Explaining Trade Flows in Renewable Energy Products: The Role of Technological Development

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Abstract

This study investigates the trade flows of renewable energy products, focusing on the role of technological development. We estimate a gravity model that explains the trade flows among 35 OECD countries from 1996 to 2010 using patent counts as a proxy for technology level. We compare the pattern of the trade flows between two representative renewable energy products: those related to wind and solar electricity generation. The results suggest that technological level is correlated with trade flows and this correlation is weaker in the model for solar products than that for wind products. When we include China in the sample in estimation, the technological level of solar energy is no longer correlated with the exports of solar power products.

Key Words: Renewable energy products; Trade; Technological development; Patent; Gravity model

JEL Classification Numbers: F14, O33, Q55

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1. Introduction

As of 2016, renewable power accounted for nearly 62% of the net additions to global power generating capacity (REN21, 2017). The growth and geographical expansion of renewable energy capacity was driven by the continued decline in the cost of renewable energy generation. Technological developments in the renewable energy sector continue to offer the potential for additional cost reductions. For example, since 2012, the cost of lithium ion battery modules has declined more than 70% (Clover, 2017). Big data and artificial intelligence can improve weather forecasting, and blockchain technology can help integrate renewable energy into the grid (Motyka, 2018). Further technological development is a key driver for the promotion of renewable energy by serving as a means to ensure a dramatic decrease in the marginal cost of power generation, to overcome intermittency, and to stabilize the electricity supply.

There are various channels of economic impacts by technological development in the renewable energy sector. First, the process of technology improvement reduces the cost of electricity generation or the cost of the improvement of productivity in the sector (Tang and Popp, 2011). A lighter wind turbine blade or a more efficient solar panel can increase the efficiency of converting renewable energy to electricity. Second, eventually, innovations in renewable energy technology will lead to the increased use of renewables for electricity generation (Popp et al., 2011). As renewable energy gains cost advantages, it becomes more attractive to adopt renewables that can produce electricity with lower carbon emissions. Third, technological development of the renewable energy sector will increase the exports of products related to electricity generation (Groba, 2014). Therefore, the accumulation of knowledge in environmental technology should positively affect the bilateral trade between countries.

This paper focuses on the last channel mentioned above and examines the relationship between technological development and the exports of renewable energy products. The effects of new innovations are not limited to the country of origin, but spread through the purchase and sale of products embedding the new technology. Therefore, the expansion of exports can be interpreted as the international spillovers of environmental technology. The proliferation of technology plays an indispensable role in climate change mitigation, which requires cooperation across the globe.

The aims of this study are threefold. First, we estimate a gravity model to explain trade flows among 35 OECD countries from 1996 to 2010 by considering patent counts as a proxy for technology level. Several studies on the determinants of technological development in the renewable energy sector have used patent counts as a proxy for a country's level of technological development (Johnstone et al., 2010; Ayari et al., 2012; Popp, et al., 2011; and Rexhäuser and Löschel, 2015). Second, we compare the pattern of trade flows between technologies for two renewable energy sources: wind and solar. Given the characteristics of the products for these two renewable energy types, we expect that the effects of technology development on export values will vary between these two energy sources. Finally, we estimate the effects of renewable energy policies on trade flows. Policies promoting renewable energy are broadly divided into international and domestic. This study examines the effect of an international agreement (Kyoto Protocol) and two domestic policy instruments [feed-in-tariff (FIT) and renewable portfolio standard (RPS)] on trade performance.

The rest of the paper is organized as follows. The next section reviews the literature on trade flows and technological development. Section 3 explains the models and the data used in the analysis, and Section 4 presents the results of the empirical study. In Section 5, we estimate the model including China in sample. The last section concludes with a summary of the main results.

2. Literature review

Several economists have investigated the interactions between trade flows and technological development with regard to environmental technologies. The prevailing motivation for these studies is the Porter hypothesis that environmental regulations will positively affect innovation and comparative advantage on the global market (Porter and van der Linde, 1995). Using a gravity model, Costantini and Crespi (2008) analyzed the determinants of and transmission channels through which environmental technologies are exported to advanced and developing countries. Their results were consistent with the Porter hypothesis: stricter environmental regulations, supplemented by a strong national innovation system, were a crucial driver of export performance in the field of energy technologies. Costantini and Mazzanti (2012) explored how the export competitiveness of the European Union (EU) has been affected by environmental regulations and innovation in the context of the Porter hypothesis. They adopted a gravity model and tested both strong and narrowly strong versions of the Porter hypothesis.[1] Although some differences emerged between the results for those two versions, overall, they found that both public policies and private innovation increase efficiency in the production process through

[1] The strong version of Porter hypothesis claims that environmental regulation will enhance economic performance for compliant firms, the regulated sector, and the economy as a whole. The narrowly strong version posits that a more stringent regulatory framework will positively affect the domestic environmental industry. On the other hand, the weak version predicts that environmental regulations will induce additional innovation.

various complementarity mechanisms. Groba (2014) focused on solar energy technology components and explored the structure and development of international trade. He estimated the impact of policy instruments on the trade flows among 21 OECD exporting countries and 118 importing countries between 1999 and 2007. The results indicated that the Porter hypothesis was valid, with the early adopters of renewable energy policies gaining a comparative advantage.

This study is different from the other seminal works mentioned above because it addresses specific renewable energy sectors. Although Costantini and Crespi (2008) and Costantini and Mazzanti (2012) investigated the environmental sector in general, their analyses do not capture the different roles that technology or policy play in trade of specific renewable energy sectors in detail. The difference between our study and that of Groba (2014) is that we compare solar and wind energy technology and use patent counts as a measure of technology development.

Our study further contributes to the literature by considering the effects of the importer country's technology level. Generally, the gravity model explains trade flows in terms of a bilateral relationship between countries. In this model, the trade flows are based on both the economic size and the distance between exporters and importers. It is highly likely that policies aiming to promote renewable energy as well as the technological level of exporters and importers will both affect trade flows. This study examines the impacts of technological level of exporters and importers on export values. Thus, we can examine the following two hypotheses: (1) a higher technological level in terms of renewable energy increases the export value of renewable energy products from that country; and (2) a lower technological level of renewable energy leads an increase in the imports of renewable energy products by that country.

3. Model and Data

3.1. Gravity model

The gravity model explains trade flows among countries by the market size, which is measured by GDP and distance between countries (Tinbergen, 1962). Our dataset consists of a panel of 35 OECD countries[2] covering the years 1996–2010. Estimates of the log-linear form of the gravity equation are biased and inconsistent because of heteroscedasticity. Therefore, we use the Poisson specification of the trade gravity model, suggested by Santos Silva and Tenreyro (2006). To mitigate potential endogeneity for variables such as technological level, policy, and import tariffs, their lagged values are used. Furthermore, the exact definition of the lag structure for environmental and innovation-independent variables is based on both theoretical assumptions and empirical findings (Costantini and Mazzanti, 2012). The estimation model used is as follows:

$$\begin{aligned} T_{ijt} &= \beta_0 + \beta_1 Mass_{ijt} + \beta_2 \ln D_{ij} + \beta_3 Control_{ijt} + \beta_4 Technology_{it-1} + \beta_5 Technology_{jt-1} \\ &\quad + \beta_6 Policy_{it-1} + \beta_7 Policy_{jt-1} + d_i + d_j + d_t + \varepsilon_{ijt} \quad \cdots(1) \end{aligned}$$

where *i* and *j* = 1, …, 35 index the cross-section unit (*i* denotes the exporting country and *j* the

[2] The 35 countries are Australia, Austria, Belgium, Canada, Chile, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Israel, Italy, Japan, Korea, Luxembourg, Mexico, the Netherlands, New Zealand, Norway, Poland, Portugal, Slovak Republic, Slovenia, Spain, Sweden, Switzerland, Turkey, the United Kingdom, and the United States.

importing country), and t = 1996, …, 2010 indexes time. The dependent variable (T_{ijt}) is the export value for each type of renewable energy. The independent variables include $Mass_{ijt}$, which reflects the total economic size of the exporting and importing countries;[3] distance between trading countries (D_{ij}); knowledge stock in exporting and importing countries (*Technology*); and the *Policy* variables, that are FIT, RPS, and the Kyoto Protocol dummy for the two countries. The control variables include import tariff as well as cultural and geographical distances among countries. Residual variation is captured by the error term ε. To control for country-specific and year-specific effects, we estimate the model including dummy variables for the exporter country, importer country, and each year.

3.2 Data

Dependent variables: Export value

The dependent variable in this study is the export data among OECD countries. The trade data used in this study were obtained from UN Comtrade (version 2016)[4] for World Integrated

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[3] Because these fixed effects might also absorb structural differences between countries, thus, reducing statistical robustness using the country dummy, we use different measures to reflect the economic size of trading partners. We apply a proxy of the impact the countries' economic mass, indicating that the trade value is greater when the overall economic space is larger: $Mass_{ijt} = \ln(GDP_{it} + GDP_{jt})$.

[4] http://wits.worldbank.org

Trade Solution (WITS), based on the relevant Harmonized System (HS) code version HS 1996.[5] As mentioned previously, this study focuses on two types of renewable energy products: wind and solar energy. We define the coverage of HS codes used to collect trade data based on Groba and Cao (2015). The consumer price index is used to convert the trade data to 2010 US dollars. Figure 1 shows the export values of wind and solar power products among the 35 OECD countries. Over the study period, there was a steady increase in the export values for both wind and solar energy products. Although the export values increased for both products, the increase in solar power products was more dramatic. Solar products are traded among a large number of countries, whereas wind power products are traded among relatively fewer countries.

Independent variables

The gravity model explains the export values by the economic size of the importer and exporter and the distance between the importer and the exporter. We add two independent variables to the general gravity model: (1) exporter and importer countries' technological level regarding renewable energy, represented by their knowledge stock, and (2) international and domestic

[5] HS codes differentiate 6,641 groups of products (in version HS 1996), whereas SITD codes classify 4,203 product groups (in version Rec. 3). HS 1996 defined renewable energy products for the first time.

policies that promote renewable energy.

Technological level

The number of patent applications is used as a proxy variable for technological development. Technological level and innovation can be measured by various indicators, such as R&D expenditure, number of researchers, and patent counts. However, R&D expenditure is an input rather than an output of innovation. In contrast, patent counts can be classified as an output indicator of innovation activity and are more related to realized innovation. Furthermore, patents serve as a source of rich information on new technologies because they are systematically screened using a considerable amount of resources by governments over a long period of time (Nagaoka et al., 2010). Because differences in patent systems and laws between countries raise an issue of compatibility, we examine applications submitted to the European Patent Office (EPO) only. The patent data in this study were obtained from the Worldwide Patent Statistical Database, PATSTAT (version 2016 autumn). We classify the patent data into each renewable energy source using International Patent Classification (IPC) codes (World Intellectual Property

Organization (WIPO), 2012)[6].

Figure 2 shows trends in the patent counts for wind energy and solar energy products among the 35 OECD countries. Similar to the trend of export values, the patent counts for both energy products show a clear increase with the patent count of solar energy being higher than that of wind energy. Table 1 reports total export and import values and patent counts for the top 10 OECD countries from 1996 to 2010. Among the OECD countries, Denmark exports the largest value of wind energy products. In terms of technological level, Denmark is likely one of the countries with the highest technology level in wind energy. Regarding solar energy, Germany is the largest exporter of these products among the OECD countries. In addition, Germany has the highest number of patents for solar energy products. Following Groba and Cao (2015), we use the following equation to calculate the knowledge stock variable:

$$KTechnology_{it} = (1-\delta)KTechnology_{it-1} + Patent_{it} \quad \cdots(2)$$

Accordingly, the knowledge stock equals the respective stock at time t–1 minus the depreciation rate δ plus the patent applications at time t. Following the previous studies (Guellec et al., 2004,

6 Appendix 1 presents the list of IPC code for renewable energy technologies.

and Groba and Cao, 2015), a depreciation rate of 15% has been adopted.[7]

Environmental policies: Kyoto Protocol, FIT, and RPS

We include two types of environmental policies that promote renewable energy—Kyoto Protocol as an international policy and FIT/RPS as domestic policies—into the gravity model. The Kyoto Protocol variable is a dummy that describes a country's level of environmental effort. The variable takes a value of one if both exporter and importer countries signed the Kyoto Protocol as Annex I countries.[8] Moreover, we include variables regarding the implementation of FIT and RPS to consider the effect of renewable energy promotion policies in the exporter and importer countries. Regarding the FIT variable, we use the guaranteed purchase price for electricity generated by solar or wind energy, and the percentage of electricity required to be generated by renewable energy (or covered by a certificate of renewable energy) for RPS. We construct the panel data for these domestic policy-related variables from the following databases and reports: (1) IEA/IRENA Global Renewable Energy Policies and Measures Database from

[7] We conducted robustness checks with a depreciation rate of 10% and 20%, and confirmed that the main result is not sensitive to the choice of depreciation rate.

[8] Because many countries signed the Protocol in 1998, the Kyoto dummy takes a value of zero from 1996 to 1997 and takes a value of one from 1998 by 2010 for those countries. On the other hand, it takes a value of one from 1998 to 2001 for the United States, which withdrew from the Protocol in 2001.

OECD/IEA and IRENA;[9] (2) Commission of the European Communities (2008); (3) Renewable Energy Policy Network for the 21st Century (REN 21, 2010 and 2013); (4) IEA reports on renewable energy (IEA, 2004, 2008, and 2011); and (5) Energy Policies of IEA Countries for respective countries. For the United States, FIT and RPS were not introduced at a country level; however, some states introduced policies to promote renewable energy. Therefore, we used state-level electricity consumption to calculate the national weighted average value of FIT and RPS.

Other variables

The gravity model assumes that trade flows are proportional to variables such as economy size (GDP of each exporting country and importing country), distance between trading countries, and control variables related to trade, such as language. GDP data are obtained from OECD statistics (version 2015). We use GDP per capita constant PPP in adjusted USD aggregated for the exporter and importer countries to represent the economic size of trading countries. Because transportation costs play a significant role in determining trade flows, we include the variable

[9] https://www.iea.org/policiesandmeasures/renewableenergy/

Distance to represent the geographical distance between the exporter and importer countries The distance data between exporters and importers are taken from the Centre d'Etudes Prospectives et d'Informations Internationales (CPEII) GeoDist dataset. The distance between the capital cities of each country is used as a proxy for trade costs. We use the import tariff applied to the products of solar and wind energy by the importing country to reflect the actual levels of trade barriers. Import tariff data are obtained from the UNCTAD TRAINS[10] database using the HS codes related to solar and wind energy products. Furthermore, to control for the impact of cultural and geographical similarity on trade flows, we include three types of dummy variables: language, contiguity, and common currency. The language variable takes the value of one for a common primary official language between the exporter and the importer. The contiguity variable takes the value of one for an exporter/ importer pair that shares a country border. Similarly, the common currency variable takes the value of one when the exporter and the importer use a common currency. These data are from the CPEII's gravity dataset (Head et al., 2010; Mayer and Zignago, 2011). Table 2 provides summary statistics of these variables. We verified correlation among explanatory variables and found it to be below 0.4.

[10] http://wits.worldbank.org

4. Results

Table 3 presents the main results. This paper mainly discusses the results of the PPML model in columns (1) and (2). In addition, we show the results of the Negative Binomial (NB) model and OLS regression in specifications (3), (4), (5), and (6). All the models include exporter country, importer country, and year dummies to control for country and year effects.

Regarding wind energy, the coefficients on *Technological Level* of exporter countries are positive and statistically significant at the 1% level. These coefficients indicate that a one-point[11] increase in the *technological level* of wind energy in an exporter countries raises that country's trade value by approximately 1.4%. In other words, it indicates that a 1,000 count increase in patent applications will raise trade value by approximately 8 million USD.[12] Regarding the solar energy, coefficients on *technological level* are positive and statistically significant at the 5% level in the PPML model. This finding means that a one-point increase in the technological level of solar energy in exporter countries will raise export values by approximately 0.3%. In other words, a 1,000 increase in the patent count will raise trade value by approximately 5 million USD. These results suggest that exporting countries with a higher tech-

[11] In this case, one point of technological level is 1,000 patents.
[12] The calculation is based on the mean export value.

nological level will have increased export values. Therefore, hypothesis (1)—a higher level of technological development in an exporter country can increase the export value of renewable energy products—is supported.

When we look at the importer side, the coefficient of *technological level* for wind energy is negative and statistically significant. These coefficients indicate that one-point increase in the *technological level* of wind energy in the importer countries will reduce trade value by approximately 1.4%. In other words, a 100 decrease in patent counts in the importer countries will increase exports to these countries by approximately 0.8 million USD. These results suggest that the importing countries having a lower technology level for wind energy technology will positively affect their import value. Therefore, hypothesis (2) is supported: a lower technological level in the importing country might increase the import value of wind energy products. For solar energy, on the other hand, we do not find a statistically significant effect of *technological level* for importer countries in all models.

Comparing the effects of solar and wind technology on export values, we find some differences in the estimated coefficients. The *technological level* of an importer is statistically significant only for the export of wind energy products. In the case of solar energy, importer *technological level* does not affect trade value. On the other hand, with regard to the *technological level* of exporter countries, statistically significant impacts exist for both energy types. Regarding the size of the technology effect between the two studied renewable energy sources, the coefficient for wind is relatively larger. This result shows that a stronger relationship exists between the technological level of the exporters and the trade flows in the case of wind energy than for solar energy.

Estimation results for policy related variables are somewhat mixed, and statistical significance varies depending on energy source and policy instruments. The coefficient for the Kyoto Protocol is positive and statistically significant at the 1% level for solar energy; however, the coefficient is not significant for wind energy. The coefficient of the importer being a signatory of Kyoto is positive and statistically significant at the 1% level for solar. However, for wind energy, that variable has no statistically significant effect on export values. These results suggest that the Kyoto Protocol has a positive impact on trade flows for solar energy products. The size of the coefficients suggest that countries that sign the Kyoto Protocol see import values rise by approximately 0.5%. In other words, these countries raise their trade value by approximately 10 million USD. For wind energy, the effect of signing Kyoto is observed on the exporter side only.

When we look at the effects of domestic policy instruments, the coefficient on FIT in importer is positive and statistically significant at the 1% level for solar. The coefficient on RPS in exporters is negative, whereas that in importers is positive for wind energy. The coefficients on RPS in exporters and importers are negative for solar energy. Therefore, regarding the RPS variable, our estimation results do not support the Porter hypothesis.

The estimated coefficients for the other variables typically included in gravity model are in line with our expectations. For example, the coefficient of *Mass* is positive and significant at the 1% level for solar energy. This result demonstrate that the economy size of both the exporter and the importer has a positive impact on export values. The coefficient on *Distance* is negative and significant at the 1% level for both types of energy source, suggesting that the distance between trading countries has a negative impact on export values. The coefficient of *Language* is positive and significant at the 1% level for wind energy and at the 5% level for solar energy. The coefficient of *Contiguity* is positive and significant at the 1% level for wind energy and at the 5% level for solar energy. The coefficient of *Common currency* is positive and statistically significant the 1% level for solar and at the 10% level for wind. The coefficient of

Import tariff is negative and significant at the 5% level for solar, suggesting that, as expected import tariffs have a negative impact on export values for solar energy products. However, tariffs are not statistically significant for wind energy.

5. Extensions

5.1 Exports from China

The estimations presented in the previous section used a dataset of trade among 35 OECD countries. In this subsection, we estimate the same model using a dataset that includes China. China has dramatically increased the production of renewable energy products in recent years. In particular, China is a major exporter of solar energy products such as solar panels. Figures 3 and 4 show trends in export values for wind and solar energy products for all the OECD countries and for China. These figures suggest that solar energy product exports from China increased remarkably after 2005. The export values of solar energy products from China reached around half the total export values of the 35 analyzed OECD countries in 2010.

The literature dealing with China's impact on the trade of renewable energy products is limited. For example, Groba and Cao (2015) investigated the exports of solar and wind energy technology components from China. They estimate a panel data model on the annual bilateral trade flows of 43 countries that imported solar PV and wind energy products from China between 1996 and 2008. Their results suggest that the Chinese PV industry entered foreign markets successfully, although the domestic market remained underdeveloped. Our analysis in this subsection differs from that of Groba and Cao (2015) in that we focus on the trade among OECD countries and China and the impact of renewable energy technology on the trade values.

Table 4 shows the estimation results using the dataset including China. The specification in column (1) for wind energy products indicates that the coefficient for exporter *technological level* is positive and that for importer is negative and both are statistically significant at the 1% level. These results support our hypotheses on the relationship between technological level and trade values. In contrast, we do not find a significant effect from *technological level* for solar energy products. Taken together with the results of Table 3, the effect of technological level for solar energy is less related to product trade values.

Despite the fact that China exports substantial amounts of solar energy products, it has fewer patent counts compared with OECD countries.[13] The total export value from China to OECD countries from 1996 to 2010 was 98 billion USD, the largest among the 36 countries involved in this study. For solar energy products, Chinese companies only registered 116 patents from 1996 to 2010, fewer than one-tenth of the number of patents registered in Japan, the US, or Germany.

[13] China's domestic patent counts have increased in recent years. Dang and Motohashi (2015) claim that a subsidy for the filing fee generated applications of lower quality of patents in China.

5.2 PCT application

The analysis in Section 4 used patent applications to EPO as a variable indicating technological level.[14] As explained in Section 3, we use EPO applications because this allows us to avoid the effect caused by different patent laws and systems among countries. In addition, the EPO data are superior to data from national patent offices because cost differences serves as a quality hurdle that can eliminate applications for low-value inventions (Johnstone et al., 2010). However, the data do not capture the patent that is applied to outside European countries. In this subsection, we re-estimate the model using PCT applications instead of EPO applications. A PCT application is used for filing a patent abroad. Some literatures indicate that patent filings abroad are qualitatively higher-grade than patent filings in a domestic patent office (Lanjouw and Mody, 1996; Lanjouw and Schankerman, 2004; Popp et al., 2011).

Table 5 presents the results using the number of PCT application as the variable indicating *technological level*. Regarding wind energy technology, the coefficient for *technological level* of exporter is positive but that of importer is negative. Both coefficients are statistically significant at the 1% level. On the other hand, the coefficient of exporter technological level is

[14] The EPO application protect patent rights in European countries. It allows patent rights to be obtained in any one or more of the European Patent Convention (EPC) contracting states by making a single European patent application to the EPO. This may be considerably cheaper than making a separate national application in each EPC member country.

not statistically significant but that for importer is negative and statistically significant, both at the 1% level. These results again suggest that *technological level* has a clearly observable effect on trade values in wind energy technology, but less so in solar energy technology.

6. Conclusion

This study has investigated the trade flows in renewable energy products, focusing on the role of technological development. We estimated a gravity model that included knowledge stocks measured using patent count data as a proxy for the technological level of exporting and importing countries. We compared the pattern of trade flows between two renewable energy technologies: wind and solar.

The findings in this study highlight three points regarding the development of renewable energy technology. First, the technological level of both exporters and importers affect the trade flows in wind energy products. These findings support our two hypotheses regarding the relationship between technological level and export values. Second, differences exist in trade patterns between wind and solar energy products. Specifically, the relationship between technological level and export values cannot be confirmed in many models for solar energy products. This result might be due to the different characteristics of wind and solar power technologies. For example, the production technology of solar power cells uses module manufacturing equipment and assembly lines. Even if a firm does not have the requisite knowledge stock, it can buy turn-key manufacturing equipment and start producing and exporting solar power products. In contrast, wind energy products does not entail such characterstics. Last, signing the Kyoto protocol has a significant impact on increasing trade flows. The impact of domestic policies such as FIT and RPS are less significant because these may not cause international diffusions of new technologies.

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Figure 1. Trade values for wind and solar energy in OECD countries

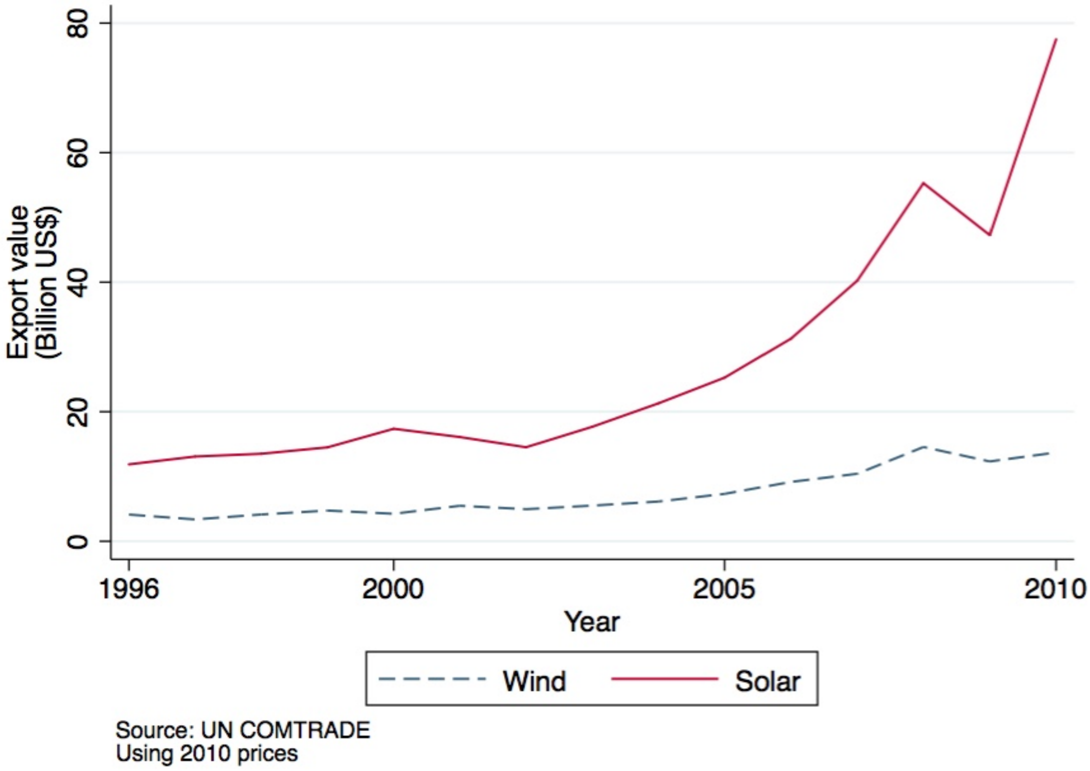


Figure 2. Patent counts for wind and solar energy in OECD countries

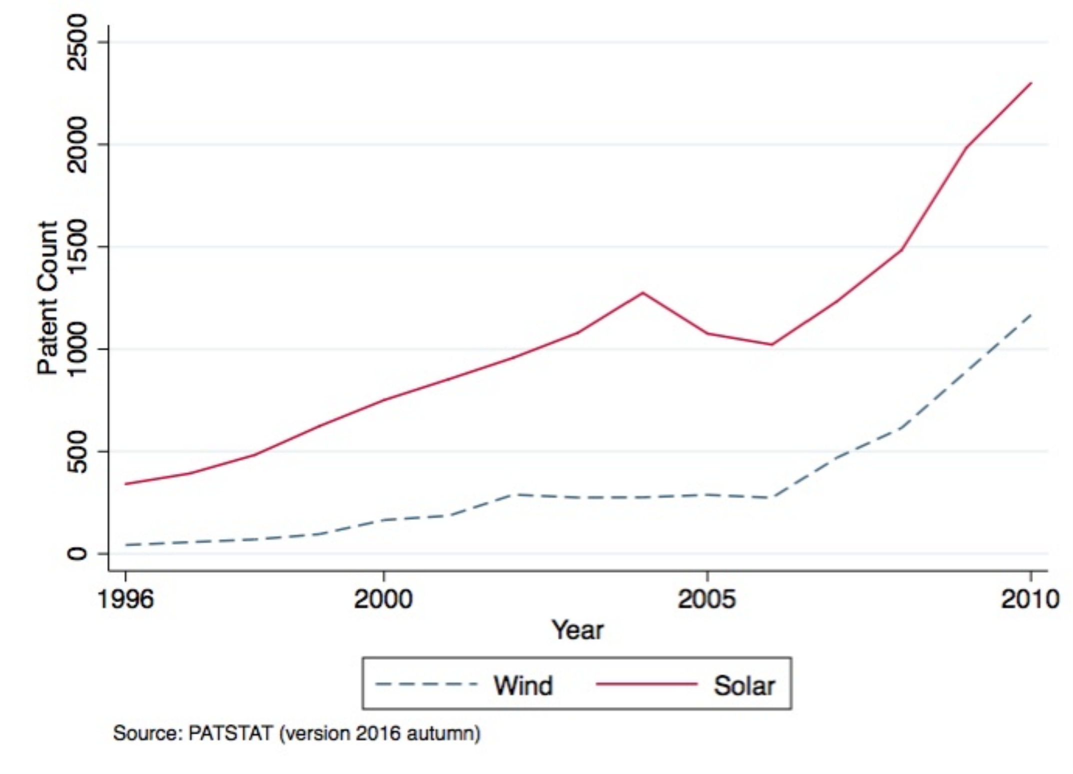
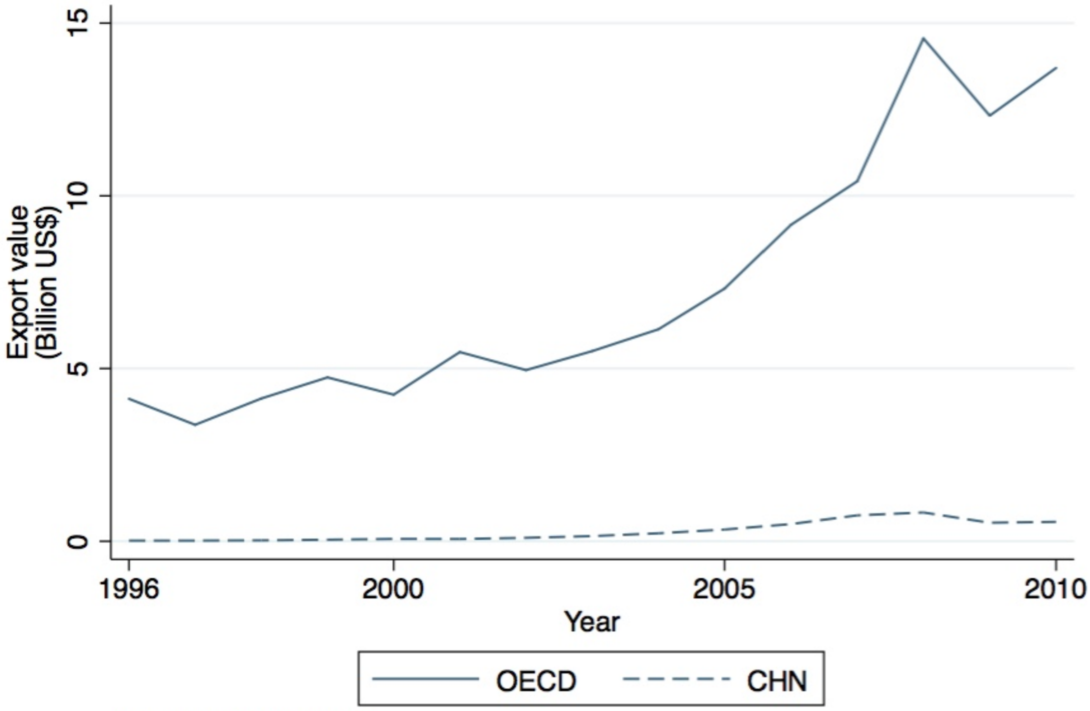


Figure 3. Export values of wind energy products in OECD countries and China



Source: UN COMTRADE
Using 2010 prices

Figure 4. Export values of solar energy products in OECD countries and China

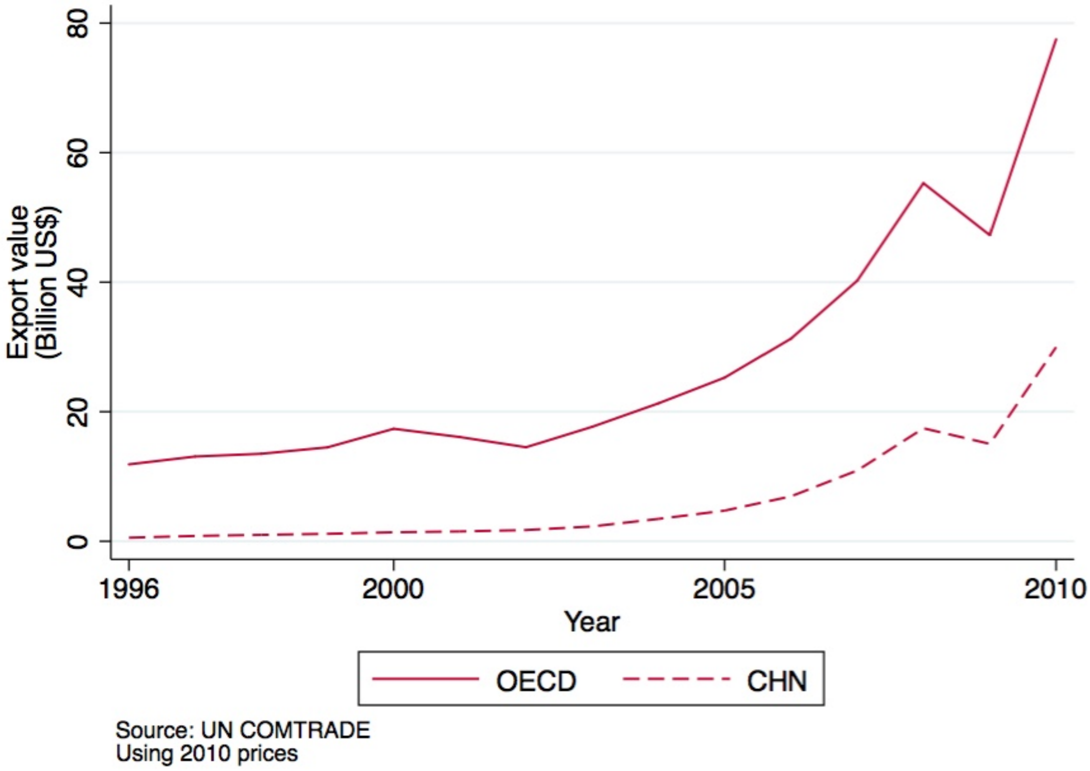


Table 1. Top 10 countries for trade values and patent counts: 1996 to 2010

Wind energy

	Exporter	Export value (Billion USD)	Importer	Import value (Billion USD)	Country	Patent counts
1	Denmark	20.1289	US	20.5918	Germany	1669
2	Germany	15.3124	Germany	13.0779	Denmark	832
3	US	14.9372	UK	8.2467	US	649
4	Italy	11.5053	Canada	7.7310	Japan	399
5	Spain	4.8716	France	6.8452	Spain	224
6	Japan	3.8503	Italy	4.0816	UK	218
7	UK	3.8392	Spain	3.9054	Netherlands	167
8	Switzerland	3.4633	Mexico	3.2147	Italy	145
9	Canada	2.9047	Turkey	2.9611	France	127
10	France	2.8755	Japan	2.6910	Sweden	96

Solar energy

	Exporter	Export value (Billion USD)	Importer	Export value (Billion USD)	Country	Patent counts
1	Germany	56.5429	Germany	52.7061	Japan	4637
2	US	46.0080	US	50.1897	US	3564
3	Japan	32.7133	Italy	21.1962	Germany	3276
4	Mexico	20.5662	France	17.0871	France	677
5	UK	19.4950	Spain	15.8746	UK	655
6	Netherlands	14.2741	UK	15.5897	Rep. of Korea	645
7	France	11.8001	Canada	13.8867	Netherlands	415
8	Italy	8.7521	Netherlands	13.2672	Switzerland	382
9	Belgium	7.6609	Rep. of Korea	9.6412	Italy	338
10	Finland	7.5404	Mexico	9.2082	Belgium	197

Table 2. Descriptive statistics

	Obs.	Mean	Std. Dev.	Min	Max
Dependent variables: Export value (million US$)					
Wind	17850	5.664	30.811	0	1106.368
Solar	17850	16.295	81.930	0	3365.387
Independent variables					
Mass $_{ijt}$ *,ln*	17850	11.008	0.328	9.541	11.928
Distance $_{ij}$ *,ln*	17850	7.988	1.174	4.088	9.883
Language $_{ij}$	17850	0.074	0.262	0	1
Contiguity $_{ij}$	17850	0.064	0.245	0	1
Common currency $_{ijt}$	17850	0.002	0.041	0	1
Import tariff of wind $_{jt-1}$	17850	0.013	0.024	0	0.153
Import tariff of solar $_{jt-1}$	17850	0.015	0.023	0	0.120
Technological level of wind $_{it-1}$	17850	0.032	0.095	0	0.992
Technological level of solar it-1	17850	0.125	0.348	0	2.381
Kyoto Protocol $_{it-1}$	17850	0.726	0.446	0	1
FIT for wind $_{it-1}$	17850	0.029	0.039	0	0.214
FIT for solar $_{it-1}$	17850	0.090	0.159	0	0.700
RPS for wind $_{it-1}$	17850	0.006	0.022	0	0.169
RPS for solar $_{it-1}$	17850	0.006	0.022	0	0.169

Note: Although several variables were constructed for technological level for exporters and importers, the table shows only one of them because their summary statistics are same. Policy variables are treated similarly. The variables of import tariff, FIT, and RPS are expressed in hundreds of units, while the technological level is expressed in thousands.

Table 3. Main results

	PPML		NB		OLS	
	(1)	(2)	(3)	(4)	(5)	(6)
	wind	solar	wind	solar	wind	solar
Mass $_{ijt}$, *ln*	0.614	4.121***	0.253	2.371***	2.809**	6.713***
	(0.900)	(1.594)	(0.745)	(0.744)	(1.255)	(1.220)
Distance $_{ij}$, *ln*	-0.734***	-0.876***	-0.962***	-1.082***	-2.085***	-1.943***
	(0.068)	(0.066)	(0.070)	(0.063)	(0.147)	(0.122)
Language $_{ij}$	0.348***	0.252**	0.503***	0.306**	0.501	0.438
	(0.122)	(0.116)	(0.160)	(0.146)	(0.335)	(0.285)
Contiguity $_{ij}$	0.389***	0.362**	0.550***	0.346**	0.308	-0.193
	(0.149)	(0.160)	(0.180)	(0.163)	(0.518)	(0.438)
Common currency $_{ijt}$	0.573*	1.327***	0.295	0.834***	0.865	1.126**
	(0.297)	(0.187)	(0.235)	(0.248)	(0.624)	(0.557)
Import tariff $_{jt-1}$	-0.801	-6.495**	4.967**	-2.431*	7.172**	6.999**
	(1.649)	(2.638)	(2.450)	(1.372)	(3.384)	(3.031)
Technological level $_{it-1}$	1.363***	0.282**	1.581***	0.373***	-0.503	-1.455***
	(0.309)	(0.140)	(0.403)	(0.138)	(0.560)	(0.242)
Technological level $_{jt-1}$	-1.434***	0.025	-0.541	-0.104	-0.365	-0.436
	(0.360)	(0.143)	(0.353)	(0.143)	(0.728)	(0.319)
Kyoto Protocol $_{it-1}$	0.129	0.587***	0.386**	0.631***	0.145	0.961***
	(0.101)	(0.094)	(0.172)	(0.121)	(0.217)	(0.220)
Kyoto Protocol $_{jt-1}$	0.069	0.588***	0.217	0.214**	0.075	0.037
	(0.150)	(0.093)	(0.133)	(0.094)	(0.232)	(0.251)
FIT $_{it-1}$	-0.411	0.076	-0.590	0.519***	1.190	0.085
	(1.358)	(0.223)	(0.897)	(0.178)	(1.549)	(0.335)
FIT $_{jt-i}$	-0.764	0.594**	-0.146	0.747***	-0.335	0.510
	(1.514)	(0.291)	(0.879)	(0.192)	(1.571)	(0.366)
RPS $_{it-1}$	-6.476***	-5.565***	-4.223***	-5.210***	-5.142**	-6.061**
	(2.078)	(1.573)	(1.431)	(1.009)	(2.102)	(2.442)
RPS $_{jt-1}$	7.250***	-4.222**	2.662	-2.242	-4.444**	-6.577***
	(2.417)	(1.923)	(1.784)	(1.802)	(2.217)	(2.436)
Constant	1.116	-38.455**	7.023	-15.933*	-13.335	-61.157***
	(10.161)	(17.992)	(8.482)	(8.380)	(14.311)	(13.873)
Year effects	Yes	Yes	Yes	Yes	Yes	Yes
Exporter effects	Yes	Yes	Yes	Yes	Yes	Yes
Importer effects	Yes	Yes	Yes	Yes	Yes	Yes
Observations	17850	17850	17850	17850	17850	17850
R-squared	0.682	0.748			0.678	0.702
Adjusted R-squared					0.676	0.700
AIC	109520.229	188457.000	50166.973	70520.688	95287.531	92379.260
BIC	110268.046	189204.817	50914.790	71268.505	96035.348	93127.077
log_likelihood	-54664.115	-94132.500	-24987.486	-35164.344	-47547.766	-46093.630

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 including China

	PPML		NB		OLS	
	(13)	(14)	(15)	(16)	(17)	(18)
	wind	solar	wind	solar	wind	solar
Mass $_{ijt}$*, ln*	2.646***	5.379***	1.655**	3.244***	3.665***	6.789***
	(0.845)	(1.271)	(0.644)	(0.615)	(1.049)	(1.011)
Distance $_{ij}$*, ln*	-0.738***	-0.773***	-0.954***	-1.070***	-2.032***	-1.915***
	(0.057)	(0.057)	(0.062)	(0.057)	(0.134)	(0.110)
Language $_{ij}$	0.351***	0.374***	0.521***	0.329**	0.536	0.431
	(0.122)	(0.145)	(0.160)	(0.145)	(0.332)	(0.281)
Contiguity $_{ij}$	0.376***	0.412**	0.574***	0.361**	0.357	-0.168
	(0.142)	(0.173)	(0.182)	(0.165)	(0.525)	(0.439)
Common currency $_{ijt}$	0.602**	1.550***	0.313	0.892***	0.955	1.228**
	(0.300)	(0.240)	(0.230)	(0.250)	(0.619)	(0.550)
Import tariff $_{jt-1}$	-1.049	-5.319***	4.874**	-2.211*	6.328**	5.523**
	(1.651)	(1.925)	(2.351)	(1.181)	(3.202)	(2.388)
Technological level $_{it-1}$	1.161***	-0.153	1.482***	0.280**	-0.703	-1.496***
	(0.292)	(0.198)	(0.398)	(0.136)	(0.542)	(0.233)
Technological level $_{jt-1}$	-1.336***	-0.046	-0.403	-0.149	-0.378	-0.483
	(0.360)	(0.257)	(0.368)	(0.145)	(0.704)	(0.307)
Kyoto Protocol $_{it-1}$	-0.001	0.242*	0.174	0.357***	-0.149	0.905***
	(0.119)	(0.132)	(0.165)	(0.123)	(0.214)	(0.205)
Kyoto Protocol $_{jt-1}$	0.036	0.531***	0.150	0.146	-0.025	-0.015
	(0.138)	(0.184)	(0.131)	(0.096)	(0.224)	(0.234)
FIT $_{it-1}$	-0.985	-0.235	-1.530*	0.321*	0.242	0.078
	(1.208)	(0.267)	(0.865)	(0.176)	(1.479)	(0.327)
FIT $_{jt-i}$	-0.764	0.667*	-0.529	0.748***	-0.350	0.450
	(1.340)	(0.366)	(0.833)	(0.198)	(1.511)	(0.356)
RPS $_{it-1}$	-7.595***	-10.389***	-5.282***	-6.957***	-6.365***	-6.470***
	(1.984)	(2.207)	(1.429)	(1.052)	(2.054)	(2.421)
RPS $_{jt-1}$	7.186***	-5.625**	2.077	-2.836	-5.179**	-6.954***
	(2.406)	(2.399)	(1.727)	(1.792)	(2.178)	(2.370)
Constant	-21.563**	-53.023***	-8.594	-25.534***	-23.148*	-62.202***
	(9.495)	(14.603)	(7.366)	(6.935)	(11.985)	(11.534)
Year effects	Yes	Yes	Yes	Yes	Yes	Yes
Exporter effects	Yes	Yes	Yes	Yes	Yes	Yes
Importer effects	Yes	Yes	Yes	Yes	Yes	Yes
Observations	18900	18900	18900	18900	18900	18900
R-squared	0.680	0.692			0.680	0.708
Adjusted R-squared					0.678	0.706
AIC	117814.023	275679.144	54425.131	78025.842	100751.433	97520.809
BIC	118583.020	276448.141	55194.129	78794.840	101520.431	98289.807
log_likelihood	-58809.011	-137741.572	-27114.566	-38914.921	-50277.716	-48662.405

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

Table 5. Results using PCT application data

	PPML		NB		OLS	
	(7)	(8)	(9)	(10)	(11)	(12)
	wind	solar	wind	solar	wind	solar
Mass $_{ijt}$, ln	0.758	3.379**	0.285	2.179***	2.796**	6.852***
	(0.932)	(1.540)	(0.750)	(0.737)	(1.270)	(1.214)
Distance $_{ij}$, ln	-0.734***	-0.881***	-0.963***	-1.080***	-2.085***	-1.944***
	(0.068)	(0.066)	(0.070)	(0.064)	(0.147)	(0.122)
Language $_{ij}$	0.347***	0.239**	0.501***	0.305**	0.500	0.442
	(0.122)	(0.118)	(0.161)	(0.146)	(0.335)	(0.285)
Contiguity $_{ij}$	0.383***	0.377**	0.546***	0.345**	0.308	-0.192
	(0.149)	(0.160)	(0.181)	(0.163)	(0.518)	(0.439)
Common currency $_{ijt}$	0.576*	1.304***	0.289	0.826***	0.864	1.130**
	(0.297)	(0.187)	(0.235)	(0.248)	(0.624)	(0.557)
Import tariff $_{jt-1}$	-0.801	-6.143**	4.900**	-2.322*	7.113**	7.261**
	(1.685)	(2.545)	(2.463)	(1.385)	(3.401)	(3.020)
Technological level $_{it-1}$	2.476***	-0.058	2.319***	0.153	-1.068	-0.989***
	(0.571)	(0.108)	(0.742)	(0.128)	(1.022)	(0.198)
Technological level $_{jt-1}$	-2.192***	-0.357***	-0.343	-0.295***	-0.397	-0.446*
	(0.649)	(0.117)	(0.651)	(0.104)	(1.304)	(0.252)
Kyoto Protocol $_{it-1}$	0.244**	0.506***	0.445**	0.595***	0.123	0.945***
	(0.102)	(0.078)	(0.177)	(0.127)	(0.219)	(0.223)
Kyoto Protocol $_{jt-1}$	-0.031	0.372***	0.210	0.158*	0.069	0.004
	(0.144)	(0.073)	(0.133)	(0.096)	(0.234)	(0.256)
FIT $_{it-1}$	-1.522	0.096	-1.080	0.539***	1.222	0.017
	(1.492)	(0.191)	(0.902)	(0.179)	(1.531)	(0.337)
FIT $_{jt-i}$	0.792	0.614**	0.120	0.747***	-0.245	0.490
	(1.706)	(0.257)	(0.870)	(0.195)	(1.559)	(0.367)
RPS $_{it-1}$	-7.657***	-5.838***	-4.885***	-5.241***	-4.838**	-5.785**
	(2.194)	(1.725)	(1.459)	(1.012)	(2.159)	(2.491)
RPS $_{jt-1}$	9.504***	-3.585*	2.769	-1.968	-4.334*	-6.242**
	(2.805)	(1.919)	(1.792)	(1.829)	(2.231)	(2.473)
Constant	-0.575	-29.471*	6.593	-13.637	-13.155	-62.631***
	(10.537)	(17.425)	(8.551)	(8.312)	(14.493)	(13.818)
Year effects	Yes	Yes	Yes	Yes	Yes	Yes
Exporter effects	Yes	Yes	Yes	Yes	Yes	Yes
Importer effects	Yes	Yes	Yes	Yes	Yes	Yes
Observations	17850	17850	17850	17850	17850	17850
R-squared	0.683	0.750			0.678	0.701
Adjusted R-squared					0.676	0.700
AIC	109742.871	187990.984	50183.408	70523.525	95287.365	92402.939
BIC	110490.688	188738.801	50931.225	71271.342	96035.182	93150.756
log_likelihood	-54775.436	-93899.492	-24995.704	-35165.763	-47547.683	-46105.470

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

Appendix

Table A1. List of IPC code for renewable energy technologies

IPC code	Explanation
Wind energy	
F03D	Wind energy
H02K 7/18	Structural association of electric generator with mechanical driving motor
B63B 35/00; E04H 12/00; (F03D 11/04)	Structural aspects of wind turbines
B60K 16/00	Propulsion of vehicles using wind power
B60L 8/00	Electric propulsion of vehicles using wind power
Solar energy	
H01L 27/142, 31/00-31/078; H01G 9/20; H02N 6/00*	Devices adapted for the conversion of radiation energy into electrical energy
H01L 27/30, 51/42–51/48	Using organic materials as the active part
H01L 25/00, 25/03, 25/16, 25/18, 31/042	Using organic materials as the active part
C01B 33/02; C23C 14/14; C30B 29/06	Silicon; single-crystal growth
G05F 1/67	Regulating to the maximum power available from solar cells
F21L 4/00; F21S 9/03	Electric lighting devices with, or rechargeable with, solar cells
H02J 7/35	Charging batteries
H01G 9/20; H01M 14/00	Dye-sensitised solar cells (DSSC)
B63H 13/00	Propulsion of marine vessels by wind-powered motors

Sorce: WIPO(2012)-IPC Green Inventory(http://www.wipo.int/classifications/ipc/en/green_inventory/)

Note: H02N 6/00 was deleted when IPC code is updated in 2014.