

Green Innovation and Green Manufacturing: Links between Environmental Policies, Innovation and Production

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Abstract

This paper addresses the claim that environmental policies stimulate domestic economies. I parse the claim into two sequential parts: the effect of policies on innovation and the effect of that innovation on resulting manufacturing production. Each of these activities - innovation and manufacturing - can either take place at home or abroad, and where they take place determines the consequences for the domestic economy. The empirical evidence is based on measures of policy, patent activity, and trade in the renewable energy sector (solar, wind, geothermal, biomass and waste) of 27 OECD countries between 1988 and 2003. The results suggest that an additional policy promoting the development or use of renewable energies is associated with a significant rise in the adoption of existing foreign technologies, but few new inventions at home. These results are robust to different measures of policies. In turn, however, the increase in (mostly foreign) patent filings is associated with a significant growth in manufacturing production proxied by exports, suggesting that at least some portion of the inputs into renewable technologies are produced domestically. Therefore, there is evidence that renewable energy policies stimulate domestic economies through manufacturing, but less through innovation.

1 Introduction

As countries attempt to grow and compete in an increasingly global economy while tackling environmental challenges, the so-called “green economy” has become an appealing way of addressing both concerns. Policy discussions regarding the relationship between the environment and growth until recently focused on the trade-off between environmental protection and economic growth. However, in many countries these discussions now emphasize the potential complementarities between addressing environmental issues and stimulating economic growth. Politicians make grand claims about a ‘win-win’ scenario where environmental policies contribute not only to improving the environment but also to encouraging firms to innovate and produce green technologies.¹ In March 2009, then-Director of the National Economic Council Lawrence Summers stated: “The evidence is clear: we can choose to lead [green] industries, with all the commensurate economic and political and environmental benefits, or we can choose to lose out on these jobs and these opportunities” (White House, 2009). On multiple occasions, President Obama has addressed the need to switch to renewable energy sources claiming that “America cannot resist this transition, we must lead it” (White House, 2013), and that he expected “those new energy sources to be built right here in the United States” (White House 2012). These claims represent just a few examples of a widespread rhetoric which asserts that a country that implements environmental policies will benefit from increased output and job creation at home, and will then export environmental technologies to other countries that adopt similar policies later on.

While the environmental goal is laudable, the link between environmental policies and domestic economic stimulus remains uncertain. In fact, this link relies crucially on green technologies being developed domestically and inputs into those technologies being manufactured at home. But economists are skeptical that environmental policies will necessarily lead to domestic innovation and manufacturing. On the one hand, trade theory suggests that green technologies should be produced in countries that have a comparative advantage, be it through policies or other inherent characteristics of their economy. On the other hand, empirical work documents a home bias in production and trade which suggests that environmental technologies might be disproportionately produced at home.

¹This argument is related to the Porter Hypothesis (Porter 1991).

To evaluate the claim that environmental policies stimulate the domestic economy through innovation and the production and trade of technologies, I provide empirical evidence focusing on the renewable energy sector of OECD countries. The results suggest that environmental policies lead to a rise in the adoption of foreign technologies but few new inventions at home. Through this innovation channel, policies are in turn associated with a significant rise in the domestic production of renewable technologies. Therefore, renewable energy policies appear to boost domestic economic activity through the manufacturing of renewable energy technologies, but much less through innovation.

I identify four potential outcomes of policies. These outcomes are combinations of two activities – innovation and manufacturing – and two locations where activities can take place – domestic or foreign (Figure 1). To be adopted on the domestic market, a technology can either be developed by a domestic firm (‘domestic technology’), or developed abroad and patented in the domestic market (‘foreign technology’). Foreign technologies can be new technologies created in response to a domestic policy, or transfers of existing technologies that were previously developed perhaps in response to a policy change in a foreign country. In either case, the domestic market is adopting a foreign technology rather than innovating at home. To be sure, adoption of foreign technologies is beneficial for growth (Eaton and Kortum 1999), but the domestic innovation industry is not directly stimulated in the sense that it does not experience increased output or jobs if it does not develop technologies.

The link between environmental policies and innovation has been studied, but the literature that touches on the differences between domestic and foreign technologies is limited. In the first part of this paper, using patent data as a measure of innovation and technology adoption, I present evidence of the degree to which environmental policies stimulate the development of domestic technologies compared to the licensing of foreign technologies. I test the robustness of my results with different measures of policies: an overall measure, a measure by policy type, and a measure which quantifies differences across countries for one of the more widely used policies.

When a technology is patented in a country, the technology and its inputs can either be produced at home or imported from other countries. If the technologies are produced at home, manufacturing output increases. If the equipment and inputs are produced abroad and imported, environmental policies could potentially have little effect on manufacturing output. To identify renewable energy

technologies and their inputs requires data using a detailed classification of manufacturing production, which is not available for all the countries in my dataset. Therefore, I proxy manufacturing production with exports to examine whether technological innovation led to an increase in the domestic production of renewable technologies or the inputs into those technologies. Examining the effect of innovation on exports also allows me to address the part of the claim which suggests that environmental policies and increased innovation will improve competitiveness. To fully address the competitiveness angle, I compare the effect of innovation on exports to the effect on imports.

To date, few papers examine the effect of environmental policies on trade, and no paper attempts to estimate whether environmental policies can stimulate the trade of environmental technologies through innovation. Hence, the second part of this project fills an important gap in the literature by estimating how exports and imports of technology-specific inputs respond to a change in environmental patents. Policies could also affect the production of technologies directly without going through innovation, and I test this direct channel as well. Finally, examining the effect of innovation on production allows me to address a potential concern of patents as a measure of innovation and technology adoption. Patents could be filed for strategic rather than commercial reasons in order to stifle competition. If that was the case, I should observe no effect of a rise in innovation on manufacturing production.

Combining the two steps allows me to identify the relative importance of each of four scenarios that might occur as a result of additional environmental policies. 1) The technology was developed at home, and the inputs were manufactured at home. This scenario would provide strong evidence that enacting environmental policies stimulates the economy in environmental sectors. 2) The technology was licensed from abroad, and the inputs imported from abroad. This channel would imply that policies create little direct domestic stimulus, despite the environmental benefits and potential positive spillovers from foreign innovation and imports. 3) The technology was developed domestically but the inputs were imported. 4) Or the technology was developed abroad and the imports were manufactured at home. The last two channels would provide only partial evidence that environmental policies stimulate the economy and differ importantly in what sector and types of occupations benefit.

The questions I pose can be answered by examining the renewable energy sector, which includes

solar, wind, biomass, and geothermal, for 27 OECD countries from 1988 to 2003.² OECD countries offer an interesting sample because they provide ample variation in environmental policies, renewable energy capacity, innovative activity, and level of economic development. Focusing on one sector allows me to identify specific technologies, the inputs into their production, and the policies that regulate the sector, all of which are necessary to complete the proposed analysis.

While this study focuses on the renewable energy sector, the framework is easily replicable and the conclusions may contribute to the wider debate on the effect of policies on innovation, production and trade. However, renewable energy policies and environmental policies generally differ from other types of policies aimed at promoting the development of local industries. Because the deterioration of the environment is a global and long-term concern, the trend towards environmentally sustainable production practices will only intensify. Countries that move first and develop the technologies early may have a competitive advantage to export these technologies once other countries follow suit. This competitiveness gain is an important element of the green economy strategy.

Finally, it is worth noting the limits of this study. I do not provide a welfare analysis of environmental policies. There could be substantial spillovers of foreign innovation and foreign production into the domestic economy. Or innovation and manufacturing in renewables could be crowding out activity in other sectors. Neither channel is captured in this analysis. Moreover, I am not making a judgment on the environmental benefits of these policies. The renewable energy policies I study in this paper could succeed or fail in achieving their environmental goals. My objective in this paper is to evaluate the policy claims that renewable energy policies will lead to increased domestic innovation and manufacturing of renewable energy technologies. These claims are abundant in policy debates, and in fact the supposed economic benefits are sometimes presented as the primary goal of environmental policies,³ yet empirical evidence of the veracity of the claims is limited.

The paper is organised as follows. Section 2 describes the links to existing theories and the literature. Section 3 examines whether policies drive innovation and technology adoption. Section 4 studies how manufacturing production and trade respond to a rise in the adoption of technologies. Both sections 3 and 4 are divided into subsections describing the data, the estimation strategy, and the

²Some OECD countries are excluded because they did not implement any renewable energy policies over the period: Estonia, Luxembourg, Slovenia, Turkey.

³For example, Economic Report of the President 2015 (White House 2015) states that the first element of the All-of-the-Above strategy for a cleaner energy future is “to support economic growth and job creation”.

results. Section 5 concludes.

2 Context and Existing Literature

2.1 Links to the Porter Hypothesis

The question I pose in this paper is related to the Porter Hypothesis. In its “weak” version, the Porter Hypothesis claims that properly-designed environmental regulation may spur innovation, be it in the form of new technologies or changes to production processes. This version does not take a stance on whether the innovation will make firms more competitive, it simply states that some policies could lead to increased innovation. In the first portion of the paper, I contribute to the evidence on the “weak” Porter Hypothesis by asking how innovation responds to environmental policies depending on the origin of the inventor. Determining the origin of innovation allows me to specifically address claims that innovation spurred by environmental regulation will be domestic.

In the “strong” version, the Porter Hypothesis suggests that the benefits from policy-induced innovation will offset the cost of regulation and increase the competitiveness of companies. If firms are unaware of profit-maximizing opportunities in pollution reductions, environmental regulation might help them identify inefficiencies and encourage them to address these inefficiencies through the production and dissemination of technologies. Firms might not identify or implement profitable pollution abatement opportunities if managers have motivations and objectives other than profit-maximization. Similarly, asymmetric information, R&D spillovers, and imperfect competition may lead to sub-optimal investment in innovation (Ambec et. al. 2013). In the second portion of the paper, I ask whether a rise in innovation translates into increased domestic production or imports, which addresses the global competitiveness portion of the hypothesis at the country-level.

2.2 Incorporating the Origin of Inventions into a Vast Literature

A policy could potentially affect three types of technology adoption: innovation in the country where the policy is implemented, innovation in other countries, and the transfer of existing technologies

across countries. The first channel has been studied extensively using various measures of policy and innovation. For example, Lanjouw and Mody (1996), Jaffe and Palmer (1997), and Brunnermeier and Cohen (2003) use pollution abatement costs as a measure of policy to study the effect of policies on innovation. The results suggest that environmental policies do not have an effect on total R&D expenditure (Jaffe and Palmer 1997), but do significantly increase filings of environmental patents (Lanjouw and Mody 1996, Brunnermeier and Cohen 2003). Other papers use energy prices as a measure of policy and find that higher energy prices induce innovation in energy-efficient technologies (Newell et al. 1999; Popp 2002; Crabb and Johnson, 2010). Alternatively, Johnstone et al (2010) studies the effect of different policy types on innovation and generally shows that more stringent environmental public policies spur patenting activity in renewables. These papers, however, look at total patent filings in a country without distinguishing between innovation that is developed by domestic or foreign inventors. Therefore, they cannot address the policy claim that policies will spur innovation by domestic inventors.

Patents owned by foreign inventors can represent a very large proportion of total patent filings in a country, even in highly innovative economies. For example, in Germany foreign patents represent on average over 65 percent of total patent filings between 1988 and 2003. Yet relatively few papers examine the links between domestic policies and either new foreign innovation or transfers of existing foreign technologies. Evidence on whether foreign inventors respond to domestic policies is mixed. Comparing the patterns of policy enactment with the patterns of patenting activity, Popp (2006) does not find that domestic regulation on air pollution control encourages patenting in foreign countries. Peters et al. (2012) suggests that some types of regulation spur foreign innovation in the solar industry. Dechezleprêtre and Glachant (2012) concludes that domestic regulation can spur innovation filed abroad, but the effect of domestic regulation on patents filed at home is 25 times higher than on patents filed abroad.

Still, if some countries have already developed relevant technologies, perhaps in response to their own regulation, other countries can license these technologies or build on this innovation. Popp (2006) finds US pollution control innovation was more likely to build on earlier Japanese and German patents when the United States introduced emissions standards later than Japan and Germany. Dechezleprêtre et al. (2013) finds that the strength of renewable energy policies - proxied by installed capacity of renewable energies - has a small but positive effect on the transfers

of patents across countries.

Only one paper distinguishes patents based on the origin on the inventor. Lee et. al. (2011) studies the effect of US automobile performance standards on firm-level innovation, where the level of regulation is proxied by regulatory expenditures for the industry. In this context, the authors interact the policy measure with a dummy for domestic firms and find mixed results. In the beginning of their time period, domestic firms appear to be more responsive to regulation than foreign firms, while at the end there is no significant difference between domestic and foreign patenting responses. The broader applicability of their study may be limited, however, due to data constraints that require the authors to restrict the analysis to the top 15 innovative auto companies in the US patent office.

In the first part of this paper, I provide the first cross-country study of the effect of environmental policies on patent filings comparing the effect on patents filed by domestic inventors to those filed by foreign inventors. In sum, this portion combines existing branches of the literature on the effect of policies on different kinds of innovation to create a framework which allows me to test the claim that environmental policies will increase domestic innovative output.

My approach has several advantages over existing work. First, the number of environmental policies enacted in one country in one year in one industry is low, and thus limiting the analysis to one country may not provide enough identifying variation. I exploit variation across time and countries to identify the effect of policies on innovation. Second, most existing work - with the exception of Lanoie et al. (2008) - only examines the contemporaneous effects of policies. Since firms might respond to policies with a lag, I estimate the longer-term effects of policies on innovation. Finally, the literature to date generally does not address the endogeneity of environmental policy measures. For example, political economy factors such as the rise of a green party to power could be the source of simultaneous causality. In some robustness checks, I examine the consequences of treating the policy measure as endogenous.

2.3 Sparse Evidence on the Links between Environmental Innovation and Trade

Empirical studies of the links between environmental policies and the competitiveness of firms or industries can be divided into two groups. On the one hand, most papers interested with country-level competitiveness investigate the opposite of the Porter Hypothesis: the claims that environmental policies will impose on companies costs that are high enough to lead them to offshore production to countries with laxer environmental standards (Clark, Marchese, and Zarrilli 2000, Xing and Kolstad 2002, Copeland and Taylor 2004, Brunnermeier and Levinson 2004). On the other hand, evidence of the “strong” version of the Porter Hypothesis focuses on firm-level analysis of the effect of policies on productivity and business performance (see for example Gollop and Roberts 1983, Berman and Bui 2001, Greenstone 2002). But few of these studies identify the source of the change in business performance (Ambec et. al. 2013). In the second part of the paper, I study specifically whether the effect of environmental policies on manufacturing production and trade occurs through innovation or other sources.

Lanoie et. al. (2011) stands out as the only paper to examine the channels through which environmental policies affect firm performance. Using a survey of firms in seven OECD countries which includes perceived environmental policy strength and estimated environmental R&D expenditures as a measure of innovation, Lanoie et. al. (2011) provides a comprehensive analysis of the different versions of the Porter Hypothesis. The authors find that policies spur innovation, and policy-induced innovation has a positive effect on business performance. Given the cross-sectional nature of the data, the authors are not able to control for unobservable firm heterogeneity and are restricted to binary measures of environmental innovation and business performance.

I focus on country-level competitiveness. Having identified the domestic and foreign innovation responses to environmental policies in the first section, I then turn to evaluating the links between environmental innovation and trade. Generally, studies of the relationship between environmental innovation and trade focus on the potential for trade as a vehicle for technology transfer (for a review, see Keller 2004). In a more recent example, Bloom et al. (2011) establishes that EU sectors that were most affected by import competition from China were more innovative. Batrakova and Dechezleprêtre (2013), on the other hand, finds that “dirty” imports from China decreases firms’ propensity to innovate in Ireland. However, to the best of my knowledge no paper attempts to

estimate how environmental innovation stimulates the trade of environmental technologies. I fill that gap in the literature by examining the links between innovation and the trade of renewable energy technologies. Combining the two sections of my paper will provide evidence of the causal chain between renewable energy policies and trade.

3 Environmental Regulation and the Origin of Technologies

To estimate the links between environmental policies and the adoption of technologies, I need a measure of innovation and a measure of environmental policies. The next subsections describe how those variables are created. I then explain the estimation procedure and present the results.

3.1 Policy Measure

For this analysis, I need a measure of the policies specific to renewable energies which varies across countries and time. As shown in Brunel and Levinson (2015), there are many obstacles to measuring policies and all currently used measures have their own drawbacks. For example, many previous studies use pollution abatement costs, but countries or states with more polluting industries will spend more on pollution abatement even if each has implemented the same policy. Few measures are available across countries, vary over time, and are technology specific. As a result, and consistent with a number of papers in the literature (e.g. Johnstone, Hascic and Popp 2010), I start with a simple count of the number of policies enacted in country i at time t that are aimed at developing renewable energy sources.⁴

The IEA/IRENA Global Renewable Energy Policies and Measures Database provides a comprehensive record of such measures for all OECD countries. These measures can be research and development (R&D) incentives, investment incentives, taxes, tariffs, tradable permits, voluntary programs, and obligations. Apart from R&D policies, most policies do not explicitly provide incentives for innovation. However, the policies decrease the relative price of the use of renewables compared to fossil fuels, or increase demand for renewable energy. In doing so, the policies supply implicit incentives for innovation.

⁴European Union countries get an extra count for each policy implemented at the European Commission level.

The simple count has the advantage of being transparent, simple, and easily interpretable but by no means is it an ideal measure. Chief among its drawbacks is that it weighs each policy type equally. To address that issue, I also present results breaking down the total count into six different counts, one for each policy type to allow for, say, tax incentives and voluntary programs to have different effects. Figure 3 presents a graphical representation of the introduction of relevant policy measures in the OECD until 2003. Each point on the graph represents the time of introduction of a measure in a particular country. Clearly, countries vary both in the timing and the type of policy instruments used. Table 3 presents the summary statistics of the policy variable. On average, countries enact 0.635 policies aimed at promoting the use of renewable energies each year. Most of these policies are economic instruments and, to a lesser extent, policy support and regulatory instruments.

However, even the breakdown by policy is an imperfect measure. The same policy can vary significantly across countries. For example, in 2000 Denmark implemented a feed-in-tariff (FIT) for wind production of 0.058 euros per kilowatt-hour. In the same year, Germany set up a feed-in-tariff of 0.091 euros per kilowatt-hour of wind. The count measure assigns the same weight to both. In an attempt to quantify these differences across countries, I use data on wind feed-in-tariffs for seven countries in my dataset: Austria, Denmark, France, Germany, Slovak Republic, Spain, and Switzerland.⁵

3.2 Innovation and Adoption of Technologies

In addition to the measure of policies, for this analysis I need a measure of innovation. I use patent data to measure innovation and adoption of new technologies in each OECD country. The data come from the PATSTAT database (EPO 2012) which includes all patent applications filed at the national patent offices of the 27 OECD countries as well at the European Patent Office (EPO).⁶ A patent grants protection for a technology only in the country where it is filed, so inventors will file in as many countries as they desire protection. Domestic patents in country i are defined as the

⁵The data were compiled by Fan Zhang and Louis Preonas for a project sponsored by the World Bank. Although FITs generally differ across countries in terms of which technologies are eligible or the mix of energy sources mandated, because in the EU rules are governed by the Commission FITs are more comparable across EU countries than any other set.

⁶Data extracted from EPO World Patent Statistical Database (PATSTAT) based on extractions developed by Ivan Hascic and colleagues at the OECD Environment Directorate and used in Popp, Hascic and Mehdi (2011).

count of renewable energy patents that were filed in the patent office of country i by an inventor residing in country i . Foreign patents are measured as the count of renewable energy patents filed in the patent office of country i by a resident of any other country. For both domestic and foreign patents, I distinguish between patents that represent new inventions - patents that were never filed anywhere else in the world - and patents that are transfers of existing technologies - patents that were first filed abroad.

Eu patents present an additional challenge. Patents that seek protection in the European Union can be filed in one of the national patent offices or at the EPO. Until 2004, EPO applications required inventors to specify in which EU member states the patent would be applicable. The cost increased proportionally to the number of countries, providing an incentive for inventors to designate only the countries where the patent would be used.⁷ In fact, on average, a patent filed at the EPO designated just 12 of the 38 member states of the EPO. The designation of states is crucial for my study as I need to assign each patent to individual EU member states. However, designation is only mandatory until the end of 2003, hence my analysis ends in 2003. Data on designated states are no longer part of PATSTAT. Hence, I collected this data by hand for over 5,000 EPO patents.

Patent data have the advantage of being classified based on the end-use of the technology in a highly disaggregated form, allowing me to determine exactly which patents are used for the development of each of the four renewable energies. I use the International Patent Classification (IPC) codes presented in Table 1 (Popp 2011). It is possible that some codes might include irrelevant technologies, while others might exclude relevant technologies. However, Popp (2011) estimates that these errors are small for renewable energies.

Patents imperfectly measure innovation for several reasons. First, the value of a patent is difficult to estimate. A patent grants the inventor the exclusive right to use the technology, but some patent owners do not exercise that right, while others make abundant use of it domestically and expand protection abroad. Following the literature, I weight each patent by the number of countries in which that invention is patented, also called family size. A patent family is a set of patents taken in various countries to protect a single invention. More valuable inventions are like to seek greater geographical coverage, and therefore to be part of larger families. This is especially important

⁷On average, in my dataset a patent filed at the EPO designated just 12 of the 38 member states of the EPO.

in my case because domestic and foreign patents could have different values. Figure 2 however shows that although the number of foreign patents is higher overall, the distribution of family size follows the same shape for domestic and foreign patents.⁸ Second, it is possible that some valuable innovation are not patented. Filing a patent involves publicly disclosing information on the technology. To maintain the secrecy of their innovations, inventors could opt to refrain from patenting their products. Dernis and Khan (2004) show, however, that few valuable innovations are not patented. In spite of these downsides, patents have been found to be an accurate indicator of the knowledge available in a country (Griliches 1990).

Table 2 presents the summary statistics for patent counts weighted by family size: total, domestic, and foreign. The mean number of domestic patents is much lower than the mean of foreign patents. This is the case even on a country-by-country basis since large economies that have high innovative capacities also attract a large amount of foreign inventions. And the standard deviations are large for all groups, with many country-year observations at zero, especially for the smaller economies. Figure 4 shows the evolution of foreign and domestic patent counts over time for each of the four renewables for my group of countries. Depending on the renewable energy, the correlation of domestic and foreign patent counts lie between 0.2 and 0.6 , which is relatively low and indicates that policies might affect domestic and foreign patents differently.

3.3 Estimation Procedure

To examine the link between renewable energy policies and innovation distinguishing between domestic and foreign innovation, I estimate the following equations:

$$DomesticPatents_{it} = \beta_1^H POL_{it} + \beta_2^H \mathbf{X}_{it} + \gamma_i^H + \delta_t^H + \epsilon_{it}^H \quad (1)$$

$$ForeignPatents_{it} = \beta_1^F POL_{it} + \beta_2^F \mathbf{X}_{it} + \gamma_i^F + \delta_t^F + \epsilon_{it}^F \quad (2)$$

where $DomesticPatents_{it}$ and $ForeignPatents_{it}$ measure adoption of domestic or foreign renewable

⁸There are other ways of accounting for the value of patents. Citations data are another popular measure. Both have been proven to be significantly correlated with patent value, but family size is the main measure used in the literature.

energy technologies in country i at time t , POL_{it} is one of the three policy measures for country i in year t , \mathbf{X}_{it} contains other controls detailed below, and γ_i and δ_t are country and time fixed effects respectively. The key parameters are β_1^H and β_1^F , which represent the effect of policies on domestic and foreign patent filings respectively. I am interested in comparing these two effects to determine whether environmental policies boost domestic innovation or the licensing of foreign technologies.

The vector \mathbf{X}_{it} includes a number of controls. The first two relate to the electricity market. First, according to the induced innovation hypothesis, as the price of substitute factor inputs increases, incentives to innovate in the area of renewable energies should increase. To account for the induced innovation channel, I control for the price of electricity obtained from the IEA Energy Price and Taxes Database (IEA 2006a). Because prices for electricity vary depending on whether the electricity is consumed by industry or households, I construct the price variable by weighting the price indices for residential and industrial use by their respective consumption levels as in Johnstone et. al. (2010). Since renewable sources represent a relatively small proportion of total electricity generation over my time period (between 3 and 7 percent), the price of electricity can be considered exogenous in this context. For the same reason, I do not consider the overall electricity price to be a function of renewable energy policies. Second, I control for potential market size since returns on innovation, and therefore incentives to innovate, are affected by potential demand. For renewables, potential market size can be proxied by electricity consumption, obtained from the IEA Energy Balance Database (IEA 2006b). Again, due to the small proportion of renewables in total electricity production, electricity consumption is assumed to be exogenous.

Other domestic and foreign factors could be affecting patent filings. Patents could be responding to a change of policy abroad. For example, an inventor could develop a technology in response to a policy in a neighboring country with which domestic firms have strong trade or investment ties. Since inventors tend to file in their home countries before filing abroad, domestic patents would increase. Similarly, other countries implementing renewable energy policies could affect innovation abroad thereby altering the stock of foreign patents that are available for transfer. Therefore, I include a variable for the count of policies in all countries but the domestic country.⁹ Moreover,

⁹Since EU Commission level policies apply to multiple countries, in the case of an EU country, a policy implemented at the EU level will count both in the policy variable of country i and in the policy count of all other countries. Therefore, the policies of country i and the policies of all other countries can add up to more than the total number of policies in any given year. As a consequence, time fixed effects are not appropriate to control for policies in foreign

whether country i invents new technologies or adopts existing technologies depends on how many relevant technologies exist in the world to date and how many have already been adopted in country i . The time fixed effects control for the world stock of renewable energy patents every year. Country fixed effects control for the stock of existing renewable energy patents in each country at the beginning of the time period.

More generally, the time fixed effects control for world trends to shift towards renewable energies in terms of innovation or production. Country fixed effects account for differences in propensity to patent across countries. For example, larger, more developed economies will generally have more domestic capacity for innovation while smaller, less developed economies might rely more intensively on licensing foreign innovation. The number of patents filed in a country could also depend on business climate: countries with more stringent intellectual property rights could have higher number of patents than countries where property rights do not exist or are not enforced.¹⁰

Finally, I control for time-varying cross-country differences which might affect patenting activity by including a linear country-specific patenting trend. The trend variable accounts for all differences across countries which are relevant to innovation and vary over time. This could be a country-specific shock to economic growth which affects all innovation or a change in intellectual property rights regulation. The trend is calculated as the sum of all patents in country i at time t , excluding energy patents - renewables and otherwise - to limit endogeneity issues.

Despite the abuse of the linear form above, I estimate equations (1) and (2) using a negative binomial since my dependent variable is an overdispersed non-negative count variable. The error terms in equations (1) and (2) might be contemporaneously correlated. Even though both equations contain the same set of regressors, estimating the two equations separately leads to efficiency losses in the case of count models (King 1989). Therefore, I use a seemingly unrelated negative binomial estimation method as developed by Winkerlmann (2000).

XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX I also present results using a Non-Linear Instrumental Variable (NLIV) estimation strategy. Identifying the effect of environmental policies on innovation is challenging due to various sources of endogeneity. First, firms that have invented

countries. The policy count of foreign countries is therefore identified by EU policies.

¹⁰Evidence on the links between intellectual property rights protection and innovation or technology diffusion is mixed. See Maskus (2010) for a review.

new technologies could be lobbying the government to implement policies that encourage the use of those new technologies. Second, some omitted sources of variation that are difficult to control for in this context could introduce bias. Each of these channels is discussed in more detail in the next section. To

3.4 Results

First, I run equations (1) and (2) on a contemporaneous measure of policy which is the total count of policies enacted in country i in year t (Table 4, columns 1 and 2). Before diving into the interpretation of the main coefficient of interest, note that the coefficients on the covariates generally comport with intuition. An increase in the price of electricity or in the demand for electricity have a positive and significant relationship to patent filings. More policies in other countries will increase the number of patent filings at home. This could be because domestic inventors create technologies in response to foreign policies but file at home before transferring their inventions abroad, or it could be that foreign policies spur innovation abroad and thereby boost the number of potential inventions that can be transferred to country i following a policy in country i . Later specifications will shed some light on this question. The coefficient on the patenting trend is negative and significant. One explanation might be that higher innovation in other sectors crowds out innovation in renewables since investment resources are limited.

More central to the question of interest, I find that an additional domestic renewable energy policy is associated with positive but not statistically significant increases of 4.5 percent and 2.3 percent in patent filings by domestic and foreign inventors respectively. However, a couple of facts might explain the lack of significance. First, inventors could need some time to file a patent in response to a policy if they develop brand new technologies. Second, contemporaneous policies could be endogenous as firms that have already innovated could lobby for additional environmental policies to promote the use of their technologies. Since firms cannot lobby for past policies and to account for the potential lag in response, I run the same regressions with environmental policies at time $t - 1$ (Table 4 columns 3 and 4).

I find that the coefficient on renewable energy policies is positive and significant for foreign patents, but small and not statistically significant for domestic patents. An additional environmental policy

at time $t - 1$ is associated with a 36.8 percent increase in patent filings by foreign inventors, and only 2.2 percent by domestic inventors. Given the mean of the policy count is 0.673, one additional policy represents a large increase, which explains the large magnitude of the foreign effect and impresses further the lack of effect on the domestic inventor side. Evaluated at the mean, these figures translate into 209 additional value-weighted patents owned by foreign inventors, and less than one additional patent held by domestic inventors. Given the average family size over the period, 50 new patents are filed following the implementation of a new renewable energy policy in the OECD, and these patents are owned by foreign inventors. The results suggest at this point that there is no effect on domestic inventors. The remainder of this sections uses the lagged policy as the main regressor of interest.

Despite the current controls and lagged variable, some endogeneity might remain. If there is persistence in the number of policies enacted each year, the lagged policy measure does not entirely remove the previously mentioned source of endogeneity whereby firms that have innovated lobby for more policies. Moreover, omitted political economy variables such as the rise of the green party to power could be positively affecting both the enactment of additional renewable energy policies and the development of the renewable energy industry, leading to a positive bias. And some shocks to economic growth might affect environmental technologies differently than other types of innovation so they would not be controlled for by the patenting trend. Such a shock might lead to more environmental policies being implemented in the hopes of stimulating the economy but less innovation as firms are financially constrained, thus creating a negative bias.

To account for these additional sources of endogeneity, I employ the Hausman and Taylor (1981) method which makes use of the panel dimension of the data to instrument for the endogenous variable using lagged values of the variable. Consistent with the literature, I remove the first two lags from the instruments to avoid further issues related to the persistence of policies. Table 4 shows that accounting for endogeneity, an additional policy at time $t - 1$ is associated with a 9.8 percent increase in foreign patents (column 6), but also a 14.9 percent increase in domestic patents (column 5). In line with intuition, the increase in the domestic patents coefficients indicates that the negative bias from omitted economic shocks affected domestic inventors more so than foreign inventors. On the other hand, foreign patents appeared to suffer from the positive bias due to omitted political economy variables. Since most foreign patents are transfers of existing

technologies, foreign inventors can respond immediately to a rise in the influence of environmentally conscious parties in anticipation of more environmental policies.

The coefficients are both significant and not statistically different from one another. Environmental policies stimulate patent filings by both domestic and foreign inventors. In fact, in terms of percentage magnitude, the effect on filings by domestic inventors (14.9 percent) is stronger than the effect on filings by foreign inventors (9.8 percent). Nonetheless, since the majority of patents are foreign, the economic magnitude of the coefficients differ significantly: these percentages evaluated at the mean and accounting for family size represent only 8 additional domestic patents but 54 new foreign patent filings. Still, the effect on patent filings by domestic inventors is strongly statistically significant.

Table 5 provides evidence that the results are robust to using alternative measures of policy. Columns (1) and (2) present results for the count of policies separated by policy types. For the main type of policy - economic instruments - the results remain: both domestic and foreign patent filings are positively and significantly affected by policies. Other types, such as regulatory instruments and R&D incentives, show a strong effect on filings by foreign inventors but no statistical response of domestic inventors. Voluntary contributions, on the other hand, only have an effect on domestic inventors, and the other policy types do not elicit a significant response of patent filings by either domestic or foreign inventors. Columns (3) and (4) use a stock of policies rather than a flow and the last two columns are run on a subset of data for wind policies and technologies in seven OECD countries. All confirm that policies significantly stimulate adoption of domestic and foreign technologies alike.

The large number of foreign patents filings does not imply that foreign inventors are developing new technologies in response to domestic policies. This figure could instead represent adoption of existing technologies. Table 6 separates patent counts between transfers of existing technologies measured as patents that were previously filed in another country, and new inventions which are patents that were not previously filed elsewhere. Columns (1) and (2) show that policies do not spur new inventions by foreign inventors, but rather incentivize foreign inventors to transfer their existing technologies to the country in question. Foreign transfers represent over three quarters of total foreign patents, so the effect of policies on patent transfers is large.

Finally, a country-by-country analysis shows that only in Japan and Germany, two countries that have high levels of innovation in the economy overall, do policies significantly stimulate mainly domestic innovation with no significant effect on foreign patent filings (Table 7). These results would support the idea of the first-mover advantage since Germany is also the first country in my dataset to have implemented policies favoring the use or development of renewable energy technologies. The case of Japan, that implemented policies later, might suggest that overall innovative capacity played a key role in positioning Japan as a center of innovation for renewables.

The next few tables provide some additional results and checks. Table 8 includes multiple lags of the policy variable and finds that patents respond to policies up to 3 years after enactment. Table 9 shows that the conclusion that foreign patent filings respond more to policies than domestic patent filings are robust to specifications including different sets of controls.

In sum, I find that policies which aim to foster the development and use of renewable energies are associated with a significant increase in patent filings of around 10 percent, but outside of highly innovative economies such as Germany or Japan, the vast majority of these patents are transfers of existing foreign technologies rather than new domestic inventions or even new foreign inventions. This result holds with different measures of policy and accounts for potential endogeneity issues. The claim that renewable energy policies stimulate innovation in renewable energy technologies therefore does not appear to be substantiated in OECD countries between 1988 and 2003. However, policies could still stimulate the domestic economy if these foreign transferred technologies spur manufacturing production.

4 Technology Adoption and the Production of Technology-Specific Inputs

An inventor will file a patent to protect his invention in a country because he plans to market the invention in that country. On the one hand, the technology or the inputs into that technology can be produced in the country where the patent was filed: a domestic inventor could produce locally, a foreign inventor could engage in foreign direct investment to produce the technology in the country where he filed, or a domestic manufacturer could license the right from the foreign innovator to produce the good locally. On the other hand, the technology or the inputs can be

produced abroad and imported to be sold in the country where the patent is filed. Environmental policies will only directly increase domestic manufacturing if technology-specific goods and inputs are produced domestically, not if they are imported. In this section, I examine how the rise in patent filings discussed above - both domestic and foreign - affected the production of the technologies, comparing the effect on the domestic manufacturing of technologies to the effect on the imports of technologies.

Manufacturing production data are not available for all countries at a level of detail which would allow me to identify inputs used exclusively for renewable technologies. As a result, I use exports as a proxy for domestic production. While exports are an imperfect proxy for manufacturing production, they do allow me to examine the competitiveness portion of the claim. As mentioned in the introduction, policymakers state that the technologies that are developed and manufactured in response to environmental policies will then be exported to other countries that implement similar policies later on. But if the rise in exports is trumped by a large inflow of imports, there could be little gains in competitiveness. To test whether policies do in fact improve competitiveness, I examine how innovation affects both exports and imports. This section therefore compares the effect of patents on exports and imports to determine whether adopted technologies are primarily produced at home or abroad, and whether the domestic economy experiences a gain in global competitiveness. The following subsections describe the data sources, estimation procedure, and results.

4.1 Data

The measure of technology adoption is patents as in the first part of the paper, but I no longer need to distinguish between domestic and foreign inventors. I assume that a firm in country i that wants to make use of a renewable technology will chose from the set of available technologies as proxied by the technologies which have been patented in this country, regardless of the country of residence of the inventor. Moreover, available technologies are not only the technologies patented in year t but all technologies patented up until year t . Thus, while the first part of the paper focused on the flows of new patents, this section requires a measure of the stock of knowledge accumulated in each country in renewable energies. Here I assume that patents provide an opportunity to manufacture and sell a technology. If instead patents are filed strategically to impose a barrier on domestic

production, then I should observe no effect in this section.

Aggregating patents into a stock by simply adding the count of patents of previous years is problematic for two reasons. First, patents become obsolete with time as new better technologies are introduced. Second, there might be a lag between the time when the patent is filed and the time when it is actually used in the economy. As a result, I aggregate patents into knowledge stocks following standard methods (Popp, Hascic and Mehdi, 2011):

$$\widehat{K}_{it} = \sum_{s=0}^{\infty} e^{-\omega_1 s} (1 - e^{-\omega_2(1+s)}) * PAT_{i(t-s)} \quad (3)$$

where ω_1 is the decay rate allowing for the fact that older patents become less relevant over time. And ω_2 corresponds to the rate of diffusion since a patent might not be utilized right away. The stock aggregates all previous years' patent counts by multiplying each year's count by a function of these decay and diffusion rates. Following Popp, Hascic and Mehdi (2011), I use a patent rate of decay of 0.1, and a rate of diffusion of 0.25. This stock represents the set of available technologies in country i at time t .

For the trade data, the difficulty lies in identifying relevant product categories for renewable energies. Using information from the Organization for Economic Cooperation and Development (Steenblik 2005), the International Trade Commission (USITC 2005, 2009), and the International Center for Sustainable Trade and Development (ITCSD 2009), I compile a list of product categories including primary renewable products and technologies as well as common components of renewable energy based systems. Table 10 presents the resulting list of products based on the Harmonized System commodity classification (HS code) at the 6-digit level. The lists has some drawbacks. Some product categories are not exclusively used for renewable energy and some subcategories are not relevant for renewables. In the robustness checks, I present results using a more conservative list of products for solar energy. I obtain export and import data at the HS 6-digit level from the United Nations COMTRADE database.

4.2 Estimation Procedure

Using trade data and the stock of patented technologies, I explore the effect of technology adoption on renewable technology exports and imports using a standard gravity model modified to include a measure of technology. Gravity models predict bilateral trade flows based on country characteristics and trade costs between country pairs. These costs are related to distance as well as common features such as a border, language, or trade agreement. Although the gravity model originated as an empirical exercise, trade theorists have since established the theoretical underpinnings of the model, and evidence suggests that gravity models have been successful in predicting trade flows (Frankel 1997, Head and Mayer 2013).

I estimate gravity equations augmented with a measure of available technologies in the following way:

$$\ln(Exports_{ijt}) = \beta_1^X \ln(K_{it}) + \beta_2^X \mathbf{X}_{ijt} + \gamma_i^X + \delta_j^X + \omega_t^X + \nu_{ijt}^X \quad (4)$$

$$\ln(Imports_{ijt}) = \beta_1^M \ln(K_{it}) + \beta_2^M \mathbf{X}_{ijt} + \gamma_i^M + \delta_j^M + \omega_t^M + \nu_{ijt}^M \quad (5)$$

where $\ln(Exports_{ijt})$ and $\ln(Imports_{ijt})$ represent log exports and imports between countries i and j at time t . I am interested in exports from the 27 OECD countries but destined for any country in the world. Similarly, the import equations includes imports from the 27 OECD countries originating from anywhere in the world. Thus in both equations, country i is one of the 27 countries in my dataset, while country j can be any country which trades with country i . For simplicity, I will call country i the “patenter”, and country j the “partner”.¹¹

K_{it} is the stock of knowledge related to renewable energies in country i at time t described in the previous section. \mathbf{X}_{ijt} contains the gravity model variables from the CEPII gravity model dataset (Head and Mayer 2010): log population in patenter and partner, log GDP per capita in patenter and partner, the log of distance between patenter and partner, and indicators for whether the pair shares a common border, a common language, colonial ties, or a regional or bilateral trade agreement. Finally, γ_i and δ_j and ω_t are patenter country, partner country, and time fixed effects respectively. Comparing the magnitude and significance of β_1^M and β_1^X will determine whether an increase in technology adoption is mostly associated with a rise of domestic production proxied by

¹¹The results section provide robustness checks with only OECD countries.

exports or an increase in imports.

Santos Silva and Tenreyro (2006) shows that under heteroskedasticity, log linearized gravity models can lead to substantial biases. The authors propose using a Poisson pseudo maximum likelihood (PPML) estimation instead to obtain consistent estimates. This method is also more appropriate for dealing with zero values in the dependent variable, which are common and create additional issues in log linearized models. I estimate the gravity equations using PPML and provide robustness checks using two other popular methods: ordinary least squares (OLS) dropping pairs with zero trade flows, and OLS with a transformed dependent variable (“OLS+1”): $\ln(Imports_{ijt} + 1)$ and $\ln(Exports_{ijt} + 1)$.

Table 11 provides the summary statistics for trade flows and the renewable patent stock. On average across OECD countries and years, imports of renewable energy technology inputs total \$11 million and exports \$12 million between 1988 and 2003. The range varies greatly across countries. Germany is the largest exporter with an average of \$63 million per year. Not far behind, Japan and the United States export on average \$45 million per year. The United States is not only one of the top exporters but also by far the main importer of renewable technology inputs: its mean import value across the time period is \$56 million.

4.3 Results

As can be seen in Table 12, the coefficients on the standard gravity model variables are in line with intuition. Across all specifications, all controls have positive and significant effects on trade, except distance. The coefficient on the variable of interest, the stock of renewable technologies, is also positive and significant for both imports and exports in all three functional forms. In the PPML regressions - the preferred specification - a 1 percent increase in the stock of renewable energy patents is associated with a 0.232 percent rise in imports, and a 0.352 percent rise in exports. Hence, the evidence suggests that while some technologies are imported, some technologies are at least partly produced domestically.

However, it could be that inventors build on the technology embodied in imports to create new technologies, which would lead to an overestimation of the import-elasticity of innovation. Or a high

level of the trade of renewable technologies might mean that existing technologies are appropriate in which case there would not be the need to innovate further, which would negatively bias the coefficients. To address these concerns, I instrument for the stock of knowledge in renewable technologies with the stock of knowledge in all other non-energy technologies. The instrument is relevant since there is a common patenting trend in each country. And it is exogenous because non-energy patents are unlikely to be directly related to the trade of renewable technologies. I estimate equations (4) and (5) using an instrumental variable approach. The results from the linear first stage are presented in Table 13 and show that the instrument is highly relevant. Accounting for endogeneity (Table 14, columns 1 and 2), a 1 percent increase in the stock of renewable energy patents is associated with a 0.679 percent increase in exports and a 0.627 percent increase in imports. Again, the results are robust to using OLS or OLS+1.

Still, exports are an imperfect proxy for domestic production. Since the results show that exports and imports both increase, it is possible that there would be no net effect on domestic production. Production of exported goods could be increasing at the expense of production of goods that are now imported. This would indicate a classic trade theory specialization story and would generate gains from trade, but would not represent an increase in manufacturing output. Column 7 therefore examines the effect of the patent stock on net exports. The coefficient on the patent stock is positive and significant, indicating that the rise in patent filings does boost net exports. This specification confirms that increased patents will be associated with a rise in domestic manufacturing production.

Table 15 provides some robustness checks. Since the majority of exports of renewable energy technologies from my sample originate in Germany, Japan or the United States, the positive and significant coefficient on exports could be driven only by these three countries, which are highly innovative nations in all industries. Columns (1) and (2) present the regressions removing Japan, Germany and the United States from the sample. For simplicity, only PPML estimates are reported. The coefficients on imports and exports remain significant and roughly of the same magnitude. Therefore, the rise in exports following an increase in the knowledge stock is not limited only to the main exporters. In all countries, some components of the technologies are produced domestically and exported.

As mentioned previously, the set of product codes identified as renewable energy technology inputs

is not exact.¹² In Table 15 columns (3) and (4), I restrict the solar trade data to photovoltaic cells and modules only. The results remain that the stock of knowledge has a positive and significant effect on exports, although the effect on imports is twice as large.

The above results allow the 27 OECD countries to trade with any country in the world. As a result, I include only the knowledge stock of the patentee and not the knowledge stock of the trading partner since I do not have that data for non-OECD countries. My estimation strategy therefore deviates from standard gravity models which includes all variables in both origin and destination countries. As a check, I restrict trading partners to OECD countries only (Table 16). In a first instance, columns (1) and (2) present the same regression as above but limited to OECD countries. An increase in the patenting stock in country i has a positive and significant effect on export, but no effect on imports. Comparing these results to those in Table 14 suggests that the effects on imports originates mostly from non-OECD countries. In a second step, columns (3) and (4) include the stock of available technologies in the partner country as well. The results show that after controlling for the patent stock in the partner country j , the higher the patent stock in country i the larger the exports from country i to j and the lower the imports from country j to i . This suggests that increased technology adoption at home will stimulate exports at the expense of imports, which could indicate that imports are being replaced by domestic manufacturing production.

Therefore, the results show that renewable energy innovation lead to a rise in exports so that at least some inputs and technologies are produced domestically. In the first part of the paper, the results suggested that one environmental policy was associated with a 10 percent increase in patents. Combining the two sections of the paper, I conclude that an environmental policy is associated with a 6.79 percent increase in exports of renewable energy technologies.¹³ These figures represent only the effect of policies on trade through the technology adoption channel. Table 17 includes the policy count from part I of the paper in the gravity model regression to examine whether policies have an additional direct effect on trade. The coefficient on the policy variable does not appear to be significant in either regression, suggesting that there is little additional effect of policies on trade beyond the technology adoption channel.

¹²For example, the two codes for solar energy are: 8541.40 - photovoltaic cells and modules, and 8504.40 - static converters. The first is exclusively solar PV technologies; the second includes both inverters for solar panels and other kinds of converters not used in renewables.

¹³These “back of the envelope” figures are calculated multiplying the effect of the first part (10 percent) by the effect of the second part (0.679 percent for exports).

5 Conclusion

The sheer magnitude of the political and monetary capital being invested into greening the economy around the world suggest the need for academic research on the links between environmental regulation, green innovation, and green manufacturing. However, the theory is inconclusive so the question of whether environmental policies stimulate the domestic economy is mainly an empirical one.

The framework I devise to identify those links is straightforward. Environmental policies affect two main levels of economic activity: innovation and manufacturing. These activities can take place at home or abroad, allowing for four possible scenarios: both innovation and manufacturing occur domestically, both happen abroad, only innovation is domestic, or only manufacturing is produced at home. I identify which scenario is most prominent in two steps, each posing a different question and requiring different data and estimation techniques.

In the first step, using patent data as a proxy for innovation and a measure of policy strength specific to renewable energies, I find that renewable energy policies result in a 10 percent increase in patent filings, but very few of these are developed by domestic inventors. Only in historically innovative economies such as Japan and Germany do domestic inventors respond significantly to the implementation of a policy. In the rest of the OECD, including in the United States, adopted technologies are largely licensing of foreign technologies rather than new technologies developed at home. In the estimation, I account for the endogeneity of environmental policies and test the robustness of the results to different measures of policies.

In the second step, I ask whether the increase in technology adoption led to a spike in domestic manufacturing production or to a rise in imports. I find that domestic production - proxied by exports - increase significantly following technology adoption. At least some of the technologies or the inputs into these technologies are manufactured domestically. Combining the two steps of the paper, an additional renewable energy policy in the OECD is associated with a 6 percent rise in domestic production. Therefore, the evidence suggests that renewable policies in the OECD stimulate the economy through manufacturing in the renewable energy sector but have little effect on the innovative sector outside of Germany and Japan.

6 References

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7 Figures and Tables

Figure 1: Channels from Environmental Regulation to Innovation and Manufacturing

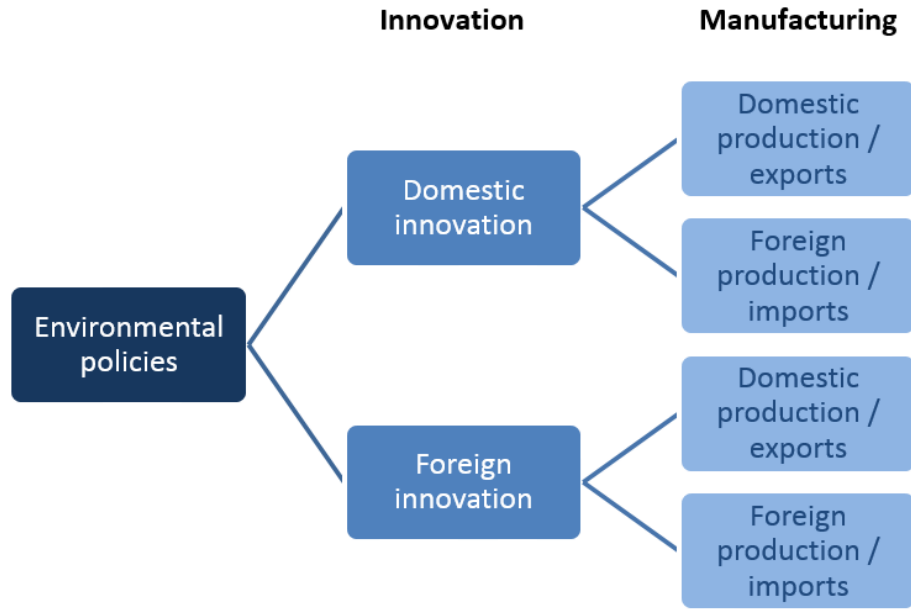


Figure 2: Frequency plot of family size by origin

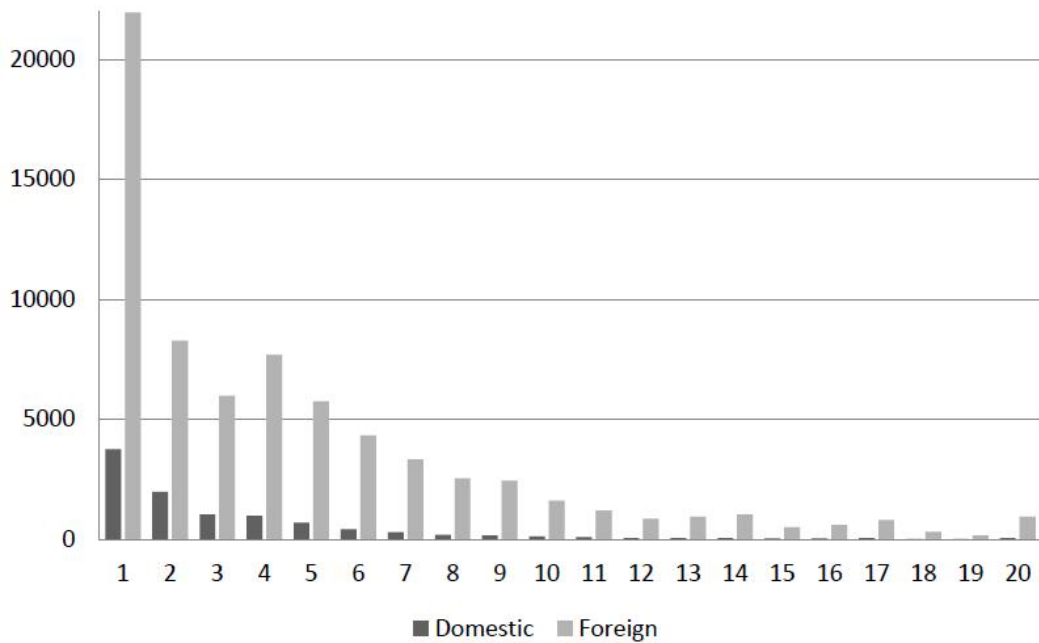
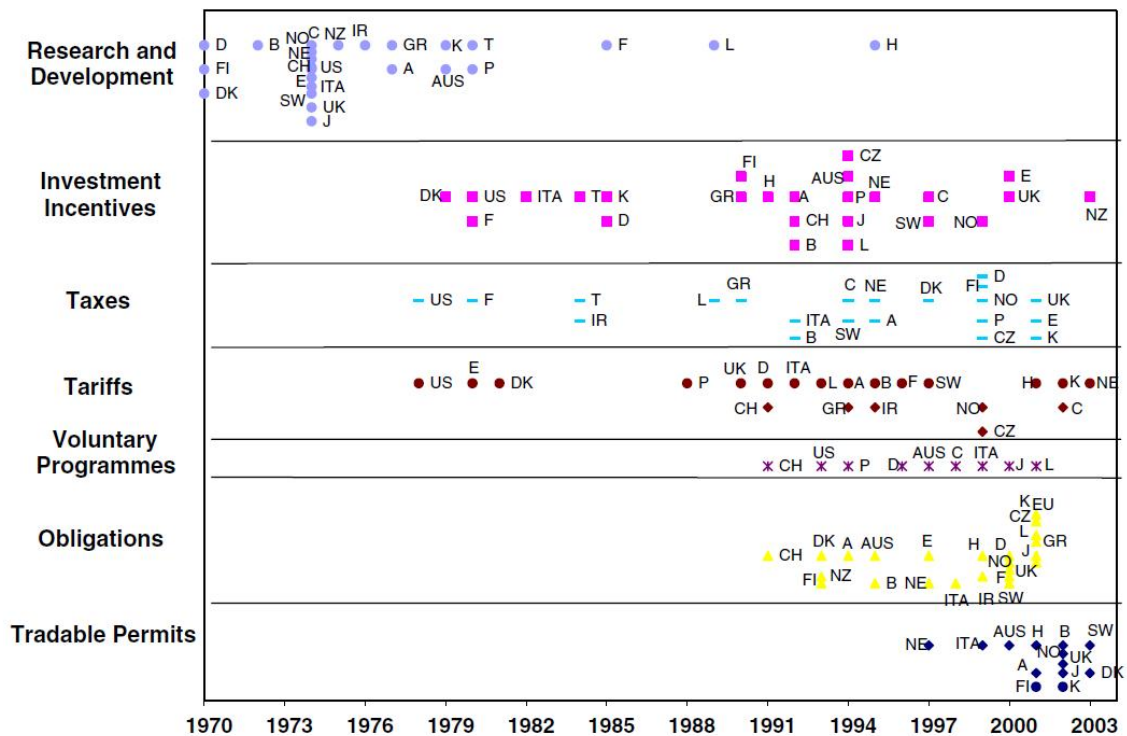


Figure 3: Introduction of Renewable Energy Policies by Type in Selected OECD Countries, 1970-2003



Source: IEA (2004)

Note: AUS Australia, C Canada, FI Finland, GR Greece, ITA Italy, L Luxembourg, NO Norway, SW Sweden, UK United Kingdom, A Austria, CZ Czech Rep., F France, H Hungary, J Japan, NE Netherlands, P Portugal, CH Switzerland, US United States, B Belgium, DK Denmark, DE Germany, IR Ireland, K Korea, NZ New Zealand, E Spain, T Turkey.

Figure 4: Renewable Patents in OECD countries, by Technology

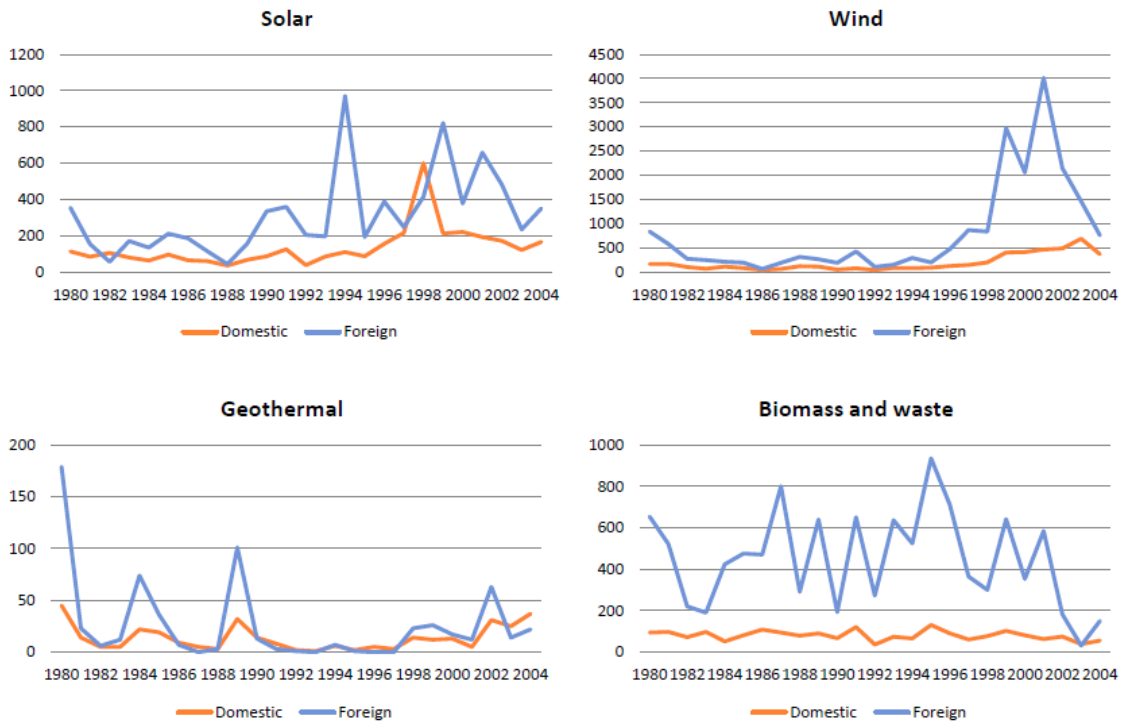


Table 1: Patent Classes of Renewable Energy Technologies

Patent classification description	IPC code
WIND	
Wind motors	F03D
SOLAR PHOTOVOLTAICS	
Semiconductor devices sensitive to infrared radiation, light, electromagnetic radiation of shorter wavelength, or corpuscular radiation and specially adapted either for the conversion of the energy of such radiation into electrical energy or for the control of electrical energy by such radiation—adapted as conversion devices, including a panel or array of photoelectric cells, e.g., solar cells	H01L 31/04-058
Generators in which light radiation is directly converted into electrical energy	H02N 6/00
Devices consisting of a plurality of semiconductor components sensitive to infrared radiation, light, electromagnetic radiation of shorter wavelength, or corpuscular radiation—specially adapted for the conversion of the energy of such radiation into electrical energy	H01L 27/142
GEOHERMAL	
Other production or use of heat, not derived from combustion—using natural or geothermal heat	F24J 3/08
Devices for producing mechanical power from geothermal energy	F03G 4/00-06
BIOMASS and WASTE	
Solid fuels essentially based on materials of nonmineral origin—animal or vegetable substances; sewage, town, or house refuse; industrial residues or waste materials	C10L 5/42-48
Engines or plants operating on gaseous fuel generated from solid fuel, e.g., wood	F02B 43/08
Liquid carbonaceous fuels	C10L1
Gaseous fuels	C10L3
Solid fuels	C10L5
Dumping solid waste	B09B1
Destroying solid waste or transforming solid waste into something useful or harmless	B09B3
Incineration of waste; incinerator constructions	F23G5
Incinerators or other apparatus specially adapted for consuming specific waste or low grade fuels, e.g., chemicals	F23G7
Plants or engines characterized by use of industrial or other waste gases	F01K 25/14
Incineration of waste—recuperation of heat	F23G 5/46
Plants for converting heat or uid energy into mechanical energy; use of waste heat	F01K27
Use of waste heat of combustion engines—Proting from waste heat of combustion engines	F02G5
Machines, plant, or systems, using particular sources of energy—using waste heat, e.g., from internal-combustion engines	F25B 27/02

Source: Popp (2011).

Table 2: Summary Statistics of Weighted Patent Counts

Variable	Mean	Std. Dev.	Min.	Max.
All patents	604	741	0	3851
Domestic patents	54	170	0	2018
Foreign patents	550	665	0	3341

Table 3: Summary Statistics of Policy Stringency Measure

Variable	Mean	Std. Dev.	Min.	Max.
Policy	0.635	1.522	0	10
Economic instruments	0.240	0.603	0	5
Regulatory instruments	0.115	0.363	0	2
R&D	0.035	0.197	0	2
Policy support	0.125	0.353	0	2
Information and education	0.070	0.283	0	2
Voluntary contributions	0.050	0.218	0	1

Table 4: Effect of Policies on Innovation

	Negative Binomial				IV - GMM	
	(1) Domestic	(2) Foreign	(3) Domestic	(4) Foreign	(5) Domestic	(6) Foreign
Policy _t	1.045 (0.101)	1.023 (0.059)				
World policy _t	1.116 (0.116)	1.098 (0.070)				
Policy _{t-1}			1.022 (0.059)	1.368*** (0.100)	1.149*** (0.019)	1.098*** (0.006)
World policy _{t-1}			1.067 (0.078)	1.582*** (0.135)	1.062*** (0.004)	1.121*** (0.004)
Elec. cons.	1.020 (0.013)	1.115*** (0.024)	1.017 (0.012)	1.105*** (0.021)	1.233*** (0.005)	1.009*** (0.008)
Elec. price	1.007* (0.003)	1.042*** (0.005)	1.007* (0.003)	1.037*** (0.004)	1.041*** (0.002)	1.011*** (0.002)
Patenting trend	0.989* (0.004)	0.960*** (0.007)	0.990* (0.004)	0.965*** (0.006)	1.088*** (0.002)	0.995*** (0.002)

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Robust standard errors in parentheses; N=400.

All regressions include country and time fixed effects.

Table 5: Effect of Alternative Measures of Policy on Innovation

	All technologies				Wind only	
	(1) Dom.	(2) Frqn	(3) Dom.	(4) Frqn	(5) Dom.	(6) Frqn
Economic instruments $_{t-1}$	1.354*	1.711**				
Regulatory instruments $_{t-1}$	1.144	1.785***				
Research and Development $_{t-1}$	1.514	2.757***				
Policy support $_{t-1}$	0.976	1.282				
Information and education $_{t-1}$	1.033	1.244				
Voluntary contributions $_{t-1}$	0.581**	0.702				
Stock of policies $_{t-1}$			1.110*	1.378***		
Stock of world policies $_{t-1}$			1.160**	1.600***		
Feed-in-tariff $_{t-1}$					1.138*	1.102**
Policy $_{t-1}$					1.039	1.38
World policy $_{t-1}$	1.249*	1.872***			1.12	1.456*
Elec. cons.	1.018	1.104***	1.005	1.041***	1.354*	1.611***
Elec. price	1.006	1.036***	1.001	1.014***	1.007	1.040***
Patent trend	0.991*	0.965***	0.997	0.995	1.017**	1.006
N	400	400	400	400	112	112

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Robust standard errors; Country and time fixed effects.

Table 6: Effect of Policies on Innovation – New Filings or Transfers of Existing Patents

	(1)	(2)
	Foreign transfers	Foreign new
Policy $_{t-1}$	1.104** (0.033)	0.387*** (0.061)
World policy $_{t-1}$	1.134*** (0.016)	1.102*** (0.007)
Elec. cons.	1.024* (0.009)	0.867*** (0.005)
Elec. price	0.989* (0.005)	1.003* (0.003)
Patenting trend	0.990** (0.003)	1.094*** (0.004)

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Robust standard errors in parentheses; N=400.

All regressions include country and time fixed effects.

Table 7: Effect of Policies on Innovation – Germany and Japan only

	(1)	(2)
	Domestic patents	Foreign patents
Policy _{t-1}	1.241*** (0.023)	1.006 (0.014)
World policy _{t-1}	1.066 (0.040)	0.998 (0.060)
Elec. cons.	1.135*** (0.036)	1.050* (0.026)
Elec. price	0.985 (0.010)	1.025** (0.009)
Patenting trend	1.027*** (0.003)	1.025*** (0.002)

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Robust standard errors in parentheses; N=400.

All regressions include country and time fixed effects.

Table 8: Effect of Policies on Innovation – Multiple Lags

	(1)	(2)
	Domestic patents	Foreign patents
Policy _{t-1}	1.029 (0.056)	1.298*** (0.068)
Policy _{t-2}	1.081 (0.081)	1.323*** (0.103)
Policy _{t-3}	4.107*** (1.058)	6.811*** (1.551)
Policy _{t-4}	1.704 (0.799)	1.387 (0.351)
World policy _{t-1}	1.005 (0.073)	1.370*** (0.081)
World policy _{t-2}	1.114 (0.103)	1.572*** (0.137)
World policy _{t-3}	4.215*** (1.080)	7.744*** (1.713)
World policy _{t-4}	1.630 (0.742)	1.515 (0.380)
Elec. cons.	1.002 (0.008)	1.040*** (0.010)
Elec. price	0.996 (0.003)	1.014*** (0.003)
Patenting trend	0.996 (0.004)	0.984*** (0.004)

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Robust standard errors in parentheses; N=400.

All regressions include country and time fixed effects.

Table 9: Effect of Policies on Innovation – Various Controls

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
	D	F	D	F	D	F	D	F	D	F	D	F
Policy _{t-1}	0.967 (0.032)	0.889 (0.060)	1.065 (0.070)	5.272** (3.251)	1.052 (0.066)	5.323** (3.315)	1.050 (0.064)	1.745*** (0.279)	1.018 (0.058)	1.408*** (0.122)	1.022 (0.059)	1.368*** (0.100)
World policy _{t-1}			1.149 (0.096)	7.055*** (4.150)	1.118 (0.090)	7.023** (4.187)	1.111 (0.087)	2.202*** (0.402)	1.062 (0.076)	1.639*** (0.165)	1.067 (0.078)	1.582*** (0.135)
Elec. cons.							1.027* (0.013)	1.229*** (0.048)			1.017 (0.012)	1.105*** (0.021)
Elec. price									1.008* (0.003)	1.048*** (0.005)	1.007* (0.003)	1.037*** (0.004)
Patenting trend					0.993** (0.002)	0.990** (0.004)	0.986*** (0.004)	0.932*** (0.012)	0.994* (0.002)	0.992** (0.003)	0.990* (0.004)	0.965*** (0.006)

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Exponentiated coefficients; Country and time fixed effects; D= Domestic, F= Foreign; N=400.

Table 10: List of Renewable Energy Technology Inputs

HS code	Product description
2207.10	Ethanol
2905.11	Methanol
3824.90	Biodiesel and waste fats and oil suitable as a fuel
4401.10	Fuel wood, in logs, in billets, in twigs, in faggots or in similar forms.
4401.30	Artificial logs made from pressed sawdust; wood waste suitable as a fuel
4402.00	Wood, shell or nut charcoal used for fuel
7308.20	Towers and lattice masts of iron and steel
8402.11	Water-tube boilers with a steam production exceeding 45 tonnes per hour.
8402.12	Water-tube boilers with a steam production not exceeding 45 tonnes per hour.
8402.19	Other vapour-generating boilers, including hybrid boilers
8412.80	Windmills
8412.90	Parts of Other Engines and Motors
8413.50	DC-powered water pumps
8413.70	DC-powered submersible water pumps
8413.81	Windmill pumps
8416.30	Mechanical stokers and related appliances used for burning biomass
8416.90	Parts for mechanical stokers and related appliances used for burning biomass
8501.31	DC generators — Of an output not exceeding 750 W
8501.61	AC generators (alternators) — Of an output not exceeding 75kVA
8502.31	Electric generating sets and rotary converters - Wind powered
8504.40	Static converters (inverters)
8541.40	Photovoltaic cells and modules
9026.80	Anemometers

Source: OECD (2005), USITC (2005, 2009), ITCSD (2009)

Table 11: Summary Statistics for Trade Flows and Renewable Patent Stock

Variable	Mean	Std. Dev.	Min.	Max.
Exports in millions USD	12.1	101.9	0	5317
Imports in millions USD	10.6	104.0	0	501
Renew. pat. stock (in 1,000)	6.0	6.6	0	37

Table 12: Effect of Innovation on Trade

	PPML		OLS		OLS (T+1)	
	(1)	(2)	(3)	(4)	(5)	(6)
	Exports	Imports	Log(X)	Log(M)	Log(X+1)	Log(M+1)
Log R.E. patent stock	0.352*** (0.028)	0.232*** (0.030)	0.150*** (0.022)	0.065* (0.028)	0.099*** (0.007)	0.090*** (0.006)
Log pop. in origin	3.198*** (0.637)	2.188*** (0.557)	1.322** (0.416)	2.439*** (0.500)	1.180*** (0.101)	2.020*** (0.099)
Log pop. in destination	0.066 (0.168)	2.081*** (0.374)	0.905*** (0.148)	0.039 (0.224)	0.142** (0.046)	0.699*** (0.036)
Log GDP p.c. in origin	0.658*** (0.078)	0.701*** (0.090)	0.405*** (0.069)	0.623*** (0.091)	0.374*** (0.023)	0.407*** (0.020)
Log GDP p.c. in destination	0.678*** (0.051)	0.932*** (0.062)	0.891*** (0.041)	0.600*** (0.062)	0.370*** (0.012)	0.281*** (0.010)
Log distance	-0.744*** (0.021)	-0.536*** (0.026)	-1.602*** (0.018)	-1.167*** (0.023)	-0.416*** (0.009)	-0.217*** (0.008)
Common border	0.483*** (0.034)	0.459*** (0.038)	0.097 (0.054)	0.548*** (0.054)	0.657*** (0.056)	0.792*** (0.055)
Common language	0.326*** (0.035)	0.331*** (0.039)	0.734*** (0.031)	0.364*** (0.043)	0.083*** (0.014)	0.004 (0.013)
Colonial ties	0.206** (0.072)	0.204* (0.081)	1.881*** (0.056)	0.893*** (0.079)	0.563*** (0.033)	0.149*** (0.028)
RTA	0.722*** (0.050)	0.873*** (0.056)	0.045 (0.034)	0.254*** (0.043)	0.487*** (0.020)	0.367*** (0.021)
<i>N</i>	74,095	74,095	44,440	29,366	74,095	74,095

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Robust standard errors; Origin, destination, and time fixed effects.

Table 13: IV - First Stage

	(1)
	Log R.E. patent stock
Log non-energy patent stock	0.208***
Log population in patenter	0.398***
Log population in partner	-0.00882***
Log GPD p.c. in patenter	0.878***
Log GDP p.c. in partner	-0.0244***
Log distance	-0.0681***
Common border	-0.111***
Common language	-0.153***
Colonial ties	0.163***
RTA	0.180***
Constant	-2.623***
<i>N</i>	74,095

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Table 14: Effect of Innovation on Trade – Instrumental Variable Approach

	PPML		OLS		OLS (T+1)		
	(1) Exports	(2) Imports	(3) Log(X)	(4) Log(M)	(5) Log(X+1)	(6) Log(M+1)	(7) Log(X-M)
Log R.E. patent stock	0.679*** (0.152)	0.627*** (0.097)	0.257*** (0.042)	0.104* (0.047)	0.395*** (0.016)	0.297*** (0.014)	0.304*** (0.017)
Log pop. in origin	0.451*** (0.105)	0.508*** (0.072)	2.583*** (0.083)	3.754*** (0.130)	0.157*** (0.028)	0.026 (0.025)	0.132*** (0.028)
Log pop. in destination	0.812*** (0.012)	0.985*** (0.022)	-1.568*** (0.158)	-0.814*** (0.200)	-0.472*** (0.058)	-0.862*** (0.051)	-0.178** (0.058)
Log GDP p.c. in origin	0.142 (0.231)	0.04 (0.132)	0.440*** (0.081)	0.538*** (0.107)	-0.04 (0.031)	0.128*** (0.027)	-0.079** (0.030)
Log GDP p.c. in destination	0.894*** (0.018)	1.547*** (0.031)	0.673*** (0.036)	0.447*** (0.051)	0.326*** (0.013)	0.275*** (0.011)	0.245*** (0.013)
Log distance	-0.859*** (0.043)	-0.557*** (0.039)	-1.529*** (0.017)	-1.075*** (0.022)	-0.421*** (0.007)	-0.219*** (0.006)	-0.340*** (0.007)
Common border	1.084*** (0.077)	1.548*** (0.110)	0.176** (0.061)	0.649*** (0.069)	0.661*** (0.027)	0.794*** (0.024)	0.339*** (0.029)
Common language	0.689*** (0.077)	0.534*** (0.110)	0.706*** (0.031)	0.303*** (0.042)	0.084*** (0.013)	0.004 (0.011)	0.079*** (0.013)
Colonial ties	1.679*** (0.133)	0.692*** (0.175)	1.862*** (0.059)	0.872*** (0.074)	0.558*** (0.025)	0.146*** (0.022)	0.586*** (0.025)
RTA	-0.459*** (0.076)	0.355*** (0.093)	0.043 (0.039)	0.332*** (0.046)	0.425*** (0.017)	0.341*** (0.015)	0.299*** (0.018)
<i>N</i>	74,095	74,095	44,440	29,366	74,095	74,095	68,341

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Robust standard errors; Origin, destination, and time fixed effects.

Table 15: Effect of Innovation on Trade – Robustness Checks

	Excl. top 3 exporters		Restricted solar codes	
	(1)	(2)	(3)	(4)
	Exports	Imports	Exports	Imports
Log R.E. patent stock	0.633*** (0.155)	0.575*** (0.107)	0.583** (0.182)	1.119*** (0.144)
Log pop. in origin	0.413** (0.129)	0.484*** (0.093)	0.642*** (0.186)	-0.166 (0.179)
Log pop. in destination	0.800*** (0.014)	0.973*** (0.024)	0.760*** (0.034)	1.020*** (0.065)
Log GDP p.c. in origin	0.145 (0.256)	0.042 (0.166)	0.769** (0.281)	-0.709*** (0.131)
Log GDP p.c. in destination	0.875*** (0.021)	1.513*** (0.031)	0.955*** (0.036)	1.594*** (0.066)
Log distance	-0.846*** (0.049)	-0.541*** (0.042)	-0.869*** (0.083)	0.057 (0.143)
Common border	1.109*** (0.209)	1.585*** (0.237)	0.852*** (0.237)	1.292*** (0.226)
Common language	0.695*** (0.075)	0.483*** (0.128)	0.647*** (0.147)	-0.661*** (0.190)
Colonial ties	1.705*** (0.120)	0.645*** (0.190)	1.318*** (0.225)	1.033** (0.366)
RTA	-0.401*** (0.080)	0.392*** (0.092)	-1.170*** (0.140)	-1.676*** (0.285)
<i>N</i>	65,483	65,483	43,819	43,819

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Robust standard errors; Origin, destination, and time fixed effects.

Table 16: Effect of Innovation on Trade – OECD Only

	PPML - IV			
	(1) Exports	(2) Imports	(3) Exports	(4) Imports
Log R.E. patent stock in i	1.438***	-0.065	1.516***	-0.214**
Log R.E. patent stock in j			-0.473***	0.379***
Log population in i	-0.078	0.810***	-0.079	0.891***
Log population in j	0.762***	0.920***	1.088***	0.708***
Log GDP p.c. in i	-0.757*	0.802***	0.862**	0.969***
Log GDP p.c. in j	0.643***	1.310***	1.216***	0.740***
Log distance	-0.534***	-0.450***	-0.695***	-0.509***
Common border	2.374***	1.518***	2.088***	1.484***
Common language	0.214*	-0.023	0.313**	0.011
Colonial ties	0.883***	0.835***	0.361*	0.708***
RTA	0.211	0.729***	0.019	0.506***

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Robust standard errors; N=11,618; Origin, destination, and time fixed effects.

Table 17: Effect of Innovation on Trade – With Policy Measure

	PPML - IV(GMM)	
	(1) Exports	(2) Imports
Log R.E. patent stock	0.724*** (0.193)	0.577*** (0.109)
Policy	-0.026 (0.025)	0.052 (0.028)
Log pop. in origin	0.423** (0.13)	0.535*** (0.078)
Log pop. in destination	0.812*** (0.012)	0.984*** (0.022)
Log GDP p.c. in origin	0.086 (0.283)	0.099 (0.142)
Log GDP p.c. in destination	0.895*** (0.018)	1.542*** (0.031)
Log distance	-0.859*** (0.043)	-0.558*** (0.039)
Common border	1.110*** (0.248)	1.538*** (0.239)
Common language	0.691*** (0.079)	0.533*** (0.111)
Colonial ties	1.669*** (0.138)	0.683*** (0.168)
RTA	-0.465*** (0.078)	0.339*** (0.091)

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Robust standard errors; N=74,095; Origin, destination, and time fixed effects.