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Climate Agreement and Technology Diffusion:
Impact of the Kyoto Protocol on International Patent Applications for Renewable Energy Technologies

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Abstract

This study examines the Kyoto Protocol's impact on the international diffusion of renewable energy technologies. Using patent application data of 133 countries from 1990 to 2013, we find that the Kyoto Protocol increased international patent applications from the countries with emission targets. When we focus on countries with more stringent targets, the effect of the Kyoto Protocol is even stronger. Moreover, we find a similar effect for the international patent applications filed in four developing countries that are large emitters of greenhouse gases: Brazil, China, India, and Mexico. These results suggest that the Kyoto Protocol stimulated international patenting activities from countries that are committed to stringent targets for climate mitigation.

Keywords: Renewable energy; Kyoto Protocol; International patent applications

JEL Classification Numbers: O33, Q42, Q55

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1. Introduction

The Kyoto Protocol commits State Parties to reduce greenhouse gas (GHG) emissions to an average of 5% below 1990 levels and sets binding emission reduction targets for countries under "common but differentiated responsibility and respective capabilities." Since then, many researchers have investigated the impact of the Kyoto Protocol on GHG emissions (Aichele and Felbermayr, 2012; Almer and Winkler, 2017; and Grunewald and Martinez-Zarzoso, 2016). These studies report that countries with binding emission targets under the Protocol have lower GHG emissions than would be the case absent those targets.

The impact of the Protocol has also been investigated from the viewpoint of technological development. Johnstone et al. (2010) found that a country's patent applications for wind and solar energy technologies increased after signing to the Protocol, suggesting expectations for future stricter regulations. Examining project design documents, Dechezleprêtre et al. (2008) found that international transfer of GHG mitigation technologies occurred in fewer than half the projects of the Clean Development Mechanism (CDM), which is one of the flexible mechanisms under the Protocol.

This study investigates whether the Protocol has influenced an increase in international patent applications with respect to renewable energy technologies. Such patent applications are of interest for two reasons. First, these can be interpreted as a measure of the cross-border diffusion of climate-friendly technologies (Dechezleprêtre et al., 2013; Haščič and Johnstone, 2011). The cross-border proliferation of knowledge regarding low-carbon technologies is a key factor in climate mitigation that requires the cooperation of countries across the globe. By focusing on international patent applications, we can investigate if the Protocol affects the international transfer of climate-friendly technologies. Second, international patent applications reflect the economic value of technology by capturing changes in inventor behavior.[1] When inventors recognize a higher expected return from a patent, they will want to secure patent protection in various countries and regions (Nagaoka et al., 2010). In other words, a higher number of international patent applications represents a higher economic profit from new technology.

This study makes three contributions to the existing literature on the economics of renewable energy technology. First, we investigate how the Protocol has affected international

[1] An international patent application has a strong relation to the "family size" of the patent. Haščič et al. (2010) explain international patent applications from that viewpoint.

patenting activity. Several studies have explored technology transfer through the Protocol's CDM projects (Dechezleprêtre et al., 2008, 2009; Haščič and Johnstone, 2011). In contrast to these project-level studies, we investigate whether the Protocol affects the total amount of international patent activity from each country. Second, we compare patterns of international diffusion by countries with different GHG targets for considerably long periods. By looking at the impact of the Protocol in countries with different target levels and in different periods, we can understand the breadth and strength of the Protocol's influence on technology diffusion. Third, we investigate international patent applications filed in four developing countries that are fast-growing emerging economies with large GHG emissions: Brazil, China, India, and Mexico. Focusing on these four countries allows us to explore the "North-to-South" technology diffusion, which has significant implications for future global GHG emissions.

The paper is organized as follows. Section 2 reviews previous literature related to the international diffusion of climate mitigation technologies. Section 3 explains the model and data used in the analysis. In this study, we use data on wind and solar energy as major renewable energy sources used in many countries. Section 4 presents the results of our empirical analysis.

Section 5 analyzes the Protocol's impact on international patent applications filed in the four developing countries. Section 6 concludes.

2. Literature Review

This study employs the number of international patent applications as a measure of technological diffusion. Previous literature has used various measures of technological diffusion, depending on their focuses. First, the number of patent citations has been used as a measure of international knowledge flows (Jaffe et al., 1993; Peri, 2005). While citations are useful to capture knowledge spillover beyond national borders, they relate more to diffusion of technical knowledge that occurs outside the market. In contrast, international patent applications can be interpreted as a proxy for market-driven knowledge flow because inventors who apply for the patents are motivated by private benefits in foreign markets. Second, there are several studies that use project-based technology transfer (Dechezleprêtre et al., 2008; Schneider et al., 2008; Seres et al., 2009). However, such information on technology transfer is based on reported data and therefore subjective. Moreover, project-based data only address technology transfer directly related to the CDM projects, thereby their focus is limited (Haščič and Johnstone, 2011).

Several studies have examined technology transfer by using the number of international patent application (Lanjouw and Mody, 1996; Popp, 2006; Haščič and Johnstone, 2011; Dechezleprêtre et al., 2013). Lanjouw and Mody (1996) investigated the invention and diffusion of environmentally friendly technologies and described in detail the process of international patenting. By using the number of foreign patent applications as a measure of technology transfer, they found that many of the patents filed in developed countries are domestic in origin, whereas most of the patents filed in developing countries are foreign in origin. Haščič and Johnstone (2011) examined the role of the CDM in the transfer of wind power technologies by analyzing patent application data between Annex I countries and non-Annex I countries. Using data for more than 100 countries during 1988–2008, their results suggest that CDM positively influenced transfer of wind power technologies from Annex I to non-Annex I countries. However, the estimated effects were relatively small compared with those of other factors and negative when considering the cumulative effect of CDM projects. Dechezleprêtre et al. (2013) investigated the international diffusion of patented inventions in climate-friendly technologies between 1995 and 2007. They emphasized the importance of intellectual property regimes in the international diffusion of patented knowledge and suggested that the technological capacities of recipient countries reduced transfer of foreign technologies.

This study defines an international patent application as one in which the nationality of the first inventor does not correspond to the country in which the application is filed.[2] In contrast to patent citations that reflect knowledge spillover, the number of international patent applications can be regarded as a proxy for market-driven knowledge flows (Dechezleprêtre et al., 2013). The number of cross-border patent applications does not reflect actual technology transfers; they are a proxy for technology diffusion. In addition, patent systems are designed to protect new technological inventions from potential imitators (Haščič et al., 2010). Patenting might prevent a technology from being transmitted to other nations; nevertheless, technology transfer often involves patent filings in the recipient country of new technologies. Therefore, international patenting can be regarded as a channel for technology diffusion (Eaton and Kortum, 1996).

[2] An innovation is legally protected only in a country in which it is patented. Thus, some part of the technology crossing borders will show up as foreign patents and knowing the nationality of inventors allows us to identify these flows (Lanjouw and Mody, 1996).

3. Model and Data

3.1 Model

To estimate the effect of the Protocol on international patent applications, we employ a difference-in-difference (DID) estimator by running the Least Squares Dummy Variable (LSDV) model.[3] We compare the change in the number of international patent applications from countries committed to reducing GHG emissions with that from countries without such commitment. The fixed-effects estimation controls for time-invariant country characteristics that may correlate with commitment to emission reduction through the Protocol. The general form of our model is as follows:

$$Patent_{it} = \beta_0 + \beta_1 Treatment \times Period_{it} + \beta_2 X_{it} + \delta_i + \gamma_t + \varepsilon_{it}, \qquad (1)$$

where i = 1, …,133 indexes countries as a cross-sectional unit, t = 1990, …, 2013 indexes the year as the time unit, X is a set of time-varying country characteristics, δ is a vector of country dummies, γ is the year dummy, and ε is the error term. Dependent variable ($Patent_{it}$) is the

[3] The voluntary nature of climate agreements leads to self-selection bias. Aichele and Felbermayr (2012) employed instrumental variable (IV) strategy to examine the effect of the Kyoto Protocol on carbon dioxide emissions. However, their results suggest that the impact may not be serious, because the estimated effect is similar between OLS and IV.

number of international patent applications for renewable energy technologies by inventors whose nationality is country *i* in year *t*. As noted in Section 2, an international patent application is defined as a patent in which the nationality of the first inventor does not correspond to the country of filing. *Treatment* is the treatment indicator that takes a value of one for countries with emission targets (Annex B countries) and zero otherwise. We use two treatment groups: 34 Annex B countries that have quantitative limitations under the Protocol (Treatment 1)[4] and 21 Annex B countries that have more stringent targets (Treatment 2).[5] Therefore, the control group is the remaining 99 countries for Treatment 1 and 112 countries for Treatment 2. *Period* denotes the treatment period, taking a value of one for years from 1997 to 2012. The dummy acknowledges that the Protocol was adopted in 1997 and its first commitment period ended in 2012.

The number of patent applications is count data and a non-negative, integer-valued, random variable. Count data models have been developed to deal with the number of event occurrences (Maddala, 1983; Cameron and Trivedi, 1998). Thus, we use a negative binomial model and maximum likelihood method to estimate Equation (1). The panel of 133 countries

[4] The 34 countries are Austria, Australia, Belgium, Bulgaria, Canada, Switzerland, Czech Republic, Germany, Denmark, Estonia, Spain, Finland, France, the United Kingdom, Greece, Croatia, Hungary, Ireland, Iceland, Italy, Japan, Lithuania, Latvia, Netherlands, Norway, New Zealand, Poland, Portugal, Romania, Russian Federation, Sweden, Slovenia, Slovakia, and Ukraine.

[5] In this study, we define stronger targets as those with lower emissions than in 1990. There are 21 countries that have emission targets lower than 1990: Austria, Belgium, Bulgaria, Canada, Switzerland, Czech Republic, Germany, Denmark, Estonia, United Kingdom, Croatia, Hungary, Italy, Japan, Lithuania, Latvia, The Netherlands, Poland, Romania, Slovenia, and Slovakia.

and 24 years (1990–2013) is available, but missing observations for some countries reduce the sample size of the models estimated.

3.2 Data

Dependent variables: International applications

We extracted the number of international patent applications from the Worldwide Patent Statistical Database (PATSTAT) (version 2016, autumn). Following Johnstone et al. (2010), we classified patent data by each renewable energy source using the IPC codes (see Table A1). Figures 1 and 2 compare the international applications for wind and solar energy technologies in Annex B countries with those elsewhere. The vertical axis shows the average number of international patent applications from Annex B countries and other countries in each year. Trends in international applications from these countries are similar prior to the adoption of the Protocol in 1997, but clearly depart afterwards. Thus, the figures suggest common trends among treatment and control groups before the Protocol and sharp deviations following the adoption. The common pre-trend is also confirmed statistically by an analysis with interaction terms between treatment indicators and year dummies, described later in this paper. Figures 3 and 4 illustrate trends in international applications by Annex B countries that have stringent targets and those of other countries. Figures 3 and 4 also indicate that the trend of international applications is similar before 1997 and differs thereafter.

Control variables

The estimation model includes four types of control variables: GDP per capita, foreign direct investment (FDI) outflows, international patent application in all technological fields, and domestic patent stock. We use GDP per capita evaluated in 2010 US dollars from the World Development Indicators.[6] FDI is direct equity flows expressed as 2010 US dollars using the CPI index from the World Bank database. We also include the variable related to international applications in all technology fields to capture the extent of patent activity abroad. Data are calculated from PATSTAT. To capture the supply of inventions in each country, we include total number of patent applications in domestic countries in the previous five years.[7] A one-year lag reflects time required to invent and apply for a patent abroad. We take logarithmic forms for all continuous variables except for domestic patent stock. Tables 1 and 2 report descriptive statis-

[6] http://databank.worldbank.org/data/home.aspx

[7] We also check the estimation results by using patent application flows and domestic application variables without lag and confirm that these estimation results do not differ with the main results.

tics of the dependent and independent variables used in each estimation.[8] A *t*-test examines whether distribution of covariates between treatment and control groups is identical. Because statistically significant differences appear between mean values of the two, we employ a fixed-effects DID model using the LSDV approach. We modeled other variables to control for these differences (e.g., GDP per capita, FDI outflows, international applications in all technological fields, and domestic patent stock), particularly between developed and developing economies.

[8] Most of correlations among explanatory variables are below 0.5. The highest (0.76) is between FDI outflows and international patent application for all technologies.

4. Empirical Results

4.1 Effect of the Kyoto Protocol on international patent applications

Table 3 reports the estimation results of models using Treatment 1 in specification (1) and Treatment 2 in specification (2). All models include the country and year fixed effects. Coefficients of the interaction term between Treatment 1 and the Kyoto dummy are positive and statistically significant at the 10% level for wind energy and at the 1% level for solar energy in specification (1). Results suggest that the Protocol stimulated international patent applications from Annex B countries after 1997. In other words, the countries that commit to emission targets of GHGs exhibit more international patent applications. This result accords with Johnstone et al. (2010), who found that the Protocol encouraged domestic patent filings of renewable energy technologies. Popp et al. (2011) also found that the share of renewable capacity rose after the Protocol was signed.

Our results suggest that the Protocol has promoted technology diffusion through international patent applications. In specification (2), coefficients of the interaction term between Treatment 2 and the Kyoto dummy are positive and statistically significant at the 1% level for wind energy and at the 5% level for solar energy. Results suggest that the Protocol promoted international patent applications from countries with stringent emission targets during 1997 and 2012.

To take a closer look at the impact of the Protocol, we estimate models with an interaction term between treatment indicators and year dummies. In Table 4, the interaction coefficients are not statistically significant before 1997, validating the common pre-trends between treatment and control groups. Post-1997 interaction coefficients turn positive and statistically significant for many years in models examining solar technology. Results suggest that the Protocol increased international patent applications by Annex B countries immediately after 1997 and that the trend persisted until the end of study period. Coefficient of interaction terms for wind energy are less significant, although we note a positive and statistically significant effect on international patent applications from stringent target countries in 2004 and 2012. These results suggest that the Protocol stimulated international patent applications from countries with emissions targets and that the effect persists considerably longer.

4.2 Robustness check

One may be concerned that the main results are driven by changes in Germany and Japan, which account for 50% of international patent applications in our dataset. In particular, a massive increase in solar power investment followed Germany's introduction of a feed-in-tariff in 2004. This concern is likely to be addressed by omitting data of Germany and Japan. Therefore, we estimate the model with sub-sample excluding these two countries as a robustness check.

In Table 5, the coefficient of the interaction term between Treatment 1 and the Kyoto dummy is statistically significant at the 1% level for solar energy. The Protocol's effect on international patent applications is positive and statistically significant for solar energy technologies and insignificant for wind energy technologies. Coefficients of the interaction term between Treatment 2 and the Kyoto dummy are positive and statistically significant at the 5% level for both energies. In summary, sub-sample estimation suggests the robustness of the effect of the Kyoto Protocol on international patent applications.

4.3 Falsification test

Another concern is that any international patent applications from countries in the treatment group may increase during the treatment period due to the reason other than the Kyoto Protocol. To check this is not the case, we perform a falsification test using an alternative dependent variable that is not likely to be influenced by the Kyoto Protocol. We use the number of international patents on tools of agricultural machinery (IPC code: A01B "Soil working in agriculture or forestry; parts, details, or accessories of agricultural machines or implements, in general") as an alternative dependent variable. Because the technological development in this sector is hardly influenced by the Kyoto Protocol, we expect that the coefficient of the treatment indicator to be insignificant. The total number of patent applications in this category (116,944) is comparable to that of wind (74,171) and solar technology (189,360). Results in Table 6 show no statistically significant in specifications (11) to (14). The Protocol had no positive effects on international applications of patents unrelated to climate-friendly technology.

5. International patent applications to developing countries

This section explores international patent applications filed in Brazil, China, India, and Mexico as developing economies with high GHG emissions. The economic growth in these countries raises their current carbon emissions and portends higher future emissions globally. For example, Energy Information Administration (2017) projects that China, the largest emitter of energy-related CO_2 emissions, will remain the largest through 2040.

Table 7 reports the estimation results. Specification (9) presents results using international patent applications to the four countries as dependent variables. Coefficients of the interaction term between Treatment 1 and the Kyoto dummy are positive and statistically significant at the 5% level for wind and solar energy technologies. The results indicate that the Protocol affects international patent applications to these economies. We further estimate the model using international patent applications filed in each of these economies as dependent variables in specifications from (10) to (13). Results suggest considerable heterogeneity in the Protocol's impact. For Brazil, coefficients of the interaction term between Treatment 1 and the Kyoto dummy are positive and statistically significant for wind and solar energy. We find a positive and significant effect of the Protocol on transfer of wind technology to China and solar technology to Mexico. International patent application to India is not significant for either energy technology. These results suggest that expectation of market development direct investors' application for international patents.

6. Conclusion

This study has investigated how the Kyoto Protocol has affected international patent applications of renewable energy technologies. Using a DID approach, we find that it increased patent applications in developed and developing economies. These findings highlight three aspects related to the globalization of renewable energy technologies. First, inventors increased the number of international applications of patents for renewable energy technology after the Protocol was adopted. This effect appeared over many years during the period studied, particularly for solar energy technology. Second, the Protocol's impact on technology diffusion is evident for Annex B countries adopting stringent GHG targets. For these countries, the Protocol's impact on the numbers of applications for international patent persisted strongly, even for wind energy technology. Third, the Protocol increased international patent applications filed in four developing economies. Although these countries are not obliged to reduce GHG emissions under the Protocol, our results suggest that firms expect higher demand for emission reduction in these countries.

This study yields two policy implications. First, results endorse the importance of climate change agreements for international diffusion of technology. The Kyoto Protocol indirectly affects climate change by increasing applications for international patents for renewable energy technologies and by reducing future emissions. This combined effect might reduce emissions further because applications for international patents can be the first step in technology transfer (Dechezleprêtre et al., 2013) or a channel for technology diffusion (Eaton and Kortum, 1996). Second, a commitment to climate agreements might spur applications for international patents to developing economies. Even though the Kyoto Protocol does not require reduced emissions by these countries, the influence of introducing an international framework can stimulate technology transfer to such countries, perhaps driven by expectations of more stringent regulation or commitments by these countries.

The 2015 Paris Agreement noted the importance of technological development and diffusion, particularly from industrialized countries to developing economies (UN, 2016). Although the impact of the Agreement on technology diffusion is unconfirmed, different levels of commitment by countries under the Agreement might have different impacts on technology diffusion. Further study into how climate agreements influence technology diffusion is important for constructing international framework to mitigate climate change.

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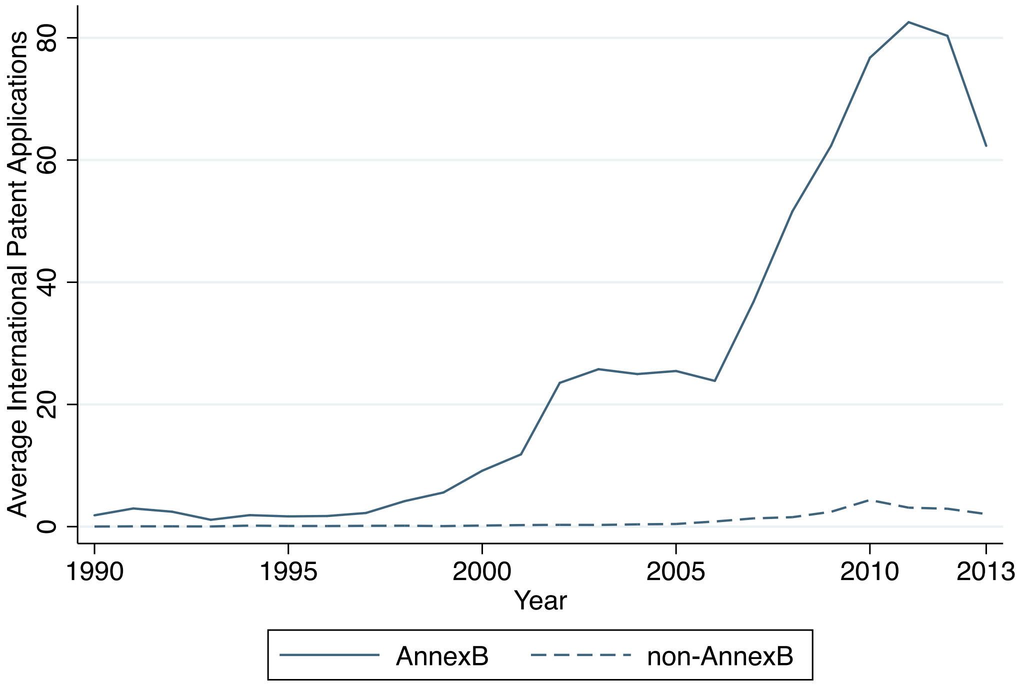
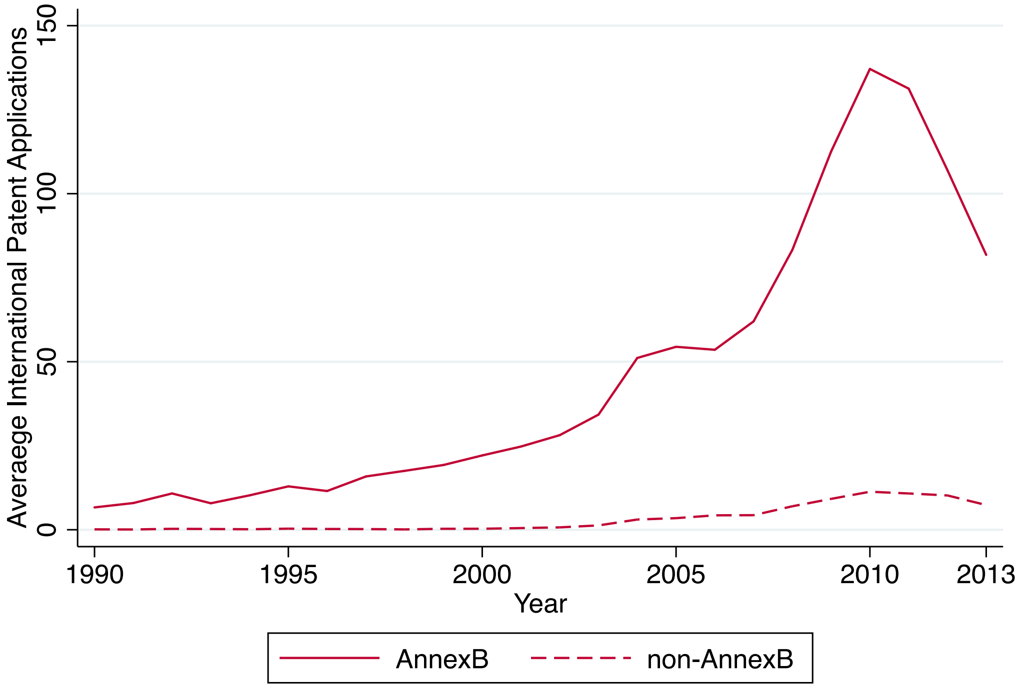
Figure 1. International patent applications of wind energy: Annex B vs. others



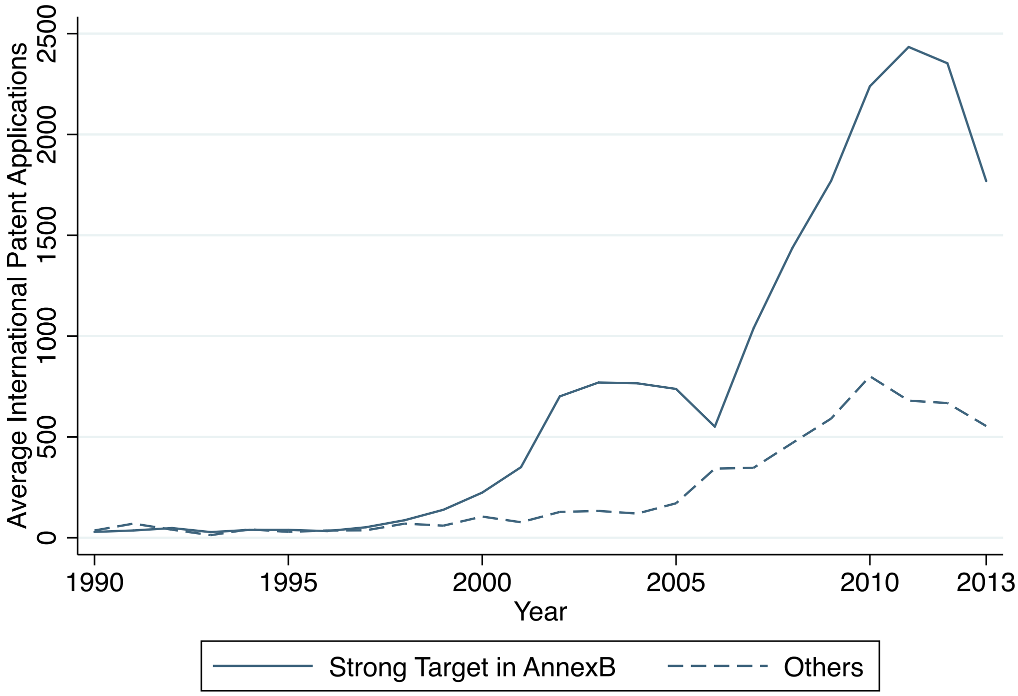
Source: PATSTAT (version 2016autumn)

Figure 2. International patent applications of solar energy: Annex B vs. others



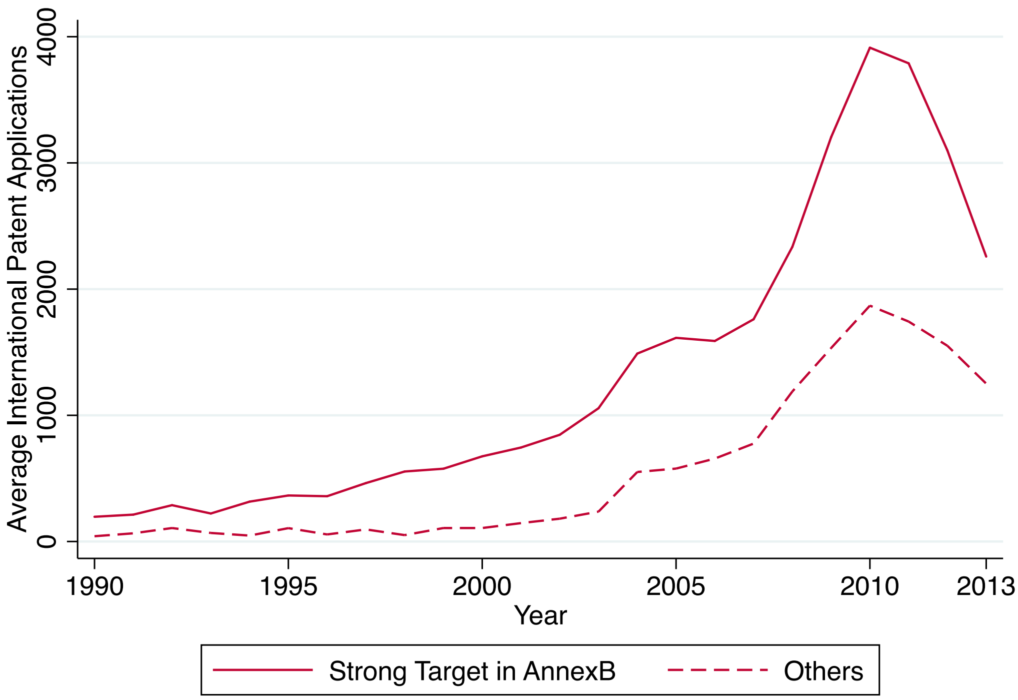
Source: PATSTAT (version 2016autumn)

Figure 3. International patent applications of wind energy: Stringent target vs. others



Source: PATSTAT (version 2016autumn)

Figure 4. International patent applications of solar energy: Stringent target vs. others



Source: PATSTAT (version 2016autumn)

Table 1. Descriptive Statistics: Treatment 1

	Treatment1					Control					T value
	Obs	Mean	Std. Dev.	Min	Max	Obs	Mean	Std. Dev.	Min	Max	(1) and (2)
Dependent											
Wind	816	25.9559	91.5621	0	908	2,376	0.88889	6.24553	0	114	-13.2591***
Solar	816	46.0012	172.039	0	1989	2,376	3.15783	32.2143	0	683	-11.5661***
Interaction term											
Treatment 1×Kyoto(1997-2012)	816	0.66667	0.47169	0	1	2,376	0	0	0	0	
Control											
GDP_{it} (ln)	788	10.0401	0.83975	7.43067	11.4251	2,331	7.90359	1.31385	4.75181	11.1215	-42.7872***
$FDIoutflow_{it}$ (ln)	703	15.1746	2.6855	4.99205	21.7955	1,740	11.0452	3.56746	-3.6431	29.0307	-27.6830***
$Interappln_{it}$ (ln)	816	7.1528	2.34649	1.60944	12.0442	1,827	2.87012	2.27904	0	10.8294	-44.2223***
Domestic stock of $wind_{it-1}$	816	40.0858	123.632	0	1499	2,376	7.30387	91.7978	0	2563	-8.0079***
Domestic stock of $solar_{it-1}$	816	73.348	268.385	0	3200	2,376	5.8771	76.3108	0	1626	-11.0274***

Note: *** indicate statistical significance at the $p < 0.01$.

Table 2. Descriptive Statistics: Treatment 2

	Treatment2					Control					T value
	Obs	Mean	Std. Dev.	Min	Max	Obs	Mean	Std. Dev.	Min	Max	(1) and (2)
Dependent											
Wind	504	35.0615	113.982	0	908	2,688	2.09115	10.7527	0	180	-14.6626***
Solar	504	63.3452	214.182	0	1989	2,688	4.87872	34.3805	0	683	-13.278***
Interaction term											
Treatment 1×Kyoto(1997-2012)	504	0.66667	0.47187	0	1	2,688	0	0	0	0	
Control											
GDP_{it} (ln)	476	9.95231	0.81191	8.18392	11.2309	2,643	8.17162	1.46537	4.75181	11.4251	-25.8061***
$FDIoutflow_{it}$ (ln)	436	14.9628	2.94733	4.99205	20.2557	2,007	11.6406	3.73608	-3.6431	29.0307	-17.4257***
$Interappln_{it}$ (ln)	504	7.06961	2.6704	1.60944	12.0442	2,139	3.5144	2.69905	0	10.8294	-26.6565***
Domestic stock of $wind_{it-1}$	504	47.6944	150.18	0	1499	2,688	9.68229	88.7529	0	2563	-7.7572***
Domestic stock of $solar_{it-1}$	504	96.9147	328.799	0	3200	2,688	9.28981	81.0762	0	1626	-12.0124***

Note: *** indicate statistical significance at the $p < 0.01$.

Table 3. Main Results

	Treatment1		Treatment2	
	(1)		(2)	
	wind	solar	wind	solar
Treatment 1×Kyoto (1997-2012)	0.445*	0.585***		
	(0.262)	(0.204)		
Treatment 2×Kyoto (1997-2012)			0.639***	0.380**
			(0.225)	(0.163)
GDP(ln)	-0.751	0.276	-0.665	0.351
	(0.561)	(0.375)	(0.561)	(0.385)
FDIoutflow(ln)	-0.082*	-0.090**	-0.089**	-0.092**
	(0.044)	(0.043)	(0.045)	(0.045)
Interappln(ln)	0.932***	1.130***	0.924***	1.080***
	(0.152)	(0.114)	(0.148)	(0.113)
Domestic stock	0.000*	-0.000	0.000*	-0.000
	(0.000)	(0.000)	(0.000)	(0.000)
_cons	0.343	-9.330***	-0.548	-9.556***
	(4.681)	(3.348)	(4.710)	(3.460)
N	2102	2102	2102	2102
AIC	5491.797	6364.284	5488.784	6366.998
BIC	6367.647	7240.134	6364.634	7242.848
log likelihood	-2590.899	-3027.142	-2589.392	-3028.499

Note: Standard errors are in parentheses. *, **, and *** indicate statistical significance at the $p < 0.1$, $p < 0.05$, and $p < 0.01$ levels, respectively.

Table 4. Results using interaction term between Treatment and year dummies

		Treatment1 (3)				Treatment2 (4)	
		wind	solar			wind	solar
Treatment1	×D 1991	0.359	1.511*	Treatment2	×D 1991	0.465	0.876
		(1.510)	(0.791)			(0.770)	(0.709)
	×D 1992	-0.147	0.965		×D 1992	-0.766	0.324
		(1.477)	(0.619)			(0.818)	(0.610)
	×D 1993	-0.223	0.488		×D 1993	0.412	0.141
		(1.536)	(0.655)			(0.788)	(0.626)
	×D 1994	-1.286	-0.176		×D 1994	-0.841	0.237
		(1.458)	(0.724)			(0.734)	(0.700)
	×D 1995	-0.177	0.822		×D 1995	-0.662	0.031
		(1.509)	(0.740)			(0.922)	(0.618)
	×D 1996	-1.582	-0.707		×D 1996	-1.097	-0.667
		(1.514)	(0.798)			(0.775)	(0.768)
	×D 1997	-1.041	1.966***		×D 1997	-0.345	0.392
		(1.338)	(0.681)			(0.646)	(0.603)
	×D 1998	-1.094	1.526*		×D 1998	-1.247**	1.305**
		(1.406)	(0.888)			(0.636)	(0.631)
	×D 1999	-0.310	1.664**		×D 1999	-0.503	1.055*
		(1.372)	(0.686)			(0.606)	(0.583)
	×D 2000	-0.200	1.673***		×D 2000	0.062	0.756
		(1.421)	(0.560)			(0.647)	(0.567)
	×D 2001	-1.233	0.648		×D 2001	0.148	0.523
		(1.410)	(0.651)			(0.825)	(0.618)
	×D 2002	0.468	0.404		×D 2002	0.789	0.270
		(1.327)	(0.815)			(0.557)	(0.640)
	×D 2003	0.580	1.224**		×D 2003	0.822	0.781
		(1.348)	(0.608)			(0.572)	(0.616)
	×D 2004	0.430	1.133*		×D 2004	1.063*	0.026
		(1.339)	(0.602)			(0.576)	(0.566)
	×D 2005	0.340	0.914		×D 2005	0.837	0.305
		(1.333)	(0.580)			(0.556)	(0.558)
	×D 2006	-0.539	1.208**		×D 2006	-0.240	0.767
		(1.344)	(0.556)			(0.579)	(0.556)
	×D 2007	0.263	0.809		×D 2007	0.377	-0.024
		(1.321)	(0.610)			(0.553)	(0.586)
	×D 2008	0.318	1.893***		×D 2008	0.601	1.462**
		(1.333)	(0.570)			(0.572)	(0.581)
	×D 2009	0.253	0.759		×D 2009	0.882	0.497
		(1.347)	(0.554)			(0.599)	(0.565)
	×D 2010	-0.590	0.746		×D 2010	0.245	0.478
		(1.339)	(0.572)			(0.574)	(0.567)
	×D 2011	-0.335	0.870		×D 2011	0.425	0.470
		(1.361)	(0.557)			(0.576)	(0.555)
	×D 2012	0.279	1.108**		×D 2012	1.218**	0.785
		(1.350)	(0.558)			(0.587)	(0.569)
	×D 2013	-0.448	1.112**		×D 2013	0.241	0.655
		(1.365)	(0.561)			(0.605)	(0.583)
	GDP(ln)	-0.887	0.264		GDP(ln)	-0.392	0.318
		(0.593)	(0.378)			(0.551)	(0.383)
	FDIoutflow(ln)	-0.076	-0.091**		FDIoutflow(ln)	-0.089*	-0.093**
		(0.046)	(0.037)			(0.048)	(0.042)
	Interappln(ln)	1.004***	1.130***		Interappln(ln)	0.959***	1.100***
		(0.153)	(0.117)			(0.142)	(0.110)
	Domestic stock	0.000	-0.000		Domestic stock	0.000	-0.000
		(0.000)	(0.000)			(0.000)	(0.000)
	_cons	0.887	-9.325***		_cons	-3.682	-9.454***
		(5.282)	(3.551)			(4.845)	(3.519)
	N	2102	2102		N	2102	2102
	AIC	5510.487	6387.194		AIC	5505.084	6395.526
	BIC	6510.651	7387.358		BIC	6505.248	7395.690
	log_likelihood	-2578.244	-3016.597		log_likelihood	-2575.542	-3020.763

Note: Standard errors are in parentheses. *, **, and *** indicate statistical significance at the $p < 0.1$, $p < 0.05$, and $p < 0.01$ levels, respectively.

Table 5. Robustness checks: Estimations without Germany and Japan

	Treatment1		Treatment2	
	(5)		(6)	
	wind	solar	wind	solar
Treatment 1×Kyoto (1997-2012)	0.344	0.599***		
	(0.264)	(0.208)		
Treatment 2×Kyoto (1997-2012)			0.480**	0.401**
			(0.243)	(0.179)
GDP(ln)	-0.463	0.185	-0.412	0.268
	(0.563)	(0.395)	(0.563)	(0.402)
FDIoutflow(ln)	-0.080*	-0.088**	-0.086*	-0.090*
	(0.044)	(0.044)	(0.045)	(0.046)
Interappln(ln)	0.911***	1.131***	0.906***	1.081***
	(0.149)	(0.115)	(0.145)	(0.114)
Domestic stock	0.000	0.000	0.000	0.000
	(0.000)	(0.000)	(0.000)	(0.000)
_cons	-1.733	-6.390**	-2.081	-7.054***
	(3.537)	(2.677)	(3.511)	(2.701)
N	2054	2054	2054	2054
AIC	4962.709	5670.905	4961.377	5673.674
BIC	5823.723	6531.919	5822.391	6534.688
log_likelihood	-2328.355	-2682.452	-2327.689	-2683.837

Note: Standard errors are between parentheses. *, **, and *** indicate statistical significance at the $p < 0.1$, $p < 0.05$, and $p < 0.01$ levels, respectively.

Table 6. Falsification test

	Treatment1		Treatment2	
	(7)		(8)	
	wind	solar	wind	solar
Treatment 1×Kyoto (1997-2012)	-0.405*	-0.417*		
	(0.235)	(0.233)		
Treatment 2×Kyoto (1997-2012)			0.020	0.024
			(0.154)	(0.154)
GDP(ln)	-0.539	-0.459	-0.613	-0.534
	(0.417)	(0.420)	(0.425)	(0.428)
FDIoutflow(ln)	0.007	0.002	0.004	-0.002
	(0.039)	(0.039)	(0.039)	(0.038)
Interappln(ln)	1.257***	1.273***	1.308***	1.326***
	(0.142)	(0.140)	(0.138)	(0.137)
Domestic stock	0.000*	0.000	0.000*	0.000
	(0.000)	(0.000)	(0.000)	(0.000)
_cons	-5.370	-6.367*	-5.128	-6.122
	(3.782)	(3.815)	(3.864)	(3.890)
N	2102	2102	2102	2102
AIC	4112.353	4112.812	4113.822	4114.374
BIC	4988.203	4988.662	4989.672	4990.224
log_likelihood	-1901.176	-1901.406	-1901.911	-1902.187

Note: Standard errors are between parentheses. *, **, and *** indicate statistical significance at the $p < 0.1$, $p < 0.05$, and $p < 0.01$ levels, respectively.

Table 7. International Applications to Developing Countries: Treatment 1

	4 countries		Brazil		China		India		Mexico	
	(9)		(10)		(11)		(12)		(13)	
	wind	solar	wind	solar	wind	solar	wind	solar	wind	solar
Treatment 1×Kyoto (1997-2012)	0.761**	0.875**	1.350*	1.727***	0.849**	0.617	-1.323	2.497	1.088	0.954*
	(0.347)	(0.351)	(0.765)	(0.527)	(0.429)	(0.416)	(1.397)	(1.568)	(0.880)	(0.549)
GDP(ln)	-2.026	-0.106	-2.846	-2.923**	-1.821	-0.215	-44.493***	-16.596***	-5.867***	0.328
	(1.540)	(0.917)	(2.358)	(1.233)	(1.593)	(1.147)	(15.988)	(5.339)	(2.184)	(1.414)
FDIoutflow(ln)	0.084	-0.098	-0.166	-0.155*	0.033	-0.060	1.296	0.656**	0.346**	-0.065
	(0.098)	(0.065)	(0.117)	(0.094)	(0.108)	(0.068)	(1.168)	(0.305)	(0.166)	(0.101)
Interappln(ln)	1.000***	0.918***	1.539*	1.511***	1.043***	0.877***	25.396**	6.561***	2.092***	0.802
	(0.359)	(0.283)	(0.818)	(0.393)	(0.352)	(0.338)	(12.319)	(1.744)	(0.752)	(0.585)
Domestic stock	0.000	0.000	0.000	0.000	0.000	0.000	-0.002	-0.000	0.000	-0.000*
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.002)	(0.001)	(0.001)	(0.000)
_cons	-11.161	-6.151	-1.467	14.324	-9.634	-5.435	129.445***	70.417*	13.442	-27.394***
	(12.060)	(7.502)	(16.942)	(10.586)	(13.010)	(9.658)	(48.652)	(39.939)	(15.447)	(9.626)
N	2102	2102	2102	2102	2102	2102	2102	2102	2102	2102
AIC	2386.569	2822.037	1112.314	1144.837	2055.363	2438.989	366.976	304.586	749.114	1111.488
BIC	3002.489	3697.887	1756.487	2020.687	2620.427	3314.839	1242.826	920.506	1274.624	1817.818
log_likelihood	-1084.284	-1256.018	-442.157	-417.419	-927.681	-1064.494	-28.488	-43.293	-281.557	-430.744

Note: Standard errors are between parentheses. *, **, and *** indicate statistical significance at the $p < 0.1$, $p < 0.05$, and $p < 0.01$ levels, respectively.

Appendix

Table A1. IPC codes

IPC code	Explanation
Wind	
F03D 1	Wind motors with rotation axis substantially in wind direction
F03D 3	Wind motors with rotation axis substantially at right angle to wind direction
F03D 5	Other wind motors
F03D 7	Controlling wind motors
F03D 9	Adaptations of wind motors for special use
F03D 11	Details, component parts, or accessories not provided for in, or of interest apart from, the other groups of this subclass
Solar	
F03G 6	Devices for producing mechanical power from solar energy
F24J 2	Use of solar heat, e.g. solar heat collectors
H01L 27/142	Devices consisting of a plurality of semiconductor components sensitive to infra-red radiation, light—specially adapted for the conversion of the energy of such radiation into electrical energy
H01L 31/04-078	Semiconductor devices sensitive to infra-red radiation, light—adapted as conversion devices
H02N 6	Generators in which light radiation is directly converted into electrical energy
E04D 13/18	Aspects of roofing for energy collecting devices—e.g. incl. solar panels

Source: Johnstone et al. (2010)