotes significance at 1% level.
All equations include unreported fixed effects and year dummies.

Our results indicate that the increase of domestic power installations has a positive effect on innovation in solar, wind and hydro power, but not in geothermal energy. The foreign growth of capacities also exerts a positive influence on the number of new inventions in all regressions. The coefficient is significant at the 1% level in all regressions. This shows that innovators react to a growing domestic or foreign market by increasing their innovation efforts. This result is robust across alternative specifications using different lags of domestic and foreign regulatory levels.

As explained in section 2, the demand for renewable energy is primarily driven by regulatory measures, such as investment tax credits, R&D subsidies, guaranteed tariffs and renewables obligations. Hence, our results suggest that pro-renewables policies have a positive effect on innovation efforts both at home and abroad. Put differently, companies respond to domestic and foreign regulatory pressures by increasing their innovation efforts.

Our results show that the elasticity of innovation to domestic and foreign market varies across technologies. A 10% increase in the size of the domestic market leads to 3% to 12% increase in the number of innovations, depending on the technology, while a 10% increase in the size of foreign markets increases the number of domestic innovations by 11% to 21%. In solar, wind, and hydro power, innovators respond more to an increase in foreign capacities than to an increase in domestic capacities. A possible explanation for this result is that inventions patented abroad are of highest value, as shown by Lanjouw and Mody (1998). In geothermal energy, innovators respond only to increases in foreign capacities. This suggests the importance of foreign markets in geothermal power. Recall that the export rate of geothermal inventions is the highest among the four technologies.

Finally, note that the discounted patent stock has a statistically significant effect on innovation in two sectors only. This result may be due to the fact that we do not control for the quality of previously accumulated knowledge. The usual way of controlling for this quality is to weight patents by the forward citations they receive (see e.g. Popp, 2002). However the Patstat database does not include citations for every patent office[42] and this prevents us from using this method. Diminishing returns to research over time may explain why we observe a negative effect of the knowledge stock in hydro power. In this very mature technology, new inventions become harder to make as the pool of opportunities has been mainly exploited.

5.3 The consequences of omitting foreign markets

What is the consequence of omitting the effect of foreign markets on domestic innovation? To answer this question we run the same regressions and simply omit R_{it}^{f}. The results are presented in Table 9. If we compare these results with Table 8, we find that omitting R_{it}^{f} produces a biased estimation of the effect of domestic regulation. In all equations, the coefficient of the domestic regulation is biased upward. The reason is that domestic and foreign regulation are positively correlated, as shown in Table 10.

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[42] Moreover, using citations as a measure of knowledge flows is not appropriate for European patents since—contrary to the US patent office—most citations are included by the patent office examiner and not by the inventor himself.

Table 9—Estimation results, omitting foreign demand

Variable	Solar	Geothermal	Hydro	Wind
R_{it}^{d}	0.0753*** (0.0203)	0.0192 (0.039)	0.0734*** (0.0163)	0.1982*** (0.0283)
$Kn\_Stock_{i,t\text{-}1}$	0.0526 (0.0597)	0.1898*** (0.0572)	0.0126 (0.0723)	0.0172 (0.0596)
Constant	1.53*** (0.2599)	0.2623* (0.1568)	0.7851*** (0.2121)	1.002*** (0.2789)
Observations	480	480	480	480

Notes: Standard error in parentheses; * denotes significance at 10% level, ** denotes significance at 5% level, *** denotes significance at 1% level.
All equations include unreported fixed effects and year dummies.

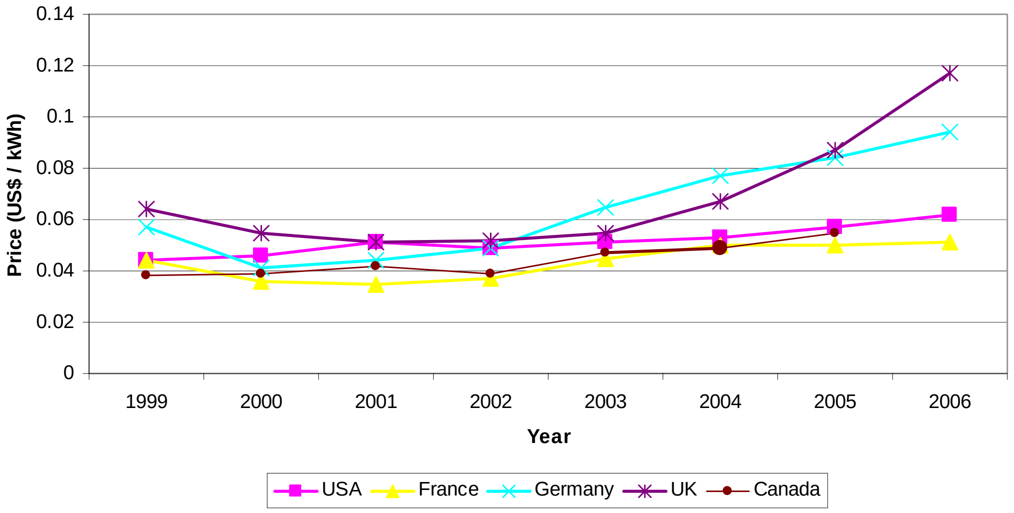
Table 10. Correlation between the evolution of domestic and foreign markets

Technology	Correlation
Solar	0.44
Wind	0.76
Geothermal	0.29
Hydro	0.45

This result suggests that previous empirical studies using patents to examine the determinants of innovation might have overlooked an important aspect of the data. For example, Popp (2002) uses a data set of patents filed at the US patent office and shows that energy prices in the US have a positive effect on the number of energy-efficient innovations patented by US inventors. Yet, US inventors are likely to be influenced by energy prices on their export markets. As shown in Figure 3, electricity prices in industry in the US and its trade partners are highly correlated. Therefore the elasticity of innovation to energy prices available in Popp (2002) may be upwardly biased. For similar reasons, the studies by Jaffe and Palmer (1997) and by Brunnermeier and Cohen (2003) might have overestimated the effect of domestic environmental regulation (as proxied by pollution abatement and control expenditures) on domestic innovation.

Figure 3. Electricity prices for industry in five countries, 1999-2006

(Source: US Department of Energy)



6 Conclusion

In this paper, we use patent data from 72 countries to analyze the influence of domestic and foreign regulation on innovation activity in four renewable energy technologies between 1990 and 2005. While previous papers focus on a single country, our data allow us to investigate the cross-border drivers of innovation.

Our results unambiguously show that companies' efforts to produce new innovations, as measured by the number of patents filed, increase in response with increases in new power capacities both at home and abroad. Since the deployment of renewable energy is the result of pro-renewable regulation, our results suggest that environmental regulation has a positive effect on domestic and foreign innovation.

The results of this paper have important policy implications. First, we show that previous studies of the effect of regulation on innovation might have overestimated the effect of regulation on domestic inventors. Part of this effect found in these studies might in fact be due to *foreign* regulation. Given the degree of the world's economic integration, analyses of the impact of regulation on innovation that do not control for the potential effect of foreign regulation are likely to produce biased estimates.

In the context of climate change mitigation, the global interdependencies uncovered here mean that technology exporters are likely to benefit from carbon emissions reduction commitments taken by foreign countries. In the context of Kyoto protocol, this means that US inventors are likely to benefit from carbon emissions reduction commitments taken by Japan and European countries. This problem should be taken into account for the design of international climate agreements.

Our findings suggest that companies are likely to respond to foreign regulatory pressures by increasing their innovation efforts. Governments seeking to encourage domestic innovation through stricter regulation may view this situation as an externality. They may be reluctant to pass new regulation for fear that it benefits to foreign innovating companies. This can lead to under-provision of regulation. In the context of a global climate change mitigation agreement, this concern may be addressed by increasing the number of signatory countries.

Part 2

Technology transfer in the Clean Development Mechanism

Research paper 4

The Clean Development Mechanism and the international diffusion of technologies: an empirical study[43]

1. Introduction

The Clean Development Mechanism (CDM) is one of the most innovative tools of the Kyoto Protocol. It allows industrialized countries which have accepted emissions reduction targets to develop or finance projects that reduce greenhouse gas (GHG) emissions in non-Annex 1 countries[44] in exchange for emission reduction credits. Since reducing GHG emissions in a less-developed country may be cheaper than doing so domestically, it helps Annex 1 countries to

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[43] This chapter is based on an article published as: Dechezleprêtre, A., Glachant, M., Ménière, Y. (2008). The Clean Development Mechanism and the international diffusion of technologies: an empirical study. *Energy Policy* 36, 1273–1283.

[44] Non-Annex 1 countries have also ratified the Kyoto Protocol but do not have any emissions reduction targets. This group has 148 members and is mainly comprised of developing countries. Large GHG emitters such as China, India, Brazil and Mexico belong to this group.

achieve their emission reduction target at a lower cost and it should contribute to the sustainable development of the host countries (see Ellis et al., 2007, for an up-to-date discussion on the CDM).

While its primary goal is to save abatement costs, the CDM is also considered by many as a key means to boost technology transfer and diffusion. If the technology used in the project is not available in the host country but must be imported, the project leads, de facto, to a technology transfer. This technology may consist of "hardware" elements, such as machinery and equipment involved in the production process, and/or "software" elements, including knowledge, skills, and know-how (OECD, 2005). Note that the CDM did not originally have an explicit technology transfer requirement in the Kyoto Protocol. This was included later in the 2001 Marrakech Accords.

Expecting international technology transfer through CDM projects sounds reasonable. However whether this is true in practice is an empirical question. In this paper, we use a dataset describing the 644 CDM projects registered up to May 1st, 2007 in order to explore this issue. More precisely, we address two types of questions. The first are descriptive. How often do CDM projects include a transfer of technology from abroad? In which sectors? Which types of technologies are transferred? Which countries are the main recipients? Who are the technology suppliers?

The second set of questions is more analytical. Using regression analysis, we investigate what drives technology transfer in the CDM. This provides insights into a range of questions. Do the host country's technological capabilities influence technology transfer? Does the presence of an official credit buyer in the project's partnership promote transfer? Is a transfer more likely in projects implemented in subsidiaries of companies based in industrialized countries?

The transfer of environmentally sound technologies in the context of climate change mitigation has recently attracted much attention in the literature. Some papers introduce technology transfer mechanisms into integrated assessment models of climate change (Yang, 1999; Jacoby *et al.* 2004; Yang and Nordhaus, 2006; Bosetti *et al.*, 2007 and 2009). Numerous case studies of successful technology transfers have been conducted in order to assess the drivers for and barriers to technology adoption (for instance, OCDE/IEA, 2001; Kathuria, 2002; Kline *et al.*, 2003; Ockwell *et al.*, 2008; Cai *et al.* 2009). With regard to the design of global climate policies, growing attention has turned to the possible role of technology-oriented agreements (TOAs) as part of the architecture of a post-Kyoto agreement (see, for example, Buchner and Carraro, 2005; Barrett, 2007; de Coninck *et al.*, 2008).

In contrast, only two papers deal with technology transfer through CDM projects using a quantitative approach[45]. Based on a limited sample of 63 registered projects, De Coninck et al. (2007) show that imported technologies originate mostly from the European Union and that the investments from industrialized countries associated with the CDM are small when compared to total foreign direct investments. Haites et al. (2006) work on a larger database involving 860 projects. They find that technology transfers occur in one third of

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[45] Since the publication of our paper, several other empirical analyses have been conducted. These analyses include Seres (2007 and 2008), Schneider et al. (2008) and Doranova et al. (2009).

the projects, accounting for two thirds of the annual emission reductions. Larger projects and those with foreign participants tend to induce technology transfer.

We depart from these papers in two respects. First, our data set provides a richer description of the countries hosting the CDM projects and of the countries supplying the technologies. It also describes in greater detail the participants involved in the projects. Second—and this is related to the previous point—a richer set of independent variables allows to run regressions that explain the technology transfer[46]. This gives insights into the design variables of the CDM that promote technological transfer, thereby leading to potentially useful policy lessons. More generally, it helps deepen our understanding of the transfer of GHG mitigation technologies, which could be useful in the current debate surrounding post-Kyoto talks.

The remaining of paper 1 is as follows. In section 2, we describe the data set. Section 3 includes the descriptive results regarding technology transfers. The econometric analysis is carried out in Sections 4 and 5. We investigate what drives not only the transfer but also the type of transfer (equipment or knowledge). Section 6 concludes.

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[46] The paper by Haites et al. (2006) also includes a regression. But its explanatory power is weak as independent variables are essentially country and sector dummies.

2. Data issues

2.1 Sources

In this section, we describe how we construct the data set. CDM projects that result in real, measurable and long-term climate mitigation benefits in non-Annex 1 countries are registered by the Executive Board of the UNFCCC. Our data describes all the 644 projects registered as of May 1st, 2007. These projects account for an expected 888.5 million tons of CO_2-equivalent ($MtCO_2eq$) emissions reductions by the end of 2012.

We use three main information sources to describe these projects: 1) the UNEP Risoe Center CDM Pipeline database[47], 2) the so-called Project Design Documents, and 3) data from international institutions such as the World Bank and the World Trade Organization for country-level economic and technological variables.

For every CDM project, the UNEP Risoe Center CDM Pipeline database includes the host country, the type of technology, the estimated amount of the annual emissions reductions, the cumulative emissions reductions to the end of the Kyoto period (31 December 2012) and the countries that will buy the carbon credits generated by the project (if already available). We have also collected the registration dates of each project and the name of every country involved, on the UNFCCC website dedicated to CDM projects[48].

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[47] The database is available at http://cdmpipeline.org/

[48] http://cdm.unfccc.int/Projects/index.html

The content of the Project Design Documents (PDD) is our main source of information. They are mandatory standardized documents of about 50 pages submitted to the Executive Board by the project developers for registration. In the PDDs, we have collected information about the technology used, whether there is a transfer or not, the type of transfer, the project implementer (name, business sector and name of parent company) and every foreign partner involved (name, location). We have also retrieved information on the role of the project partners: are they credit buyers, consulting companies, PDD consultants or equipment suppliers?

Host country characteristics, including information on GDP, trade or FDI flows have been obtained from the World Bank's World Development Indicators 2006[49]. We have completed this information with economic performance indicators from the Earth Trends database of the World Resource Institute[50]. To proxy the technological capability of a country to import and use advanced technology, we have used the composite index Arco developed by Archibugi and Coco (2004).

2.2 Information on technology transfers

Given our questions, it is worth describing carefully how we encode information on technological transfers. To begin with, we define technology transfer as the import of a technology from abroad.

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[49] Available online at http://devdata.worldbank.org/wdi2006

[50] http://earthtrends.wri.org/

We consider two forms of technology transfer. The first, which we call a *knowledge transfer*, takes place if the local project developer benefits from the transfer of knowledge, know-how, information or technical assistance from a foreign partner. The second form is an *equipment transfer*. It consists in importing equipment, such as wind turbines or gas burners, from a supplier located in a foreign country. Of course, a project can involve both a transfer of equipment and a transfer of knowledge.

We get this information from the PDDs. In these documents, the technology to be employed in the project activity is described in section A.4.3. The Guidelines for completing the PDD available from UNFCCC indicate that "this section should include a description of how environmentally safe and sound technology, and know-how to be used, is transferred to the host Party(ies)." But this is not a compulsory requirement, and no section is specifically devoted to technology transfer. Indeed, claims of technology transfer can often be found in other sections such as "Description of the project activity" (A.2) or "Barrier analysis" (B.4). Section G ("Stakeholders' comments") sometimes contains interesting information on equipment suppliers. Further information on the technology employed may also be displayed in the annex. In order to get relevant information, we have read carefully all the PDDs.[51]

In order to illustrate how we have proceeded in practice, consider two examples. Project #247 involves a *knowledge transfer*. It consists in replacing fossil fuel with biomass in the production of cement at Lafarge Malayan Cement

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[51] For efficiency purposes, we first searched the PDDs for the words "technology", "transfer", "equipment", "supplier", "import", "manufacturer" and "training". If no information on technology transfer could be found through this search, we then read through the entire PDD.

Company in Malaysia. The technology to process and use local biomass has been developed by Lafarge Malayan Cement's parent company, Blue Circle Industries. Their research centre is based in Europe. The PDD makes it clear that "knowledge and expertise have been actively transferred in the development of the project by European expert deployment in Malaysia." Training of local staff and engineers has been provided by experts from Blue Circle as well as from Lafarge Europe (Blue Circle's parent company).

Project #839 is an example of *equipment transfer*. It aims at generating electricity from biogas at a landfill in Talia, Israel. The PDD informs us that "the high temperature flare, blower, gas analyzer, industrial computer are all imported from Europe" but does not give any further information on the equipment supplier's involvement beyond the sale. Technology suppliers certainly transfer some knowledge, at least in the form of an instructions leaflet. Hence an equipment transfer should be seen as a transfer of technology that comes with the minimum possible transfer of knowledge.

How reliable is this information? There are several potential problems which we have tried to mitigate. In some PDDs, a transfer of technology may refer to the simple adoption of a new technology. If the technology provider is clearly located within the country, the project involves no international transfer; consequently our database records no international transfer for that project in that country.

Another difficulty concerns specifically the import of equipment. From a general point of view, the import of goods does not always entail a technology transfer. For instance, importing a DVD player made in China and imported into the U.S. does not. The same is true for CDM projects which might include the import of generic devices. In this regard, we have considered that the import of equipment is associated with a technology transfer as soon as the PDD claims that it is.

It remains that PDD editors have an incentive to overstate the existence of technology transfer as it helps project registration. Accordingly, type I errors are unlikely while type II errors could be frequent even if any claim of technology transfer should be justified in the PDD[52]. Therefore, descriptive statistics regarding technology transfer percentages are probably less reliable than other figures[53]. This is a usual difficulty with this type of study. But one can realistically assume that this bias is randomly distributed over the PDD-writing population. Therefore, this problem probably does not damage our econometric results.

3. Descriptive statistics regarding technology transfers

In this section we provide a detailed description of technology transfers occurring in CDM projects.

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[52] A type I error consists of wrongly describing a project as not involving any technology transfer. Conversely, a type II error occurs when a project is wrongly described as not involving any technology transfer.

[53] Haites et al. (2006) find that 33% of the projects involve transfer, compared to 43% in our data set. One possible reason is that the datasets are slightly different. Another is the procedure used in both papers for encoding technology transfer. We read the entire PDDs whereas Haites et al. (2006) only searched for the word “technology”.

3.1 Frequency and nature of technology transfers

Table 1 shows that 279 projects out of 644 involve technology transfer. They represent 43% of projects and 84% of the expected annual CO_2 emissions reductions. Projects with transfer are thus larger-scale on average than those without. This discrepancy is partly explained by the fact that all 13 HFC-destruction projects, representing more than 59 million tons of annual CO_2eq reductions, involve technology transfer[54].

Table 1—Nature of technology transfer involved in the CDM projects

Nature of technology transfer	Number of projects	% of projects	% of annual emission reductions	Average reduction per project (ktCO_2eq/yr)
Transfer	279	43 %	84 %	403
Equipment	57	9 %	6 %	133
Knowledge	101	15 %	14 %	185
Equipment + Knowledge	121	19 %	64 %	714
No transfer	365	57 %	16 %	59
Total	644	100%	100 %	208

In Table 1, we see that transfers limited to the import of equipment are much less frequent than the transfer of knowledge alone (9% of the projects as opposed to 15%).

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[54] Excluding the HFC-destruction projects, 42% of the projects, accounting for 71% of the expected annual CO2 emissions reductions, involve technology transfer.

The transfer of both equipment and knowledge is observed in 19% of the projects. This illustrates the key role of technical skills in the diffusion of carbon mitigation technologies.

3.2 Transfer by type of technology

Using the 21 technology categories established by the UNEP Risoe Center CDM pipeline, Table 2 shows that the number of projects and the likelihood of transfer vary greatly across types of technology.

All projects aiming at the destruction of HFC-23 entail a transfer. HFC-23 is a by-product of HCFC-22, a widely used ozone-friendly refrigerant. The global warming potential of HFC-23 gas is 12,000 times higher than that of carbon dioxide (IPCC, 2001). Projects mitigating HFC thus generate very large amounts of CERs and are extremely profitable. A few companies located in Europe and in Japan have developed technologies to destroy HFC. They are key partners in any HFC decomposition CDM project. Projects avoiding the emission of nitrous oxide (N_2O) in the chemicals industry and recovering methane (CH_4) in landfills and farms also exhibit a very high transfer rate.

In the energy sector, equipment for solar and wind power generation are usually imported from Annex 1 countries. More precisely, about 60% of wind power projects import turbines which are of higher capacity than locally produced ones. This is not surprising as local companies like Goldwind in China and Suzlon in India only produce small-capacity turbines. This explains why projects using imported turbines have an average total capacity of 53 MW in comparison with 28 MW for projects using local devices.

Table 2—Technology transfer by type of technology

Type of technology	Number of projects	Percentage of projects involving tech transfer	Share of transfers that include equipment	Average project size (annual $ktCO_2eq$)
Biomass energy	141	19%	81%	56
Hydro power	112	22%	68%	50
Biogas recovery in agriculture	104	70%	10%	43
Wind power	80	63%	96%	84
Energy efficiency measures in industry	65	25%	75%	112
Landfill gas recovery	51	80%	80%	279
Fossil fuel switch	14	43%	100%	34
Biogas recovery (other)	14	29%	75%	45
Reduction of the share of clinker in cement production	14	7%	0%	144
HFC decomposition	13	100%	92%	4612
Energy efficiency / supply side	7	14%	0%	33
N_2O destruction	6	100%	83%	3141
Geothermal power	5	40%	50%	293
Solar power	4	100%	100%	11
Recovery of fugitive gas	3	100%	33%	621
Power generation from coal mine methane	3	67%	100%	462
Energy efficiency measures in households (insulation)	3	67%	100%	14
Energy efficiency measures in the services sector	2	100%	100%	8
Tidal power	1	100%	100%	315
Reforestation	1	0%	–	26
Transport	1	0%	–	247

A large share of projects recovering biogas in breeding farms also involves technology transfer. The purpose of this type of project is to mitigate and recover biogas resulting from the decomposition process of animal effluents. Each project includes the installation of covered lagoons and a combustion system that destroys the captured biogas. Although the technologies are not very elaborate, knowledge transfer is frequent because these projects are mainly initiated by developers located in Annex 1 countries like AgCert. This Irish company provides farmers with turnkey solutions, including training sessions on how to operate the technology. The offered service includes specification and design of the complete technology solution, identification of appropriate technology providers, supervision of the project installation, farm staff training and ongoing monitoring.

Table 3—Technology transfer by sector

Sector	Number of projects	Percentage of projects involving technology transfer	% of equipment transfer in projects with transfer
Waste	51	80%	80%
Agriculture (incl. reforestation)	105	70%	10%
Energy	264	39%	87%
Industry	223	27%	79%
Transport	1	0%	–

3.3 Transfer by mitigation mechanism

Table 4 distinguishes different mitigation mechanisms. Transfers largely concern end-of-pipe technologies that remove gaseous pollutants from effluent streams at the end of the production process. The “new units” category describes the setting up of new production units with reduced GHG emissions. It gathers biomass-fired and hydro power plants that essentially use local technology as well as wind farms that often benefit from technology transfer. In contrast, projects that modify existing production processes involve far less transfers. Input switch refers to projects involving a change of production inputs (e.g., biomass instead of coal in a power plant).

Table 4—Technology transfer by mitigation mechanism

Mechanism	Number of projects	% of technology transfer
End-of-pipe	205	69%
New unit	286	36%
Input switch	39	33%
Change in the production process	111	20%

3.4 Technology transfer by host country

While CDM projects are located in 44 non-Annex 1 countries, 73% of them are located in Brazil, China, India and Mexico, with 35 % in India alone. 24 countries host 3 projects or less and among these, 12 countries host only one.

Table 5 shows technology transfers in the main host countries. They appear very heterogeneous in their capability to attract technology transfers.

Table 5—Technology transfer for selected host countries

Country	Number of projects	% of technology transfer
India	225	12%
Brazil	99	40%
Mexico	78	68%
China	71	59%
Chile	17	35%
Malaysia	15	87%
South Korea	13	77%
Honduras	10	30%

3.5 Technology suppliers

In 71% of the 154 projects that explicitly mention the origin of imported equipment, it comes from European suppliers. Within Europe, the main exporting countries are Germany, Spain and Denmark, which accounted for 45% of the exported machinery. Non-European suppliers are mostly located in the USA (19%) and Japan (10%).

This means that the money spent by Annex 1 countries to finance CDM projects—through the purchase of carbon credits—is only marginally used to buy machinery from countries that have not ratified the Kyoto Protocol. Does it mean that each country subsidizes its own technologies through the Clean Development Mechanism? This argument has been widely used by CDM opponents. But a closer look at our data invalidates this assertion: an Annex 1 country hosts both the credit buyer and the equipment supplier in only 2% of the projects.

Table 6 reports the main countries of origin and of destination by technology. Spain mainly exports wind turbines manufactured by Gamesa Eolica. Other wind turbine exporters include Vestas in Denmark and Enercon in Germany. The French company Vichem is the main technology provider for HFC decomposition projects. Technologies for N_2O destruction are provided by Japanese companies or by UHDE (a ThyssenKrupp company).

Table 6—Main countries of origin and of destination by type of technology

Type of technology	**Main countries of origin**	**Main countries of destination**
Biomass energy	Belgium, Denmark, Japan	Malaysia, India, Brazil, Indonesia
Wind power	Denmark, Germany, Spain, USA	China, India, Brazil, Mexico
Landfill gas	Italy, UK, France, USA, Ireland, Netherlands	Brazil, Mexico, Argentina, Chile, China
HFC decomposition	France, Germany, Japan	China, India
Hydro power	France, Germany, UK, Spain	Ecuador, Panama, Honduras, South Korea, Mongolia
Agriculture	Ireland, Canada, UK	Mexico, Brazil, Philippines, Ecuador
Energy efficiency in industry	Japan, Italy, USA	India, China, Malaysia
N_2O destruction	Germany, Japan, France	South Korea

3.6 Partnerships

Initially, it was thought that CDM projects could be initiated by companies from Annex 1 countries to cut emissions at a lower cost through technological partnerships that would also benefit developing countries. An example in line with these expectations is Project # 526. The Heidelberg group—a German cement company—has developed this project to cut carbon emissions in its Indonesian subsidiary, Indocement. The project aims at producing a new type of blended cement which reduces CO_2 emissions. It has benefited from research and development activities conducted in Europe by Heidelberg Cement.

However, if we look at the data, a limited number of projects follow a similar pattern. Only 8% are implemented in subsidiaries of companies located in Annex 1 countries. Among these projects, only 21 parent companies offered technical assistance to their local subsidiary. This means that, in total, less than 5% of all CDM projects involve a transfer from an Annex 1 country company to its subsidiary.

Instead, the CDM business has generated unexpected forms of technological partnership. Companies such as AgCert, EcoSecurities, Carbon Resource Management, Agrinergy or Carbon Asset Services Sweden are now key players in the production and sale of carbon credits. We refer to these companies as CDM project designers. They manage the whole CDM project cycle, from PDD writing to credit sale. Their diversified portfolio of CDM projects allows risk minimization and exploitation of economies of scale in administrative tasks. Some of them directly transfer the technology to local project developers. For example, AgCert transfers know-how in Animal Waste Management Systems to livestock farms in Brazil and Mexico. Others simply help local firms with finding technology suppliers and assessing their technologies.

As shown by Table 7, nearly 50% of the credit buyers are CDM project designers. Carbon traders—either banks like ABN AMRO or companies involved in commodity trading like Nuon Energy or EDF Trading—are not very active on the primary market, although the Noble group has created a dedicated subsidiary, Noble Carbon Credits. Private companies also frequently buy credits.

Table 7—Types of credit buyer

Type of credit purchaser	**Number of projects (percentage)**
CDM project designer	179 (47%)
Carbon trader (mostly banks)	18 (4.7%)
Private company	96 (25.1%)
Private fund	5 (1.3%)
Government fund	45 (11.8%)
Public-private fund	9 (2.4%)
World Bank fund	29 (7.6%)
TOTAL	381 (100%)

Note: a project may have more than one credit buyer involved.

4. The determinants of technology transfers: an econometric analysis

In the previous section, we have presented statistics describing technology transfers through the CDM. They give a detailed view on these issues but do not help us to understand what drives the transfer. For instance, we know from Table

5 that 69% of the Chinese projects involve a transfer while the percentage is only 12% in India. Why is this? Is it because the technological capability of India is less than that of China? Or is it due to sector composition effect, Indian projects may take place in economic sectors where a transfer is less likely? Is it due to project characteristics? For instance, is it because Chinese projects are implemented more frequently in subsidiaries of Annex 1 companies, assuming that this type of partnership increases the likeliness of transfer?

Understanding the rationale underlying the technology transfer through CDM projects is necessary to derive policy implications and, more generally, to give a clearer view of the diffusion of GHG mitigation technologies. In this section, we rely for this on econometric analysis.

4.1 The econometric model

We test a model in which the likelihood of technology transfer is determined by a set of variables. Econometric analysis allows us to determine the specific effect of each variable on this likelihood, all other factors being held constant.

We now describe in details the specific model that is estimated. Let $TECH\_TRANSFER$ denote a binary variable equal to 1 if a project involves a technology transfer (regardless of the nature of this transfer), and to 0 otherwise. To examine the relationship between $TECH\_TRANSFER$ and a set of explanatory variables, the following logit equation is estimated:

$$\Pr(TECH\_TRANSFER = 1) = \frac{e^{\Omega}}{1 + e^{\Omega}}$$

with:

$$
\begin{aligned}
\Omega = {} & \alpha_0 + \alpha_1(LOGSIZE) + \alpha_2(CREDIT\_BUYER) + \alpha_3(SUBSIDIARY) \\
& + \alpha_4(SIMILAR\_PROJECTS) + \alpha_5(TRADE) + \alpha_6(FDI\_INFLOWS) \\
& + \alpha_7(GDP\_GROWTH) + \alpha_8(TECH\_CAPACITY) \\
& + \alpha_9(LOG\_POPULATION) + \alpha_{10}(GDP\_PERCAPITA) + \alpha_i SECTOR_i + \alpha_j COUNTRY_j + \varepsilon
\end{aligned}
$$

α_i is a vector of coefficients to be estimated and ε is a random term identically independently distributed following a Gumbel extreme distribution.

We now discuss in depth the different explanatory variables. LOGSIZE[55] is the log of the project size, as measured by its annual emissions reduction. The underlying hypothesis is that CDM projects entail transaction costs that are fixed and that are likely to be higher when some technology transfer is involved (Maskus, 2004). Such transaction costs are an impediment to small projects. It may be assumed that the larger a project, the higher its probability to involve technology transfer.

CREDIT_BUYER is a dummy variable indicating the participation of one or more credit buyers in the project. Before the project developer can sell the credits, the UNFCCC must first certify, issue and register the emission reduction and this administrative process takes time. Selling credits through a forward contract can be of great help. It reduces the risk surrounding the investments by adding a guaranteed revenue stream. Most credit buyers are not pure financial actors as shown in Table 7.[56] One can assume that they also give advice and bring expertise that may ease technology transfer.

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[55] Using the logarithm of the size ensures that the few very large HFC projects do not have a disproportionate influence on the results

[56] Only 18 credit buyers are banks.

SUBSIDIARY is a dummy variable indicating whether the project is implemented in the subsidiary of a company located in an Annex 1 country. In this case, the local project developer can probably benefit from the expertise or from the technology of the parent company (Jahn et al., 2004).

The number of other CDM projects using the same technology within the host country is described by the variable SIMILAR_PROJECTS. We see this variable as a proxy for the local availability of the technology in the country. Accordingly, the higher the number of similar projects, the lower the probability of transfer.

We also include country variables. In this regard, there is empirical evidence in the general economic literature that international trade and Foreign Direct Investments (FDI) promote the transfer of technology across countries (Coe et al., 1997). Accordingly, we use the variable TRADE, which is the sum of exports and imports of merchandise divided by GDP. FDI_INFLOWS is the level of incoming FDI divided, again, by the host country's GDP.

As richer and larger countries are likely to have more technologies already available locally, we include the country size (LOG_POPULATION) and the per capita GDP (GDP_PERCAPITA) as control variables. In order to take into account the possible influence of economic dynamism, we also use GDP_GROWTH, the average annual rate of GDP growth 2000 to 2004.

Furthermore, empirical evidence indicates that the adoption of a new technology is strongly associated with human capital, supporting infrastructure and research and development activities (Blackman, 1997). In order to measure this technological capability (TECH_CAPABILITY), we use the ArCo technology index developed by Archibugi and Coco (2004). This composite indicator captures three aspects determining technological capabilities: the creation of technology (number of patents and number of scientific articles), the technological infrastructures (internet penetration, telephone penetration and electricity consumption) and the development of human skills (percentage of tertiary science and engineering enrolment, mean years of schooling and literacy rate).

TECH_CAPABILITY may have contrasting effects on technology transfers. On the one hand, the influence may be positive as the establishment of a new technology in a country may require technical competencies and a skilled workforce. On the other hand, high technological capabilities mean that many technologies are already available locally, thereby reducing the probability of transfers through CDM projects. These antagonistic effects may have different weights across sectors. This leads us to estimate two variants of the model:

In Model A, we simply use the index TECH_CAPABILITY, thereby assuming that the effect of technological capability does not vary across sectors.

In Model B, the variable TECH_CAPABILITY interacts with 11 sector dummies allowing differentiated effects across sectors. We use AGRICULTURE, ENERGY, WASTE[57] and 8 other dummies describing industrial sectors.

Finally, $SECTOR_i$ and $COUNTRY_i$ are vectors of sector dummies and country dummies, respectively. They control for sector- and country-specific characteristics that are not captured by the other variables.

Table 8 yields precise definitions, summary statistics and the expected signs of the coefficients.

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[57] We have excluded the transport sector which only concerns one project.

Table 8—Definition of variables and summary statistics

Variable	Definition	Obs.	Mean	Std. Dev.	Expected impact
LOGSIZE	Log of the size of the project (expected annual reductions in ktCO$_2$eq).	644	3.716	1.532	+
CREDIT_BUYER	= 1 if the project has one or more credit buyer, 0 otherwise	644	0.607	0.489	+
SUBSIDIARY	= 1 if the project developer is the subsidiary of a company from an Annex 1 country, 0 otherwise	644	0.171	0.377	+
SIMILAR_PROJECTS	= log (N) where N is the number of projects already using the same type of technology within the host country	644	1.959	1.386	–
GDP_GROWTH	Average annual growth of GDP from 2000 to 2004	644	4.688	2.560	+
TRADE	Sum of exports and imports of merchandise divided by the value of GDP. Average for 2000-2004	644	25.62	17.06	+
FDI_INFLOWS	Sum of net inflows of FDI divided by GDP. Average for 2000-2004	644	2.374	1.534	+
TECH_CAPABILITY	Index of technological capability * 100 (source: Archibugi and Coco 2004)	644	30.05	8.80	?

GDP_PERCAPITA	GDP per capita 2004	644	3779	3871	–
LOG_POPULATION	Log of total population in million (2004)	644	5.38	1.80	–

4.2 Results

Empirical results are displayed in Table 9. The overall quality of the estimations is reasonably good. The McFadden pseudo R-squared is around 0.35-0.4 depending on the model. The model correctly predicts 80 % of the observations and the results are robust across the two specifications (models A and B).

We now interpret the influence of the different variables. To begin with, technology transfer positively depends on the size of the project (LOGSIZE). This is in line with the expectation that larger projects are better able to exploit economies of scale in technology transfer.

Having a credit buyer also increases the likelihood that the project involves technology transfer. But calculations show that the marginal effect of CREDIT_BUYER is low: a project with a credit buyer has only a 16% higher probability of involving a technology transfer.

Being the subsidiary of a company from an Annex 1 country (SUBSIDIARY) clearly favors the transfer of technology. The coefficient is highly significant in all specifications and much larger than that of CREDIT_BUYER. In marginal terms, the transfer likeliness of a project located in the subsidiary of an Annex 1 company is 50% higher. This confirms the conjecture that pre-existing capital links strongly promote the import of a new technology.

As expected, the probability of technology transfer decreases with the number of projects using the same type of technology in the country (SIMILAR_PROJECTS).

Turning next to country variables we confirm that, all other things being equal, the openness of the economy positively influences transfer probability. In contrast, the share of FDI inflows in GDP does not have any significant impact. This is not all that surprising, since capital links are already captured by the variable SUBSIDIARY.

Results regarding technological capabilities are very interesting. First, Model A tells us that technological capability has a positive overall effect on technology transfer. However, introducing the possibility of differentiated effects across sectors (Model B) modifies this finding. In fact, TECH_CAPABILITY has a positive influence only in the energy sector and in the chemicals industry. The effect is strongly negative in agriculture and not significant in most industry sectors and in waste management.

Recall the two antagonistic effects of technological capabilities. One the one hand, they promote transfer as local implementers have skills to use the technology. On the other hand, high technological capabilities increase the local availability of technologies. Our results suggest that the latter effect dominates the former in agriculture, while the opposite is true in the energy sector and the chemicals industry. The interpretation is that technologies transferred in the agriculture sector are not very elaborate, implying that they might be introduced without high technical skills. In contrast with this, wind turbines, solar panels in the energy sector or abatement devices in the chemicals industry would require technically qualified manpower to be built and operated. In the other sectors in which coefficients are not significant, the two effects might compensate each other.

At the country level, GDP growth exerts a stronger influence than economic openness. The technological capability has a strong effect—either negative in agriculture or positive in the energy sector.

Table 9—Regression results of models explaining $TECH\_TRANSFER$

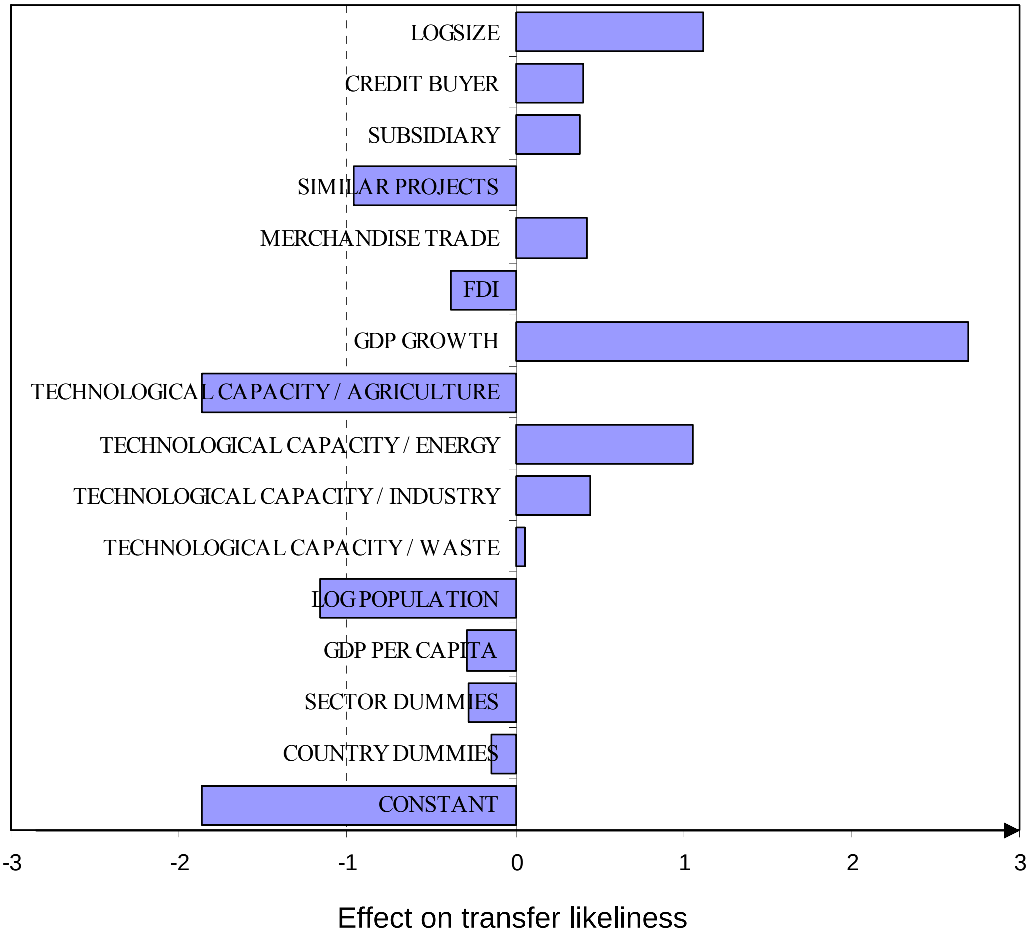
Dependant variables	**Model A**	**Model B**
LOGSIZE	0.2792 *** (0.0842)	0.2590 *** (0.0929)
CREDIT BUYER	0.5122 ** (0.2504)	0.6282 *** (0.2635)
SUBSIDIARY	2.3508 *** (0.3578)	2.2463 *** (0.3621)
SIMILAR_PROJECTS	-0.4192 *** (0.1204)	-0.2782 ** (0.1310)
TRADE	0.0104 * (0.0056)	0.0103 * (0.0060)
FDI_INFLOWS	-0.2587 * (0.1368)	-0.1045 (0.1452)
GDP_GROWTH	0.6153 *** (0.2219)	0.5124 ** (0.2184)
TECH_CAPABILITY	0.0686 * (0.0395)	
TECH_CAPABILITY * AGRICULTURE		-0.3474 ** (0.1730)
TECH_CAPABILITY * ENERGY		0.0825 * (0.0471)
TECH_CAPABILITY * WASTE		0.0134 (0.0508)
TECH_CAPABILITY * CHEMICALS		0.1088 ** (0.0522)

Dependant variables (continued)	**Model A**	**Model B**
TECH_CAPABILITY * CEMENT		0.0428 (0.0485)
TECH_CAPABILITY * FOOD		0.0497 (0.0475)
TECH_CAPABILITY * IRON & STEEL		0.0392 (0.0542)
TECH_CAPABILITY * PAPER		0.0089 (0.0617)
TECH_CAPABILITY * TEXTILE		0.0538 (0.0690)
TECH_CAPABILITY * WOOD		0.0209 (0.0576)
TECH_CAPABILITY * OTHER INDUSTRY		0.0553 (0.0574)
GDP_PERCAPITA	-0.0001 (0.0001)	-0.0001 (0.0001)
LOG_POPULATION	-0.2546 (0.2645)	-0.1614 (0.2643)
SECTOR$_i$	—	—
COUNTRY$_i$	—	—
# observations	643	643
Pseudo-R2	0.3568	0.3861
Percent correct prediction	80.1 %	79.9 %
Notes: Standard error in parentheses; * denotes significance at 10% level, ** denotes significance at 5% level, and *** denotes significance at 1% level.		

In order to compare the size of the effects of different explanatory variables, we draw Figure 1 using model B's results. Using the same metric, each bar measures the impacts of the variable on an average CDM project.

Figure 1 is based on the following calculation. Let $\bar{x}_i$ be the average value of the variable x_i in the data set and let β_i denote the value of its coefficient. Then, the product $\beta_i \bar{x}_i$ represents the average impact of x_i on the linear predictor Ω. Calculating the value of $\beta_i \bar{x}_i$ for every variable allows setting the average weight of each variable against the decision to transfer technology. Figure 1 represents these weights.

Fig. 1. Comparative impacts of the independent variables in a representative project



This representation shows that, among project variables, the size of the project and the number of similar projects within the host country have the most important impact on technology transfer.

CREDIT_BUYER and SUBSIDIARY have similar effects but for different reasons. SUBSIDIARY increases the transfer probability by 50%, but only 8% of the projects are implemented in subsidiaries of Annex 1 companies. CREDIT_BUYER has a weaker marginal effect (+16%), but credit buyers participate in 61% of the projects.

5. Explaining the type of transfer

In this section, we concentrate on the projects involving a technology transfer and we seek to identify what drives the type of transfer project developers engage in: the transfer of equipment or the transfer of knowledge.

Let *HARD_ TRANSFER* denote the binary variable that indicates whether or not the technology transfer concerns equipment. A straightforward solution would be to estimate a standard logit model on the sub-sample of projects involving transfers. But results would be biased because this sub-sample is not random. In technical terms, there is a so-called sample selection bias. The reason is that unobserved factors may influence both the probability of transfer—and thus the probability for a project to belong to the sub-sample—and the type of transfer.

A solution to this problem has been suggested by Heckman (1976). This is a two-step estimation procedure. In a first phase, the probability that a project leads to technology transfer is estimated. This is the sample selection equation: it allows us to set up a selection hazard index which is included as a regressor to estimate the type of transfer in the second phase (for more details on the Heckman model, see for instance Greene, 2003).

We have implemented the Heckman procedure: Table 10 reports the results of the second stage. In comparison with the previous models, we have excluded some dependent variables, either because there was no reason to assume they would influence the type of transfer (for example, GDP_GROWTH) or because they were not significant.

Results show interesting patterns. First of all, the probability that the transfer concerns equipment decreases with the number of projects using the same type of technology in the country (SIMILAR_PROJECTS). A developer who needs a technology has two options: either to buy it locally or to import it. In the economic literature, the first is termed *horizontal diffusion* and the second *vertical diffusion*. Our results suggest that *horizontal diffusion* dominates when the technology is equipment.

As regards technological capabilities, Models C and D show that the pro-transfer effect dominates for equipment in the energy and waste management sectors. Agriculture is still specific, confirming that the equipment used in agricultural projects do not require significant technological skills.

Table 10—Estimation results of the Heckman model's for HARD_TRANSFER

Dependant variables	C	D
LOGSIZE	0.0132 (0.0638)	0.0021 (0.0667)
SIMILAR_PROJECTS	-0.3108 *** (0.0982)	-0.2417** (0.1136)
TRADE	0.0030 (0.0028)	0.0031 (0.0030)
TECH_CAPABILITY	0.0227 ** (0.0114)	
TECH_CAPABILITY * AGRICULTURE		-0.9387 * (0.5051)
TECH_CAPABILITY * ENERGY		0.0427 ** (0.0197)
TECH_CAPABILITY * INDUSTRY		-0.0018 (0.0142)
TECH_CAPABILITY * WASTE		0.0510 * (0.0283)
SECTOR_i	–	–
COUNTRY_i	–	–
Uncensored observations	279	279

Standard error in parentheses; * denotes significance at 10% level, ** denotes significance at 5% level, and *** denotes significance at 1% level.

6. Conclusion

This paper focuses on transfers of GHG mitigation technologies induced by the Clean Development Mechanism. We have examined technology transfers in the 644 CDM projects registered up to May 2007.

From a descriptive point of view, the data shows that international technology transfers take place in less than half of CDM projects. Very few projects involve the transfer of equipment alone. Instead, projects often include the transfer of knowledge and operating skills, allowing project implementers to appropriate the technology.

Technology transfers mainly concern two areas. The first is end-of-pipe destruction of non-CO_2 greenhouse gas with high global warming potentials, such as HFCs, CH_4 and N_2O. This concerns the chemicals industry, the agricultural sector and the waste management sector. The second is wind power. Other projects, such as electricity production from biomass or energy efficiency measures in the industry sector, mainly rely on local technologies. Moreover, Mexican and Chinese projects more frequently attract technology transfers while European countries are the main technology suppliers.

We have also developed econometric models in order to characterize the factors underlying these patterns. They show that there are economies of scale in technology transfer: all other things being equal, transfers in large projects—in terms of emissions reductions—are more likely. Furthermore, the probability of transfer is 50% higher when the project is developed in a subsidiary of an Annex 1 company. Having an official credit buyer in the project also exerts a positive influence on transfer likeliness, albeit much smaller (+16%).

As regards the host countries' features, the most interesting econometric findings involve technological capabilities. In theory, this factor has ambiguous effects. On the one hand, high capabilities may be necessary to adopt a new technology. On the other hand, high capabilities imply that many technologies are already available locally, thereby reducing transfer likelihood. Our estimations show that the first effect strongly dominates in the energy sector and in the chemicals industry. By contrast, the second effect is stronger for agricultural projects. This suggests that the agricultural technologies transferred in these projects tend to be simple.

What are the policy implications? First, these results suggest policy lessons for CDM design. Encouraging large projects—or project bundling—allows exploitation of increasing returns in technology transfer. Promoting projects in subsidiaries of Annex 1 companies could also be of great use to foster technology transfer. In practice, one could imagine different ways of providing incentives for companies to do so (e.g. additional credits, simplified administrative procedures). To a lesser extent, credit buyers, which are generally not pure financial actors, can also play a positive role.

Our analysis may also give lessons regarding general measures. In particular, the study suggests that programs of technological capacity building would be particularly profitable in the energy sector and in the chemicals industry.

Last, let us pinpoint some limitations of this exercise. First, the information on technology transfer in this paper is provided by project participants in the PDDs, and could not be verified against independent sources of information. This may have led us to overestimate the level of technology transfer. Second, the data describes projects registered during a very short period (about 2 years). This prevents using this information to characterize the dynamic aspects of diffusion. Third, the data does not permit investigation of the diffusion of technology within host countries, which may be as significant as international transfers.

Other methodological weaknesses are the lack of sector-specific variables in comparison with project design variables and country-specific variables, and the fact that information on technology transfer may be biased as it is self-reported by the project developers in the PDD.

Research paper 5

Technology transfer by CDM projects: a comparison of Brazil, China, India and Mexico[58]

1. Introduction

The success of post-Kyoto climate policies will crucially hinge on the involvement of fast growing emerging countries such as China, India or Brazil. In this paper we compare international technology transfers induced by the CDM in four emerging countries—namely China, India, Brazil and Mexico—which are also the main recipients of CDM projects.

We follow the econometric approach used in paper 1. We use the same data and similar econometric models to explain inter-country differences. The four countries we focus on—Brazil, China, India, and Mexico—gather about 75% of the CDM projects. We seek to highlight and to explain the national specificities of technology diffusion by the CDM, such as differences in the percentage of projects where a technology is imported from abroad. Although our main focus is

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[58] This chapter is based on an article published as: Dechezleprêtre, A., Glachant, M., Ménière, Y. (2009). Technology transfer by CDM projects: a comparison of Brazil, China, India and Mexico. *Energy Policy* 37, 703-711.

on international transfers of technology, we also take into account and discuss country differences as regards the diffusion of purely domestic technology.

The remainder of this paper is organized as follows. In section 2 we give descriptive statistics by country on the frequency of transfer, on the types of technology involved, etc. In Section 3, we use the econometric model presented in paper 1 to explain inter-country differences with respect to technology transfer. We conclude in Section 4.

2. Descriptive statistics by country

In this section, we describe the international technology transfers occurring in CDM projects in Brazil, China, India and Mexico. As shown in Table 1, the share of projects involving such transfers varies greatly across countries. 68% of projects set up in Mexico involve an international technology transfer, but only 12% of projects located in India.

In most cases international transfers are not limited to the import of equipment. The transfer of both equipment and knowledge is observed in 42% of Chinese projects and 46% of Indian projects. Transfers of knowledge alone are very frequent in Brazil (23%) and in Mexico (68%). This is mainly due to the high number of projects taking place in the agricultural sector in these two countries.

Table 2 gives additional information on the projects. In average, Chinese projects are much larger. This is essentially due to the presence of 7 huge projects of HFC-23 destruction. The percentage of projects which are located in the subsidiary of Annex 1 countries' companies is interesting as one might expect more transfers in these projects. In this regard, China and India sharply differ from Brazil and Mexico, where such projects are much more frequent. Finally, the presence of a foreign credit buyer may also facilitate transfer. They are involved in most projects in China and Mexico, but only in 36% of the Indian projects.

Table 1—International technology transfer by host country

Country	Total number of projects *[N]*	Number of projects involving technology transfer			Percentage of technology transfer *[(E+K+B)/N]*
		Equipment only *[E]*	Knowledge only *[K]*	Equipment + Knowledge *[B]*	
India	225	10	5	13	12%
Brazil	99	8	23	9	40%
Mexico	78	4	45	4	68%
China	71	11	1	30	59%
Total	473	33	74	56	34%

Table 2—Project characteristics by host country

Variables	China	India	Brazil	Mexico
Average size (ktCO$_2$eq/year)	816.7	85.2	160.0	76.5
Median size (ktCO$_2$eq/year)	110	26	42	17
Projects implemented in a subsidiary of annex I company	0%	3%	28%	56%
Projects with a foreign credit buyer	89%	36%	52%	97%

We now give more specific information on the types of technology that are transferred in each country.

2.1 Brazil

CDM projects in Brazil belong to two main types: renewable energy production and biogas recovery in breeding farms and landfills (see table 3). Renewable energy projects mostly consist of hydro power and biomass energy production. The latter are usually set up in sugar mills where bagasse - a residue from sugarcane processing—is used as a feedstock for cogeneration of heat and electricity. These power plants rely on direct-fired systems that are very similar to usual fossil-fuel fired power plants. Thus there is no need to import technologies. Hydropower is also common in Brazil as it supplies more than 80% of electricity in this country. A few wind energy projects use turbines supplied by Enercon, Germany.

The second most popular type of CDM projects in Brazil is biogas recovery. They generally entail technology transfer. In particular, projects in breeding farms mitigating biogas resulting from the decomposition process of animal effluents present interesting channels of technology diffusion. 85% of these projects benefit from technology transfers from AgCert. This Irish consulting company provides farmers with turnkey solutions, including training sessions on how to operate the technology. It also operates in Mexico as will see below.

However, in terms of emission reductions, the most important projects concern landfill gas capture and N_2O destruction. Projects in landfills mainly use foreign technology. In particular, several projects set up in subsidiaries of French companies Veolia Environnement and Suez benefited from internal transfers of know-how.

As for the N_2O destruction project, there is only one huge project in a chemical facility producing adipic acid. It amounts for nearly 6 million tons of annual CO_2eq reductions, i.e. 38% of the annual reductions in Brazil by CDM projects. The plant is owned by Rhodia and the Brazilian facility benefits from transfers of know-how from the facility of Chalampé located in France.

Table 3—Main project types and international technology transfers in Brazil

Type of technology	Number of projects	Percentage of projects involving tech. transfer	Average project size (annual ktCO_2eq)	Total annual reductions (ktCO_2eq)
Biomass energy	34	9%	51	1747
Biogas recovery in agriculture (breeding farms)	20	90%	74	1477
Hydro power	19	11%	45	852
Landfill gas recovery	13	85%	402	5225
N_2O destruction	1	100%	5961	5961
Wind power	4	75%	42	169
Energy efficiency (industry)	2	0%	47	93
Fossil fuel switch	5	20%	20	99
Fugitive gas recovery	1	100%	220	220

2.2 China

China also implements many renewable energy projects as shown in Table 4. The country can rely on local technologies for hydro power and biomass energy projects but depends upon imported turbines for wind power projects. The main suppliers of wind turbines are Gamesa Eolica (Spain) with 12 projects and Vestas (Denmark) with 8 projects. Notably, 55% of the wind projects registered in April 2007 use turbines manufactured by the local firm Goldwind. Imported turbines have higher capacities on average than locally produced turbines (1.11 MW against 750 kW).

China is the leading country for HFC-23 destruction projects. These 7 projects represent 80% of the annual reductions in China and they always entail a technology transfer. The French company Vichem provides the HFC destruction technology of 4 out of 7 projects. The rest is supplied by Japanese corporations.

As landfill gas capture and flaring is new in China, local CDM developers have frequently cooperated with foreign suppliers such as Waste Management New Zealand or Energi Gruppend Jylland Denmark. This leads to an 85% rate of technology transfer in this area.

Table 4—Main project types and international technology transfers in China

Type of technology	Number of projects	Percentage o projects involving tech transfer	Average project siz (annual $ktCO_2eq$)	Total annual reductions ($ktCO_2eq$)
Wind power	34	74%	112	3807
Hydro power	13	0%	104	1349
HFC decomposition	7	100%	6743	47200
Biomass energy	5	20%	160	802
Methane destruction	3	66%	462	1387
Energy efficiency (industry)	3	66%	804	2413
Landfill gas recovery	4	100%	163	652

N_2O destruction	1	100%	350	350
Reforestation	1	0%	26	26

2.3 India

India is the main host country for CDM projects but as mentioned above, international technology transfer is very limited. However this does not imply that there is no technology diffusion. As in China, biomass energy and hydro power projects rely on local technologies (see Table 5). But, contrary to China, most wind power projects use equipment produced by local manufacturers (mainly Suzlon and Enercon India).

Energy efficiency measures in industry - power generation from waste heat recovery or reduction of steam consumption - are usually designed locally. However, technology partnerships have been set up in a few projects. For example, Technovacuum Russia has supplied a technology aiming at reducing steam consumption in a petroleum refinery and Giammarco-Vetrcoke Italy has implemented a solution to reduce energy consumption at an ammonia plant. The technology used in the three HFC destruction projects also comes from Europe (Ineos UK, SGL Acotec and Caloric Anlagenbau Germany).

Interestingly, the unique solar power project in India has been developed through a partnership between a German physicist Wolfgang Scheffler—who has invented the so-called Scheffler reflectors for solar cooking - and Indian institutions.

Table 5—Main project types and international technology transfers in India

Type of technology	Number of projects	P Percentage of projects involving tech. transfer	Average project size (annual $ktCO_2eq$)	Total annual reductions ($ktCO_2eq$)
Biomass energy	78	8%	38	2926
Energy efficiency (industry)	54	17%	85	4595
Hydro power	30	0%	34	1030
Wind power	26	23%	29	763
Reduction of the share of clinker in cement production	13	0%	119	1544
Biogas (other)	7	0%	32	224
HFC decomposition	3	100%	2589	7766
Fossil fuel switch	4	25%	43	171
Energy efficiency (services)	1	100%	3	3
Energy efficiency (supply side)	6	0%	6	38
Solar power	1	100%	1	1

2.5 Mexico

Mexico is very specific: almost 90% of CDM projects concern biogas recovery in breeding farms (Table 6). AgCert—the Irish company previously evoked for Brazil—has initiated 41 projects involving technology transfers through training of local staff. Granjas Carroll Mexico - the largest commercial pig producer in Mexico - has developed 24 projects with the help of the EcoSecurities (though no technology transfer is claimed in this case). The CDM has clearly enhanced the diffusion of biogas mitigation among Mexican pork producers.

Among the other Mexican projects with technology transfer, there is one large HFC project, which yields more annual emission reductions than the 69 biogas recovery projects altogether, and three wind power projects using turbines supplied by Gamesa Eolica. Two landfill gas projects have been developed through a partnership between EcoMethane and technology providers from UK, Biogas Technology Ltd and ENER*G.

Table 6—Main project types and international technology transfers in Mexico

Type of technology	Number of projects	Percentage of projects involving tech. transfer	Average project size (annual $ktCO_2eq$)	Total annual reductions ($ktCO_2eq$)
Biogas recovery in agriculture (breeding farms)	69	65%	31	2146
HFC decomposition	1	100%	2155	2155
Hydro power	2	50%	43	87
Landfill gas	2	100%	186	373
Wind power	3	100%	400	1201
Biogas (other)	1	100%	4	4

3. Econometric analysis of cross-country differences

In the previous section, we have presented statistics describing inter-country differences in international technology transfers by CDM. These statistics do not help us to understand what drives these differences. For instance, 59% of the Chinese projects involve an international transfer while the percentage is only 12% in India. Why is it so? Is it because the technological capability of India is less than that of China or, by contrast, because India can rely on local technology? Is it due to sector composition effect—Indian projects may take place in economic sectors where a transfer is less likely? Is it due to project characteristics? In this section, we use the econometric model presented in paper 1 to answer these questions.

3.1 Model and estimation results

TECH_ TRANSFER is a binary variable equal to 1 if a project involves a technology transfer, and to 0 otherwise. To examine the relationship between *TECH_ TRANSFER* and a set of explanatory variables, the following logit equation is estimated:

$$\Pr(TECH\_TRANSFER = 1) = \frac{e^{\Omega}}{1 + e^{\Omega}} \tag{1}$$

with:

$$\begin{aligned}\Omega = \alpha_0 &+ \alpha_1(LOGSIZE) + \alpha_2(CREDIT\_BUYER) + \alpha_3(SUBSIDIARY) \\ &+ \alpha_4(SIMILAR\_PROJECTS) + \alpha_5(TRADE) + \alpha_6(FDI\_INFLOWS) \\ &+ \alpha_6(GDP\_GROWTH) + \alpha_7(LOG\_POPULATION) \\ &+ \alpha_8(GDP\_PERCAPITA) + \alpha_9(CARBON\_INTENSITY) \\ &+ \alpha_{10}\left(TECH\_CAPACITY\right) + \alpha_n\left(SECTOR_n\right) + \alpha_o\left(COUNTRY\right)_o + \varepsilon\end{aligned}$$

where α_i is a vector of coefficients to be estimated and ε is a random term identically independently distributed following a Gumbel extreme distribution.

The only difference with the model presented in paper 1 is that we added the carbon intensity of the economy as a control variable. This followed several requests to do so by readers of previous versions of this work. As could be expected, we find no significant effect of this control variable.

Results are displayed in Table 7. As noted above, the variable CO2_INTENSITY has no significant effects in the regression. The value of the coefficients is very similar to those presented in paper 1.

Table 7—Regression results of model explaining *TECH_ TRANSFER*

Dependant variables	**Coefficients**
LOGSIZE	0.2806*** (0.0843)
CREDIT_BUYER	0.5050** (0.2509)
SUBSIDIARY	2.3511*** (0.3579)
SIMILAR_PROJECTS	-0.4103*** (0.1206)
TRADE	0.0090* (0.0057)
FDI_INFLOWS	-0.2674* (0.1363)
GDP_GROWTH	0.6882*** (0.2225)
GDP_PERCAPITA	-0.0001 (0.0001)
LOG_POPULATION	-0.2566 (0.2641)
CARBON_INTENSITY	0.0002 (0.0003)
TECH_CAPABILITY	0.0722* (0.0400)
$SECTOR_i$	–
$COUNTRY_i$	–
Nb of observations	643
Pseudo-R2	0.36
Percentage of correct predictions	79.8 %

Notes: Standard errors in parentheses; * denotes significance at 10% level, ** denotes significance at 5% level, and *** denotes significance at 1% level.

3.2 Cross-country comparison

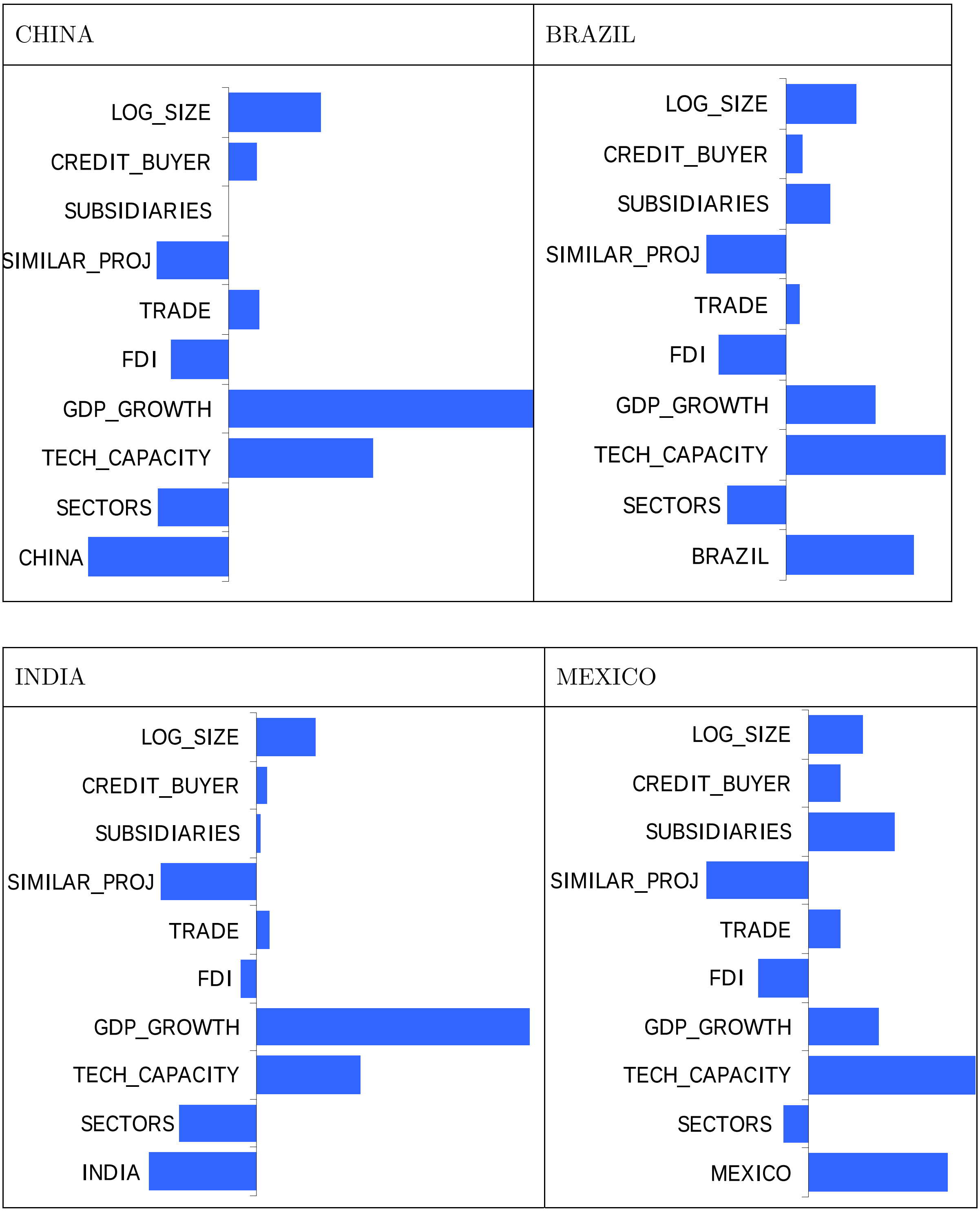
In this section, we use the econometric model presented above in order to analyze the impact of the explanatory variables on the overall rate of technology transfer in the different host countries. The discussion about the sign of the coefficients does not yield information about the size of the effects of the explanatory variables. In order to compare these effects across countries, we draw Figure 1 using the model's results. Figure 1 is based on the following calculation.

Let $\overline{x}_i$ be the average value of the variable x_i in a sample of projects and let β_i denote the value of its coefficient. Then, the product $\beta_i\overline{x}_i$ represents the average impact of x_i on the linear predictor Ω of Equation (1). Calculating the value of $\beta_i\overline{x}_i$ for every variable allows setting the average weight of each variable against the decision to transfer technology. Figure 1 represents these weights for the different countries. Using the same metric, each bar measures the impact of the variable on an average CDM project in each country. Finally, we only represent statistically significant variables.

Let us use Figure 1 to compare the different countries. Consider first the effect of the project variables in Figure 1. The stronger impact of PROJECT_SIZE in China is clearly due to its large HFC projects. The two other variables, namely CREDIT_BUYER and SUBSIDIARY, denote important differences in countries' capacities to attract foreign partnerships. China and Mexico have clearly benefited from the involvement of foreign credit buyers. The advantage of Mexico is even stronger as regards foreign subsidiaries, for which Brazil is also well positioned. In contrast, India performs poorly with respect to both variables.

Turning next to country variables, the strong effect of GDP_GROWTH clearly indicates that international technology transfers are more likely in fast growing economies. Although all countries have substantial growth rates, the very fast economic growth in India and in China seem to be decisive factors in their abilities to generate projects involving technology transfers.

Figure 1—Comparative impacts of the explanatory variables for the different countries



International technology transfers are also strongly correlated to national technology capabilities (TECH_CAPACITY). Beside a small lag in the case of India, all countries benefit in equal proportions from attractive technological capabilities. One must however balance this effect with the impact of the variable SIMILAR_PROJECTS which denotes the number of other CDM projects using the same technology within the host country. Local availability of technologies has comparable negative impacts on the likelihood of technology transfers in each country. It mitigates the positive effect of TECH-CAPACITY, without suppressing it entirely. Again, the net impact is the lowest in India, which suggest that India has been particularly successful in relying on domestic technology capabilities to diffuse carbon mitigation technology through the CDM.

Sector dummies are interesting in that they reflect the sector-composition effect. Figure 1 suggests that inter-country differences are not that much influenced by this. The exception is Mexico. One possible explanation is that this country gets very specialized in biogas recovery in breeding farms which frequently entail technology transfer.

Finally, the country dummies—BRAZIL, CHINA, INDIA and MEXICO—capture factors that are not taken into account by the other country-level variables (TRADE, FDI, GDP_GROWTH and TECH_CAPACITY). They may reflect administrative peculiarities—difference in intellectual property regimes, etc. —which are not described in the database. Figure 1 shows that these unobserved factors play a strong role in explaining country differences. Although, by nature, these effects are difficult to interpret, it is likely that the national policies with respect to CDM play an important role. China has for instance been slow in setting up a Designated National Authority (DNA) to help setting up CDM projects. In contrast, Mexico and Brazil seem to benefit of more proactive policies vis-à-vis CDM projects[59].

We can now complete the discussion by relating these results with each country's performance in terms of technology transfers. Comparing the countries in Figure 1 suggests two different types of country profiles, namely Mexico and Brazil on the one hand, and China and India on the other hand.

The relative success of Mexico (where the transfer rate is 68%) in attracting foreign technology when compared to other countries is mainly due a sector-composition effect (in particular, there are many projects of biogas recovery in breeding farms, a sector where transfers prevails) combined with good technological capabilities and a strong involvement of parent companies in Mexican subsidiaries. Brazil has a similar profile but in lesser proportions. The effect of GDP_GROWTH is slightly stronger than in Mexico, while the positive impact of sector composition, foreign subsidiaries and technological capabilities is weaker.

The profiles of India and China are quite different. Indeed neither of them has experienced a strong involvement of foreign partners. The transfer rate of 59% in China is mostly explained by the dynamism of its economy (GDP_GROWTH), combined with good technological capabilities. In comparison with China, the lower rate of international technology transfers (12%) in India can be explained

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[59] Remember that every host country must give its approval to CDM projects through its DNA. Interestingly, the Brazilian Designated National Authority (DNA) is hosted by the Ministry of Science & Technology, while in the great majority of cases, the DNA is hosted by the Ministry of Environment or by some national environmental protection agency.

by a (relative) smaller advantage in terms of growth rates and technological capabilities, but also by a stronger propensity to rely on domestic capabilities to diffuse technology through the CDM.

4. Conclusion

In this paper we have described the international transfers of GHG mitigation technologies induced by the Clean Development Mechanism in Brazil, China, India and Mexico using a dataset including 644 CDM projects registered until May 2007.

Our analysis shows very large differences across countries. The percentage of projects where an international technology transfer takes place ranges from 12% in India to 68% in Mexico. Moreover, very different technologies are concerned. In Brazil and Mexico, projects recovering biogas in breeding farms represent an important share of the overall transfer. In China, Mexico and Brazil, the import of wind turbines is widespread whereas India mainly relies on local suppliers. Nevertheless, some technologies are imported whatever the country. This is true for HFC or N_2O destruction technologies used in very large projects in the chemical industry. This is also the case of landfill gas capture and flaring.

Note that a high transfer rate does not mean that the country performs better than others. Consider the example of Indian wind power projects. India would seem to perform badly in this area since transfer frequency is low (23%) as compared to others (between 75% and 100%). But it is so because India is in fact more advanced in this area and has leading domestic producers like Suzlon.

We also use econometric analysis to investigate what drives these transfers. Our results highlight various patterns of technology diffusion. Transfers to Mexico (68% of CDM project) and Brazil (40%) are related to the same factors, namely the strong involvement of foreign partners and good technological capabilities. The high Mexican rate seems to be due to a relative advantage against Brazil with respect to these factors. Mexico moreover benefits from a sector-composition effect: many Mexican projects concern biogas recovery in breeding farms, a sector where transfers prevail.

The pattern of technology diffusion is quite different in China (59%) and India (12%). The involvement of foreign partners is less frequent, and international transfers seem rather related to the investment opportunities generated by fast growing economies. Our results suggest that technological capabilities may play different roles in both countries. Strong technology capabilities are positively correlated with international transfers in China. By contrast, the technology capabilities of India seem to be rather geared towards the replication of CDM projects involving domestic technologies only.

What are the policy lessons of this analysis? Excluding macro variables like GDP growth, the results stress the importance of project partnerships: promoting projects in subsidiaries of Annex 1 countries' companies and involving a credit buyer in the project clearly alleviate barriers to international transfers. Our results also highlight the importance of capacity building as a means to accelerate technology diffusion. A strong technology capability facilitates the import of foreign technology, but it is also a source of domestic technologies to be diffused locally. Depending on which aspect is emphasized, it may thus be leveraged for very different patterns of technology diffusion.

Annex 1 - Projects and technology transfers by type of technology

Type of technology	Total number of projects (and projects involving transfer)							
	Brazil		China		India		Mexico	
	Total	w/TT	Total	w/TT	Total	w/TT	Total	w/TT
Biogas recovery (other)					7	0	1	1
Biogas recovery in agriculture (breeding farms)	20	18					69	45
Biomass energy	34	3	5	1	78	6		
Energy efficiency / supply side					6	0		
Energy efficiency measures in industry	2	0	3	2	54	9		
Energy efficiency measures in the services sector					1	1		
Fossil fuel switch	5	1			4	1		
HFC decomposition			7	7	3	3	1	1
Hydro power	19	2	13	0	30	0	2	1
Landfill gas recovery	13	11	4	4	2	1	2	2
N_2O destruction	1	1	1	1				
Power generation from coal mine methane			3	2				
Recovery of fugitive gas	1	1						
Reduction of the share of clinker in cement production					13	0		
Reforestation			1	0				
Solar power					1	1		
Wind power	4	3	34	25	26	6	3	3
TOTAL	99		71		225		78	

Conclusion

This dissertation contributes to the literature in three ways. First, we provide an up-to-date description of innovation in low carbon technologies and of their international diffusion at a global scale. Secondly, we empirically analyze the factors that promote or hinder the international diffusion of climate-friendly technologies. Third, we examine the influence of pro-renewable energy policies on foreign innovation activity.

This final section summarizes the main results of the papers. We derive general conclusions in light of the full set of studies presented in the dissertation. We focus the discussion on the policy implications of our findings. In the presence of market failures such as pollution externalities, achieving an efficient outcome requires government intervention. Therefore, unlike other technologies, public policy is an essential factor in the development and diffusion of climate-related technologies. We close with some possible directions for future research.

1 Main results and policy implications

Climate-friendly inventions are also developed in the South

This dissertation sheds light on the geography of innovation in climate change mitigation technologies. We show that innovation is highly concentrated in three countries—Japan, Germany and the USA—which account for two thirds of total innovations in the thirteen technologies. With over 40 percent of the number of inventions patented every year in the world, Japan is the leader in climate-related innovation.

Given the distribution of R&D expenditures around the world, the performance of these countries is hardly unexpected. What is more surprising is that innovation activity in emerging economies appears very significant. According to the ranking presented in the first paper, Japan, USA and Germany are followed by three emerging economies, namely China, South Korea and Russia. Together, they represent about 15% of the total number of inventions worldwide and this share is constantly growing. The analysis of CDM projects confirms this finding. Nearly 60% of the projects in our data set use local technology, and this percentage is 88% in India.

Climate policy causes innovation in green technologies

An important result that emerges from this work is that climate policy causes innovation in green technologies. We provide the first evidence in the literature of a correlation between innovation in climate-related technologies and the signing of the Kyoto protocol. While innovation in climate change technologies and innovation in all technologies were growing at the same pace until the mid-nineties, the former has started to develop much faster after the protocol was signed. This suggests that innovators react swiftly to policy changes by increasing their R&D efforts.

Innovators think global

This work reports the first empirical evidence of cross-border induced innovation. We find strong evidence in the third paper that inventors respond to foreign pro-renewables policies by increasing their innovation effort. This result has important policy implications. It suggests that inventor countries that have not committed themselves to reducing carbon emissions—such as the US and China—may free ride *twice* on carbon emissions reduction commitments taken by Japan and European countries: first, by experiencing less global warming; and second, by selling climate mitigation technologies abroad. This problem should be taken into account for the design of the next international climate agreement. In particular, this result calls for including all major innovators in the future post-Kyoto agreement.

North-South technology transfer is still limited—let alone South-South transfer

We show that international technology diffusion mostly occurs between developed countries, which represent 75% of exported inventions worlwide. Exports from developed countries to emerging economies are still limited (18%) but are growing rapidly. This suggests a significant potential for the development of North-South transfers. 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.

National policies can foster technology diffusion

This dissertation presents the first econometric study using patent data to analyze specifically the diffusion of climate change mitigation technologies at a global level. Our analyses show that strong technological capabilities help adopting advanced technology. Moreover, specific skills seem to be more important than generic qualifications, as measured by the population's level of tertiary education. This result highlights the importance of capacity building as a means to accelerate technology diffusion. Our estimations also show that restrictions to international trade—e.g., high tariff rates—negatively influence the international diffusion of climate technologies. Stronger intellectual property regimes would encourage the transfer of patented technologies. In contrast with the empirical literature dealing with non-climate technologies, we find that barriers to foreign direct investments may promote climate-related technology diffusion. This result means that regulations applying to foreign direct investments may promote technology transfer.

Global climate policy can promote technology transfer

Our results also show that climate policy may encourage technology diffusion. We find that technology transfer takes place in 43% of projects set up under the Clean Development Mechanism. The analysis of CDM projects suggests policy lessons for the design of future project-based mechanisms. Econometric analysis shows that transfers in large projects—in terms of emissions reductions—are more likely. Encouraging project bundling—or sector-level projects—allows exploitation of increasing returns in technology transfer. Furthermore, the probability of transfer is 50% higher when the project is developed in a subsidiary of a company located in an Annex 1 country. Promoting such projects could foster technology transfer. In practice, one could imagine different ways of providing incentives for companies to do so (e.g. additional credits, simplified administrative procedures).

2 Directions for future research

Going beyond patent data

We have explained in this dissertation why patents are imperfect proxies of technology transfer. Technology diffusion mostly occurs through non-market channels, which are not reflected in foreign patent filings. An important research area is to determine whether the transfer of patented technologies is positively correlated with non-patented knowledge flows. A possible way to investigate this issue would be to conduct a case study of a specific sector. The objective of this work would be to identify the channels of technology diffusion within the sector, including trade in equipment goods, FDI, licensing, mergers and acquisitions, patent examination, etc. This analysis would provide a comparative assessment of the importance of each of these channels and assess whether they are complements or substitutes. Given the number of studies that rely on one particular channel to analyze technology diffusion (e.g., patents, trade flows, FDI), the results would have important implications.

Sector-level project mechanisms

Our studies conclude that the CDM contributes to North-South technology transfer. Although there are nearly 4500 projects currently registered or under examination, the CDM's contribution to technology deployment is likely to prove insufficient given the challenge at stake. For this reason, the idea to scale up the CDM to the sectoral level has been recently introduced. Several proposals for sectoral crediting mechanisms have been put forward. However, whether sectoral approaches can be an effective remedy to the shortfalls of the CDM remains an open question. In particular, it is not clear why transaction costs would be lower for sector-level projects than for CDM projects. This point requires further analysis. The ability of sector-level projects to enhance technology diffusion is another important research direction.

Horizontal technology diffusion

The process by which a country acquires a foreign technology can be divided in two steps. In the first step, the technology is transferred from a party, located in country i, to another party, located in country j. In the second step, the technology is transferred to other parties *within* the country. In the economic literature, the first step is referred to as vertical diffusion and the second step as horizontal diffusion.

The main shortcoming of this dissertation is that it focuses on vertical diffusion and says little about horizontal diffusion. This shortcoming is mainly due to data constraints. By nature, a patent is only filed once in a country, and information about how widely the technology is used is sparse. As for the CDM projects, our data set describes projects registered during a short period of about 2 years, which prevents using this information to characterize the dynamic aspects of diffusion.

Nevertheless, it would be certainly valuable to investigate the horizontal aspects of technology diffusion. In this regards, CDM projects may be further analyzed. An interesting question is whether technologies transferred through CDM projects have diffused within the host country. A possible way to investigate this issue would be to analyze if the proportion of CDM projects involving a technology transfer decreases as time goes by. Another possible research direction would be to complement CDM data with firm-level data in order to analyze the technology diffusion between CDM developers and other local companies.

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