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Green innovation and green Imports:Links between environmental policies, innovation, and production

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ABSTRACT

This paper addresses the claim that environmental policies stimulate domestic economies. The claim is parsed 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 of 31 OECD countries between 1988 and 2003. The results from regression analysis suggest that renewable energy policies have had some success in stimulating domestic economies. While renewable energy policies are associated with little domestic innovation outside of Germany, Japan, and the United States, they do boost the adoption of foreign technologies overall. In turn, when patenting occurs the results detect an increase in manufacturing production of renewable energy technologies as well as a rise of the country's international competitiveness through exports.

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. In many countries these discussions now emphasize the potential complementarities between addressing environmental issues and stimulating economic growth. In January 2017, the Chinese National Energy Administration unveiled a plan to spend more than $360 billion through 2020 on renewable power sources suggesting the plan would create more than 13 million jobs.[2] 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",[3] and that he expected "those new energy sources to be built right here in the United States".[4] 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. The references to being a leader in the field also point to a first-mover advantage allowing for the export of 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

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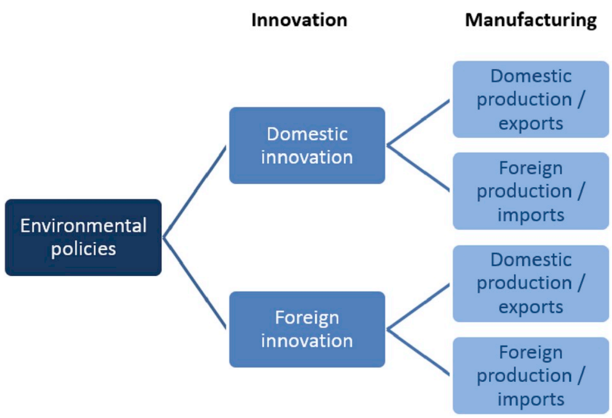

Fig. 1. Channels from environmental regulation to innovation and manufacturing.

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 (Obstfeld and Rogoff, 2001) which suggests that environmental technologies might be disproportionately produced at home.

To evaluate the claim that environmental policies stimulate the domestic economy through innovation and the production and trade of technologies, this paper provides empirical evidence focusing on the renewable energy sector of OECD countries. There are 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 (Fig. 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 using various measures of policies and innovation (Jaffe and Palmer, 1997; Popp, 2002; Johnstone et al., 2010). In particular, some papers examine the effects of regulation in one country on innovation abroad (Peters et al., 2012; Dechezlepretre and Glachant, 2014), or on the transfers of technologies (Popp, 2006; Dechezlepretre and Meniere, 2013; Verdolini and Bosetti, 2017). However, the literature that compares the response of domestic and foreign technologies to policies is limited to Lee et al. (2011), which only covers 15 US auto companies. In the first part, using patent data as a measure of innovation and technology adoption, this paper provides the first cross-country study of the degree to which environmental policies stimulate the development of domestic technologies compared to the use of foreign technologies. The analysis allows for policies to have long-term effects and be endogenous, and tests the robustness of the 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, manufacturing production are proxied with exports to examine whether technological innovation led to an increase in the domestic production of renewable technologies or the inputs into those technologies. While the effect on exports is only a lower bound for the production effect, 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, the results compare the effect of innovation on exports to the effect on imports.

Ambec et al. (2013) explains that although papers have examined the links between environmental policies and trade (Copeland and Scott Taylor, 2004; Brunnermeier and Levinson, 2004; Brunel, 2017) or productivity (Berman and Bui, 2001; Greenstone, 2002), only Lanoie et al. (2011) provides evidence on the source of the change in business performance. Given the cross-sectional nature of the data, the authors are not able to control for unobservable heterogeneity and are restricted to binary measures of innovation and business performance. 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.[5] Policies could also affect the production of technologies directly without going through innovation, and this paper tests the direct channel as well. Finally, examining the effect of innovation on production addresses 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, we should observe no effect of a rise in innovation on manufacturing production.

Combining the two steps, this paper identifies 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) 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 posed above can be answered by examining the renewable energy sector, which includes solar, wind, biomass, and geothermal, for 31 OECD countries from 1988 to 2003.[6] 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 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.

The results suggest that overall renewable energy policies lead to a

[5] For papers on the links between patenting and trade beyond the renewable energy industry, please refer to Brunel and Zylkin (2019), Palangkaraya et al. (2017), Chalioti et al. (2017), and De Rassenfosse et al. (2016).

[6] Four OECD countries are excluded because of data unavailability: Chile, Iceland, Korea, Latvia.

rise in the adoption of foreign technologies but few new inventions at home. Important exceptions exist, however, as significant increases in domestic innovation occur for specific countries – Germany, Japan, and the United States – and to a lesser extent for solar energy. Through this innovation channel, policies are in turn associated with a significant rise in the domestic production of renewable technologies, especially for wind. On average, renewable energy policies appear to boost domestic economic activity through either innovation or manufacturing depending on the renewable energy. Only Germany, Japan, and the United States have been able to benefit from a boost in both activities.

While this study focuses on the renewable energy sector, the framework is replicable for other sectors 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. This study 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, no judgment is passed on the environmental benefits of these policies. The renewable energy policies studied in this paper could succeed or fail in achieving their environmental goals. The objective here 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,[7] yet empirical evidence of the veracity of the claims is limited.

The paper is organized 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,[8] the estimation strategy, and the results. Section 5 concludes.

2. Environmental regulation and the origin of technologies

To estimate the links between environmental policies and the adoption of technologies, one needs a measure of innovation and a measure of environmental policies. The next subsections describe how those variables are created, followed by a description of the estimation procedure and a presentation of the results.

2.1. Policy measure

The necessary measure of policies should be specific to renewable energies and vary across countries and time. As shown in Brunel and Levinson (2016), 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 (Johnstone et al., 2010), the analysis starts with a simple count of the number of new policies enacted in country i at time t that are aimed at developing renewable energy sources.[9] This count therefore essentially captures the change in policy from year to year.

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 on polluting activities, tariffs, tradable permits, voluntary programs, and obligations. Apart from R&D policies, most policies do not explicitly provide incentives for innovation. However, by decreasing the relative price of the use of renewables compared to fossil fuels or increasing the demand for renewable energy, these policies supply implicit incentives for innovation.

The simple count has the advantage of being transparent, simple, and easily interpretable but is by no means an ideal measure. Chief among its drawbacks is that it weighs each policy type equally. To address that issue, the results are also presented by 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. Fig. A1 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 of implementation and in the type of policy instruments used, with many countries implementing more than one type of policy. Table A2 presents the summary statistics of the policy variable.[10] 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, regulatory instruments and policy support.

However, even the breakdown by policy is an imperfect measure. The same policy can vary significantly across countries. For example, in 1996 Belgium implemented a feed-in-tariff (FIT) for wind production of 0.025 euros per kilowatt-hour. In the same year, Italy set up an FIT for the same technology at almost five times the level: 0.120 euros per kilowatt-hour. The count measure assigns the same weight to both. In an attempt to quantify these differences across countries, data on feed-in-tariffs for all the technologies and all the countries were obtained from the OECD/ENV Renewable Energy Policy Dataset which builds on the Johnstone et al. (2010) dataset.[11]

In sum, the paper presents results using three different measures of policy: an overall count, a count by measure type, and a continuous measure quantifying the level of one of the most widely-used policies.

2.2. Innovation and adoption of technologies

In addition to the measure of policies, this analysis requires a measure of innovation. Here, patent data is used to measure innovation and adoption of new technologies in each OECD country. The data come from the PATSTAT database which includes all patent applications filed at the national patent offices of the 31 OECD countries as well at the European Patent Office (EPO).[12] A patent grants protection

[7] For example, Economic Report of the President 2015 (ERP, 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”.

[8] The data is available from the author upon request.

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

[10] All patent variables have been submitted to a Breitung panel unit root test. The test is rejected at the 5% level for all of them, indicating that there are no unit roots.

[11] FITs generally differ across countries in terms of which technologies are eligible or the mix of energy sources mandated. In the EU rules are governed by the Commission and thus FITs are more comparable across EU countries than any other set.

[12] Data 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 et al. (2011).

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 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, the measure can 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.

These patent counts are weighted by family size to account for the value of the patent. 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, each patent is weighted by the number of countries in which that invention is patented, also called family size. Citations data are another popular measure for accounting for the value of patents. Both citations and family size have been proven to be significantly correlated with patent value (Harhoff et al., 2003) but given that citation practices differ across countries, family size is a better value indicator for international comparisons (de Rassenfosse, 2013). A patent family is a set of patents taken in various countries to protect a single invention. More valuable inventions are likely to seek greater geographical coverage, and therefore to be part of larger families. This is especially important in my case because domestic and foreign patents could have different values. Fig. A2 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.

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. The International Patent Classification (IPC) codes used are presented in Table A1 (Popp et al., 2011). It is possible that some codes might include irrelevant technologies, while others might exclude relevant technologies. However, Popp et al. (2011) estimates that these errors are small for renewable energies.

Patent data presents some challenges. First, patents that seek protection in the European Union can be filed in one of the national patent offices or at the EPO. EPO applications require inventors to specify in which EU member states the patent would be applicable. The cost increases proportionally to the number of countries, providing an incentive for inventors to designate only the countries where the patent would be used. In fact, in my dataset a patent filed at the EPO designated on average just 12 of the 38 member states of the EPO. The designation of states is crucial for this study which needs to assign each patent to individual EU member states. However, data on designated states are no longer part of PATSTAT. Hence, this data was collected by hand for over 5,000 EPO patents through 2003.

Second, it is possible that some valuable innovations 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 A2 presents the summary statistics for patent counts weighted by family size: total, domestic, and foreign.[13] 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. Fig. A3 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.

2.3. Estimation procedure

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

$$DomesticPatents_{it} = \beta_1^H POL_{it} + \beta_2^H \boldsymbol{X_{it}} + \gamma_i^H + \delta_t^H + e_{it}^H \tag{1}$$

$$ForeignPatents_{it} = \beta_1^F POL_{it} + \beta_2^F \boldsymbol{X_{it}} + \gamma_i^F + \delta_t^F + e_{it}^F \tag{2}$$

Domestic Patents$_{it}$ and *Foreign Patents*$_{it}$ measure adoption of domestic or foreign renewable energy technologies in country i at time t. POL_{it} is one of the three policy measures for country i in year t. The vector $\boldsymbol{X_{it}}$ contains other controls detailed in the next paragraph. γ_i and δ_t are country and time fixed effects respectively, and H and F superscripts represent home and foreign respectively. The key parameters, $\beta_1{}^H$ and $\beta_1{}^F$, represent the effect of policies on domestic and foreign patent filings respectively. Comparing the two will determine whether environmental policies boost domestic innovation or the use of foreign technologies.

The vector $\boldsymbol{X_{it}}$ 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, the regression includes a control for the price of electricity obtained from the IEA Energy Price and Taxes Database. Because prices for electricity vary depending on whether the electricity is consumed by industry or households, the price variable is constructed by weighting the price indices for residential and industrial use by their respective consumption levels (Johnstone et al., 2010). Since renewable sources represent a relatively small proportion of total electricity generation for each country over my time period – between 3 and 7 percent –, the price of electricity can be considered exogenous in this context.[14] For the same reason, the overall electricity price can reasonably be considered to not be a function of renewable energy policies.[15] Second, potential market size is controlled for since returns on innovation, and therefore incentives to innovate, are affected by potential demand. For renewables, potential market size can be proxied by the growth in electricity consumption since renewable energies are more likely to capture new electricity generation than they are to replace existing electricity generation capacity.[16] These data are obtained from the IEA Energy Balance Database. 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

[13] All policy variables have been submitted to a Breitung panel unit root test. The test is rejected at the 5% level for all of them, indicating that there are no unit roots.

[14] Alternatively, proxying electricity prices through oil prices yields similar results.

[15] As detailed later, the paper also provides robustness checks excluding one or both of these controls.

[16] Results using electricity consumption levels instead of growth are qualitatively similar and available from the author upon request.

countries implementing renewable energy policies could affect innovation abroad thereby altering the stock of foreign patents that are available for transfer. Therefore, the analysis includes the total count of policies in all other OECD countries.[17] Moreover, 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 embody 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 account for world trends to shift towards renewable energies in terms of innovation or production. Country fixed effects capture 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 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 numbers of patents than countries where property rights do not exist or are not enforced.[18]

Finally, the estimation controls 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, equations (1) and (2) are estimated using a negative binomial since my dependent variable is an over-dispersed non-negative count variable. The error terms in equations (1) and (2) might be contemporaneously correlated as the decision an inventor makes about where to patent is strategic. 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, the estimation is done using a seemingly unrelated negative binomial method as developed by Winkelmann (2000).[19]

The next section also presents results using an Instrumental Variable (IV) estimation strategy in a robustness check. Identifying the effect of environmental policies on innovation is challenging due to various sources of endogeneity. First, firms that have invented 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.

2.4. Results

The contemporaneous effect of renewable energy policies on patent filings is positive but not significant for either domestic or foreign patents (Table 1, columns 1 and 2). However, inventors could need some time to file a patent in response to a policy if they develop brand new technologies. Moreover, contemporaneous policies could be endogenous as firms that have already innovated 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, columns 3 and 4 show regressions with environmental policies at time *t-1*. An additional environmental policy at time *t-1* is associated with a statistically significant 31.2 percent increase in patent filings by foreign inventors.[20] Domestic inventors, on the other hand, do not significantly respond to the policies even accounting for the lag.[21] Given the mean of the policy count is 0.673 a year, one additional policy represents a sizable increase, which explains the large magnitude of the foreign effect and impresses further the lack of effect on the domestic inventor side. Beyond the lack of significance, the percentage increase for domestic is smaller than for foreign in magnitude and the amount of domestic patents is significantly smaller than the amount of foreign patents (see Table A2). Evaluating the coefficients at the mean of the respective patent counts and considering the average family size over the period, a total of 53 new patents are filed following the implementation of a new renewable energy policy in the OECD, at most one of which is a patent owned by a domestic inventor.[22] Therefore, the rise in technology adoption overwhelmingly originates from foreign patents.

Looking into the long-run effects of the policies indicates again that foreign patent filings respond more than domestic patent filings (Table 2).[23] Foreign patents appear to respond positively to policies up to 2 years after the year of enactment. In the next year, the negative binomial coefficient represents a negative effect of policies on patents. This is most likely explained by international patenting rules. Foreign inventors can respond to a policy by developing a brand new technology, but it is also possible that they could simply transfer an existing technology that has just become relevant in another country due to a newly implemented policy. Table 3 columns 1 and 2 separate foreign patents into transfers of existing technologies – defined as patents that were previously filed in another country – and new technologies – patents that were not previously filed elsewhere. The results suggest that policies do not spur new inventions by foreign inventors but rather incentivize foreign inventors to transfer their existing technologies to the country with the new policy.[24] According to international patenting rule, transferring a patent to another patent office can only be done within a restricted period of time after the patent was granted, usually less than 18 months but up to three years if going through the Patent Cooperation Treaty rules. Therefore, the negative effect at time $t+3$ could be slump in patent filings due to transfers no longer being possible.

Beyond the temporal variation in the effects, there are also some important differences across countries. In Japan, Germany and the United States – three countries that have high levels of innovation in the economy overall – policies in fact significantly stimulate domestic innovation (Table 3 columns 3–6). These results would support the idea of the first-mover advantage since Germany is also the first country in

[17] Since 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 countries. The policy count of foreign countries is therefore identified by EU policies.

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

[19] Further explanation of the methodology is provided in Appendix B.

[20] The coefficients are exponentiated so numbers beyond one represent a percentage increase, and below one a percentage decrease.

[21] Table A3 shows that the conclusion that foreign patent filings respond more to policies than domestic patent filings is also present in specifications including different sets of controls.

[22] The formula: mean weighted patent count * coefficient/average family size. The average family size is 6 over the period.

[23] Note that another advantage of the lagged specification is that if there is persistence in the number of policies enacted each year, the lagged policy measure alone did not entirely remove the previously mentioned source of endogeneity whereby firms that have innovated lobby for more policies. This lagged specification therefore provides more consistent estimates.

[24] Note that these could be transfers within a multinational corporation (Bilir, 2014).

Table 1
Effect of policies on innovation.

	Seemingly Unrelated Negative Binomial			
	(1)	(2)	(3)	(4)
	Domestic	Foreign	Domestic	Foreign
Policy_t	1.090	1.027		
	(0.111)	(0.072)		
World policy_t	1.154	1.079		
	(0.117)	(0.095)		
Policy_{t-1}			1.070	1.386**
			(0.054)	(0.142)
$\text{World policy}_{t-1}$			1.123	1.643***
			(0.069)	(0.200)
Electricity consumption growth	1.023	1.152	1.019	1.135
	(0.028)	(0.088)	(0.026)	(0.077)
Electricity price	1.006	1.035***	1.005	1.032***
	(0.004)	(0.011)	(0.004)	(0.009)
Patenting trend	0.989	0.951	0.989	0.957*
	(0.010)	(0.025)	(0.009)	(0.021)

Notes: *p < 0.05, **p < 0.01, ***p < 0.001. Standard errors are clustered at the country-level; N = 445. All regressions includes country and time fixed effects.

Table 2
Effect of policies on innovation – multiple lags.

	(1)	(2)
	Domestic	Foreign
Policy_{t-1}	1.101	1.320***
	(0.063)	(0.091)
Policy_{t-2}	1.161	1.344*
	(0.093)	(0.202)
Policy_{t-3}	0.988	0.841**
	(0.070)	(0.048)
Policy_{t-4}	1.937	1.366
	(0.941)	(0.573)
$\text{World policy}_{t-1}$	1.149*	1.564***
	(0.075)	(0.135)
$\text{World policy}_{t-2}$	1.298*	1.967***
	(0.133)	(0.321)
$\text{World policy}_{t-4}$	1.807	1.616
	(0.858)	(0.689)
Electricity consumption growth	6.930	2.124
	(14.521)	(3.180)
Electricity price	1.003	1.030***
	(0.004)	(0.006)
Patenting trend	0.995	0.997
	(0.004)	(0.005)

Notes: *p < 0.05, **p < 0.01, ***p < 0.001. Standard errors are clustered at the country-level; N = 445. All regressions includes country and time fixed effects. $\text{World policy}_{t-3}$ is excluded because of collinearity. The vector inflation factor for this variable is 40, much larger than the accepted threshold of 10.

my dataset to have implemented policies favoring the use or development of renewable energy technologies. The case of Japan and the United States, which implemented policies later, might suggest that overall innovative capacity played a key role in positioning them as a center of innovation for renewable energies. Foreign innovation is also boosted by the policies, in line with the aggregate results and consistent with the idea that highly innovative and large markets attract foreign inventors. The other 28 countries benefit from adopting foreign technologies but do not develop their own.

Breaking down the policy variable into different categories shows that economic instruments (emission allowances, infrastructure investments, fiscal incentives), regulatory instruments (product standards, building codes, auditing and monitoring), and Research, Development and Deployment (RD&D) are the main drivers of the policy effect (Table 4). Interestingly, domestic patent filings respond positively and significantly to economic instruments and RD&D. However, for each of these categories, the effect is stronger on foreign in terms of both statistical significance and economic magnitude. Using a stock rather than a flow of policies confirms this as well.

Policies do not affect all renewable energy types in the same way. Feed-in-tariffs have a significant effect on foreign patent filings for wind technologies (Table 4 columns 5–12).[25] In fact, in the case of wind, no other policy seems effective for boosting the transfer of foreign technologies. However, other policies are more effective for solar and stimulate both the transfer of foreign technologies as well as domestic innovation in an important way, though again the strongest effect comes from foreign patent filings. On the other hand, policies aimed at geothermal and biomass and waste do not appear to affect innovation at all.

The remainder of this section provides a series of checks that the association previously identified between policies and patenting is not confounded by unobserved characteristics and can be interpreted as causal. Table 3 columns (9) and (10) shows a falsification test using policy in period $t+1$, which should not have any effect on current patenting trends. The coefficients are indeed statistically zero for both domestic and foreign patent filings. Despite the current controls and lagged variables, some endogeneity might remain. 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. In addition, 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, the Hausman and Taylor (1981) method 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, the first two lags are removed from the instruments to avoid further issues related to the persistence of policies. Table 3 columns (7) and (8) shows that accounting for endogeneity, an additional policy at time *t-1* is associated with a 36.7 percent increase in foreign patents, but also a 11.2 percent increase in domestic patents, which represents two additional patents evaluated at the mean (column 5). Therefore, the conclusion remains that environmental policies primarily stimulate foreign patent filings.

Before finishing off this section, it is worth noting that the coefficients on the covariates generally comport with intuition. An increase in the price of electricity or in the demand for electricity has a positive 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 the country that implemented the policy. The coefficient on the patenting trend is negative, which might suggest that higher innovation in other sectors crowds out innovation in renewable energies since investment resources are limited, although the coefficient is not significant in most regressions. Table A3 provides regressions excluding one or more of the above variables gradually. For example, electricity prices could be a proximate outcome of the policies and therefore a "bad control" as defined by Angrist and Pischke (2008). Removing electricity prices from the regression does not significantly alter the magnitude of the policy coefficients. Finally, regressions using alternative controls –

[25] The data by technology provides much less variation since both the amount of patents and the level of the policies are significantly reduced. Therefore, the coefficients are less significant overall.

Table 3
Effect of Policies on Innovation – Other specifications.

	Foreign type		Country subgroups				Causality			
			DE, JP, US		Other 28		NLIV		Falsification	
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
	Trans.	New	Dom.	Frgn	Dom.	Frgn	Dom.	Frgn	Dom.	Frgn
$\text{Policy}_{t\text{-}1}$	1.379**	0.986	1.383***	1.115**	1.045	1.430***	1.112*	1.367**		
	(0.140)	(0.076)	(0.037)	(0.037)	(0.064)	(0.160)	(0.060)	(0.150)		
Policy_{t+1}									1.039	0.977
									(0.043)	(0.034)
$\text{World policy}_{t\text{-}1}$	1.638***	0.983	1.309***	1.149*	1.087	1.711***	1.171	1.583***	1.033	1.280***
	(0.199)	(0.082)	(0.064)	(0.068)	(0.090)	(0.230)	(0.100)	(0.200)	(0.064)	(0.095)
Electricity consumption growth	1.048*	0.991	1.116***	1.029	1.030	1.049	1.020	1.133*	1.044	1.063*
	(0.025)	(0.024)	(0.010)	(0.016)	(0.027)	(0.030)	(0.020)	(0.070)	(0.026)	(0.031)
Electricity price	1.042***	1.009	1.052***	1.055*	1.007	1.042***	1.005	1.031***	1.008	1.046***
	(0.009)	(0.006)	(0.007)	(0.005)	(0.005)	(0.010)	(0.000)	(0.010)	(0.005)	(0.010)
Patenting trend	0.992	0.993	1.001	1.011*	0.968	0.969	0.990	0.960*	0.996	0.994
	(0.005)	(0.005)	(0.005)	(0.004)	(0.033)	(0.050)	(0.010)	(0.020)	(0.004)	(0.005)
N	445	445	48	48	397	397	445	445	418	418

Notes: *p < 0.05, **p < 0.01, ***p < 0.001. Standard errors are clustered at the country-level. All regressions includes country and time fixed effects. Foreign transfers refer to transfers of existing foreign technologies measures as patents that were previously filed in another country. Foreign new refers to patents that were not previously filed elsewhere. DE = Germany, JP = Japan, US = USA. Dom = domestic, Frgn = foreign.

Table 4
Effect of alternative measures of policy on innovation.

	All technologies				Wind		Solar		Geothermal		Biomass & waste	
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
	Dom.	Frgn	Dom.	Frgn	Dom.	Frgn	Dom.	Frgn	Dom.	Frgn	Dom.	Frgn
$\text{Economic instruments}_{t\text{-}1}$	1.362*	1.861*										
$\text{Regulatory instruments}_{t\text{-}1}$	1.202	1.717*										
$\text{Research \& Development}_{t\text{-}1}$	1.583*	2.859***										
$\text{Policy support}_{t\text{-}1}$	0.984	1.210										
$\text{Information \& education}_{t\text{-}1}$	1.211	1.362										
$\text{Voluntary contribution}_{t\text{-}1}$	0.575**	0.668										
$\text{Stock of policies}_{t\text{-}1}$			1.147**	1.291***								
$\text{Stock of world policies}_{t\text{-}1}$			1.194**	1.614***								
$\text{Feed-in-tariffs}_{t\text{-}1}$					0.968	1.031*	0.872	1.002	0.796	1.023	0.032	1.008
$\text{Other policies}_{t\text{-}1}$					0.96	1.124	1.240*	1.367*	0.569	0.991	0.731	1.151
$\text{World policy}_{t\text{-}1}$	1.299**	2.002***			0.884	1.246*	1.291	1.610*	0.517	0.974	0.719	1.331*
Electricity consumption growth	1.031	1.044	1.020	1.000	1.005	0.984*	0.989*	0.991	0.997	0.986*	0.986*	1.001
Electricity price	1.005	1.040***	0.999	1.017**	1.037*	1.009	1.031	1.040	1.051	0.993	0.959	1.031
Patenting trend	0.996	0.994	0.998	1.009	0.989*	1.023*	1.001	1.036*	1.001	1.006	1.010	1.031*

Notes: *p < 0.05, **p < 0.01, ***p < 0.001. Standard errors are clustered at the country-level; N = 445. All regressions includes country and time fixed effects. Dom = domestic, Frgn = foreign.

electricity consumption in levels instead of growth, or a more general economic trend using GDP in place of the patenting trend – are qualitatively similar and available from the author upon request.

In sum, this section finds that policies which aim to foster the development and use of renewable energies are associated with a significant increase in patent filings of around 30 percent, but outside of highly innovative economies such as Germany, Japan, or the United States, 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 is robust to addressing potential endogeneity issues. Even in the few regressions where domestic patents respond significantly, the economic magnitude is small – one or two patents per year at most. Important differences are present by renewable energy type: wind responds to FITs only through an increase in foreign patents, while solar responds to other policies and exhibits an increase in domestic patent filings as well; geothermal and biomass and waste appear unaffected. The claim that renewable energy policies stimulate innovation in renewable energy technologies therefore finds support limited to some countries and some technologies. However, policies could still stimulate the domestic renewable energy sector more broadly if these foreign transferred technologies spur manufacturing production.

3. 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. This section examines 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. It is therefore implicitly assuming 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 we should observe no effect.

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, this section uses exports as a proxy for domestic production. Exports are an imperfect proxy for domestic manufacturing production as they only allow to capture the part of domestic production that is exported, not the part for domestic consumption. As a result, the results will understate the effect of innovation on domestic production.

However, one benefit of exports, beyond being available at the necessary level of disaggregation, is that they 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, this paper examines 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.

3.1. Data

The measure of technology adoption is patents as in the first part of the paper, but we no longer need to distinguish between domestic and foreign inventors. 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.

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 economyy. As a result, patents are aggregated into knowledge stocks following standard methods (Popp et al., 2011):

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

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 et al. (2011), the patent rate of decay is set to 0.1 and the rate of diffusion to 0.25, which implies a patent life peaking at 4–5 years. 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. A list of product categories including primary renewable products and technologies as well as common components of renewable energy based systems is compiled using information from the Organization for Economic Cooperation and Development (Steenblik, 2005), the International Trade Commission (Lane and Pearson, 2005; Rogowsky, 2009), and the International Center for Sustainable Trade and Development (Wind, 2008). Table A4 presents the resulting list of products based on the Harmonized System commodity classification (HS code) at the 6-digit level. Export and import data at the HS 6-digit level come from the United Nations COMTRADE database.

3.2. Estimation procedure

The trade data and the stock of patented technologies are used to 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 agreements. 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, 2014).[26]

The gravity equations augmented with a measure of available technologies are estimated in the following way:

$$\ln(Exports_{ijt}) = \beta_1^X \ln(K_{it}) + \beta_2^X \boldsymbol{X_{ijt}} + \gamma_{ij}^X + \delta_t^X + v_{ij}^X \tag{4}$$

$$\ln(Imports_{ijt}) = \beta_1^M \ln(K_{it}) + \beta_2^M \boldsymbol{X_{ijt}} + \gamma_{ij}^M + \delta_t^M + v_{ij}^M \tag{5}$$

where $ln(Exports_{ijt})$ and $ln(Imports_{ijt})$ represent log exports and imports between countries *i* and *j* at time *t*. This paper includes exports from the 31 OECD countries but destined for any country in the world. Similarly, the import equations includes imports from the 31 OECD countries originating from anywhere in the world. Thus in both equations, country *i* is one of the 31 countries in the dataset, while country *j* can be any country which trades with country *i*.[27]

K_{it} is the stock of knowledge related to renewable energies in country *i* at time *t* described in the previous section. $\boldsymbol{X_{ijt}}$ contains the gravity model variables from the CEPII gravity model dataset (Head et al., 2010): log population in patenter and partner, log GDP in patenter and partner, an indicator for whether the pair has signed a regional or bilateral trade agreement, and an unweighted average of the tariff rates. Finally, γ_{ij} and δ_t are country-pair and time fixed effects, respectively. Comparing the magnitude and significance of $\beta_1{}^M$ and $\beta_1{}^X$ will determine whether an increase in technology adoption is mostly associated with a rise of domestic production proxied by 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. This paper thus estimates the gravity equations using PPML and provides robustness checks using ordinary least squares (OLS).

Table A5 provides the summary statistics for trade flows and the

[26] Appendix B provides additional background on the gravity model.

[27] The robustness checks provide a more classical gravity model for trade restricted to the 31 OECD countries for both patenter and partner.

Table 5
Effect of innovation on trade – PPML and OLS.

	PPML		OLS		
	(1)	(2)	(3)	(4)	(5)
	Exports	Imports	Log(X)	Log(M)	Log(X-M)
Log R.E. patent stock	0.124***	0.007	0.143***	0.000	0.130***
	(0.034)	(0.024)	(0.018)	(0.020)	(0.130)
Log population in origin	0.279	2.338*	2.123***	0.557	2.803***
	(1.067)	(0.960)	(0.579)	(0.733)	(0.729)
Log population in destination	1.361***	0.084	2.120***	0.997**	1.442***
	(0.398)	(0.822)	(0.218)	(0.339)	(0.236)
Log GDP in origin	0.379**	0.621***	0.324***	0.635***	0.037
	(0:118)	(0:109)	(0:086)	(0:108)	(0:102)
Log GDP in destination	0.498***	0.735***	0.970***	0.556***	0.962***
	(0.080)	(0.118)	(0.051)	(0.076)	(0.055)
RTA	0.559***	0.639***	0.426***	0.300***	0.267***
	(0.083)	(0.094)	(0.058)	(0.068)	(0.069)
Tariffs	0.023	−0.045	−0.029	0.001	0.029
	(0.077)	(0.040)	(0.034)	(0.024)	(0.073)
N	74,095	74,095	44,440	29,366	38,540

Notes: *p < 0.05, **p < 0.01, ***p < 0.001. Standard errors are clustered at the country-level. All regressions includes country-pair and time fixed effects.

Table 6
Instrumental variable approach – first stage.

	(1)
	Log R.E. patent stock
Log non-energy patent stock	1.208***
Log population	1.488***
Log GDP	2.406***
N	74,095

Notes: *p < 0.05, **p < 0.01, ***p < 0.001. Standard errors are clustered at the country-level. All regressions includes country-pair and time fixed effects.

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.

3.3. Results

Both the PPML and the OLS specifications demonstrate that the stock of renewable technologies is associated with a significant rise in exports (Table 5). In the PPML regressions – the preferred specification – a 1 percent increase in the stock of renewable energy patents is associated with a 0.124 percent rise in exports – $15,004 evaluated at the mean from Table A5 – and no significant change in imports. These two trade effects combined suggest that patents are being filed with the aim of producing locally, rather than protecting foreign-produced goods. Since imports do not increase, the increase in exports alone suggests a net increase in domestic production. Nonetheless, exports are an imperfect proxy for domestic production and thus column (5) presents 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 boosts net exports, confirming that increased patents will be associated with a rise in domestic manufacturing production.

Table 7
Effect of innovation on trade – instrumental variable approach.

	IV-PPML	
	(1)	(2)
	Exports	Imports
Log R.E. patent stock	0.146***	−0.080
	(0.037)	(0.048)
Log population in origin	0.404	2.468*
	(1.129)	(0.978)
Log population in destination	1.382***	−0.189
	(0.401)	(0.806)
Log GDP in origin	0.335**	0.673***
	(0.110)	(0.101)
Log GDP in destination	0.492***	0.726***
	(0.080)	(0.117)
RTA	0.571***	0.662***
	(0.081)	(0.096)
Tariffs	0.017	−0.040
	(0.078)	(0.039)
N	74,095	74,095

Notes: *p < 0.05, **p < 0.01, ***p < 0.001. Standard errors are clustered at the country-level. All regressions includes country-pair and time fixed effects.

Table 8
Effect of innovation on trade – domestic and foreign patents.

	IV-PPML	
	(1)	(2)
	Exports	Imports
Log R.E. domestic patent stock	−0.088**	−0.115***
	(0.032)	(0.027)
Log R.E. foreign patent stock	0.208***	0.003
	(0.041)	(0.039)
Log population in origin	0.634	2.032*
	(1.084)	(0.932)
Log population in destination	1.403***	−0.169
	(0.394)	(0.792)
Log GDP in origin	0.246	0.583***
	(0.136)	(0.111)
Log GDP in destination	0.501***	0.728***
	(0.079)	(0.115)
RTA	0.577***	0.669***
	(0.082)	(0.093)
Tariffs	0.029	−0.026
	(0.077)	(0.038)
N	80,415	66,765

Notes: *p < 0.05, **p < 0.01, ***p < 0.001. Standard errors are clustered at the country-level. All regressions includes country-pair and time fixed effects.

However, trade can be a vehicle for technology transfer (Keller, 2004; Bloom et al., 2011; Autor et al., 2016; Batrakova and Dechezlepretre, 2013) and therefore the coefficients could both suffer from a bias. For example, 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. Alternatively, 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, the stock of knowledge in renewable technologies is instrumented with the stock of knowledge in all other non-energy technologies. Since the endogeneity issue is a concern for the contemporaneous portion of the stock, only that part is instrumented. The instrument is relevant since there is a common

Table 9
Effect of innovation on trade – robustness checks.

	Country subgroups				By Technology			
	DE, JP, US		Other 28		Solar		Wind	
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	Exports	Imports	Exports	Imports	Exports	Imports	Exports	Imports
Log R.E. patent stock	0.721***	0.790***	0.091*	0.040	0.054	0.067*	0.164**	−0.194***
	(0.150)	(0.140)	(0.040)	(0.050)	(0.040)	(0.030)	(0.060)	(0.050)
Log population in origin	13.050***	17.485***	6.887***	7.406***	2.212	2.440	2.842	−0.709
	(1.730)	(1.590)	(1.980)	(1.110)	(1.510)	(1.460)	(2.010)	(2.130)
Log population in destination	1.344**	0.051	1.160**	0.452	−1.097	−0.841	1.516*	−0.919
	(0.430)	(0.840)	(0.410)	(1.080)	(0.080)	(1.100)	(0.760)	(1.800)
Log GDP in origin	0.722**	1.059***	0.576*	0.503*	0.161	0.602**	0.296	0.970**
	(0.260)	(0.280)	(0.220)	(0.220)	(0.150)	(0.190)	(0.250)	(0.370)
Log GDP in destination	0.707***	0.915***	0.514***	0.719***	0.591**	1.058***	0.443*	0.141
	(0.120)	(0.170)	(0.080)	(0.120)	(0.210)	(0.210)	(0.190)	(0.170)
RTA	0.509***	0.769***	0.479***	0.691***	0.480***	0.362**	0.575***	0.895***
	(0.120)	(0.130)	(0.080)	(0.120)	(0.110)	(0.120)	(0.120)	(0.230)
Tariffs	0.176*	0.225*	−0.173***	−0.023	0.028	0.067	0.116**	0.076
	(0.070)	(0.090)	(0.030)	(0.020)	(0.040)	(0.040)	(0.040)	(0.040)
N	8,596	7,805	72,132	59,227	63,443	48,684	58,838	37,440

Notes: *p < 0.05, **p < 0.01, ***p < 0.001. Standard errors are clustered at the country-level. All regressions includes country-pair and time fixed effects.

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. Equations (4) and (5) are estimated using an instrumental variable approach. The results from the linear first stage (Table 6) show that the instrument is highly relevant.

Accounting for endogeneity confirms the direction of the previous results. As can be seen in Table 7, a 1 percent increase in the stock of renewable energy patents is associated with a 0.146 percent increase in exports and no statistically significant effect on imports. Since the regression controls for tariffs, the lack of effect on imports is not due to domestic protection which might occur simultaneously.[28] Technology adoption is associated with an increase in domestic production. Interestingly, separating the stock between domestic and foreign patents, it appears that domestic patents lead to a reduction in exports and an even larger reduction in imports (Table 8). The coefficients are statistically different from one another so the net effect suggests that domestic patents might be geared towards domestic production for domestic consumption. Foreign patents on the other hand boost exports with no effect on imports.

Since the majority of exports of renewable energy technologies in the sample originate in Germany, Japan or the United States, the above effect on exports could be driven entirely by these three countries, which are highly innovative economies in all industries. Table 9 columns (3) and (4) however show that removing the main three exporters the conclusion remains that more patent filings is associated with a rise in domestic production and exports. Although the effect is an order of magnitude higher for the three top exporters, it is not the case that only the top three exporters benefits from technology adoption. In fact, for the top three exporters, patents filed are associated with a rise in both flows of trade suggesting that the overall competitiveness effect might be less positive for these three than for the rest of the group.

There is some important heterogeneity across the four renewable technologies. An increase in patent filings in the solar industry does not boost domestic production (Table 9 columns 5–8). Instead, it appears to lead to an increase in import competition. Although my dataset only goes to 2003, by then China already accounts for 22 percent of solar products imports into OECD countries. This share has only increased since 2003 and therefore indicates that the effect on imports might be larger now. The effect on domestic production being underestimated since this only accounts for domestic production that is exported, it is still possible that domestic solar manufacturing production for domestic consumption increases but cannot be captured here. For wind however, there is a large boost to domestic production coming both from an increase in exports and a decrease in import competition. The net effect is therefore an overwhelming boost to domestic production. Wind is a highly protected industry and although tariffs are controlled for, non-tariff barriers are not accounted for. The decrease in imports for wind might therefore be partially driven by trade barriers rather than technology adoption.

Finally, the above results allow the 31 OECD countries to trade with any country in the world. As a result, the analysis includes only the knowledge stock of the origin and not the knowledge stock of the destination since the data for non-OECD countries is not within the dataset. The estimation strategy therefore deviates from standard gravity models which includes all variables in both origin and destination countries. As a check, Table A6 restricts trading partners to OECD countries only. In a first instance, columns (1) and (2) present the same regression as above but limited to intra-OECD trade. An increase in the patenting stock in country *i* has a positive and significant effect on exports, and no significant effect on imports. Comparing these results to those in Table 7 suggests that the previous coefficients were driven mostly by intra-OECD effects. In a second step, columns (3) and (4) include the stock of available technologies in the partner country as a control. Patents in the partner country boost imports: the more the trading partner has innovated in terms of renewable energies, the higher the quantity of imports from that country, which is symmetric to the effect of the patent stock on the origin country on exports.

In sum, renewable energy innovation led to a rise in domestic production on average, though Germany, Japan, and the United States also face increased import competition. The wind industry seems to be the main benefiter of increased production. Combining the two sections of the paper, an environmental policy is associated with a 4.38 percent increase in exports of renewable energy technologies.[29] These figures

[28] Protectionist measures are common in renewable energy industries and the main producers and consumers of solar panels and wind turbines – the US, European Union, and China – are essentially engaged in a three-way trade war on those goods (Brewster et al., 2016).

[29] These “back of the envelope” figures are calculated multiplying the effect of the first part (30 percent) by the effect of the second part (0.146 percent for exports - IV result).

represent only the effect of policies on trade through the technology adoption channel. Table A7 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 is significant in both regressions, suggesting that there is an additional effect of policies on trade beyond the technology adoption channel. However, the effect of innovation on exports remains even in the presence of the policy variable and the size of the coefficient is qualitatively similar to the regressions excluding the policy variables. Moreover, the innovation channel dominates the direct effect of the policy by an order of magnitude, which clearly indicates that the innovation channel is an important driver of the effects of policies on manufacturing production and international competitiveness.

4. Conclusion

The sheer magnitude of the political and monetary capital being invested into greening the economy around the world suggests 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 devised here 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. The most prominent scenario is identified 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, the analysis finds that renewable energy policies result in a 30 percent increase in patent filings, but few of these are developed by domestic inventors. Only in historically innovative economies such as Germany, Japan, and the United States do domestic inventors respond significantly to the implementation of a policy. In the rest of the OECD, adopted technologies are largely licensing of foreign technologies rather than new technologies developed at home. However, examining the four renewable technologies individually reveals that policies aimed at solar are associated with a statistically significant but economically small increase in domestic production.

In the second step, the paper asks whether the increase in technology adoption led to a spike in domestic manufacturing production or to a rise in imports. Results show that domestic production – proxied by exports – increased significantly following technology adoption and the effect is strongest for the wind industry. 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 4.38 percent rise in domestic production through the innovation channel, and a further effect directly on manufacturing. Therefore, the evidence suggests that renewable policies in the OECD stimulate the economy through manufacturing but much less through innovation outside of a few select countries.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2019.109290.

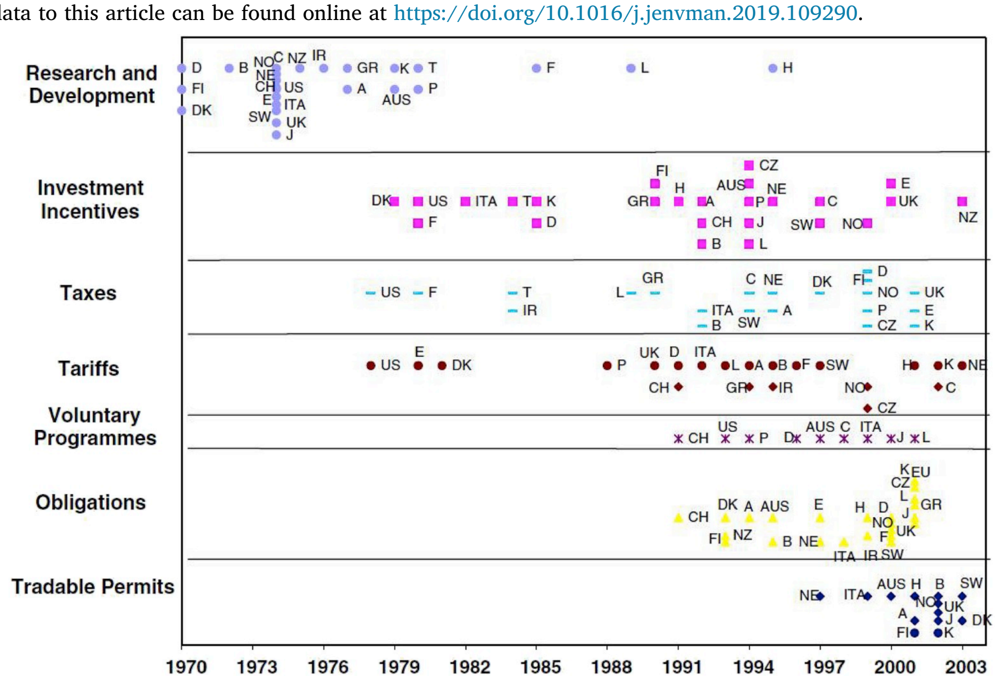

Fig. A1. Introduction of Renewable Energy Policies in the OECD. Source: IEA (2004)

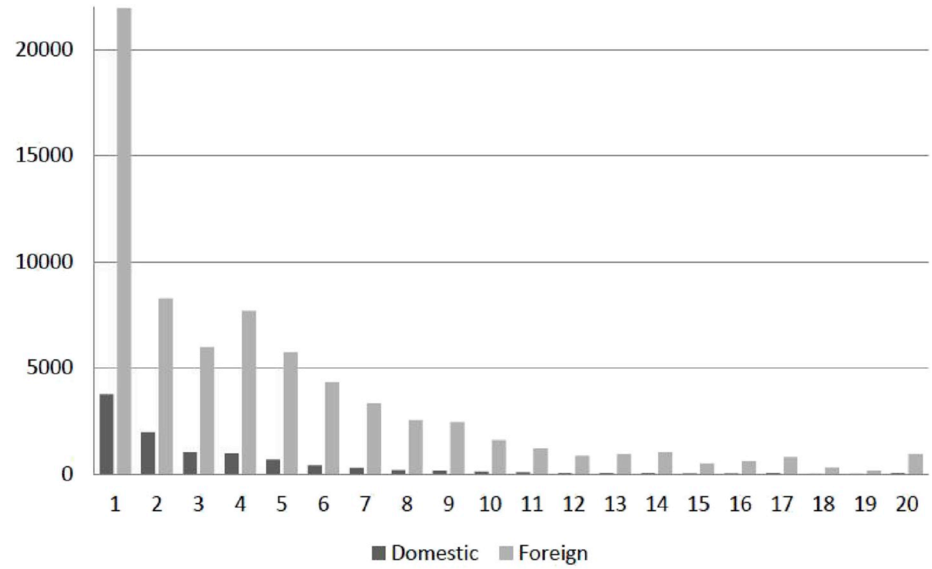

Fig. A2. Frequency Plot of Family Size by Origin. Source: Author's calculations

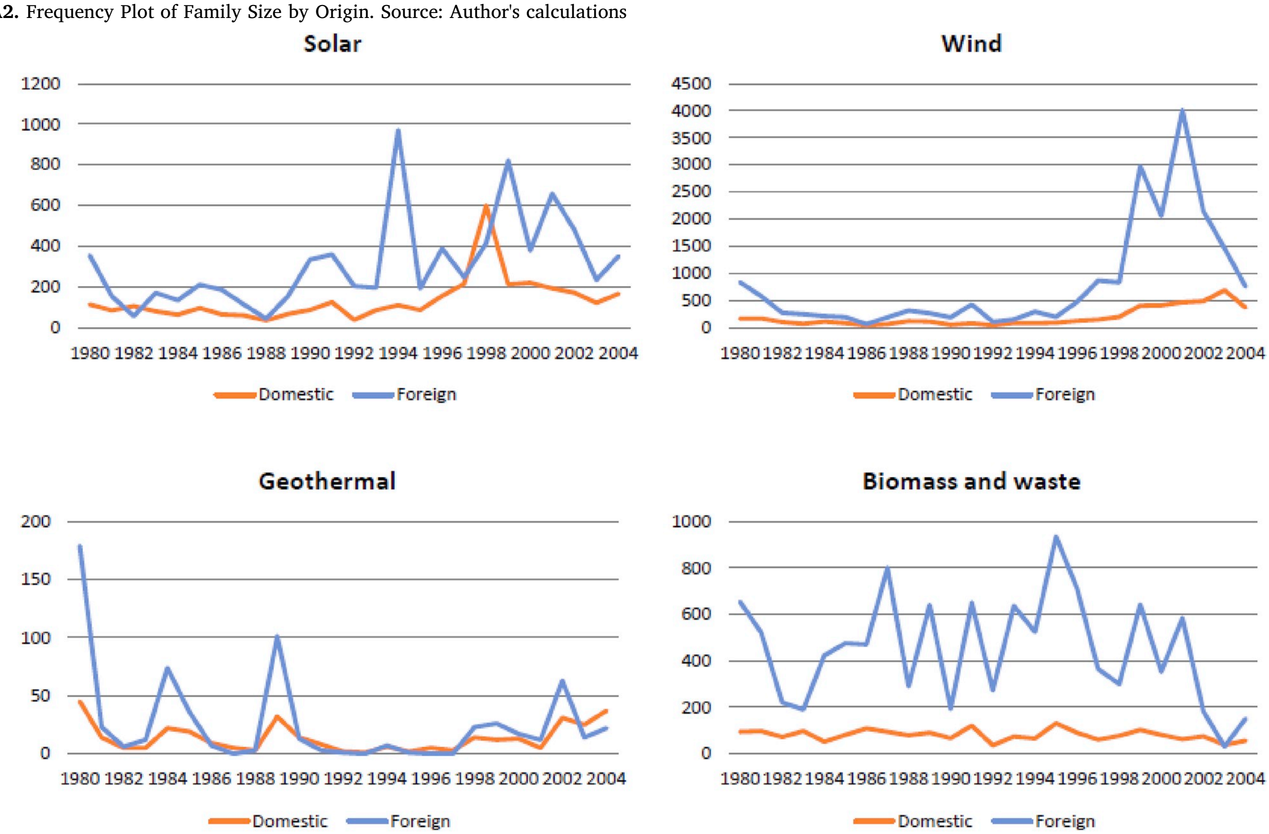

Fig. A3. Renewable Patents in OECD countries, by Technology. Source: Author's calculations

Appendix

Table A1
Patent Classes of Renewable Energy Technologies

Patent 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
GEOTHERMAL	
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 fluid energy into mechanical energy; use of waste heat	F01K27
Use of waste heat of combustion engines-Profiting 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 A2
Summary Statistics of Policy Stringency Measure and Weighted Patent Counts

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
Feed-in-tariffs (€/kWh)				
Wind	0.021	0.050	0	0.81
Solar	0.021	0.068	0	0.81
Geothermal	0.015	0.049	0	0.81
Biomass and waste	0.014	0.045	0	0.81
Patents	604	741	0	3851
Domestic patents	54	170	0	2018
Foreign patents	550	665	0	3341

Table A3
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}	1.002	0.878	1.097	4.353	1.092	4.500	1.091	1.349	1.075	1.413^{**}	1.080	1.312^{**}
	(0.035)	(0.081)	(0.058)	(4.139)	(0.056)	(4.300)	(0.057)	(0.283)	(0.053)	(0.159)	(0.055)	(0.120)
World policy_{t-1}			1.139	5.641	1.119	5.711	1.113	1.544	1.128^{*}	1.670^{***}	1.134^{*}	1.527^{***}
			(0.092)	(5.326)	(0.085)	(5.425)	(0.082)	(0.433)	(0.069)	(0.216)	(0.072)	(0.164)
Elec. consumption							1.025	1.277^{*}			1.019	1.135
							(0.028)	(0.131)			(0.026)	(0.077)

(continued on next page)

Table A3 (*continued*)

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
	D	F	D	F	D	F	D	F	D	F	D	F
Electricity price									1.006	1.044***	1.005	1.032***
									(0.005)	(0.010)	(0.004)	(0.009)
Patenting trend					0.992*	0.985*	0.986	0.914*	0.994	0.992	0.989	0.957*
					(0.004)	(0.006)	(0.010)	(0.034)	(0.004)	(0.005)	(0.009)	(0.021)
Observations	496	496	496	496	496	496	492	492	445	445	445	445

*p < 0.05, ** p < 0.01, ***p < 0.001 Exponentiated coefficients; Standard errors clustered by country; Country and time fixed effects; D= Domestic, F= Foreign.

Table A4
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: Steenblik (2005), Lane and Pearson (2005), Rogowsky et al. (2009), Wind (2008)

Table A5
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 A6
Effect of Innovation on Trade – OECD Only

	PPML - IV			
	(1)	(2)	(3)	(4)
	Exports	Imports	Exports	Imports
Log R.E. patent stock in origin	0.151***	-0.085	0.155***	-0.080
	(0.041)	(0.057)	(0.041)	(0.055)
Log R.E. patent stock in destination			0.049	0.084***
			(0.029)	(0.021)
Log population in origin	0.353	2.608*	0.438	2.491*
	(1.524)	(1.101)	(1.522)	(1.102)
Log population in destination	2.057	1.041	1.529	0.474
	(1.576)	(1.576)	(1.590)	(1.535)
Log GDP in origin	0.447***	0.672***	0.456***	0.689***
	(0.129)	(0.111)	(0.130)	(0.112)

(*continued on next page*)

Table A6 (*continued*)

	PPML - IV			
	(1)	(2)	(3)	(4)
	Exports	Imports	Exports	Imports
Log GDP in destination	0.431*	0.571***	0.366*	0.491**
	(0.179)	(0.161)	(0.183)	(0.163)
RTA	0.783***	0.752***	0.707***	0.694***
	(0.107)	(0.113)	(0.107)	(0.105)
Tariffs	0.056	-0.025	0.048	-0.028
	(0.088)	(0.038)	(0.087)	(0.037)

*p < 0.05, **p < 0.01, ***p < 0.001Standard errors clustered by country; Country-pair and time fixed effects; N = 13,780.

Table A7
Effect of Innovation on Trade – With Policy Measure

	PPML - IV	
	(1)	(2)
	Exports	Imports
Log R.E. patent stock	0.134***	-0.088
	(0.035)	(0.048)
Policy_{t-1}	0.018**	0.021***
	(0.006)	(0.005)
Log population in origin	0.486	2.318*
	(1.113)	(0.969)
Log population in destination	1.375***	-0.194
	(0.397)	(0.799)
Log GDP in origin	0.342**	0.683***
	(0.111)	(0.100)
Log GDP in destination	0.500***	0.734***
	(0.079)	(0.116)
RTA	0.572***	0.666***
	(0.082)	(0.095)
Tariffs	0.024	-0.032
	(0.077)	(0.039)

*p < 0.05, **p < 0.01, ***p < 0.001 Standard errors clustered by country; Country-pair and time fixed effects.

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