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Competitive Advantage in the Renewable Energy Industry: Evidence from a Gravity Model

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Abstract

Pioneering domestic environmental regulation may foster the creation of new eco-industries. These industries could benefit from a competitive advantage in the global market place. This article examines empirical evidence of the impact of domestic renewable energy policies on the export performance of renewable energy products (wind and solar PV). We use a gravity model of international trade with a balanced dataset of 49 (for wind) and 40 (for PV) countries covering the period 1995-2013. The stringency of renewable energy policies are proxied by installed capacities. Our econometric model shows evidence of competitive advantage positively correlated with domestic renewable energy policies, sustained in the wind industry but brief in the solar PV industry. We suggest that the reason for the dynamic difference lies in the underlying technologies involved in the two industries.

Key-words

Competitive Advantage, Gravity Model, Wind Industry, Solar PV Industry, Green Growth

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1. Introduction

The concept of green growth is increasingly gaining momentum in policy and academic circles. The green growth concept can be said to turn the debate on costly environmental constraints on the economy into a narrative on potentially attractive opportunities - aligning environmental protection, particularly with respect to climate change, with new jobs, technologies, and competitiveness of domestic industries (Bowen and Fankhauser 2011). Green industrial policies to foster green growth are advocated (e.g. Karp and Stevenson 2012; Rodrik 2014) and implemented by a growing number of countries and regions such as for example the European Union, China, and South Korea (Fankhauser et al. 2013). Although clear definitions of green growth and green industrial policy are still lacking (Bowen and Fankhauser 2011), and have more sceptically been labelled as oxymorons that intend to bundle different and partly contradictory interests (Brand 2012), a major element in green industrial policy is to speed-up the development and deployment of low-carbon alternatives to fossil fuels.

Global investment in renewable power and fuels projects are rapidly increasing and totalled USD 242bn in 2016, contributing to the recent plateau in global CO_2 emissions (REN21, 2017). These investments have benefitted from policies to promote the production and use of renewable energy that are implemented in an increasing number of countries around the world. REN21 (2017) reports that by the end of 2016 nearly all countries in the world directly supported renewable energy technology development and deployment through some mix of policies.

Renewable energy support policies come in many forms and shapes, including grants for research, development and demonstration, fiscal and financial incentives for investors and price-based and quantity based incentives such as feed-in tariffs, feed-in premiums, net metering, renewable portfolio standards, renewable energy certificates, and competitive procurement. Feed-in tariff (FIT) schemes require electric utilities to purchase the electricity produced by renewable energy producers in their service area at a pre-determined tariff for a specified period of time, usually 20 years. Feed-in-premiums guarantee a fixed premium on top of the wholesale electricity market price. Renewable portfolio standards (RPS) schemes require electric utilities to produce a specified fraction of their electricity from renewable energy sources. REN21 (2017) reports that 110 FIT schemes and 100 RPS or quota systems were in place at either state, province or country level around the world in 2016.

The support schemes involve large financial incentives. The Financial Times (2017) reports that based on information from the International Energy Agency, subsidies to aid the deployment of renewable energy technologies were USD 112bn in 2014, with another USD 23bn spent on supporting biofuels, although it should be added that this total subsidy amount is still four times smaller than subsidies on fossil fuels (Financial Times, 2017). Renewable energy support in Germany totals an annual expense of more than EUR 20bn, largely funded by a renewable surcharge on the energy tariffs on private households and industry (Kreuz and Müsgens, 2017). Other countries that have invested heavily in renewable energy support are the U.S, Italy, Spain, and China.

There is little debate about whether this support has been effective in terms of increasing the capacity of renewable energy sources. Over the period 2007-2016, total renewable energy capacity in the world doubled, while wind capacity quadrupled and solar PV capacity had an astonishing growth rate of more than 3000 percent (IRENA, 2017). In total, modern renewables increased at more than twice the rate of the increase in global energy demand (RES21, 2017). During that time, the unit costs of renewable energy also declined, to the extent that solar PV and onshore wind power are now competitive with new fossil fuel generation in an increasing number of locations in the world (RES21, 2017).

There is debate, however, about the efficiency of renewable energy support schemes , and about the additional benefits that were promised by green growth advocates, particularly the opportunities in terms of jobs, technologies and competitiveness of domestic industry (e.g. Schmalensee 2012; Helm 2014; Cullen 2016). Recently, the tremendous investments in renewable energy capacities in China (Schmitz 2013) and at a smaller scale in Korea (Fankhauser et al. 2013) were at least as much driven by the «green race» rush than climate change mitigation concerns. However, it is not certain whether climate pioneers always enjoy competitive advantages over late movers. Domestic renewable energy support policies also induce innovation in foreign countries as it was shown by Peters et al. (2012) for the solar PV industry and Dechezleprêtre and Glachant (2014) for the wind industry.

Further, differences among countries are likely to lessen through the diffusion of knowledge and technologies (Keller 2004, Dechezleprêtre et al. 2011). Trade is an important channel (Copeland 2012), but technological transfer can also be achieved by licensing arrangements, mergers and acquisitions or joint development as shown in the Chinese and Indian wind industry by Lewis (2007, 2011). Finally, there are also advantages for late adopters (Cleff and Rennings 2012, Voituriez and Balmer 2012), such as freeriding on first-mover investments, less incumbent inertia, and leapfrogging[2] (Fudenberg et al. 1983) allowed by reduced market, technological and regulatory uncertainty. As Pegels and Lütkenhorst (2014) put it, the question is whether it is «the early bird that catches the worm or the second mouse that gets the cheese». Many theoretical effects have been identified, which point in opposite directions as to whether moving first is recommended, while little evidence exist. Yet empirical studies show a drastic reduction of the interval between the commercialisation of a new product and the entry by competitors. According to Agarwal and Wort (2001), this reduction is due to easier transfer of knowledge and skills across firms.

The objective of this paper is to empirically estimate the effect of renewable energy support policies on the competitive advantage of domestic manufacturing firms that produce renewable energy technologies. Competitiveness and competitive advantage are somewhat elusive concepts (Neary 2006), and their meanings vary with the level at which they are being considered (Ekins and Speck 2012). Competitiveness at the sector level can be defined as the 'ability' of firms in that sector to sell goods and services in the market and stay in business, as compared to international rivals (Adams 1997). Ability itself is difficult to measure, what can be measured are its determinants (e.g., productivity) or consequences (e.g., stock value, volume of activity, market share, or trade flows). Algieri et al. (2012) use the relative export price of photovoltaic panels in their study on the determinants of exports of the U.S. solar industry. They find that the volume of exports is sensitive to the relative export price as well as to income (as a proxy for demand) in the importing countries. Sawhney and Kahn (2012) study the determinants of imports of wind and solar power-generation equipment into the U.S. and find, among other things, that effective renewable support policies enacted by the national governments of exporting countries (using the volume of domestic supply of renewable energy as a proxy), is a significant explanatory variable for import into the U.S. These domestic renewable support policies might create competitive advantage through so-called 'home market effects' (Krugman 1980). The 'home market effect' hypothesis posits that industries that may benefit from economies of scale (production at a larger scale can be achieved at a lower unit cost of production) and are sensitive to transportation costs, might want to concentrate in those markets where demand for their products is highest. Combining the results of the two studies suggests that exports of renewable energy equipment are positively related to increases in foreign demand and lower relative export prices that may be due to a 'home market effect' that is caused by domestic renewable support policies that created a large domestic market. Hence, domestic support policies

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[2] The idea of leapfrogging is that as long as small innovations are incremental, the dominant firm/country stay ahead, but radical innovations may allow new firms and countries to leapfrog, i.e. take the lead. The mechanism at stake is that the dominant firm/country has less incentive to innovate due to the rents earned from the old technology. Studies about leapfrogging include Cho et al. (1998) who study the semi-conductor industry in Korea and Japan.

might enhance the competitive advantage of renewable energy equipment manufacturers as witnessed by increased sales on the world market.

The objective of this paper is to empirically estimate the effect of renewable energy support policies on the competitive advantage, in terms of an increase in export flows, of domestic manufacturing firms that produce renewable energy technologies. In this paper, we focus exclusively on competitive advantage as measured by an increase in export flows which is an important element of the green growth promise (see e.g. Bowen and Fankhauser 2011). The recent trade deficit in PV cells in Germany and other European countries has led to an emotionally-charged debate (Kierkegaard et al. 2010, Pegels and Lütkenhorst 2014). Moreover, renewable energy subsidies have been subject of several trade disputes that have been brought before the World Trade Organization (WTO) (Hughes and Meckling 2017, Asmelash 2015, Kulovesi 2014) and led to trade frictions, for example between the EU and China (McCarthy 2016). Hence, the issue of international competitiveness and the international trade of renewable energy technologies is of importance.

Previous studies on this issue include Algieri et al. (2011) and Sawhney and Kahn (2012) who studied renewables technologies trade from the point of view of the US[3] with simple models but with great product detail. While Algieri et al. (2011) set aside policies and only consider price and income elasticities in the solar photovoltaic sector (hereafter solar PV), Sawhney and Kahn (2012) find that domestic renewable power generation of the exporting countries play a significant positive role in export performance. Lund (2009) establishes a statistical correlation between large domestic markets and large export shares in the wind industry.

The closest studies to ours are Costantini and Crespi (2008), Costantini and Mazzanti (2012), Groba (2014) and Groba and Cao (2015). The studies of Costantini and Crespi (2008) and Costantini and Mazzanti (2012) focus on the effect of environmental policy stringency on the export of the broad category of 'environmental goods' of a set of industrialized countries for the period 1996-2005/07. They proxy environmental policy stringency with different indicators such as environmental protection expenditures or energy and environmental tax revenues. Using a gravity model of international trade, they find some evidence of competitive advantage in the new eco-industries markets and the related export opportunities for pioneering countries. Groba (2014) focuses on the effect of a regulatory framework supporting renewable energy (proxied by a large number of policy variables), on the export success of solar PV from OECD countries. They find evidence for a positive

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[3] For which trade data at the 10 digits level is more reliable than at the global level.

effect. While Groba (2014) did not include China as an important emerging solar PV exporter in his analysis, Groba and Cao (2015) specifically focus on the export performance of solar PV and wind of China. The results of our study are in line with the findings of Costantini and Crespi (2008) and Costantini and Mazzanti (2012) in that we also find some evidence of a positive effect of domestic environmental policy on the competitive advantage of the renewable energy equipment manufacturing industry. Contrary to Groba (2014), however, we find no evidence of a robust first-mover advantage in the solar industry as we find that policy-induced competitive advantages in this industry are only short-lived.

Also using the gravity model of international trade, we expand on the results of Costantini and Crespi (2008), Costantini and Mazzanti (2012), Groba (2014) and Groba and Cao (2015) in several aspects. First, our regressions covers the period 1995-2013, five to six years more, which may matter as renewables' industries evolve extremely quickly. Second, our dataset is more comprehensive on sectoral and geographical coverage: we focus on both wind and solar PV, and use balanced dataset of 49 (for wind) and 40 (for PV) countries comprising major developed and emerging countries. Given the recent emergence of wind and solar PV manufacturing industries in countries such as China and India, the traditional focus on the exports of EU or OECD countries is no longer warranted. Third, we use a different variable proxying the stringency of renewable energy policies, and fourth, we pay particular attention to the dynamic nature of the competitive advantage. Our econometric model shows evidence of competitive advantage correlated with domestic renewable energy policies, sustained in the wind industry and brief in the solar PV industry.

The remained of this paper is structured as follows. Section 2 presents and discusses our empirical model and the data we used. Section 3 presents the results, while section 4 discusses the results, offers conclusions and suggests policy implications.

2. Empirical Model

2.1 Gravity Model

The gravity model of trade is the «workhorse» of the applied international trade literature (Shepherd 2013, Head et al. 2014), used in thousands of studies, mostly investigating the impact of policies like tariffs and regional agreements on trade. The importance of geography and national borders in trade (highlighted by the «missing trade» (Trefler 1995) and the McCallum (1995) puzzle) gives empirical strength to this model, which is applied not only to goods but also to trade in services (Kimura and

Lee 2006), immigration (Lewer and Van den Berg 2007) or knowledge flows through patent citations (Peri 2005, Picci 2010).

It is named after an analogy to Newton's law:

$$T_{o,d} = G \times \frac{M_o^{\beta_1} M_d^{\beta_2}}{D_{od}^{\beta_3}}$$

The trade flow from country o (origin) to country d (destination) is positively linked to the economic sizes of the two countries (usually expressed in Gross Domestic Product (GDP)), M_o and M_d and negatively linked to the distance between them D_{od} (which refers to geographical distance but also other trade barriers). G is a constant measured by the inverse of the value of world production. The model is then log-linearized for estimation.

First developed by Tinbergen (1962) as an intuitive explanation of bilateral trade flows, this model was dismissed for a long time for lacking theoretical foundations (Bergstrand 1985), whereas it was providing robust empirical findings (Leamer and Levinsohn 1995). The first attempt to give micro-foundation to the gravity model can be traced back to Anderson (1979), which was followed by successful attempts to derive the gravity equation from different structural models (Bergstrand 1985, 1990, Helpman and Krugman 1985, Deardorff 1998). Still, it was only in the early 2000's, with two prominent articles (Eaton and Kortum 2002, Anderson and Van Wincoop 2003) that the gravity model was finally acknowledged as theoretically-grounded. More recently, the convergence with the heterogeneous firm literature (Helpman et al. 2008, Melitz and Ottaviano 2008) finally achieved to provide recognition to the gravity model in the field of international trade. This turning point led to a considerable number of publications and a change in estimation methods. In their famous «gravity with gravitas» model, Anderson and Van Wincoop (2003) introduced multilateral resistance terms of trade, which can be captured by importer and exporter fixed effects[4] (Feenstra 2002, Redding and Venables 2004).

2.2 Model specification

The dependent variables are bilateral export flows for wind and solar PV goods, from country o to country d at time t. We include time t in the in the model as there are a number of well-known advantages of using panel data instead of cross-sectional data to estimate a gravity model. These advantages include the efficiency of estimation and the treatment and estimation of time-invariant bilateral trade costs between any pair of countries with country-pair fixed effects (Head and Mayer, 2014). We clearly separate wind and solar PV industries in the regression in order to reduce

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[4] Omitting them is considered as the «gold medal mistake» by Baldwin and Taglioni (2006).

aggregation biases as suggested by Anderson and Yotov (2012). We use a balanced dataset of 49 and 40 countries for wind and solar PV respectively (see Table A1 in Appendix). The choice of countries is data-driven: we kept countries which either had significant installed capacities (virtually all installed capacities are in these countries) or are big exporters (in the world top 20 of exporters, such as Malaysia for solar PV).

The subsets of countries represent at least respectively 85% and 90% of world trade for wind and solar PV goods[5] corresponding to our classification of goods. For this classification we use the so-called 6-digit Harmonized System (HS) classification that is a commonly used and globally harmonized classification system to distinguish between goods that are internationally traded. The 6-digit level of the HS classification is the most detailed level of this classification that is internationally harmonized. The time period of the study is 1995-2013 (though because of lags estimation the time series often start in 1996 or 1997).

The estimated model is:

$$\ln\left(T_{o,d,t}\right) = \beta_0 + \beta_1 \ln\left(GDP_{o,t}\right) + \beta_2 \ln\left(GDP_{d,t}\right) + \beta_3 \boldsymbol{G_{o,d,t}} + \beta_4 \ln(RDEMAND_{d,t}) + \beta_5 RPOLICY_{o,t-3} + \alpha_o + \alpha_d + \alpha_t + \varepsilon_{o,d,t}$$

The variables are:

- $T_{o,d,t}$ is the bilateral export flow of wind or solar PV goods in millions of US dollars. Section 2.3 details how data is collected and computed.
- GDP, in nominal rather than real terms (as recommended by, for example, Shepherd 2013, and Baldwin and Taglioni 2006), are used to proxy economic sizes. They are taken from the World Development Indicator database of the World Bank.
- $\boldsymbol{G_{o,d,t}}$ is a vector of variables for geography.The main geographical variable is ln〚DIST〛_(o,d) which is the natural logarithm of geographical distance weighted by population between two countries as computed by CEPII (Mayer and Zignago 2011).We also tested common variables used in gravity models:〚LANG〛_(o,d),〚COLONY〛_(o,d),〚RTA〛_(o,d,t) and 〚CONTIG〛_(o,d) are dummy variables for respectively common language, past colonial relationship, regional trade agreements and contiguity (common border).These variables are also taken from the

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[5] Own computation from Comtrade.

CEPII database (data end in 2006 but the historical, cultural and geographical variables will not change and we assume that ⟦RTA⟧_(o,d,t) is invariant thereafter[6]).

- $RDEMAND_{d,t}$ is the demand in the destination country. We expect that an increase in demand in the destination country will lead to more exports to that country. The demand (*Dt*) includes mainly new installed capacity ($K_t - K_{t-1}$), where K_t stands for total capacity in year *t*, but also a rough estimation of maintenance and replacement of old installations($\delta_1 K_{t-1}$), where δ_1 is the rate of maintenance and replacement. We use a threshold of minimum demand (D_{min}) because very small demands may be unreliable due to measurement errors, while null demand would be dropped out of the sample as we express them in logarithm to be coherent with the main variable. More precisely we have $RDEMAND_{d,t}$= $(\max(D_{min}, D_t))$ where $D_t = [K_t - K_{t-1}] + \delta_1 K_{t-1}$. D_{min} and $\delta_1$take values of 5 MW and 0.5% for wind and 2.5 MW and 0.25% for solar PV[7]. We extracted annual installed wind capacities from the interactive map on the website[8] of the Global Wind Energy Council (GWEC) which is the world association of the wind industry and from Enerdata (2014) (as there is no equivalent displayed figure) for the solar PV industry.
- ⟦RPOLICY⟧_(o,t) is a proxy of the effectiveness of renewable energy policies in the country of origin. It is our main explanatory variable since the purpose of the study is to investigate the linkage between home renewable policies and export performance. Measures of the effectiveness of renewable energy policies and environmental policies in general can in principle be input-oriented and output-oriented (Van Beers and van den Bergh 1997). Input-oriented measures quantify the efforts devoted to the support of renewable energy generation. Examples are Public Research and Development (R&D) Expenditures, and the implied subsidies in feed-in tariffs and renewable portfolio standards. However, as we argued in the introduction of this paper, renewable energy support policies come in many forms and shapes and are hardly comparable across countries (even a given feed-in tariff can hide different incentives because of network junction pricing for example). Output-related measures quantify the results of the support policy, in terms of additional renewable energy capacity being installed. In assessing the effect of general environmental policies on trade

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[6] The CEPII database has recently been updated with trade agreement variables up to 2015. For our country dataset, the difference in trade agreement variable between 2006 and 2013 occurs only in 5% of country pairs. We re-ran the main regressions with the updated variable and the results were almost similar and did not affect our conclusions.

[7] Those are guestimates, but changing them does not change significantly the results. First, data is piecemeal for decommissioned capacity. In the EU 324 MW were decommissioned in 2013 (EWEA 2014) out of 106 454 installed MW in the beginning of this year (so 0.3%). Data for maintenance (replacing parts of wind turbines for example) is even harder to estimate.

[8] http://www.gwec.net/global-figures/interactive-map/

flows, Van Beers and van den Bergh (1997) prefer output-oriented measures of environmental stringency. With respect to support to renewable energy, many authors follow their recommendations and use output-oriented measures of policy effectiveness (e.g., Sawhney and Khan 2012; Groba 2014). In addition, Groba (2014) also uses dummies for input-oriented measures (feed-in tariff, renewable energy quota, R&D support, and tax measures or investment grants) and finds no statistically significant effects for the demand-oriented policies. Using an output-oriented measure of policy effectiveness, one can ask whether the output (additional renewable energy capacity being installed) can be fully ascribed to the policy or whether other factors might also have played a role. There is strong evidence that, for the past at least, renewable capacities investments were primarily induced by dedicated policies (Kirkegaard et al. 2010; Popp et al.2011). While this may no longer hold presently due to the increased competitiveness of solar PV and onshore wind power, we assume that it did largely hold for the period of analysis. Renewable energy policies are however hardly comparable across countries (even a given feed-in tariff can hide different incentives because of network junction pricing for example). For lack of a better metric, we consider that installed capacities (in proportion of the size of the electric sector in the country) are the best proxy to compare them. 〖RPOLICY〗_(o,t) is then equal to the share of solar PV or wind installed capacity at year t relative to the total capacity of the electric sector (in percentage points). As for $RDEMAND_{d,t}$, we use a threshold, defined as 0.01% for both Wind and PV[9]. The temporal delay used in the main regression is three years, but we try different lags of this variable to study temporal effects.

As errors are likely to be correlated by country-pair in the gravity model context (Moulton 1990), we provide robust standard errors clustered by geographical distance (Shepherd 2013). We also use directional (for source and destination country) fixed effects to model multilateral resistance terms (Anderson and Van Wincoop 2003, Feenstra 2004) as common best practice, as well as time fixed effects to capture exogenous shocks common to all countries (such as the price of oil, or recessions).

A much-discussed issue of in the gravity model is the treatment of the many zeros that appear in bilateral trade flows. In its simplest form (OLS), as the logarithm of zero is undefined, zero observations are dropped from the sample, leading to potentially biased estimates. The two most used alternative estimators are the Poisson Pseudo-Maximum Likelihood (PPML) developed by Santos Silva and Tenreyro (2011) and the Heckman Sample Selection Estimator developed by

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[9] Changing this threshold does not significantly change the results.

Helpman et al. (2008). The differences between these two estimators are explained in Sheperd (2013). In this study we present results for both estimation methods as common good practice. For the Heckman Sample Selection method, we use the geographical variables (except the distance) only for the sample selection equation.

2.3 Trade data in renewable energy technologies

Data from export flows in the solar and wind industries are extracted from the UNCTAD COMTRADE database. A caveat for using trade data is that the matching between 6-digit HS codes and renewable energy technologies is far from being perfect. Indeed HS codes are related to components for which the usage is unknown: the same components may be used in renewable energy or other industries. In addition the categories may be relatively wide and correspond to several products. Following Wind (2008), the International Centre for Trade and Sustainable Development (ICTSD) identified HS 6-digits product category codes according to the different renewable energy sectors (Jha 2009, Vossenaar and Jha 2010). Their product categorization is displayed in the Appendix, Tables A2 and A3.[10] Because of multiple-use products, the aggregated trade flows of these categories are likely to be overestimated and only partially correlated to «real» trade flows corresponding to renewable energy technologies.

In this study, we focused on HS codes which are most likely to contain renewable energy supply technologies. To do so, we used the detailed methodology of Jha (2009) to sub-selected product categories (with * in the Appendix, Tables A2 and A3). In the wind sector, selected categories correspond to towers (730820), blades (841290) and parts of the engine (850164, 850231 and 850300). In the solar sector, the two selected categories correspond roughly to PV cells and inverters[11] representing then a good approximation of trade in the solar PV sector (hereafter we will use the term solar PV rather than solar). Total trade flows with this specification correspond to 32% and 62% of the wide classification for respectively wind and solar.

Another common problem of trade data is the mismatch between importer and exporter data. Because of measurement errors, reported exports from country A to country B may differ from reported imports in country B from country A. Usually data from imports are considered more reliable as countries spend more resources in measuring imports to implement tariffs. However the

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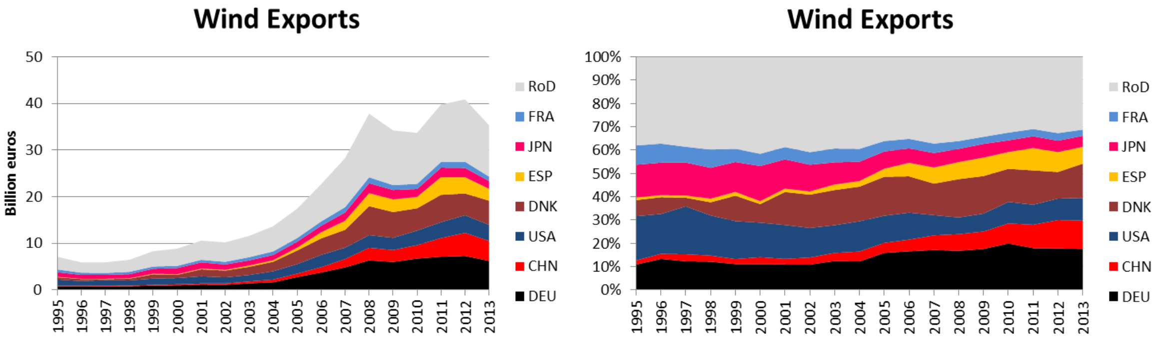
[10] The original categorization is made by HS 2007 codes. We used UN Stats conversion tables to extract trade data up to 1995.

[11] HS 854140 also includes light-emitting diodes, unrelated to solar PV products (Kirkegaard et al. 2010).

point is reversed in the EU because of the way VAT is collected (Baldwin and Taglioni 2006). In our case, the mismatch was more important for the solar PV industry (reported imports around 10% higher than reported exports) than for the wind industry (similar amounts). We took the maximum of reported flows as common practice in the field of international trade.

Figure 1: Exports of wind good in selected countries (France, Japan, Spain, Denmark, USA, China and Germany)



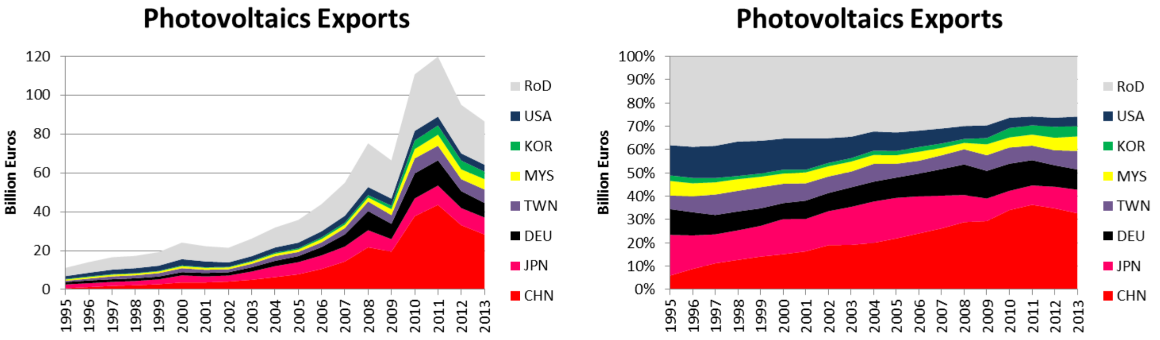
Total

Shares

N.B. Country name abbreviations can be found in the Appendix. RoD stands for Rest of the Database.

Source: UNCTAD COMTRADE.

Figure 2: Exports of solar PV good in selected countries (USA, Korea, Malaysia, Taiwan, Germany, Japan and China)



Total

Shares

N.B. Country name abbreviations can be found in the Appendix. RoD stands for Rest of the Database.

Source: UNCTAD COMTRADE.

Figures 1 and 2 display exports of solar PV and wind goods, representing explicitly only the top 7 exporters[12]. Because our HS classification only partially reflects the «true» trade in renewable goods, variations are more relevant than absolute values in the following. Wind exports were worth around

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[12] Only exports of our country dataset are represented.

5 billion US dollars at the end of the 1990's and almost doubled in the beginning of the 2000's. They increased sharply (a threefold increase) up to 2008 then stayed approximately around this order of magnitude with some fluctuations due to the financial crisis and the subsequent recession. Photovoltaics exports exhibit a more important increase: from around 20 billion US dollars at the beginning of the 2000's, they increased significantly after 2005 (three years later than for wind goods). Slightly hit by the recession, they nearly doubled between 2009 and 2010. In 2011, they reached 120 billion US dollars (a six times increase in less than ten years) but further decreased in 2012 and 2013 (85 billion US dollars).

In terms of market shares, the top 7 exporters account for around 60% of total exports of wind goods in our dataset. Japan, the US and France lost market shares during the last decade. China gained continuously market shares from a couple percent of world exports to about 10%, and three European countries (Germany, Denmark and Spain) increased their market shares especially before 2010 (in 2008 they accounted for about 35% of exports).

In the solar PV industry, the top 7 exporters represent between 60 and 70% of world exports.
China which was already among the top exporters in the early 2000's with a 15% market share, doubled its position in 2011, being the world leader by far. The US and Japan lost substantial market shares during the last decade while Korea and Malaysia increased significantly their market share after 2008.

Because trade flows are bilateral, information about exporters only give a partial view of international trade. First, international trade is highly concentrated, with a few bilateral trade flows representing a significant amount of total trade. In addition, the concentration is noticeably higher in the PV sector than in the Wind sector. At their highest level of international trade (2011 for solar PV and 2012 for Wind), 10% of the country pairs in the dataset accounted for 85% of total trade for both PV and wind. However the top 5 bilateral trade flows represented 24% of total trade for PV compared to 12% for wind. Even with a high concentration, the global picture is still complex, as there is a very high number of potential bilateral trade flows. Further, trade flows are to a large extent bi-directional (large exporters are very often large importers as well, such as Germany), showing the presence of intra-industry trade.

3. Results

Results of the model in reduced form are displayed in Table 1. An advantage of the gravity model is that the values of its coefficients are easy to interpret: they correspond to elasticities as it is a log-log regression. The GDP of the country of origin, 〖GDP〗_o, is always statistically significant with an elasticity of around +1.The GDP of the country of destination, 〖GDP〗_d, is also statistically significant (except for wind with the PPML estimation), with a lower elasticity (about one third lower). The elasticity of distance is negative, with estimates in line with those of the trade literature (Kepatsoglou et al. 2010, Head et al. 2013), suggesting that even for these high value goods, distance is a serious impediment for trade. Further, trade in wind goods is more sensitive to distance than international trade in solar PV goods (elasticity of -1/-1.5 versus -0.7/-1.1). This is consistent with the fact that wind turbines are more costly to transport (per unit of value), because of their unusual size and lower value per tonne compared to PV panels.

Table 1: Main results

VARIABLES	(1) PV Heckman	(2) PV PPML	(3) Wind Heckman	(4) Wind PPML
$GDP_{o,t}$	1.344***	0.939***	1.046***	1.124***
	(0.0971)	(0.140)	(0.111)	(0.110)
$GDP_{d,t}$	0.942***	0.691***	0.510***	0.0765
	(0.0922)	(0.126)	(0.0977)	(0.130)
$DIST_{o,d}$	-1.162***	-0.709***	-1.554***	-1.011***
	(0.0413)	(0.0510)	(0.0554)	(0.0452)
$RDEMAND_{d,t}$	0.154***	0.201***	0.0640***	0.0669***
	(0.0129)	(0.0247)	(0.0128)	(0.0230)
$RPOLICY_{o,t-3}$	0.146***	0.0479***	0.0654***	0.0842***
	(0.0153)	(0.0150)	(0.00977)	(0.0111)
Exporters FE	Yes	Yes	Yes	Yes
Importers FE	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes
Observations	31,622	28,080	48,162	42,336
R-squared		0.784		0.682

Standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1
Note: variables are logged except $RPOLICY_{o,t-3}$

Table 2: Robustness Tests

VARIABLES	(1) PV Heckman	(5) PV Heckman No China	(6) PV Heckman Before 2003	(7) PV Heckman After 2003	(3) Wind Heckman	(8) Wind Heckman No China	(9) Wind Heckman Before 2003	(10) Wind Heckman After 2003
$GDP_{o,t}$	1.344***	1.210***	1.452***	0.254**	1.046***	0.609***	0.671***	0.522***
	(0.0971)	(0.114)	(0.164)	(0.116)	(0.111)	(0.116)	(0.178)	(0.123)
$GDP_{d,t}$	0.942***	0.907***	1.309***	0.0322	0.510***	0.593***	1.074***	0.0316
	(0.0922)	(0.106)	(0.143)	(0.114)	(0.0977)	(0.100)	(0.141)	(0.122)
$DIST_{o,d}$	-1.162***	-1.197***	-1.152***	-1.173***	-1.554***	-1.557***	-1.529***	-1.561***
	(0.0413)	(0.0449)	(0.0421)	(0.0465)	(0.0554)	(0.0593)	(0.0586)	(0.0603)

$RDEMAND_{d,t}$	0.154***	0.162***	0.0861**	0.138***	0.0640***	0.0707***	0.0575***	0.0735***
	(0.0129)	(0.0138)	(0.0421)	(0.0135)	(0.0128)	(0.0130)	(0.0188)	(0.0148)
$RPOLICY_{o,t-3}$	0.146***	0.145***	-0.519	0.0659***	0.0654***	0.0657***	0.0723***	0.0699***
	(0.0153)	(0.0156)	(0.446)	(0.0134)	(0.00799)	(0.00816)	(0.0124)	(0.0157)
Exporters FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Importers FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Observations	31,622	30,050	19,142	15,600	48,162	46,206	29,346	23,520
Wald test of indep. eqns.	0.0006	0.0003	0.7674	0.0001	0.2698	0.0683	0.1692	0.0003

Standard errors in parentheses
*** $p<0.01$, ** $p<0.05$, * $p<0.1$
Note: variables are logged except $RPOLICY_{o,t-3}$

The variable of demand in the destination country, ⟦RDEMAND⟧_d , is statistically significant with the expected sign, both for wind and solar PV. The estimated value is slightly higher for PV goods than for wind goods (0.15/0.20 versus 0.07/0.06). It means that everything else hold constant, if a country doubles its yearly installed capacity (for example installing 100 MW instead of 50 MW in the previous year), its imports are going to increase by 5%[13] for wind goods and by 13% for solar PV goods. Most of the demand is then provided by local production.

Our variable of interest, $RPOLICY_o$, gives robust results indicating a competitive advantage.
For both industries, the estimated coefficients are statistically significant at the 1% level for both estimators. The estimated values are quite similar for the PV industry for both estimators: 0.06 and 0.08. However they don't have the same order of magnitude for the Wind industry (0.15 for the Heckman estimator and 0.05 for the PPML estimator). It means that everything else hold constant, a country where wind power represented 10% of electric capacities three years earlier will have exports 112%[14] higher than a country where wind power represented 5% of electric capacities. The figure would be 35% for PV under the same configuration.

In Table 2 we test the robustness of the results by removing China from the dataset, and testing two time periods, before and after 2003 (we only display estimations with the Heckman methodology). 2003 splits our dataset into two roughly equal sets and also corresponds to a turning point in renewable energy technologies trade (see Figures 1 and 2). Except the estimation of the elasticity of

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[13] If we use the average of both coefficients estimations (PPML and Heckman), we have a coefficient of 0.0665. Then the increase is $2^{0.0665}-1=5\%$

[14] $= e^{5\times 0.15} - 1$

⟦GDP⟧_o for the wind industry, results are robust when China is removed from the dataset. Further, the elasticities of GDP are much lower or insignificant after 2003, mainly for the PV industry but also to a lesser extent for the wind industry. The estimation of the distance elasticity remains invariant. The estimation of the elasticity of $RDEMAND_{d,t}$ increases noticeably after 2003 (especially for the PV industry), probably revealing a growing internationalization of the renewable goods market. Finally, the parameter $RPOLICY_{o,t-3}$ is only significant after 2003 for the PV industry but remains stable for the wind industry.

Trying different lags (see Table 3), results remain robust for the wind industry: competitive advantage in the global market place is maintained during seven years (it diminishes in intensity after two years for the PPML estimation but peaks at four years for the Heckman estimation). However for solar PV, estimates turn statistically non-significant after four or five years. The estimates in Table 3 therefore suggest that the effect of domestic support policies on competitive advantage in the wind industry is significant and sustained over a longer time period, while the effect on the competitive advantage in the solar industry is significant but brief.

Table 3: Temporal effects.

	$RPOLICY_{o,t-1}$	$RPOLICY_{o,t-2}$	$RPOLICY_{o,t-3}$	$RPOLICY_{o,t-4}$	$RPOLICY_{o,t-5}$	$RPOLICY_{o,t-6}$	$RPOLICY_{o,t-7}$
PV Heckman	0.0516***	0.0547***	0.0659***	0.0503**	-0.0160	-0.0770	-0.159*
	(0.00781)	(0.00931)	(0.0134)	(0.0233)	(0.0381)	(0.0616)	(0.0890)
PV PPML	0.0361***	0.0403***	0.0479***	0.0668**	0.0819*	0.0625	0.0244
	(0.00794)	(0.00995)	(0.0150)	(0.0268)	(0.0459)	(0.0573)	(0.0743)
Wind Heckman	0.0560***	0.0643***	0.0699***	0.0728***	0.0708***	0.0634***	0.0508***
	(0.0146)	(0.0157)	(0.0157)	(0.0153)	(0.0144)	(0.0134)	(0.0130)
Wind PPML	0.0843***	0.0854***	0.0842***	0.0800***	0.0725***	0.0626***	0.0508***
	(0.0106)	(0.0107)	(0.0111)	(0.0120)	(0.0124)	(0.0130)	(0.0131)

Standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1
Note: variables are logged except $RPOLICY_o$

4. Discussion and conclusions

The results confirm those of previous econometric studies (Costantini and Crespi 2008; Costantini and Mazzanti 2012; Groba 2014; and Groba and Cao 2015) on the positive effect of environmental regulation on the export of the renewable energy manufacturing industry, and generalize to them to the context of a truly global industry, where both industrialized countries and emerging countries compete for market shares. The results are also in line with non-econometric studies. Lewis and Wiser (2007), with a cross-country analysis, show that policies that support a sizable home market for wind power most likely result in the establishment of an internationally competitive wind industry. Pegels and Lütkenhorst (2014) find that in Germany the wind sector has a larger revealed competitive advantage than the solar sector. Voituriez and Balmer (2012) distinguish the conventional competition with sustained competitive advantage that has occurred in the wind industry from the hyper competition and «temporary advantage» (D'Aveni et al. 2010) in solar PV.

The dynamic difference between the wind and solar PV industries are in line with recent results of industrial catching-up literature (Huenteler et al. 2016; Binz et al. 2017) that suggest that catching-up dynamics by latecomers are influenced by the underlying technology involved across different technologies. Binz et al. (2017) in this respect see a large difference between the solar PV industry that is characterised by a traditional technology life cycle model where an initial focus on product innovation is followed by process innovation once a dominant design is established, and the wind energy industry where innovations shift between different types of product innovations. The solar PV industry can, once a dominant design is established, benefit from the economies of scale in producing standardized, modular goods, while wind turbines remain design-intensive, technologically complex goods. In a very detailed analysis of the development of the solar PV and wind industries in China, Binz et al. (2017) show these differences and also show that the development of the solar PV industry in China was not the result of demand-pull policies, and not even the result of an explicit industrial strategy of the Chinese government, but rather the results of the opportunities that were offered by the accession of China to the WTO in 2001, that were grasped by local entrepreneurs and were supported by generic support from local authorities in high-tech development zones and foreign partners. Strategic policy support, including large domestic deployment programs, was only established after the decline in export demand from Europe due to the financial crisis in 2008. For design-intensive goods such as wind turbines where the emphasis is on continuous innovation in different components, Binz et al. (2017) argue that intimate user–producer interaction is crucial and therefore a strong home market is more important.

Our quantitative study has the merit of a wide geographical and temporal coverage linked by common metrics, but is limited by the quality of available data, especially on the classification of wind and solar PV components in international trade. The HS-6 classification that we used is rather broad, and a more detailed classification would be preferred. However, as yet it is not possible to find such data at the global scale. Admittedly, while we believe that our main explanatory variable, installed capacity, is for our purposes the best overall indicator for a country's commitment to promote renewable energy, it would be interesting to assess which specific policies (feed-in tariffs, R&D spending, etc.) contribute most to export success. Introducing policies as explanatory variables in the regression would be difficult since these policies can hardly be summarised by a single value.

For instance, feed-in tariffs policies often set differentiated tariffs across locations and differ by contract duration. Moreover access to the grid and authorisation procedures can be as important as the feed-in-tariff. Yet looking at wind exports by country of origin (Figure 1), a stylised fact seems to emerge: exports have grown in countries which have implemented a feed-in-tariff (Germany, China, Denmark, Spain). For PV, things are not that clear.
Moreover, while we captured the temporal dimension of the link between renewable energy policies and export performance to some extent, a more extensive analysis would be extremely valuable.

Finally, the picture becomes more complex when looking at the firm level than just focusing on exports at the national level. Firms may outsource production of certain components while holding a significant share of the value added[15]. Further, several European firms (mostly small wind manufacturers) have served as sources of technology for firms based in China, India or South Korea through joint development (Lewis 2011). Suzlon, an Indian company has R&D units in Denmark, Germany and the Netherlands to benefit from local knowledge networks (Lewis 2007). These countries have then benefited to some extent from the development of companies abroad. A study into the relationship between renewable energy policies and business performance would likely provide additional insights that would be very interesting for policy makers.

Our econometric model shows evidence of a positive effect of policies that promote the use of renewable energy on the export performance and competitive advantage of renewable energy manufacturing industries. Our main results suggest that, everything else hold constant, a country where wind power represented 10% of electric capacities three years earlier will have exports 112% higher than a country where wind power represented 5% of electric capacities. For solar PV the exports would be 35% higher under the same configuration. Several statistical tests confirmed the robustness of these results. However, while policy-induced competitive advantage appears to remain stable over time for the wind industry, competitive advantage tapers off in the solar PV industry after four or five years.

Demand-pull policies such as feed-in-tariffs have proved extremely efficient to foster renewables development and many countries have been implemented them to replicate pioneers' success. Our results support such ‘green economy’ arguments to a certain extent, but may also be used to manage expectations. The temporal dynamics of competitive advantage in the solar PV industry

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[15] The prominent example of such value capture is the iPod (Linden et al. 2007), where value added to the product through assembly in China is probably a few dollars at most.

show that competitive advantage, once gained, may not last forever. In fact it may dissipate within a few years due to competitive newcomers in the global market place that can replicate early successes and can even improve on them.

Competitive advantage based on a strong home market can best be maintained as the technology requires continuous innovations where intimate user–producer interaction is crucial. If it would be possible to distinguish between 'design-intensive' and 'process-intensive' technologies from the outset, from the 'green growth' perspective governments could best promote design-intensive technologies to support domestic manufacturing firms. A technological assessment on this aspect might be included in criteria for support.

However, either way, enhanced competition on the global market decreases the market prices of renewable energy technologies. For solar PV technologies, market price decreases have been much faster than anyone could have imagined, say, ten years ago and they are projected to continue to decrease at a fast pace (IRENA, 2016). This will undoubtedly contribute to easing the transition to a low-carbon economy that is high on political agendas since the successful conclusion of the Paris Agreement on climate change in December 2015.

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Appendix

Table A1: List of countries

Country	Code	Wind	PV	Country	Code	Wind	PV
Argentina	ARG	Yes		Italy	ITA	Yes	Yes
Australia	AUS	Yes	Yes	Japan	JPN	Yes	Yes
Austria	AUT	Yes	Yes	South Korea	KOR	Yes	Yes
Belgium	BEL	Yes	Yes	Lithuania	LTU	Yes	Yes
Bulgaria	BGR	Yes	Yes	Luxembourg	LUX		Yes
Brazil	BRA	Yes		Morocco	MAR	Yes	
Canada	CAN	Yes	Yes	Mexico	MEX	Yes	Yes
Switzerland	CHE	Yes	Yes	Malta	MLT		Yes
Chile	CHL	Yes		Malaysia	MYS		Yes
China	CHN	Yes	Yes	Nicaragua	NIC	Yes	
Costa Rica	CRI	Yes		Netherlands	NLD	Yes	Yes
Cyprus	CYP	Yes	Yes	Norway	NOR	Yes	Yes
Czech Republic	CZE	Yes	Yes	New Zealand	NZL	Yes	
Germany	DEU	Yes	Yes	Pakistan	PAK	Yes	
Denmark	DNK	Yes	Yes	Philippines	PHL		Yes
Egypt	EGY	Yes		Poland	POL	Yes	
Spain	ESP	Yes	Yes	Portugal	PRT	Yes	Yes
Estonia	EST	Yes		Romania	ROM	Yes	Yes
Ethiopia	ETH	Yes		Singapore	SGP	Yes	Yes
Finland	FIN	Yes	Yes	Slovakia	SVK		Yes
France	FRA	Yes	Yes	Slovenia	SVN		Yes
United Kingdom	GBR	Yes	Yes	Sweden	SWE	Yes	Yes
Greece	GRC	Yes	Yes	Thailand	THA	Yes	Yes
Croatia	HRV	Yes		Tunisia	TUN	Yes	
Hungary	HUN	Yes	Yes	Turkey	TUR	Yes	
India	IND	Yes	Yes	Taiwan	TWN	Yes	Yes
Ireland	IRL	Yes		Ukraine	UKR	Yes	Yes
Israel	ISR		Yes	United States	USA	Yes	Yes

Table A2: HS 2007 codes used for the wind industry

HS Code	Product
730820*	Towers and lattice masts, of Iron or Steel
841290*	Parts of Other Engines and Motors
848210	Ball Bearings
848220	Tapered Roller Bearings, Including Cone and Tapered Roller Assemblies
848230	Spherical Roller Bearings
848240	Needle Roller Bearings
848250	Other Cylindrical Roller Bearings
848280	Other Bearings, Including Combined Ball or Roller Bearings
848340	Gears and Gearing; Ball Screws; Gear Boxes and Other Speed Changers
850161	Ac Generators of an Output Not Exceeding 75kva
850162	Ac Generators of an Output Exceeding 75kva But Not Exceeding 375kva

850163	Ac Generators of an Output Exceeding 375kva But Not Exceeding 750kva
850164*	Ac Generators of an Output Exceeding 750kva
850230	Other Generating Sets
850300*	Parts, of Motors, of Generators, of Generating Sets, of Rotary Converters
850421	Liquid Dielectric Transformers, Not Exceeding 650kva
850422	Liquid Dielectric Transformers, Power Handling Capacity 650-10,000kva
850423	Liquid Dielectric Transformers, Exceeding 10, 000kva
850431	Other Transformers, Power Handling Capacity Not Exceeding 1kva
850432	Other Transformers, Exceeding 1kva But Not Exceeding 16kva
850433	Other Transformers, Exceeding 16kva But Not Exceeding 500kva
850434	Other Transformers, Power Handling Capacity Exceeding 500kva
854459	Other Electric Conductors, Exceeding 80v But Not Exceeding 1, 000v
854460	Other Electric Conductors, for a Voltage Exceeding 1, 000v
890790	Other floating structures
902830	Electricity meters
903020	Cathode-ray oscilloscopes and cathode-ray oscillographs
903031	Multimeters
903081	With a recording device(Volt Meters, Am Meters, Circuit Testers)

Table A3: HS 2007 codes used for the solar industry

HS 2007 Code	Product
700991	Unframed Glass mirrors
700992	Framed Glass mirrors
711590	Other articles of precious metal or of metal clad with precious metal
732290	Solar Collector, Air Heater, Hot Air Distributor, and Parts Thereof
830630	Photograph, picture or similar frames; mirrors; and parts thereof , of Base Metal
841280	Other Engines and Motors
841919	Other Instantaneous or Storage Water Heaters, Non-electric
841950	Heat Exchange Units
841989	Other Apparatus for Treatment of Materials By Temperature
841990	Parts of Apparatus for Treatment of Materials By Temperature
850230	Other Generating Sets
850440*	Static converters
854140*	Photosensitive Semiconductor Devices; Light Emitting Diodes
900190	Other: prisms, mirrors and other optical elements, of any material, unmounted, other than such elements of glass not optically worked
900290	Other Optical Elements, of Any Material, Mounted
900580	Other instruments: Monoculars, Other Optical Telescopes; Other Astronomical Instruments