Les déterminants de l’innovation et des transferts internationaux de technologies sobres en carbone: une analyse quantitative sur données de brevets

Projet de rapport final d’une étude pour le Conseil Français de l’Energie

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Introduction

Ce rapport a été préparé par Antoine Dechezleprêtre, Matthieu Glachant et Yann Ménière du CERNA, Mines ParisTech pour le Conseil Français de l'Energie. Il s'inscrit dans le programme de recherche du CERNA "Technology Transfer and Climate Change".

Il développe une analyse économétrique des déterminants (i) de l’innovation et (ii) des transferts internationaux de technologies sobres en carbone. Il est constitué de deux articles en anglais présentés successivement dans la suite du rapport :

- *Does foreign regulation influence domestic inventors? The case of innovation in wind power*
- *What Drives International Transfers of Climate Change Mitigation Technologies? Empirical Evidence from Patent Data*

Les deux articles exploitent une base de données qui décrit les dépôts de 280 000 brevets dans 80 pays entre 1990 et 2005 et dans 12 catégories de technologies sobres en carbone : éolien, solaire, géothermie, énergie marine, biomasse, hydroélectricité, énergie tirée des déchets, destruction de méthane, procédés de réduction des émissions de CO2 pour la fabrication de ciment, efficacité énergétique dans le bâtiment, moteurs à injection, éclairage basse consommation. Cette base de données a été constituée par le Cerna et l’OCDE lors d’un travail achevé fin 2008. C’est une extraction de la base PATSTAT développée par l’Office Européen des Brevets.

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Does foreign regulation influence domestic inventors? The case of innovation in wind power

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Abstract

This paper examines the influence of domestic and foreign regulation on innovation activity in wind power technology, using patent data from OECD 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. This result also has important implications for global climate policies.

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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 2006. We focus our investigation on wind power technology. We use patent data from the World Patent Statistical Database (PATSTAT) to measure the development and the international diffusion of new inventions in this technology. 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.

We complement the patent data set with data on additional wind power capacities annually added in each country. We use this data to proxy the level of pro-wind power policies in each country. 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. Data on installed power capacities are expressed in megawatts (MW), which make them suitable for cross-country comparisons. Moreover, additional power capacity installed in foreign countries may be summed up, thereby offering a measure of the foreign regulatory level that potentially influences domestic inventors. This methodology allows us to jointly analyze the effect of domestic and foreign regulations on companies' innovation efforts.

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. Our basic specification is as follows:

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

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 wind power capacity installed in country *i* in year *t* to measure the level of regulations promoting wind power 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 12 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*.[1]

Importantly, WindCorp's decision depends on its *expectations* about future installations. We assume that these expectations are based on observations at year *t*.[2] This assumption is in line with previous studies. Newell et al. (1999) and Popp (2002) use past prices to proxy expected future prices[3].

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

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

[3] 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.

Brunnermeier and Cohen (2003) use current PACE to measure perceived regulatory stringency, while Jaffe and Palmer (1997) use lagged values of PACE.

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 future 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[4].

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[5]. 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 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 wind 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

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[4] 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.

[5] 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.

deployment of renewable energy worldwide. An overview of these measures is available from the Global Renewable Energy Policies and Measures database[6] 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.

Wind power did not offer a competitive alternative to conventional sources of electricity on the power grid during the time-period covered by our analysis (see Neuhoff 2005, IEA 2003). Added power capacities are therefore a good measure for the level of regulation promoting these energies.

We will first simply define R_{it}^{f} as the sum of the capacities added in the rest of the world in year t. There are many reasons to suspect that the foreign market actually taken into consideration by innovators from country i—which we refer to as the *accessible* market—is smaller than the sum of all foreign markets. Various barriers have been shown to influence the market diffusion of technologies, including geographical factors—such as distance, language, trade blocks, and cultural differences—and institutional factors—e.g., tariffs, the quality of the patent system (see Keller, 2004, for a review of these factors). These barriers may prevent inventors from country i to consider country j as a potential market. Consequently, we will experiment with several measures of the accessible foreign market. For example we will distinguish between contiguous countries and others.

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:

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

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

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. A time trend and other time-varying variables account for time-specific events that could have OECD-wide effects on the pace of innovation.[7]

3 Data

3.1 Patent data

We use the EPO/OECD World Patent Statistical Database (PATSTAT) to extract all patents filed worldwide from 1990 to 2006 in wind power technology. Patent applications are identified using the International Patent Classification (IPC) code F03D, which covers wind motors. Using patent classifications does not allow us to include all patents relevant to wind power. Therefore, our dataset can be seen at worst as a good proxy of innovative activity in wind power. Our dataset includes 15,835 patent applications filed in 72 patent offices[8].

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

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[7] 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.

[8] 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.

discussed at length in the literature (for a good overview, see OECD 2009). For our purpose, the main advantage of patent data is that they are available both at a disaggregated technological level and on a global scale. Moreover, 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 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 12 months. Patents filed in 2007 but pertaining to inventions first filed in 2006 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 2006.

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). This is not a problem in this study as we run separate regressions for each of the 5 technologies analyzed. But the propensity to patent also varies across countries: patenting is more likely to concern countries with high technological capabilities and a strict enforcement of intellectual property rights. As we will see, econometric models allow us to partly control this problem.

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. Dechezleprêtre et al. (2009) show that the average invention is patented in two countries.[9] 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 (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. 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), such as assigning weights based on the number of times a patent is cited in subsequent ones. Unfortunately our data do not allow us to implement these methods.

3.2 Data on installed power capacity

Data on installed capacities for wind power production are taken from the International Energy Agency (IEA) Renewables information database[10]. They are available for all OECD countries from 1990 onwards. For non-OECD countries, the IEA only provides data on energy production from wind power but not on installed capacity. We estimate installed capacity in non-OECD countries by running a pooled linear regression of energy capacities on energy production[11], using the data from OECD countries from 1990 to 2006. We use this model to make out-of-the-sample predictions of capacities in non-OECD countries based on their production. This allows us to proxy the market size in non-OECD

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

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

[11] We do not include any constant term as production is obviously nil when capacities are nil.

countries, which might influence inventors located in OECD countries. The results of this regression are shown in Table 1. The quality of the estimations is very good.

Table 1. Regression results of capacities on production

Variable	Wind capacities
Production	6.967** (0.0609)
R-squared	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 early evidence on the influence of foreign markets on innovators.

4.1. Innovation activity and power capacity at the global level

Figure 1 compares the trend in innovation activity with additional wind power capacity installed between 1991 and 2006[12]. The number of inventions annually patented across the world in wind power technology has been multiplied by a factor of six between 1991 and 2006. There has been a strong acceleration in innovation activity at the end of the 1990s and then again in 2004. In the meantime, annual installations of wind power capacities have increased dramatically. While only 200 MW were installed in 2001, the new turbines installed in 2006 amounted to 11,400 MW. At the world level, the correlation between new installations and innovation is striking. The acceleration of the deployment of new power capacity in the 1990s corresponded to a similar increase in the number of inventions, while the slowing up in the early 2000 affected both innovation and deployment.

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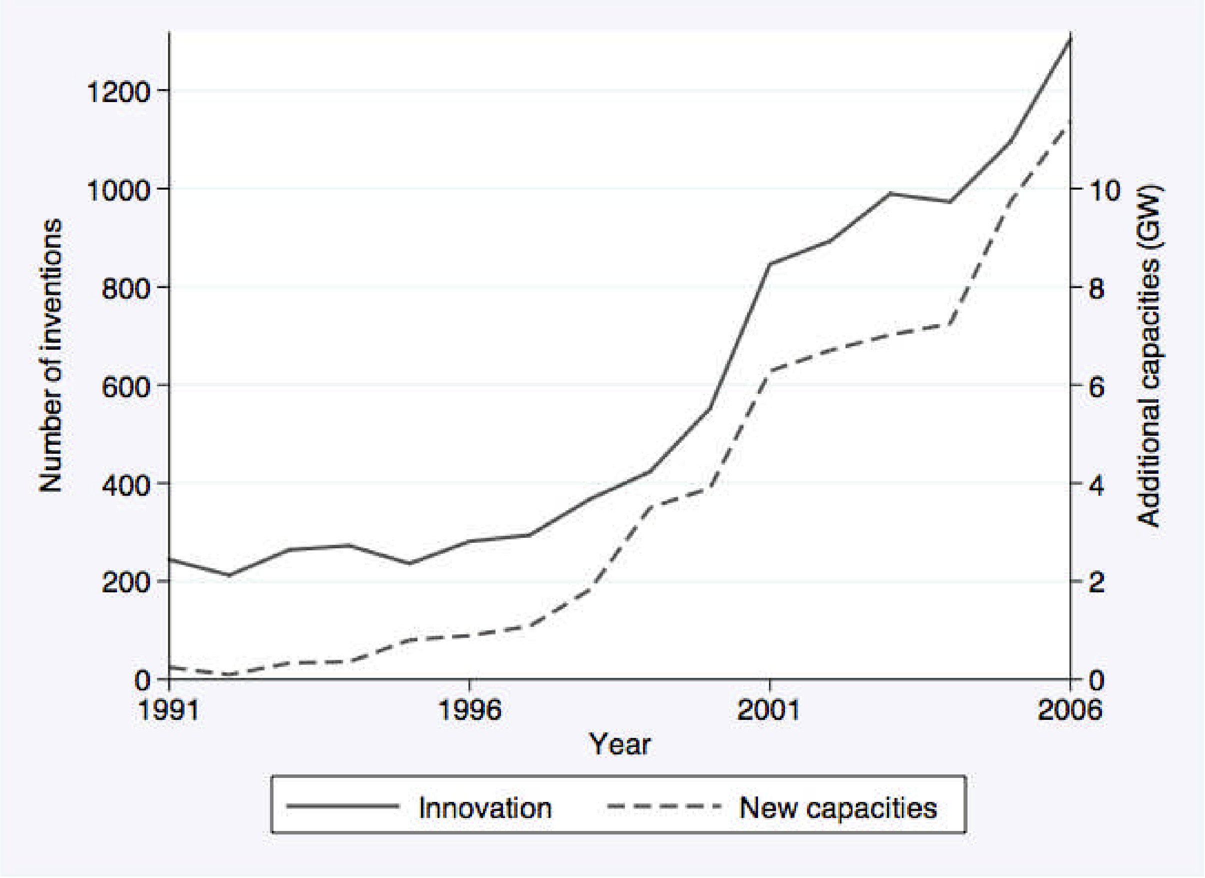
[12] Since data on installed capacities starts in 1990, data on annual added capacity obviously starts in 1991.

Figure 1. Worldwide innovation activity and annual additional capacities



4.2. The importance of foreign patenting

What is the proportion of inventions that cross borders? Our database includes 9,245 distinct inventions. Of these, 76% have been patented in only one country. This seems to suggest that the majority of inventions is designed for local markets. However, the remaining 24% have been patented in an average 4.7 countries (including the country of origin). This distribution is typical of patent data: the majority of inventions are of rather low value and are only protected in one country, while a minority of high-value patents are filed in numerous offices worldwide. Table 2 presents the distribution of the size of patent families. This distribution is much skewed. The largest patent family in our data set includes 27 countries. Around 2.5% of inventions are patented in 10 countries or more. Interestingly, the proportion of international inventions (i.e., inventions patented in several countries) has tripled during the 1990s.

Because a small share of patents are filed in many countries, 49% of the patents in the data set are filed by inventors whose country of residence is different from the country in which protection is sought[13] (e.g. a patent filed in the US by a German inventor). This result is suggestive of a clearly global market for wind power technologies.

Table 3 shows the rate of patent export for the 10 main OECD inventor countries. The rate of export is defined as the share of the country's inventions that are patented in at east one foreign country. Interestingly, export rates vary widely across countries. Nearly 70% of US inventions are exported. Inventors from European countries export around half of their inventions, but the export rate is only around 10% for Japan and South Korea.

Table 2. Frequency distribution of the size of patent families

Family size	Frequency distribution (%)
1	76.3
2	8.0
3	4.7
4	2.7
5	1.8
6	1.5
7	1.4
8	0.7
9	0.6
10+	2.4

Table 3. Export rate for the 10 main OECD inventor countries

Country	Export rate
Canada	44.8%
France	31.8%
Germany	49.0%
Japan	11.0%

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[13] Excluding patents filed at the European Patent Office, the figure is 42%.

Netherlands	61.4%
S Korea	11.7%
Spain	57.7%
Sweden	66.7%
UK	45.5%
USA	68.7%

To sum up, the data strongly suggest that foreign markets do matter for inventors, and that the importance of foreign markets varies across countries.

5 Estimation and results

5.1 Basic econometric specification and results

Recall that our dependent variable is N_{it}, the number of inventions patented by inventors from country i in year t.[14] 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:

$$\begin{aligned} N_{it} &= \alpha_0 + \alpha_1 \log(R_{it}^d) + \alpha_2 \log(R_{it}^f) + \alpha_3 \log(Dom\_Kn\_Stock_{it\text{-}1}) \\ &+ \alpha_4 \log(For\_Kn\_Stock_{it\text{-}1}) + \alpha_5 YEAR + \alpha_6 IPR_t + \beta_i + \varepsilon_{it} \end{aligned} \tag{1}$$

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, $Dom\_Kn\_Stock_{it-1}$ is the stock of locally developed innovations, $For\_Kn\_Stock_{it-1}$ is the stock of patents filed by foreign inventors, β_i is a vector of fixed-effects for each inventor country, IPR_t is an index of the average strictness of patent systems in the world at year t and ε_{it} is the error term. Note that by construction R_{it}^f would be highly correlated with times dummies. For this reason, we instead use a time trend and the patent systems index.

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[14] 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.

A notable feature of our data is that most countries produce very few innovations, implying that the data is highly over-dispersed, the standard deviation being much higher than the mean. For this reason, in line with previous studies, we use a negative binomial regression model, which tests and corrects for over-dispersion. Moreover, we estimate equation (1) using a fixed effects model. We also used a random effects model, but a Hausman test rejects the hypothesis that unobserved heterogeneity is uncorrelated with the explanatory variables. This supports the inclusion of country fixed-effects.

We also use OLS estimation as a robustness check. In that case we use a log-log regression framework and estimate the following equation[15]:

$$\begin{aligned}\log(1+N_{it}) &= \alpha_0 + \alpha_1 \log(R_{it}^d) + \alpha_2 \log(R_{it}^f) + \alpha_3 \log(Kn\_Stock_{it\text{-}1}) \\ &+\alpha_4 \log(For\_Kn\_Stock_{it\text{-}1}) + \alpha_5 YEAR + \alpha_6 IPR_t + \beta_i + \varepsilon_{it}\end{aligned} \qquad (2)$$

The panel extends over 15 years, from 1991 to 2005, and covers the 30 OECD countries. Descriptive statistics for the variables used in the analysis are shown in table 4.

Table 4—Descriptive statistics

	Obs.	Mean	Std. Dev.	Min	Max
N_{it}	450	13.91	38.06	0	347
$\ln(1+N_{it})$	450	1.57	1.31	0	5.85
$\ln(R_{it}^d)$	450	2.08	2.24	0	8.09
$\ln(R_{it}^f)$	450	7.55	1.30	5.19	9.36
$\ln(Dom\_Kn\_Stock_{it\text{-}1})$	450	3.18	1.52	0	7.29
$\ln(For\_Kn\_Stock_{it\text{-}1})$	450	2.84	1.45	0	6.39

Estimation results of equation (1) are shown in table 5. Results are consistent across the negative binomial and the OLS specifications. Our estimations indicate that the increase of domestic wind power installations has a positive effect on innovation. An increase in foreign capacities also exerts a positive influence on the number of new inventions. The coefficient is significant at the 5% level in

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

both regressions. This shows that innovators react to a growing domestic or foreign market by increasing their innovation efforts.

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 policies encouraging the use of renewable energy have a positive effect on innovation efforts both at home and abroad.

Table 5 — Estimation results

Variable	Negative binomial	OLS (Indep. var.: $\ln(1+N_{it})$)
$\ln(R_{it}^{d})$	0.0820*** (0.0225)	0.0826*** (0.0243)
$\ln(R_{it}^{f})$	0.3359** (0.1590)	0.3137** (0.1551)
ln(*Dom_Kn_Stock*$_{it-1}$)	0.4848*** (0.0783)	0.2948*** (0.0815)
ln(*For_Kn_Stock*$_{it-1}$)	-0.1280* (0.0669)	-0.2371* (0.0543)
Constant	47.495 (73.809)	-37.374 (78.404)
Observations	450	450

Notes: Standard error in parentheses; * denotes significance at 10% level, ** denotes significance at 5% level, *** denotes significance at 1% level.
Both equations include unreported fixed effects, time trend, IPR index and US pre-2000 dummy.

Our estimations allow us to compare the effect of domestic and foreign markets on innovation. The coefficients of the OLS estimation indicate that a 10% increase in the size of the domestic market leads to an 8% increase in the number of innovations, while a 10% increase in the size of the foreign market increases the number of domestic innovations by 31%. However, the foreign market is on average much larger than the domestic market. A more sensible way of approaching this issue is to calculate the marginal effect on domestic innovation of an additional MW installed at home or abroad.

Using the negative binomial model, we find that, on average[16], one additional MW installed at home increases the number of domestic innovations by 0.0044 whereas one additional MW installed abroad increases the number of domestic innovations by 0.0006. This means that the influence of the domestic market on local innovation is approximately 8 times larger than the influence of foreign markets. Marginal effects calculated using the OLS specification leads very similar results.

Why are innovators primarily influenced by their domestic market? A first possible explanation is that wind power technologies are tailored to national specificities. Although some wind power innovations aim at adapting wind turbines to extreme conditions found only in specific regions, most wind power technologies have a general application. A more plausible explanation is that barriers to technology diffusion - such as geographical distance, language and cultural differences, tariffs and non-tariffs barriers to trade - prevent innovators from considering foreign markets as a potential recipient for their technologies. Presumably, in a world where technologies can be transferred from one country to another, the location of innovators would not matter. Therefore, an important consequence of our findings is that barriers to technology diffusion also discourage innovation. Looking at the marginal effects can help us get some sense of the size of this effect. If there was no barrier to technology diffusion at all, innovation would respond similarly to an increase in wind power installations at home or abroad. This means the impact of foreign markets on domestic innovation would be 8 times higher.

Unsurprisingly, the discounted stock of local innovations has a statistically significant effect on innovation. Perhaps more interestingly, we also find that the stock of “imported” patents has a negative and significant effect on innovation. This result suggests that domestic and foreign technologies are substitutes, implying that a strong presence of foreign competitors discourages innovation.

5.2 The consequences of omitting foreign markets

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[16] We calculate the marginal effect of the variables on an average project.

Previous empirical studies on the links between environmental regulation and innovation have neglected the potential impact of foreign markets. To the extent that PACE or energy prices in different countries are positively correlated, overlooking this important aspect of the data might have led these studies to overstate the effect of domestic regulation on innovative activities. In order to investigate this issue, we run the same regressions as in the previous section and simply omit R_{it}^{f}. The results are presented in Table 6. If we compare these results with those of Table 5, we find that omitting R_{it}^{f} does not produce a biased estimation of the effect of domestic regulation. The reason is that foreign regulation does not vary much across groups and is therefore properly controlled for by the time trend. Previous empirical studies using patents to examine the determinants of innovation, including Jaffe and Palmer (1997), Popp (2002), and Brunnermeier and Cohen (2003), only look at domestic regulation. However, our results show that including time effects (year dummies) allows them to control for foreign regulation. Hence their results are unlikely to be biased.

Table 6 — Estimation results, omitting foreign demand

Variable	NB	OLS
$\ln(R_{it}^{d})$	0.0780*** (0.0224)	0.0784*** (0.0243)
ln(*Dom_Kn_Stock*$_{it-1}$)	0.4765*** (0.0774)	0.2888*** (0.0817)
ln(*For_Kn_Stock*$_{it-1}$)	-0.1227*	-0.2379***
	(0.0664)	(0.0545)
Constant	-33.217 (64.343)	-130.80 (63.584)
Observations	450	450

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, time trend, IPR index and US pre-2000 dummy.

5.3 Identifying the accessible foreign market

Equation (1) distinguishes between the domestic regulatory level R_{it}^{d} and the foreign regulatory level R_{it}^{f}, where R_{it}^{f} is simply defined as the sum of the wind power capacities added in the rest of the world. We can further break down the foreign regulatory level into two parts: the accessible foreign market R_{it}^{fA} and the inaccessible foreign market R_{it}^{fNA}. We define the *accessible* foreign market as the share of the world's market taken into consideration by innovators when they make decisions on R&D activity. Consequently, we estimate:

$$\begin{aligned} N_{it} &= \alpha_0 + \alpha_1 \log(R_{it}^{d}) + \alpha_2 \log(R_{it}^{fA}) + \alpha_3 \log(R_{it}^{fNA}) + \alpha_4 \log(Dom\_Kn\_Stock_{it\text{-}1}) \\ &+ \alpha_5 \log(For\_Kn\_Stock_{it\text{-}1}) + \alpha_6 YEAR + \alpha_7 IPR_t + \beta_i + \varepsilon_{it} \end{aligned} \qquad (3)$$

where R_{it}^{fA} is the accessible foreign market and $R_{it}^{fA} = R_{it}^{fNA} - R_{it}^{f}$.

There are many reasons why the market in country *j* may not be considered as a potential market by innovators from country *i*: for example, if country *j* is located very far from country *i*; if both countries speak different languages; or if country *i* has a poor enforcement of intellectual property rights. Basically, barriers to technology diffusion prevent innovators from considering each and every foreign country as a potential market for their technologies. However, what exactly makes a foreign market accessible is an open question. In this section we experiment with different ways of breaking down the foreign market, in order to investigate which markets are considered accessible by innovators.

We try four measures of the accessible foreign market: (i) countries contiguous to the inventor country; (ii) countries with a strong enforcement of IP rights; (iii) countries with low barriers to FDI; and (iv) importers of locally produced wind power devices.

We obtained information on coutiguous countries from the online CEPII data sets[17]. To measure the strictness of intellectual property rights, we use the index built by Park and Lippoldt (2008). A country's IPR regime is considered strict if it is above the median IPR index between 1990 and 2005. Barriers to FDI are proxied by the index of international capital market controls, provided by the Economic Freedom of the World 2008 Annual Report[18]. Again, barriers to FDI are considered low if

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[17] Available at http://www.cepii.fr/anglaisgraph/bdd/distances.htm

[18] Missing years were filled by interpolation.

they are below the median strictness. Finally, we obtain data on trade related to wind power devices from the COMTRADE database. Country *j* is considered an customer of country *i* if it imported wind power devices from country *i* at least once between 1997 and 2005.

The results of our investigations are presented in table 7. We report only the estimations using negative binomial model. OLS yields similar results[19]. Our results show that additional wind power installations in contiguous countries has a positive and significant effect on domestic innovation, but the impact of more distant countries is not statistically significant. Similarly, new wind power installations in countries that import local wind devices induce more innovation domestically, but installations among non-trading partners don't.

Patent systems do not appear strongly discriminating: domestic innovation seems to be influenced by capacity increases both in countries with strong patent systems and in countries with weak IP rights. However, the accessible market has a strongly statistically significant impact while the rest of the world has a weaker statistically significant impact.

Surprisingly, domestic innovation seems influenced by wind power regulation in countries with *strong* barriers to FDI and not by countries with low barriers. A possible explanation is that controls over foreign capital increase the risk of losing control of transferred technology, thus leading foreign investors to rely more heavily on patents as a way to secure their intellectual assets. This, in turn, translates into more patented innovations, which is what we measure. Another 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. This, again, would lead to more patented innovations.

If one looks at the variables' marginal effects (shown in table 8), we find that the influence of the accessible foreign market on local innovation is larger than the influence of the rest of the world when the accessible market is measured by contiguous countries or by trade partners. The opposite is true for IPR.

Table 7 — Estimation results

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[19] Results are available from the authors on request.

	The accessible foreign market R_{it}^{fA} is measured by:			
Variable	Contiguous countries	Countries with strong IPR	Countries with low barriers to FDI	Trade partners for wind power devices
$\ln(R_{it}^{d})$	0.0791*** (0.0227)	0.0827*** (0.0225)	0.0774*** (0.0221)	0.0837*** (0.0227)
$\ln(R_{it}^{fA})$	0.0625** (0.0285)	0.3446*** (0.1379)	0.0774 (0.0589)	0.3623*** (0.1354)
$\ln(R_{it}^{fNA})$	0.1225 (0.1235)	0.0745* (0.0405)	0.2208*** (0.0594)	0.0706 (0.0483)
ln(*Dom_Kn_Stock*$_{it-1}$)	0.5018*** (0.0807)	0.4959*** (0.0793)	0.5016*** (0.0802)	0.4795*** (0.0785)
ln(*For_Kn_Stock*$_{it-1}$)	-0.1275* (0.0669)	-0.1379* (0.0667)	-0.1439* (0.0663)	-0.1252* (0.0668)
Constant	26.941 (76.165)	-0.0976 (82.765)	163.97 (115.58)	67.714 (74.059)
Observations	450	450	450	450

Table 8 — Marginal effects

	The accessible foreign market R_{it}^{fA} is measured by:			
Variable	Contiguous countries	Countries with strong IPR	Countries with low barriers to FDI	Trade partners for wind power devices
R_{it}^{d}	0.00428	0.00486	0.00484	0.00515
R_{it}^{fA}	0.00076	0.00070	0.00039	0.00090
R_{it}^{fNA}	0.00024	0.00181	0.00070	0.00058

7 Conclusion

In this paper, we use patent data from OECD countries to analyze the influence of domestic and foreign regulation on innovation activity in wind power technologies between 1991 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 wind energy is primarily the result of regulation in favor of renewable energy, our results suggest that innovation is influenced both by local and by foreign regulation.

We further investigate what parts of the world are considered by innovators as potential markets. We find that additional wind power installations in contiguous countries have a positive and significant effect on domestic innovation while more distant countries have no significant impact. Innovation is influenced by countries with strong patent systems but not by countries with weak IP rights. New installations in trading partners induce more innovation domestically. Surprisingly, domestic innovation seems influenced only by wind power regulation in countries with *strong* barriers to FDI and not by countries with low barriers.

These findings show that barriers to technology diffusion also discourage innovation. An important consequence of this is that policies aiming at limiting the barriers to cross-country technology diffusion are likely to foster innovation at the same time.

A symmetric way to look at our main finding is to say that environmental regulation has a positive effect both on domestic *and* on foreign innovation.

This result has important policy implications 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 the 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.

Moreover, if companies 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.

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What Drives International Transfers of Climate Change Mitigation Technologies? Empirical Evidence from Patent Data

Antoine Dechezleprêtre, Matthieu Glachant et Yann Ménière

Abstract

Using patent data from 76 countries for the period 1990-2003, we characterize the factors which promote or hinder the international diffusion of climate-friendly technologies on a global scale. Regression results show that technology-specific capabilities of the recipient countries are determinant factors. In contrast, the general level of education is less important. We also show that restrictions to international trade—e.g., high import tariff rates—and lax intellectual property regimes negatively influence the international diffusion of patented knowledge. Barriers to foreign direct investments have seemingly less influence. Furthermore their impacts are counter-intuitive as they can even promote transfers in certain cases. We discuss different possible interpretations.

Key words: Climate change, technology diffusion, technology transfer.

JEL Code: O33, O34, Q54

1 Introduction

The international diffusion of climate mitigation technologies 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. North South technology transfers are of particular interest as technologies have been developed mostly in industrialized countries while they are urgently required to mitigate GHG emissions in fast-growing emerging economies. However, ensuring transfers 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 paper examines these issues by identifying the factors which promote or hinder the international diffusion of climate-friendly technologies. Are local technology absorptive capacities important? Do strict Intellectual Property Rights induce more transfers? Or do barriers to trade or foreign direct investments significantly reduce the import of technologies? Finally does domestic innovation crowd out technology imports?

We address these questions with patent data from 76 countries for the period 1990-2003 extracted from the World Patent Statistical Database (PATSTAT). We focus the analysis on twelve classes of technologies: seven renewable energy technologies (wind, solar, geothermal, ocean energy, biomass, waste-to-energy, and hydropower), methane destruction, energy conservation in buildings, climate-friendly cement, motor vehicle fuel injection, and energy-efficient lighting. Although not all climate-friendly technologies are covered, they represent nearly 50% of all GHG abatement opportunities beyond business as usual until 2030—excluding forestry—identified by McKinsey and Vattenfall (2007).

The empirical literature on international technology diffusion is well developed (for a good survey, see Keller, 2004). But, to the best of our knowledge, our work is the first study using patent data to analyze specifically the diffusion of climate-mitigation technologies at a global level. A paper by Lanjouw and Mody (1996) is the most closely related to our work. These authors focus on patents on environmentally responsive technology in Japan, Europe, the USA and fourteen developing countries. They identify the leaders in environmental patenting and find that significant transfers occur to developing countries. Barton (2007) discusses from a legal perspective whether strong intellectual property rights in emerging economies would hinder or promote the transfer of green technology.

As a measure of diffusion, our approach is similar to that of Lanjouw and Mody (1996), or Eaton and Kortum (1999). We count the number of patent applications in recipient countries which protect technologies invented abroad. As the data tells us in which country is located the inventor, we know precisely the geography of technology flows and we can run regressions to understand what drives cross-country technology exchanges.

This approach presents apparent similarities to a method based on patent citations which is used in several studies to measure international knowledge flows (see Jaffe et al. 1993, Peri 2005). But there is an important difference. The count of citations made to previous patents in new patents is an indicator of knowledge *spillovers* whereas our indicator is a proxy for private knowledge flows as inventors obviously patent abroad to reap private benefits.

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

1.1. 2 Patents as indicators of technology transfer

In the empirical literature, a number of solutions for the measurement of international technology transfer have been proposed. As major transmission channels of knowledge across countries include international trade and foreign direct investments (FDI), many papers use import flows of intermediate goods or FDI to proxy international transfer (for example, Coe, Helpman and Hoffmaister, 1997; Lee and Mansfield, 1996). Interestingly, these data are easily available from a large number of countries, thereby allowing a very broad geographical coverage. However, they are highly aggregated which prevents their use to measure the flows of climate-friendly technologies. More generally, they are only very indirect proxies of knowledge transfer.

This is why more recent papers tend to rely on patent data[i]. 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 will be discussed below.

In order to provide an accurate explanation of how we use patent data in this paper, it is necessary to briefly recall how the patent system works. Consider a simplified innovative process. In the first stage, an inventor from country *i* discovers 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 a country *i* if he plans to use it there. The set of patents related to the same invention is called a patent family.

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 *i* and filed in country *j* as an indicator of the number of innovations transferred from country *i* to country *j*. As mentioned in introduction, this indicator has already been used in previous work (see for instance Lanjouw and Mody, 1996; or Eaton and Kortum, 1999). And it differs from indicators based on patent citation used in the literature to measure knowledge spillovers (see Jaffe et al. 1993).

Our approach is obviously imperfect. 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. However we will see that the econometric models developed below control 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 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 recall that patenting protects inventions in the country where the patent is filed only. This precludes strategic behavior of inventors who would protect their inventions abroad to prevent the use of the technology to produce a good imported by foreign competitors in their domestic markets

Finally the value of individual patents is heterogeneous and its distribution is skewed: as many patents have very little value, the number of patents does not perfectly reflect the value of innovations. This problem is probably less acute in this paper than in other works as we focus on international diffusion: only about a quarter of total inventions cross borders and they should probably be the highest-value ones.

1.2. 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. 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 1990 to 2003 in 12 climate-mitigation fields: 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, and energy-efficient lighting. The 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[ii]. On average, climate-related patents included in our data set represent 1% of the total annual number of patents filed worldwide.

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.
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.

(2) 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.)

(3)

(4)

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

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. Further details on data construction can be found in Dechezlepretre et al. (2009).

1.3. 3 Theoretical model

We now present a model which will be estimated in the next section. Our ultimate goal is to estimate cross-country knowledge flows. This would require a structural model accounting for the interplay between inventors and technology adopters, and for the dynamics of innovation and diffusion as inventors arguably anticipate diffusion outcomes when they define their innovation strategy. This type of model has been developed for instance by Eaton and Kortum (1999). But their econometric estimation requires much data-for instance, on R&D expenditures- which are not available in our case given the broad geographical scope of our study and its focus on climate technologies. In contrast, we could use very simple gravity-like models which are frequently used in literature dealing with knowledge spillovers, but this would hinder the economic interpretation of the results.

For these reasons, we have opted for an intermediate solution: a structural model of diffusion in which innovation is exogenous. The model characterizes the flow of technology between a country *i* where inventors are located and country *j* which either adopts domestic inventions or imports technologies with *i*, *j* = 1.., *M* and *i* ≠ *j*. Let U_{jt} the aggregate utility of all adopters located in the recipient country *j*. We adopt a Cobb-Douglas functional form:

$$U_{jt}\left(n_{1jt}..n_{ijt},..n_{njt}\right) = D_{jt}(1+n_{jjt})^{a_1}\left(\prod_{i\neq j}(1+n_{ijt})\right)^{a_2} K_{jt}{}^{a_3} \tag{1}$$

where D_{jt} is a variable capturing factors affecting the demand for technology in the recipient country. n_{ijt} is the number of inventions invented in country *i* and adopted in country *j* in year *t*. Unity is added to the n_{ijt} to take into account that the number of imported inventions can be zero. Note that we make the simplifying assumption that all the inventions invented elsewhere than in country j exhibits the same elasticity. K_{jt} is the stock of knowledge accumulated in the recipient country. This captures a usual view in the literature on technology diffusion that accumulated knowledge increases the ability to exploit new technologies. Finally a_1, a_2, and a_3 are coefficients which do not vary over time and across countries.

Turning next to inventors, let N_{it} denote the total number of technologies invented in country i and in year t and thus available for adoption in any country. We assume that N_i is exogenously given. This is how we rule out analyzing innovation aspects.

We assume that inventors are monopolists who can perfectly discriminate technology adopters. They are thus able to reap all the surplus of technology adopters. This simplifies the analysis as we can ignore technology prices and focus on the adopters' utility maximization program. Country j solves:

$$\begin{array}{l} \max S_{jt} = U_{jt}\left(n_{1jt}..n_{ijt},..n_{njt}\right) - \left(\sum_{i\neq j} n_{ijt}C_{ijt}\right) \\ \text{subject to} \quad n_{ijt} \leq N_{it},\, q = 1,..,n \end{array} \tag{2}$$

Here, C_{ij} is the transfer cost of the technology, excluding price, which captures factors hindering the import of technology (e.g., patenting costs, import tariffs in the case the technology is embodied in an intermediate good, geographical distance). It is assumed that the transfer cost for local inventions is zero ($C_{jj} = 0$).

Solving this utility program is then straightforward. To begin with, $C_{jj} = 0$ implies that total surplus increases with n_{jjt}. Denoting n_{jjt}^* the equilibrium value of n_{jjt}, we obviously have $n_{jjt}^* = N_{it}$. This result is in line with the data: almost all patented inventions are filed in the inventor's country in our dataset. The data also shows that, in the case where $i \neq j$, the constraints $n_{qit} \leq N_{qt}$ are never binding in equilibrium.[vi] Accordingly, they are ignored in the resolution. The n_{ijt}^* with $i \neq j$ are thus given by the M-1 first order conditions:

$$\frac{\partial S_{jt}}{\partial n_{ijt}} = a_2 D_{jt}(1+N_{jt})^{a_1}\left(\prod_{k\neq i,j}(1+n_{kjt})^{a_2}\right)(1+n_{ijt})^{a_2-1}K_{jt}^{a_3} - C_{ijt}^{\ b} = 0, \quad \text{for } i \neq j \tag{3}$$

These equations can be solved to give reduced-form equations expressing the n_{ijt}^* as a function of the exogenous variables. Calculations yield:

$$1+n_{ijt}^* = \left[\frac{C_{ijt} \prod_{k \neq i,j} \left(C_{kjt} / C_{ijt} \right)^{a_2}}{a_2 D_{jt} \left(1+N_{jt}\right)^{a_1} K_{jt}^{a_3}} \right]^{\frac{1}{(M-1)a_2-1}} \qquad \text{for } j \neq i \qquad (4)$$

Interestingly, this expression highlights the competition between exporting countries: knowledge flows imported in country *j* from country *i* obviously depend on the transfer cost C_{ijt} between the two countries, but also on the ratio C_{kjt} / C_{ijt} which reflects the difference between C_{ijt} and the transfer cost from the other exporting countries.

Estimating equation (4) poses a practical problem as we do not observe the number of inventions, but the number of new patents. As explained in Section 2, not all inventions are patented and the propensity to patent varies across sectors and countries.

Cross-sector heterogeneity is not a serious problem in our study as we estimate the models by technology. In order to deal with cross country differences in propensity to patent-and patent breath-, let Φ_j denote a country-specific factor such that the relationship between inventions and patents is $(1+P_{ijt}) = \Phi_j (1+n_{ijt})$, where P_{ijt} is the number of patents in country *j* protecting inventions from country *i*. Note that Φ_j does not vary with time. Substituting in (4) yields

$$1+P_{ijt}^* = \Phi_j^{1+a_1 \frac{1}{(M-1)a_2-1}} \left[\frac{C_{ijt} \prod_{k \neq i,j} \left(C_{kjt} / C_{ijt} \right)^{a_2}}{a_2 D_{jt} \left(1+F_{jt}\right)^{a_1} K_{jt}^{a_3}} \right]^{\frac{1}{(M-1)a_2-1}} \qquad \text{for } j \neq i$$

where F_{jt} is the number of patent families whose inventors is located in country *j*. Taking the logs of both sides and adopting new notations for the coefficients, we get:

$$\ln\left(1+P_{ijt}^*\right) = \alpha_0 + \alpha_1 k_{jt} + \alpha_2 c_{ijt} + \alpha_3 \sum_{k \neq i,j} c_{kjt} + \alpha_4 \ln(1+F_{jt}) + \alpha_5 d_{jt} + \alpha_6 \varphi_j \qquad (5)$$

where lower case letters denote the logs of the initial variables. This is the equation we estimate in the next section.

1.4. 5 Empirical issues and results

A straightforward econometric specification of (5) is

$$\ln\left(1+P_{ijt}^{*}\right)=\alpha_0+\alpha_1 k_{jt}+\alpha_2 c_{ijt}+\alpha_3\sum_{k\neq i,j} c_{kjt}+\alpha_4\ln(1+F_{jt})+\alpha_5 d_{jt}+\alpha_6\varphi_j+\alpha_6 t+\varepsilon_{ijt} \qquad (6)$$

We have simply added a time trend and a zero-mean error term $\varepsilon_{i,j,t}$ which includes unobservable country-pair specific effects, $\mu_{i,j}$ and random-time varying effects, v_{ijt}; that is $\varepsilon_{ijt} = \mu_{ij} + v_{ijt}$.

We construct a panel data set for each technology class previously described. This is a strong point of our study: estimating the model on each technology field allows us to control for technology-specific factors. The panels go over 13 years, from 1990 to 2003.

PATSTAT only yields information on P_{ij}, and F_j. The variable φ_j is not a problem as this is assumedly a time time-invariant effect which can be controlled by panel data estimation techniques. We use different proxies for the other variables 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}, the discounted stock of previously filed patents in the technology. This is an indicator of the local absorptive capabilities which 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:

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

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).[vii] In accordance with similar studies, we lag the variables by one year to predict transfers in year t given the stocks in year t-1.

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

The transfer cost c_{ijt}

We use five variables to measure the cost of transferring a patented invention from country *i* to country *j*. ipr_{jt} is a country-specific index built by Park and Lippoldt (2008) which measure the strictness of Intellectual Property Rights in the recipient country. Several papers highlight the fact that a lax patent system can be a barrier to the import of foreign technologies (see for example Maskus, 2000 and Barton, 2007). This issue is hotly debated in the political arena.

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 Economic Forum and the International Monetary Fund. $trade\_bloc_{ijt}$ is a dummy variable indicating whether the countries are part of the same trade bloc. Arguably, such restrictions may hinder the transfer of technologies embodied in capital equipment goods.

As usual in the trade literature, we also include $distance_{ij}$ which is simply the log of the geographic distance[viii] between country *i* and country *j*. In the empirical literature this is generally viewed as a proxy for transportation costs. Empirical evidence shows that knowledge flows are affected by distance (Peri, 2005)—though less than trade flows.

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

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. $language_{ij}$ 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 technology classes: $growth_j$, pop_j and $kyoto_{jt}$[x].The first describes country j's growth rate; the second is the log of its population, and the last is a dummy variable equal to one if $t > 1997$ and if country *j* is an Annex 1 country which has ratified the Kyoto Protocol. We also use technology-specific demand variables that are listed in Table 2.

Table 2. Description of demand variables, by technology

Technology field	Variable	Definition and sources
Biomass	$elec\_biomass_{jt}$	Energy production from biomass (ktoe)
Buildings	$urban_{jt}$	% of urban population
Fuel injection	$cars_{jt}$ gas_price_{jt}	Total # of cars Gasoline price
Geothermal	$elec\_renew_{jt}$	Production of renewable energy (ktoe)
Hydro	$elec\_hydro_{jt}$	Production of hydro electricity (ktoe)
Lighting	$urban_{jt}$	% of urban population
Methane	$agriculture_{jt}$	% agriculture in GDP.
Ocean	$elec\_renew_{jt}$	Production of renewable energy (ktoe)
Solar	$elec\_renew_{jt}$	Production of renewable energy (ktoe)
Waste	$elec\_renew_{jt}$	Production of renewable energy (ktoe)
Wind	$elec\_renew_{jt}$	Production of renewable energy (ktoe)

Sources: International Energy Agency and World Bank 2008

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 frequently equals zero. This obviously prevents the use of OLS estimator. But the Poisson distribution is also very restrictive as it imposes the mean to be equal to the variance when dealing with count data with many zeros. This is the reason why we use a negative binomial regression model which tests and corrects for over-dispersion.

In addition, we select a random-effects model for different reasons. First, parameters of time-invariant variables cannot be estimated with the fixed-effects model. This would have meant excluding several variables that are likely to have a significant impact such as distance or common language. Second, using a fixed-effects model would cause all groups with 0 patent transferred during the 1990-2003 period to be dropped from the regression. This would induce a selection bias as we would exclude many potential technology suppliers from the sample. Last, the random effect negative binomial model provides more efficient estimators than the fixed effect model.

Results are shown in Tables 3a and 3b. The model converges for all technologies. Coefficients do not exhibit absurd signs and they are frequently significant. Importantly, they do show strong differences between technologies as none of the statistically-significant variables show opposite signs for different technologies.

We will not comment on every variable. We focus the interpretation on five policy-relevant questions.

1) Does accumulated knowledge facilitate the import of technology? The local stock of technology-specific knowledge S_{jt} has a clear positive impact on the flows of patents in all regressions. The coefficient is even statistically significant at the 0.1% level in ten fields out of 11. Undoubtedly, 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 six regressions. This suggests that generic absorptive capabilities are less important than technology-specific knowledge.

2) Does local innovation crowd out the import of foreign technologies? Results suggest a negative answer as the variable $\ln(1+F_{jt})$ is never significant. Two alternative interpretations come to mind. It might mean that local and imported technologies have different markets or applications. Or, it may reflect that they are substitutes in certain cases and complements in others so that no visible relationships is observed at the aggregate level.

3) Do strict Intellectual Property Rights promote technology transfer? As mentioned previously, this issue is very high in the political agenda. Our results lend support to the interest of strengthening IPR regime to increase transfers. In eight regressions out of twelve, stricter patent protection increases patent flows. Exceptions are four renewable energy technologies: ocean energy, solar energy, hydro power and geothermal energy. However, one should be careful when deriving policy implications. We measure knowledge transfers that occur through the patent system. The positive relationship is therefore not that surprising. But it could reflect a substitution between patented and non-patented knowledge.

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

5) Do restrictions on Foreign Direct Investments hinder technology transfer? Finally strict international capital control has a statistically significant effect in less than half of the cases. However the coefficient is counter-intuitively positive in cement, lighting technologies, energy conservation in building, methane destruction, and wind power. Several interpretations are possible. First, we do not know the precise contents of FDI regulations in the different countries as we use a synthetic index developed by the World Economic Forum. It is possible that a strict control consists in requiring the transfer of technology in foreign investments. A second interpretation may be that restrictions on FDI shift technology transfer to other channels-such as licensing to local users-are more patent-intensive than FDI.

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

Variable	waste	cement	light	building	methane	fuel injection
S_{jt}	.322***	.1713**	.1864***	.3649***	.2159***	.1576***
edu_{jt}	-0,00097	.0081*	.0098***	-0,0011	.0066*	-0,0023
$\ln(1+F_{jt})$	0,00019	0,0015	0,000085	0,00045	0,0014	-1.8e-04*
ipr_{jt}	.2462**	.4246***	.1624*	.2782***	.2127*	.2916***
$tariff_{jt}$	-.0419***	-.0409***	-.0212**	-.0432***	-.0229*	-.0152*
$trade\_bloc_{jt}$	.3962***	0,1884	.598***	-0,0795	.3586**	.1987*
$fdi\_control_{jt}$	0,0317	.1027**	.0607**	.0823***	.0983***	-0,0025
$distance_{ijt}$	-0,0919	-.2515**	0,0626	-.3844***	-.3974***	-.2123***
$language_{ijt}$	1.191***	.8863***	.6363***	.912***	.5118*	0,0404
$\sum_{k\neq i,j} trade\_bloc_{kjt}$	.0032***	0,00018	.0044***	.0032***	0,00073	.0032***
$\sum_{k\neq i,j} distance_{kjt}$	2.4e-04*	0,00028	-0,00019	4.3e-04***	0,00024	3.0e-04**
$\sum_{k\neq i,j} language_{kjt}$	-.0016***	-0,0011	-.001**	-9.7e-04*	-0,00051	-.0018***
$kyoto_{jt}$	.3619**	.4859**	.2768**	.3811**	0,2092	.4779***
$growth_{jt}$	-0,0145	0,0166	0,0018	0,00043	0,0136	-0,015
pop_{jt}	.1503**	.3886***	.2774***	.298***	.4408***	.4013***
$elec\_renew_{it}$	7.7e-06***					
$urban_{jt}$		0,0084	0,0063	0,0006		
$agriculture_{jt}$					-.0869***	
gas_price_{jt}						.3199**
$cars_{jt}$						.0019***
ln_r _cons	1.44***	4.544**	.7005***	1.821***	2.745***	.6577***
ln_s _cons	-1.546***	-1.399***	-2.035***	-1.484***	-1.353***	-2.124***

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

Variable	**wind**	**ocean**	**solar**	**hydro**	**biomass**	**geothermal**
S_{jt}	.3735***	.2528***	.478***	.4047***	.1132*	.2559***
edu_{jt}	-0,0051	.0069*	-0,0025	0,00085	.0071**	.0149***
$\ln(1+F_{jt})$	-8.2e-04*	0,0037	0,000024	-0,0059	-0,001	-0,0000019
ipr_{jt}	.4201***	0,2187	0,1325	0,2574	.3669***	0,0439
$tariff_{jt}$	-.0442***	-.0434***	-0,0077	-0,0183	-.0324***	-.0311*
$trade\_bloc_{jt}$	.3715**	1.255***	0,0036	.5627**	0,0331	.5404**
$fdi\_control_{jt}$	.0758**	0,0155	0,0341	-0,0064	-0,0017	0,0433
$distance_{ijt}$	-.3041***	-0,0071	-.274***	-.2034*	-.2512**	-0,0435
$language_{ijt}$	0,2324	.8948***	.7636***	.6774**	1.364***	.8934***
$\sum_{k\neq i,j} trade\_bloc_{kjt}$	.0019**	0,0016	.0036***	.0039***	.0025**	0,0019
$\sum_{k\neq i,j} distance_{kjt}$	5.3e-04***	6.2e-04***	3.6e-04***	7.6e-04***	0,00024	0,00023
$\sum_{k\neq i,j} language_{kjt}$	0,00012	-0,00043	0,00048	-0,00082	-.0011*	-0,00094
$kyoto_{jt}$	.6882***	.9872***	.4509***	0,384	.5814***	1.407***
$growth_{jt}$	-0,011	-.0351*	-0,0059	-0,0197	-0,0146	-0,0115
pop_{jt}	0,0779	0,0946	0,0956	.2139**	.3296***	0,0861
$elec\_renew_{it}$	6.4e-06***	1.2e-05***	4.7e-06**			1.1e-05***
$elec\_hydro_{jt}$				5.3e-05***		
$elec\_biomass_{jt}$					6.6e-06**	
ln_r _cons	1.413***	4.339***	1.925***	3.818***	1.703***	1.98***
ln_s _cons	-1.563***	-.9247***	-1.691***	-1.095***	-1.799***	-.9623***

1.5. 6 Conclusions

In this paper we use the PATSTAT database to analyze the international diffusion of patented inventions in twelve climate-related technology classes between 1978 and 2003. This allows us to draw major conclusions about the 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 have also sought to identify the impacts of different policy barriers. The results stress that restrictions to international trade—e.g., high import tariff rates—and lax intellectual property regimes negatively influence the international diffusion of patented knowledge.

Barriers to Foreign Direct Investments seem to have a more limited influence as the factor is significant in only five technology classes out of twelve. In addition, results suggest that, contrary to the expectations, barriers to FDI promote technology transfer in these cases where the coefficients are significant. This puzzle may have different interpretations. A first one may be that strict FDI regulations include requirements of technology transfers. A second interpretation may be that restrictions on FDI shift technology transfer to other channels require more patenting than FDI. This is for example the case if inventors decide to license their inventions to local users.

In conclusion, it is useful to recall that patents are imperfect proxies of technology transfer, and we have explained why 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 into 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. Clearly, further work is necessary to clarify these points.

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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
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
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
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

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[i] Alternatively Branstetter, Fisman and Foley (2006) or Smith (2001) use royalty payments and licenses which is arguably

[ii] 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.

[iii] 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.)

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

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

[vi] Exceptions are countries without inventions ($N_{it} = 0$) for which we obviously have $n_{ijt} = N_{it}$. But they are not included them in the samples used for estimations as the existence of inventions is a precondition for transfers.

[vii] A problem is that we do not have patent data 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.

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

[ix] 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.

[x] GDP growth and population were obtained from the World Bank’s World Development Indicators 2008.