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Trade as a Channel for Environmental Technologies Diffusion: The Case of the Wind turbine Manufacturing Industry

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Only a small number of companies, located in a few countries, have specific technological expertise in wind turbine manufacturing. New quantitative analysis shows this expertise to be a significant driver of trade in wind turbines. Moreover, countries' wind power generation efficiency is shown to depend on access to higher quality wind turbines available in international markets. Trade in wind turbines thus provides access to technologies with a level of efficiency that cannot be replicated domestically in importing countries. These results have important policy implications: i) barriers to trade in wind turbines are also barriers to the dissemination of key environmental technologies which are not otherwise widely available; ii) trade-discriminatory measures can also negatively impact non-manufacturing job creation in the renewable sector, as this relies on the continuous deployment of wind energy, which in turn depends on access to high quality turbines from international markets; and iii) policies should not focus on the creation of national champions, but rather on ensuring that domestic firms can apply their specific capabilities to new opportunities in the global value chains of renewables industries.

Keywords: Trade, wind energy, environmental technologies, patents

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Key messages

- Only a small number of companies, located in a few countries, have specific technological expertise in wind turbine manufacturing.
- Such technological expertise is found to be a significant driver of trade in wind turbines.
- In addition, it is found that countries' wind power generation efficiency depends on having access to higher quality wind turbines available in international markets.
- Trade in wind turbines can thus be seen as tantamount to trading (wind) technologies that deliver a level of efficiency that cannot be replicated in importing countries.
- These results have important policy implications:
  - Barriers to trade in wind turbines are also barriers to the dissemination of key environmental technologies needed by countries where they have not been developed.
  - Trade-discriminatory measures can also be a hurdle to non-manufacturing job creation as the latter hinges on the continuous deployment of wind energy, which in turn depends on access to international markets where high quality wind turbines are found.
  - Industrial policies should not focus on the creation of national champions but rather on ensuring that domestic firms can apply their specific capabilities to new opportunities in global industries.

Executive summary

It is often argued that international trade accelerates the cross-country diffusion of environmental technologies (WTO and UN Environment, 2018[1]; World Bank, 2017[2]; Pigato et al., 2020[3]). The rationale put forward is that open markets improve access to new technologies that make local production processes more efficient and environmentally sound. For instance, importing renewable energy equipment may lead to a reduction of environmentally harmful by-products such as pollutant emissions. While intuitively appealing and with potentially important policy implications for trade liberalisation, robust empirical evidence supporting this assertion has been limited to date.

The goal of this paper is to fill this gap. It provides empirical evidence that trade supports the diffusion of environmental technologies in the wind turbine manufacturing industry. Technology can be thought of as a set of information that is materialised in tangible goods (Glachant, 2013[4]). An obvious channel for the diffusion of wind technologies is to simply ship the products that embody them – i.e. wind turbines. Once imported, they can displace older and dirtier technologies. In other words, through trade, wind turbines might flow from where they are invented to where they are needed in order to replace fossil fuel-based power generation.

The paper begins with a quantitative exploration of the complexity of wind technologies based on patent data. In line with previous qualitative research (Garud and Karnøe, 2003[5]), findings suggest that wind turbines embody a continuous accumulation of sophisticated knowledge and know-how. As a result, only a few companies, located in a few countries, have developed expertise in wind technologies, with their technological advantage growing over time. In addition, given the importance of cumulative and tacit knowledge in the sector, expertise in wind technologies seems to be difficult to transfer and to duplicate across borders (Schmidt and Huenteler, 2016[6]).

Using a gravity model, the paper then demonstrates that patented innovations in wind technologies – which proxy for the degree of expertise in this technological field – are a significant driver of trade in wind turbines. Whether technology drives trade in wind turbines is an empirical question because, in principle, such trade could be accounted for by many factors other than technology – e.g. a labour force skilled at manufacturing such products, manufacturing capacities, and availability of required materials. If technology is easy to replicate, wind turbines could be reverse-engineered by local manufacturers and associated technologies could then be quickly acquired locally. Trade flows would not then *per se* be responsible for disseminating wind power technologies, but rather follow a pattern of specialisation accounted for by these other factors (e.g. relating to relative production costs).

Finally, panel data regressions show that, for a given installed wind power generation capacity, the larger the share of imported wind turbines, the larger the amount of wind electricity generated by a country. They show that the quality of wind turbines matters as wind projects are more effective if they diversify their sourcing through international trade. These empirical results provide evidence that relying on a high share of imported turbines – as opposed to locally manufactured wind turbines only – contributes to the competitiveness of wind power generation and, critically from an environmental perspective, contributes to the displacement of old, environmentally harmful technologies.

These results have important policy implications. They shed light on the debate on the role of "green protectionism" to achieve dual environmental and economic goals by simultaneously reducing carbon emissions and creating a local manufacturing industry to supply renewable equipment. Such a policy strategy risks hurting both trade and the environment. In fact, significant local job creation hinges on the continued deployment – rather than the manufacture – of wind energy, which is possible only if wind farms can compete with older power generation technologies. As this study shows, the competitiveness of wind energy depends on access to the higher quality wind turbines available in international markets. This, in turn, implies that government support to renewable energy should not discriminate against foreign suppliers. Indeed, the viability of ambitious climate policies – which depends, among other things, on their (perceived) economic benefits to foster public acceptability (Klenert et al., 2018[7]) – can be strengthened by a more open trade regime for renewable equipment.

1. Introduction

It is often argued that international trade accelerates the cross-country diffusion of environmental technologies (WTO and UN Environment, 2018[1]; World Bank, 2017[2]; Pigato et al., 2020[3]). The rationale put forward is that open markets improve access to new technologies that make local production processes more efficient and environmentally sound. However, robust empirical evidence supporting this assertion has been limited to date. To fill this gap, this paper examines the wind turbine manufacturing industry to investigate the extent to which trade supports the diffusion of environmental technologies.

This paper begins with a quantitative exploration of the complexity of wind technologies based on patent data. In line with previous qualitative research (Garud and Karnøe, 2003[5]), findings suggest that wind turbines embody a continuous accumulation of sophisticated knowledge and know-how. As a result, only a few companies, located in a few countries, have been able to build expertise in wind technologies, with their technological advantage growing over time. In addition, given the importance of cumulative and tacit knowledge in the sector, expertise in wind technologies seems to be difficult to transfer and to duplicate across borders (Schmidt and Huenteler, 2016[6]).

Next, relying on a gravity model, the paper shows that patented innovations in wind technologies – which proxy for the degree of expertise in this technological field – are a significant driver of trade in wind turbines. Whether technology drives trade in wind turbines is an empirical question because, in principle, such trade could be accounted for by many factors other than technology – e.g. a labour force skilled at manufacturing such products, manufacturing capacities, and availability of required materials.

Finally, panel data regressions show that, for a given installed wind power generation capacity, the larger the share of imported wind turbines, the larger the amount of wind electricity generated by a country. They show that the quality of wind turbines matters as wind projects are more effective if they diversify their sourcing through international trade. These empirical results therefore provide evidence that relying on a high share of imported turbines – as opposed to locally manufactured wind turbines only – not only contributes to the competitiveness of wind power generation, but critically from an environmental perspective, contributes to the displacement of old, environmentally harmful, technologies.

The rest of the paper is organised as follows. The next section sets out the discussion on environmental technology diffusion. It defines the notion of environmental technologies and provides a conceptual framework on trade as a channel for cross-country dissemination of these technologies. Based on patent data analysis, section 3 then discusses the complex nature of wind technologies and what this means for possibility of replication. It also shows that wind technology innovations are path dependent and incremental. Section 4 presents econometric results supporting the claim that technology drives trade in wind turbines, which in turn drives the deployment of wind power and the displacement of old technologies. Section 5 discusses the policy implications of these results. Section 6 concludes, highlighting areas for further research. The empirical methodology is detailed in the annexes to this study.

2. Trade as a channel for environmental technologies

2.1. What are environmental technologies?

Technology can be thought of as a specific set of information that is embodied in tangible goods (Glachant, 2013[4]). It can be the result of investments in R&D and in human capital (e.g. engineering skills), leading to incremental or radically new inventions. Inventions and resulting technologies can be complex and expertise in such a process can create a competitive advantage in international markets (Posner, 1961[8]; Porter, 1990[9]; Fagerberg, 1996[10]).

Environmental technologies are embodied in so-called environmental goods, which “measure, prevent, limit, minimise or correct environmental damage to water, air and soil, as well as problems related to waste, noise and eco-systems. This includes cleaner technologies, products and services that reduce environmental risk and minimise pollution and resource use" (OECD and Eurostat, 1999[11]).[1] The term is often used interchangeably with environmentally friendly, environmentally related, green, and clean technologies. Environmental technologies target a wide variety of environmental media including air and water pollution, waste management, and climate mitigation.

The development of environmental technologies are considered essential to address acute environmental problems (OECD, 2011[12]; OECD, 2012[13]; OECD, 2015[14]). They are needed to replace old, environmentally harmful, production methods. This is especially true for renewable energy technologies that aim to reduce carbon emissions and their global externalities. The diffusion of renewable energy needs to accelerate if countries want to achieve a substantial emissions reduction through a gradual substitution of fossil-fuels based power generation (Henderson and Newell, 2011[15]; Allan, Jaffe and Sin, 2013[16]; OECD, 2015[14]; IEA, 2019[17]; IEA, 2020[18]; IRENA, 2020[19]).

2.2. What drives environmental technologies?

A large body of the literature shows that environmental technologies – and related innovations – are induced by stringent environmental policies because they can reduce firms' compliance costs (OECD, 2008[20]; Veugelers, 2012[21]; Guerzoni and Raiteri, 2015[22]; Costantini, Crespi and Palma, 2017[23]; Popp, 2019[24]; IEA, 2020[25]).[2] Market-based instruments – such as emissions taxes and emissions trading systems (ETS) – price negative environmental externalities and create incentives to develop new technologies to reduce emissions. For instance, Calel and Dechezleprêtre (2016[26]) find that firms under the EU ETS have increased their innovation activity in low-carbon technologies by 30% relative to unregulated firms. In another context, Aghion et al. (2016[27]) show that in reaction to higher gasoline prices, automotive firms tend to produce more innovations for electric and other pollution-abating car engines.

Command-and-control regulations – such as performance- and technology-based standards – are viewed as less effective than market-based instruments at meeting environmental targets and therefore at inducing environmental innovations (Popp, Newell and Jaffe, 2010[28]; de Serres, Murtin and Nicoletti, 2010[29]). However, there is also some evidence that environmental standards increase the innovation rate in environmental technologies (Popp, 2003[30]; Johnstone, Haščič and Popp, 2010[31]; Lanoie et al., 2011[32]). For instance, Johnstone, Haščič and Popp (2010[31]) find that quantity-based policies – i.e. renewable energy credits – favour the development of wind technologies.

In addition, because of market failures associated with the process of technological change[3], innovation policies are likely to be important parts of the policy portfolio addressing environmental issues (Jaffe, Newell and Stavins, 2005[33]). Such policies are found to be effective if they create a functioning innovation system that connects all relevant stakeholders – i.e. firms, research and financial institutions, regulators, and consumers (Hekkert et al., 2007[34]; Bergek et al., 2008[35]; Bergek et al., 2015[36]; IEA, 2020[25]) – and allow firms to undertake processes based on learning-by-doing, learning-by-searching and learning-by-cooperation (Ibenholt, 2002[37]; Verdolini and Galeotti, 2011[38]; Nemet, 2012[39]; Tang and Popp, 2015[40];

[1] While this definition follows previous OECD work, there is no clear-cut definition of "environmental technologies" because they are "(…) intended to be a reflection of the public consensus on the utility of certain technological approaches in reducing environmental impacts, as compared to available alternatives. Hence, by definition, the notion of which technologies are considered "environmental" evolves over time" (OECD, 2011, p. 214[12]). See also the OECD's identification and measures of environment-related technologies (OECD, 2011[12]; OECD, 2012[13]; Haščič and Migotto, 2015[72]; Haščič, Silva and Johnstone, 2015[73]) and the list of climate change mitigation technologies co-developed by the United Nations Environment Programme and the European Patent Office (UNEP and EPO, 2015[121]). As for the concept of environmental goods, the *Combined List of Environmental Goods* (CLEG) has been developed from indicative lists of environmentally-related goods and corresponding Harmonized System (HS) codes by the OECD, WTO's "Friends Group" countries, and the Asia-Pacific Economic Cooperation (APEC). For the full CLEG list, its methodology and discussion, see Sauvage (2014[122]) and Garsous (2019[123]).

[2] See also Horbach, Rammer and Rennings (2012[124]) and Del Río, Peñasco and Romero-Jordán (2016[125]) for surveys on the determinants of environmental innovations.

[3] As the benefits of environmental technologies tend to accrue to society at large, rather than to the adopter of such technologies, market forces alone provide little incentives to develop environmental technologies (Popp, Newell and Jaffe, 2010[28]).

Tang, 2018[41]). In that respect, R&D subsidies and public procurement are found to play significant roles (Guerzoni and Raiteri, 2015[22]; Fu et al., 2018[42]).

In sum, given that environmental issues are often the consequence of several interacting market failures, an appropriate policy response should involve a mix of complementary instruments (de Serres, Murtin and Nicoletti, 2010[29]; OECD, 2011[12]; OECD, 2012[13]). If well-designed, such policy packages are a main driver of environmental innovations (Veugelers, 2012[21]; Popp, 2019[24]).

2.3. Do environmental technologies diffuse through trade?

The idea that international trade acts as a channel for technology diffusion is not new: the theoretical foundations were laid out over 30 years ago and can be found in Rivera-Batiz and Romer (1991[43]), Coe and Helpman (1995[44]), Grossman and Helpman (1995[45]), and Eaton and Kortum (2002[46]). Put simply, as countries open to trade, they gain access to different and better intermediate and capital goods that increase their productivity.[4]

Some empirical evidence shows that environmental technologies are being diffused across countries (Lanjouw and Mody, 1996[47]; Haščič et al., 2010[48]; Dechezleprêtre et al., 2011[49]; Haščič and Johnstone, 2011[50]). Significant channels for such a diffusion are: trade (Tébar Less and McMillan, 2005[51]; Lovely and Popp, 2011[52]; Glachant, 2013[4]), foreign direct investment (Tébar Less and McMillan, 2005[51]) and to a lesser extent, international programmes such as the UN Clean Development Mechanism[5] (Dechezleprêtre, Glachant and Ménière, 2008[53]; Dechezleprêtre, Glachant and Ménière, 2009[54]; Lema and Lema, 2013[55])[6]. In the specific context of the wind power industry, Dechezleprêtre and Glachant (2014[56]) and Halleck-Vega, Mandel and Millock (2018[57]) find that bilateral trade can be an important determinant of technology diffusion between two countries. Schleich and Walz (2018[58]) find that exports of wind turbines are positively correlated to measures of innovation such as R&D expenditure and patenting activities.[7]

However, these papers focus on the adoption of technology and the role of domestic policies rather than the channel of trade *per se*. There is no conceptual discussion on the determinants of international trade in goods that embody environmental technologies – beyond the creation of demand through government support, as discussed above. In principle, many factors other than technology could play a role – e.g. a labour force skilled at manufacturing such products, manufacturing capacities, and availability of required materials. Whether technology drives trade in environmental goods remains an open empirical question. Simply put, if local manufacturers could reverse-engineer environmental goods, they would quickly acquire associated technologies. Then trade flows would not, *per se* disseminate environmental technologies but rather follow a pattern of specialisation accounted for by other determinants such as relative production costs.

[4] A seminal empirical paper on technology dissemination through trade by Coe and Helpman (1995[44]) finds that countries' productivity is positively associated with imports from high-R&D countries. This supports the argument that international trade is a channel for technology diffusion. Keller (1998[126]), however, casts doubt on these results as he finds that similar conclusions can be obtained by using randomly-generated shares of imports from low and high R&D countries. Refining the analysis by focusing on specialized machinery goods, Keller (2000[140]) finds a positive correlation between imports and productivity growth. See Keller (2004[127]) for a literature review on the empirics of international technology diffusion.

[5] The Clean Development Mechanism (CDM) allows a country with an emission-reduction or emission-limitation commitment under the Kyoto Protocol to implement an emission-reduction project in developing countries. Importantly, the authors of these papers point out that technology transfers depend strongly on the local technological capabilities of the host countries of the CDM projects.

[6] Many papers have addressed the relationship between environmental regulation and productivity (an important determinant of firms' competitiveness on international markets). However, results from this literature are largely inconclusive with papers reporting negative impacts on productivity, while others provide evidence of the opposite effect (see Kozluk and Zipperer (2014[128]) and Dechezleprêtre and Sato (2017[129]) for literature reviews).

[7] As in this study, Schleich and Walz (2018[58]) use patent data to explore the effect of innovation on countries' exports of wind turbines. However, their sample is limited to 12 OECD countries and their econometric approach relies on panel-data regressions and not a robust gravity model.

To explore this question, this paper conceptualises the notion of technology diffusion through trade as a three-step process (Figure 1). First, innovation occurs in one country thereby enabling the production of new, improved, goods. Second, when technology is complex, these goods are exported because this innovation is hard to replicate.[8] Expertise in a particular technology is therefore a source of competitive advantage – and a driver of trade. Third, new technologies are used in importing countries and tend to displace old technologies.

The rest of this paper provides empirical evidence that such process occurs in the specific case of wind technologies.

Figure 1. Environmental technologies diffusion through trade

Source: Authors' elaboration.

3. The complexity of wind technologies

Wind turbines are complex products based on a "design-intensive" technology (Schmidt and Huenteler, 2016[6]). That is, designing and manufacturing wind turbines involves the assembly and integration of thousands of electrical and mechanical components into systems to produce electricity. Such process requires a continuous accumulation of knowledge and know-how acquired from years of technology development (Kamp, Smits and Andriesse, 2004[59]; Kamp, 2007[60]; Söderholm and Klaassen, 2007[61]; Lindman and Söderholm, 2016[62]; Tang, 2018[41]). The most successful wind turbine manufacturers have followed slow-but-steady technological development – as opposed to development driven by breakthrough innovations – that has eventually led to the production of highly reliable and competitive products (Garud and Karnøe, 2003[5]).[9] For instance, accumulating data on weather patterns and turbine performance over long periods of time enabled the construction of accurate models to predict wind speed and other relevant weather conditions and enable the optimal programming of turbines' regulation systems (EWEA, 2009[63]; IBM, 2011[64]; Siemens Gamesa Renewable Energy, 2019[65]).[10]

[8] It is therefore assumed that there is a demand for such new products in importing countries.

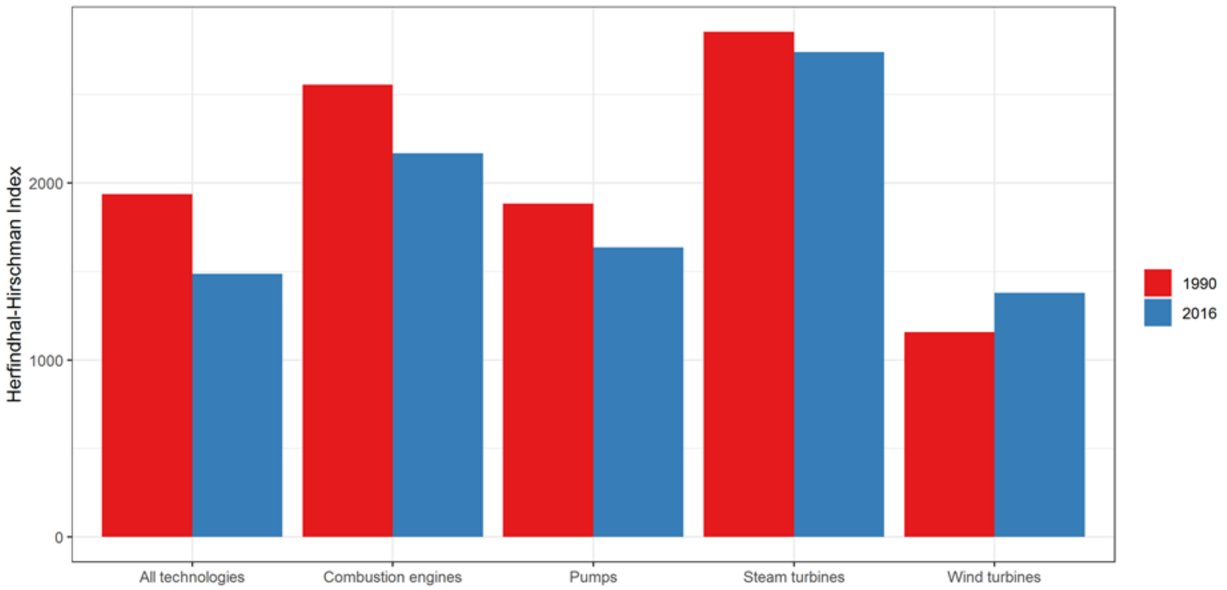
[9] The history of the Danish wind turbine manufacturing industry offers a relevant example. From the outset in the 1970s, the industry's development was characterised by incremental innovation through an information-sharing network connecting all relevant stakeholders – producers, suppliers, owners, users, government and regulators (Garud and Karnøe, 2003[5]; Pasqualetti, Righter and Gipe, 2004[139]; Vestergaard, Brandstrup and Goddard, 2004[130]).

[10] The pitch regulation system – one of the core technologies of wind turbines – allows the wind turbine to adjust the angle of the rotor blades in order to adapt to changing wind orientation. If the wind is too fast, the pitch regulation system adapts the angle of the rotor blades to avoid damage caused by sudden pressure changes. Conversely, if the wind speed is slow, the system exposes the blades to maximize the kinetic wind energy usage. Thus, the ability to adjust to wind speed is crucial for the overall performance of wind turbines and turbines that can predict the wind speed and adapt accordingly are more likely to optimize the wind captured (Suryanarayanan and Dixit, 2005[131]; Burton et al., 2011[132]).

The complex nature of wind technologies is reflected in patent data. Between 1990 and 2016, the cross-country concentration of patented innovations – measured by the Herfindahl-Hirschman Index – has increased for wind technologies but decreased for all technologies and for a set of benchmark technologies with manufactured output similar to wind turbines[11] (Figure 2). This trend is explained by the limited number of countries that have been driving the (substantial) growth of the global knowledge stock of wind technologies (Figure 3), which stands in contrast with the finding that an increasing number of countries – most notably emerging economies – have been participating to the development of new technologies more generally (Puga and Trefler, 2010[66]; Branstetter, Li and Veloso, 2015[67]; Miguelez et al., 2019[68]).

Furthermore, the progressive development of wind technologies – as opposed to development punctuated by breakthrough innovations – is also suggested by patent data. For wind technologies, countries' past knowledge stocks are strong predictors of contemporary knowledge stocks – and even stronger than for steam turbine technologies (Figure 4). This suggests that building knowledge in wind technologies takes more time (and possibly more resources) than in other comparable technologies. It can also be observed that leapfrogging, by which new players replace incumbents, is seldom seen in wind technologies. Almost no country with small initial knowledge stocks can outstrip (or even catch up with) those with initially large knowledge stocks. This stands in contrast to the case of steam turbines – see top-left corner of Figure 4 where red data points (steam turbines) outnumber blue data points (wind turbines).

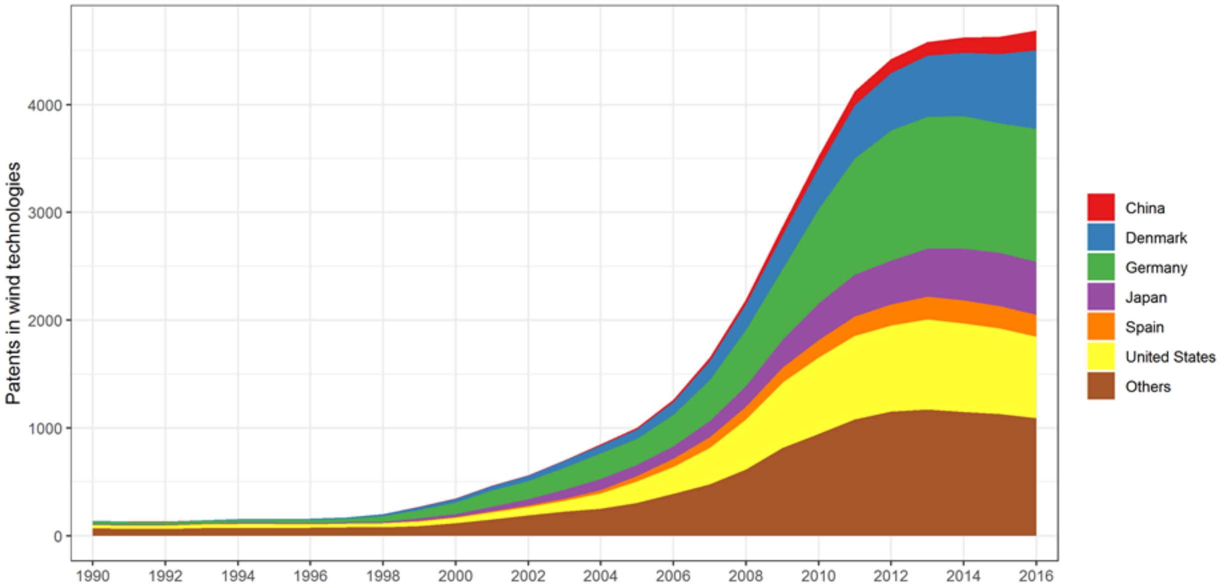
Figure 2. Knowledge concentration has increased for wind technologies



Note: The Herfindahl-Hirschman Index is calculated as the sum of the squared countries' share of patents in the total number of patents associated with a given technology.
Source: Authors' calculations based on OECD, STI Micro-data Lab: Intellectual Property Database, http://oe.cd/ipstats, Spring 2020.

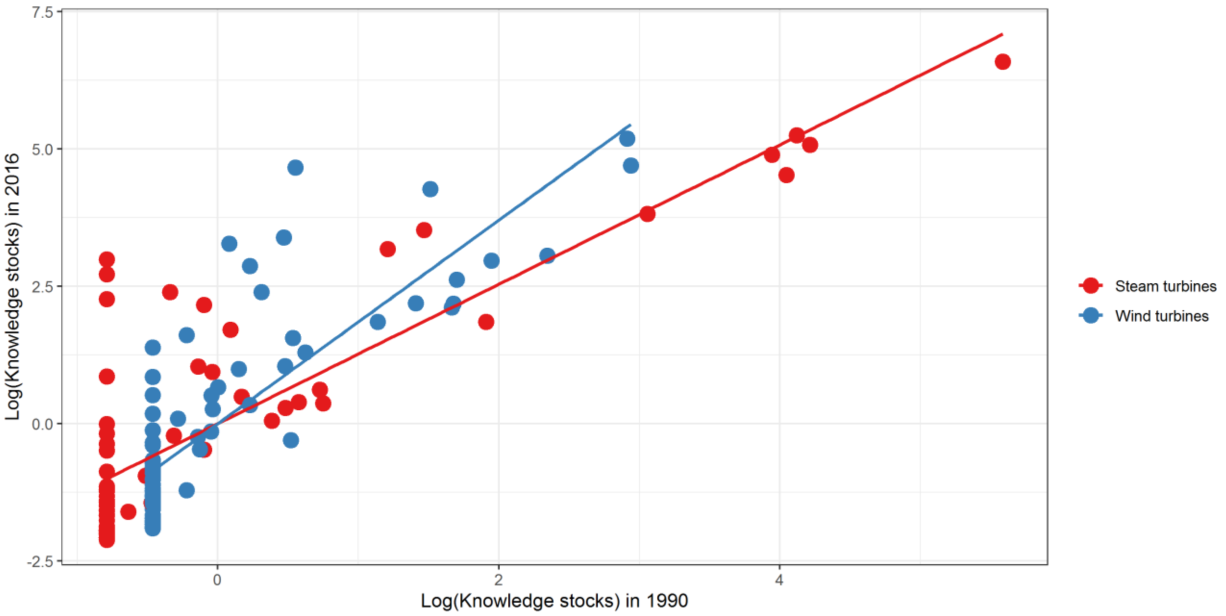
[11] Throughout this paper, combustion engines, steam turbines, and pumps are considered benchmark products (or benchmark technologies) to be compared with wind turbines (or wind technologies). The rationale for selecting these products (or technologies) as benchmarks is set out in Annex D.

Figure 3. A few countries are driving growth in the global knowledge stocks of wind technologies



Note: Countries' knowledge stocks are measured by the counts of patent applications in a given year and all previous ones, with a depreciation rate of 15%. See Annex C for methodological details.
Source: Authors' calculations based on OECD, STI Micro-data Lab: Intellectual Property Database, http://oe.cd/ipstats, Spring 2020.

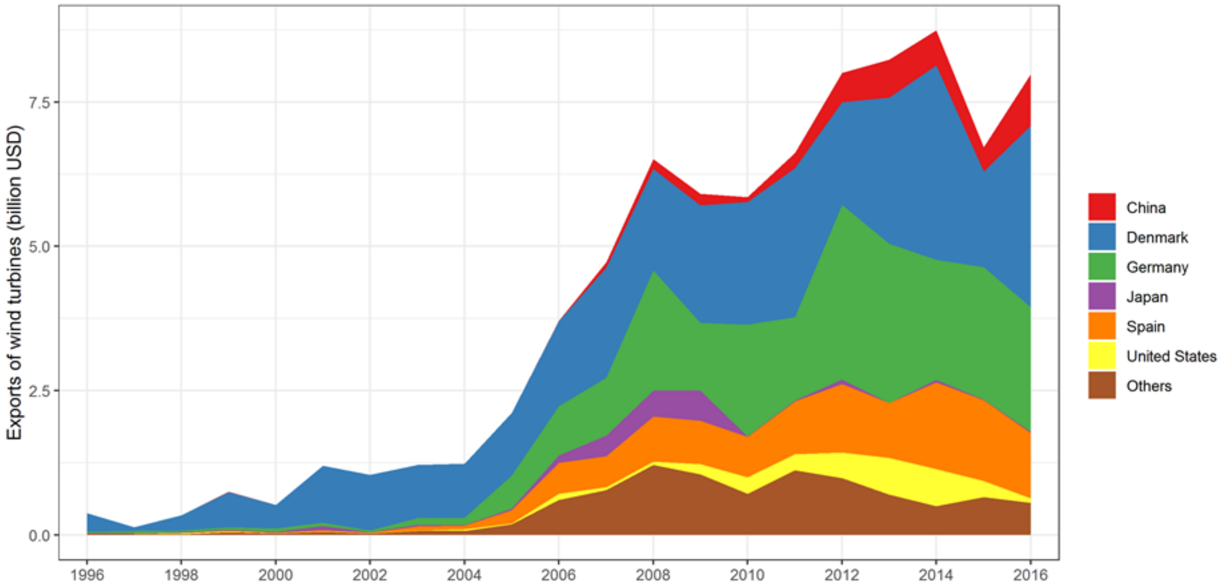
Figure 4. Building knowledge in wind turbines takes time



Note: Countries 'knowledge stocks are measured by the counts of patent applications in a given year and all previous ones, with a depreciation rate of 15%. See Annex C for methodological details. Data points have been mean-centred.
Source: Authors' calculations based on OECD, STI Micro-data Lab: Intellectual Property Database, http://oe.cd/ipstats, Spring 2020.

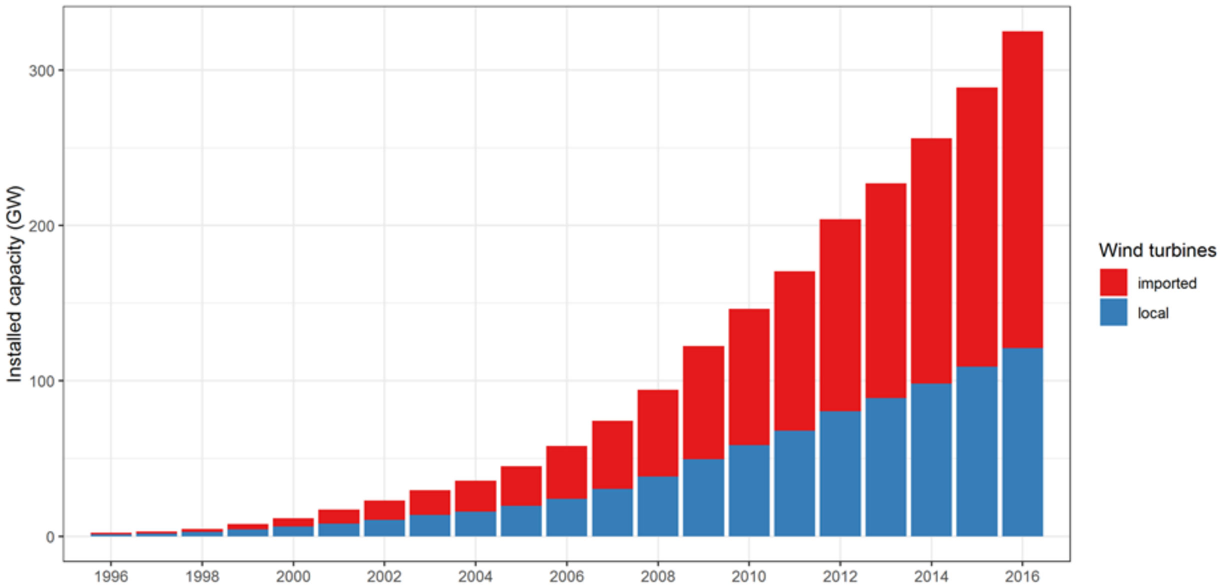
Concentration also appears to characterise trade in wind turbines. In 2016, five countries – Denmark, Germany, Spain, the United States, and the People's Republic of China (hereafter "China") – accounted for 92% of global exports of wind turbines (Figure 5). This essentially corresponds to the countries that dominate the field of wind technology (Figure 4). In addition, while wind power installed capacity has been increasing globally, most of the added installations have been wind turbines made by foreign manufacturers (Figure 6). For instance, in 2015, approximately 70% of the global added capacity was accounted for by imported wind turbines.

Figure 5. Exports of wind turbines are dominated by a few countries



Note: Exports in wind turbines are measured with the HS code 850231 (Electric generating sets; wind-powered, excluding those with spark-ignition or compression-ignition internal combustion piston engines). See Annex D for methodological details.
Source: Authors' calculations based on BACI database.

Figure 6. Installed capacity of wind turbines increasingly relies on imports



Note: Installed wind power capacity in gigawatts (GW) by year distinguishing between local and foreign wind turbine manufacturers.
Source: Authors' calculations based on the wind farms database from www.thewindpower.net.

In sum, developing wind technologies is a slow, complex, and hard-to-replicate process. Being tacit by nature, knowledge and expertise in wind technologies are difficult to transfer, greatly complicating the late entry of new wind turbine manufacturers into the global markets (Schmidt and Huenteler, 2016[6]). Thus, only a small number of countries have been able to build up and consolidate the specific expertise based on a continuous accumulation of knowledge and know-how that defines competitive advantage in trade in wind turbines.

Trade in wind turbines can thus be seen as tantamount to trading (wind) technologies that deliver a level of efficiency that cannot be replicated in importing countries. That is, an obvious channel for the diffusion of wind technologies is shipping the products that embody them – i.e. wind turbines – where they are needed with a view to displacing old technologies and thereby supporting a low-carbon transition. Figure 7 – adapted from Figure 1 – illustrates this dissemination process.

Figure 7. Wind technologies diffusion through trade

Source: Authors' elaboration.

4. Empirical analysis

Empirically, the two last stages of the technology dissemination process of Figure 7 can be explored through a two-step strategy: first, to test whether technical expertise in wind technologies drives trade in wind turbines; and second, to test whether imports of wind turbines drive the deployment of wind power and the displacement of older technologies.

4.1. Technology as a driver of trade in wind turbines

A gravity equation is used to test whether technology drives exports in wind turbines. The gravity model is the "workhorse" model in international economics and has been widely used to quantify the role of various determinants of trade including GDP, distance, population, and trade agreements (Yotov et al., 2016[69]). It is designed to estimate the effects of variables in accounting for bilateral trade flows between an exporter and an importer.

In this study, the variable of interest is the exporter's degree of technological expertise. It is estimated whether this variable is a significant determinant of exports in wind turbines compared against the benchmark of other selected manufactured products, namely steam turbines, combustion engines, and pumps. [12] This comparison is necessary because technology is an important driver of exports more generally (Wolff, 1995[70]; Fagerberg, 1996[10]). Hence, if the exporter's technological expertise is a stronger determinant in the case of exports of wind turbines, it would provide empirical evidence to corroborate the argument in the previous section that wind technologies are more complex and harder to replicate than the benchmark technologies.

[12] See Annex D for the rationale to using steam turbines, combustion engines, and pumps as benchmarks.

Table 1. Gravity estimation results

Dependent variable: Exports	(1)	(2)	(3)	(4)	(5)	(6)
Exporter's knowledge stock	0.524***					
	(0.170)					
Exporter's knowledge stock*(Wind turbines=1)	0.435***					
	(0.0786)					
Exporter's knowledge stock		0.485***				
		(0.168)				
Exporter's knowledge stock*(Wind turbines=1) *(t-2)*		0.394***				
		(0.0793)				
Exporter's knowledge stock			0.452***			
			(0.163)			
Exporter's knowledge stock*(Wind turbines=1) *(t-4)*			0.373***			
			(0.0821)			
Exporter-importer technological gap				0.240		
				(0.153)		
Exporter-importer technological gap*(Wind turbines=1)				0.177***		
				(0.0424)		
Exporter-importer technological gap					0.226	
					(0.149)	
Exporter-importer technological gap*(Wind turbines=1) *(t-2)*					0.177***	
					(0.0463)	
Exporter-importer technological gap						0.220
						(0.146)
Exporter-importer technological gap*(Wind turbines=1) *(t-4)*						0.186***
						(0.0512)
Observations	540 324	505 924	464 688	540 324	505 924	464 688
Country-year fixed effects	Yes	Yes	Yes	Yes	Yes	Yes
Partner-year fixed effects	Yes	Yes	Yes	Yes	Yes	Yes
Country-partner-year fixed effects	Yes	Yes	Yes	Yes	Yes	Yes
Sector fixed effects	Yes	Yes	Yes	Yes	Yes	Yes

Note 1: All results from the gravity model specification described in Annex A. Point estimates report full elasticities.
Note 2: Robust standard errors clustered at the exporter and importer levels in parentheses, *** p<0.01, ** p<0.05, * p<0.1.

An exporter's degree of technological expertise in a given field can be proxied by the accumulation of related patent applications filed by its residents, which defines its "knowledge stock" in the relevant field. This is argued to be the most appropriate metric to measure the innovation rate of a country in given technologies and their potential use for manufacturing products (Griliches, 1990[71]; Haščič and Migotto, 2015[72]; Haščič, Silva and Johnstone, 2015[73]) – see Annex C for a discussion. Once constructed, this metric can easily be introduced in a gravity equation that estimates whether exporters' knowledge stock is a significant determinant of exports (see Equation 1 in Annex A). The effect of the technological gap between exporters and importers – measured as the difference in knowledge stocks of a given technology – is also estimated (see Equation 2 in Annex A).

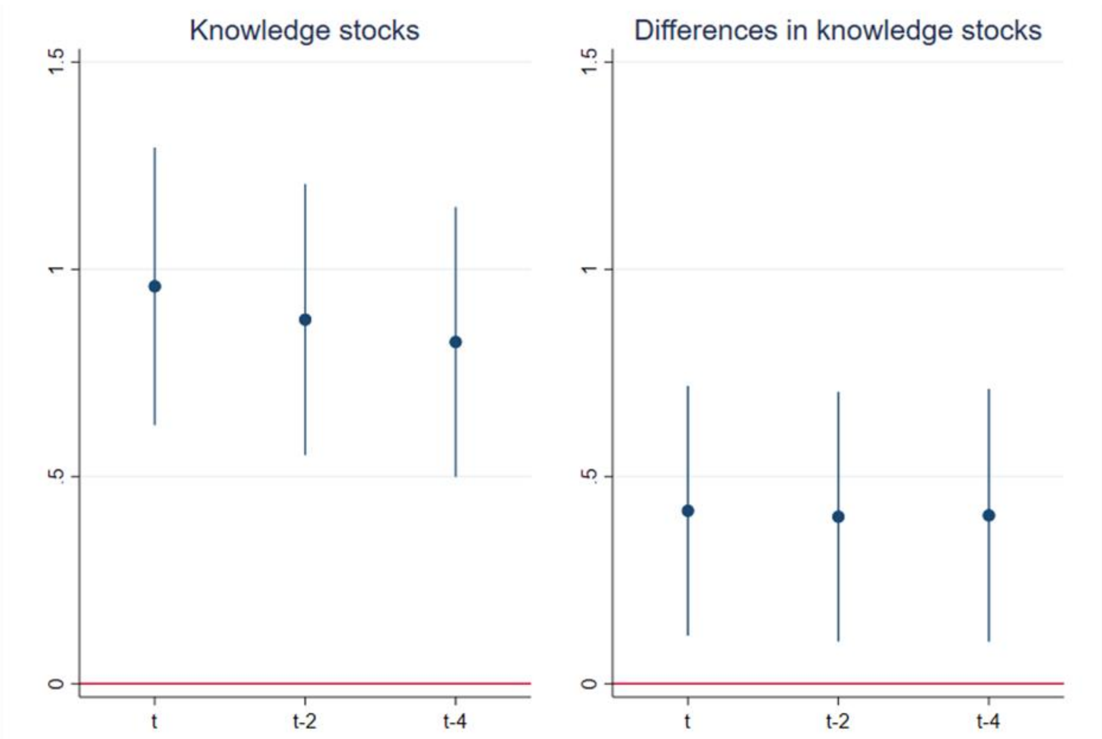
Estimation results show that, on average, a 1% increase in the exporter's knowledge stock is associated with a 0.52% increase in exports, with this effect being significantly stronger for wind turbines by an additional 0.43% (column 1 of Table 1). Past values of knowledge stocks also have a quantitatively similar effect on contemporary values of exports (columns 2-3 of Table 1).[13] Computing the (total) marginal effect of contemporary, 2-year lagged, and 4-year lagged values of the knowledge stock on wind technologies

[13] Such estimations allow to limit a potential reverse causality bias as they rely on knowledge stocks' past values that cannot be influenced by contemporaneous values of wind turbines exports.

on exports of wind turbines yields statistically significant coefficients of 0.96%, 0.88%, and 0.83% respectively (left-hand panel of Figure 8), showing the persistence of this effect over time.

Moreover, while the effect of the knowledge gap between exporter-importer, measured by the difference in knowledge stocks, is statistically insignificant on average, is again found to be stronger for wind turbines (columns 4 – 6 of Table 1). Computing the (total) marginal effect of contemporaneous, two-year lagged, and four-year lagged values of the exporter-importer difference in knowledge stocks on wind technologies on exports of wind turbines exports yields statistically significant coefficients of 0.42%, 0.40%, and 0.40% respectively (right-hand panel of Table 1), showing again the persistent positive impact that these differences have on exports in wind turbines.

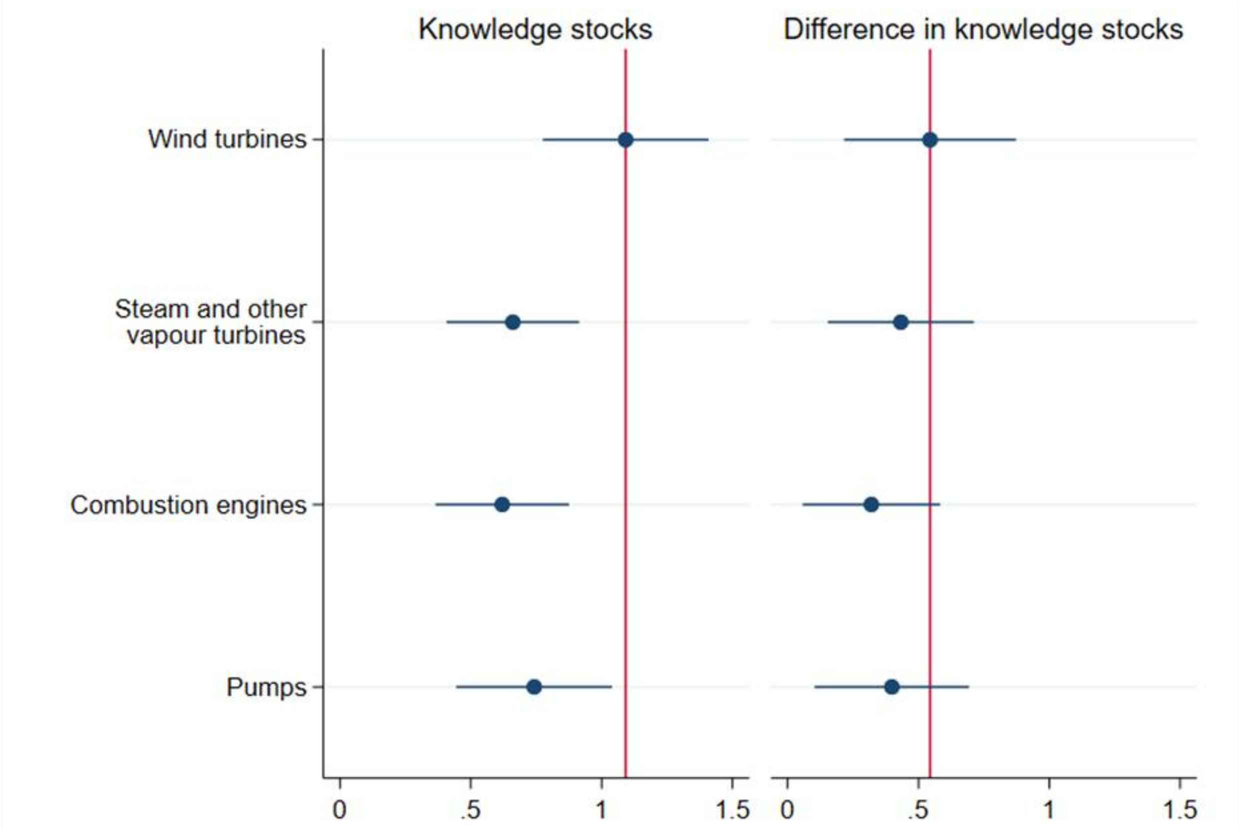
Figure 8. Marginal effects of technologies on exports



Note: Point estimates and confidence intervals of the total marginal effects of knowledge stocks and difference in knowledge stocks – at time t, t-2, and t-4 – on exports of wind turbines. These point estimates are calculated using the "margin" command in the statistical software STATA with the gravity estimation results of Table 1 They report full elasticities.
Source: Author's calculation based on a gravity model specification described in Annex A.

Based on additional regressions using the specification of columns 1 and 4 of Table 1, the marginal effects of both knowledge stock and technological gap on each category of exports were computed. Results show that the magnitude of the coefficients for wind turbines are larger compared to other benchmark categories of products (Figure 9). These findings provide evidence that, on average, increases in technology and technological gaps between countries increase trade in all of the products considered in this analysis, but that the effect is stronger for exports of wind turbines.

Figure 9. Marginal effects of technologies on exports by products



Note: Point estimates and confidence intervals of the total marginal effects of knowledge stocks and difference in knowledge stocks – at time t, t-2, and t-4 – on exports in wind turbines and benchmark products. They report full elasticities.
Source: Author's calculation based on gravity model described in Annex A.

These results provide evidence that technology is an important driver of trade in wind turbines – even more so than for other similar manufactured products such as steam turbines or combustion engines. They therefore suggest that countries import wind turbines because of technological innovations elsewhere – i.e. because of an increase in exporters' knowledge stocks.[14] These findings reinforce the argument in section 3 that complex wind technologies cannot be easily replicated and for that reason, high quality wind turbines are manufactured in only a handful of countries. These countries export their wind technologies – embodied in wind turbines – to places where they are needed but cannot easily be invented. As such, trade is a channel for the diffusion of wind technologies.

4.2. Imports as a driver of displacement of older technologies

The second-step of the empirical strategy is to explore the relationship between imports of wind turbines and efficiency of installed wind power capacity. It is investigated whether countries that have a higher share of imported wind turbines – therefore sourcing their wind farms projects from international markets, where arguably the best technologies are available – also generate more wind electricity. If true, this result would suggest that imports of wind turbines render wind power more competitive to alternative existing

[14] Estimation results provided in this section arguably have a causal interpretation. The robust fixed-effect structure of the gravity model allows to control for potential confounding factors that also explain trade in wind turbines – see Yotov et al. (2016[69]) for a discussion. Therefore, the effects of knowledge stocks and of the exporter-importer technological gap on trade flows are appropriately captured and disentangled from other effects.

technologies, thereby contributing to displace the latter in importing countries – the third step of the technology diffusion process described in Figure 7.

A fixed-effects panel regression is estimated to examine these claims (Equation 3 in Annex B). Estimation results show that, for a given installed wind power capacity, the larger the share of imported wind turbines, the larger the volume of wind electricity generated. A 10 percentage point increase – i.e. a 10-unit increase – in the share of imported wind turbines is associated with an increase of 4.2% in wind electricity generation on average (column 1 of Table 2). Similarly, a 1% increase in installed wind power capacity is associated with a 1% increase in wind electricity – i.e. a 1-to-1 relationship. Further robustness checks show that the same regressions, run over the restricted sample of countries that have a local wind turbine manufacturing industry, have similar results (column 2 of Table 2).[15]

Table 2. Fixed-effects estimation results

	(1)	(2)	(3)	(4)
Dependent variable (in natural logarithm)	Wind electricity		Share of wind electricity in total energy mix	
Share of imported wind turbines	0.00425***	0.00440***	0.00503**	0.00449**
	(0.00143)	(0.00123)	(0.00215)	(0.00159)
Installed capacity	0.996***	0.999***	0.987***	0.978***
	(0.0278)	(0.0357)	(0.0324)	(0.0394)
Observations	1,126	409	1,126	409
R-squared	0.961	0.978	0.947	0.972
Number of countries	82	22	82	22
Country fixed effects	Yes	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes	Yes
Controls included	Yes	Yes	Yes	Yes

Note 1: All results are from the panel fixed-effect model specification described in Annex B. Point estimates of the share of imported wind turbines report semi-elasticities – i.e. the percentage change in the dependent variable for a 1 percentage point (or 1-unit) increase in the share of imported wind turbines. Point estimates of installed capacity report full elasticities – i.e. the percentage change in the dependent variable for a 1% increase in installed capacity.
Note 2: Robust standard errors clustered at the country level in parentheses, *** p<0.01, ** p<0.05, * p<0.1.

Next, the ratio of wind electricity to total power generation is used as an alternative dependent variable. These regression coefficients directly show the effect of the share of imported wind turbines on wind electricity output relative to the total amount of electricity generated in a given country (columns 3-4 of Table 2). They are significant positive, indicating that a higher share of imported wind turbines is associated with larger share of wind power in the energy matrix of a country, thereby indicating that imported wind turbines have displaced existing older (and presumably less environmentally friendly) technologies for power generation.

These regression results provide evidence that both the quantity and quality of wind turbines matter. Perhaps not surprisingly, if installed capacity is ramped up, wind power generation will be increased in roughly the same proportion on average. However, if wind farms diversify their sourcing through international trade and include a high share of imported turbines, wind power generation will be even larger.

These findings are illustrated by two countries with opposing strategies in terms of opening up to trade in wind turbines. China had no local wind turbine manufacturing industry initially and was consequently importing almost all of its wind power capacity (Figure 10 – left-hand side of top panel). Then, a local manufacturing industry progressively developed and took over substantial shares of the country's installed

[15] This robustness check is conducted because an important number of countries do not have a local wind turbine manufacturing industry, and import the totality of their installed capacity. As a result, their share of imported wind turbines does not vary over time – i.e. it is 100% for all years – and these data points bring little information to panel-data regressions that exploit time-varying variables.

capacity. Conversely, Spain initially had a reasonably developed local wind turbine manufacturing industry, with a significant degree of expertise in wind technologies (Figure 3) and significant wind turbine exports to international markets (Figure 5) However, the share of imported wind turbines in the Spanish installed capacity has grown over time as wind power operators have been increasingly relying on foreign sources to develop wind farms (Figure 10 – right side of top panel).

Figure 10. A tale of two countries: China and Spain

Note: This figure illustrates changes in the share of imported wind turbines and installed capacity performance over time in China and Spain. The panel-data regressions results from Table 2 exploit the same (within-group) time-variation and capture the extent to which changes in the share of imported wind turbines explain the performance of installed wind power capacity in a given country. The wind power generation per unit of installed capacity is calculated with a 3-year moving average to smooth year-on-year variations.
Source: Author's calculations based on wind farms database from www.thewindpower.net and the IEA's World Energy Statistics and Balances.

The performance of wind farms – measured by the amount of wind electricity generated per unit of installed capacity – has been decreasing and increasing in China and Spain respectively (Figure 10 – bottom panel). While this divergence cannot be entirely attributed to imports of wind turbines, the regressions results of Table 2 – which control for other factors – show that the share of imported wind turbines has potentially played a significant role in this dynamic.

The observed decrease in the share of imported wind turbines in installed wind power capacity in China has taken place while government policies have directly supported the development of wind energy – e.g. through financial incentives for wind developers or by mandating public grid companies to purchase wind energy (Lewis, 2012[74]; Yuan et al., 2015[75]). However, discriminatory measures, directly benefiting Chinese wind turbine manufacturers, were also introduced. For instance, between 2005 and 2009, government approval for new wind farms was conditional on meeting a local content requirement of 70% (IEA, 2009[76]). In 2008, Chinese manufacturers received a production subsidy of RMB 600 (USD 100) per kWh for the production of the first 50 turbines (Ministry of Finance of the People's Republic of China, 2008[77]). As a result, at the end of 2010, there were more than 100 domestic wind turbine manufacturers in China, against only six in 2004 (Yuan et al., 2015[75]).

Notwithstanding this government support, China's domestic wind turbine manufacturing industry appeared unable to compete with leading companies on international markets (Yuan et al., 2015[75]; Lam, Branstetter and Azevedo, 2017[78]). Most Chinese manufacturers could not take advantage of the newest technology. Their products have been subject to high defect rates, usually related to faulty designs of high-technology components in the control systems (Ming et al., 2013[79]). Chinese turbines have also exhibited lower returns in terms of electricity generation. They have operated with a low "capacity factor", which is calculated as the ratio of energy produced to the theoretical maximum. Chinese wind farms using foreign models had an average 5% higher overall capacity factor than those using domestic turbines (Cyranoski, 2009[80]).

Chinese manufacturers have responded to the emergence of the global wind power industry by focusing on finding solutions for scaling-up and mass producing existing technologies rather than inventing new ones – i.e. innovative manufacturing (Nahm, 2017[81]). In parallel, they have relied on licensed foreign technologies to fill the technological gap (Lewis, 2011[82]; Lewis, 2016[83]; World Bank, 2017[2]). For instance, Goldwind, the largest wind turbine manufacturer in China, used government R&D support not to develop new technologies, but rather partnered with the German firm Vensys to improve its engineering capabilities in adjusting, improving, and preparing turbine designs for mass production. More than a decade later, the division of labour between the two firms remains the same, with Goldwind finding solutions to efficiently manufacture technologies developed by Vensys (Nahm, 2017[81]).

5. Policy implications

Overall, the discussion in Section 3 and the empirical results presented in section 4 provide evidence that only a handful of countries have a sufficiently high degree of expertise in wind technologies to manufacture wind turbines and that this expertise is best disseminated through international markets. In addition, imports of high quality wind turbines contribute to displacing old power generation technologies, thereby helping a low-carbon transition. There are a number of policy implications of these results.

First, trade in wind turbines bring low-carbon technologies to where they are needed yet not developed. Therefore, barriers to trade in wind turbines are also barriers to the dissemination of key environmental technologies. This is a significant issue because while tariffs are found to be low on average for finished wind turbines,[16] they contain many inputs that may cross borders multiple times in global supply chains, thereby causing tariffs and non-tariff barriers to escalate and increasing the final costs of wind projects (Hook, 2019[84]). Better market access should therefore focus on improving conditions for trade in components and capital goods necessary to produce wind turbines, not just for the finished products (WTO and UN Environment, 2018[1]).

[16] In 2016, the trade-volume weighted average tariff on finished wind turbines (HS code 850231) was approximately 1.46% (calculated from the OECD trade and environment indicators available at https://stats.oecd.org/).

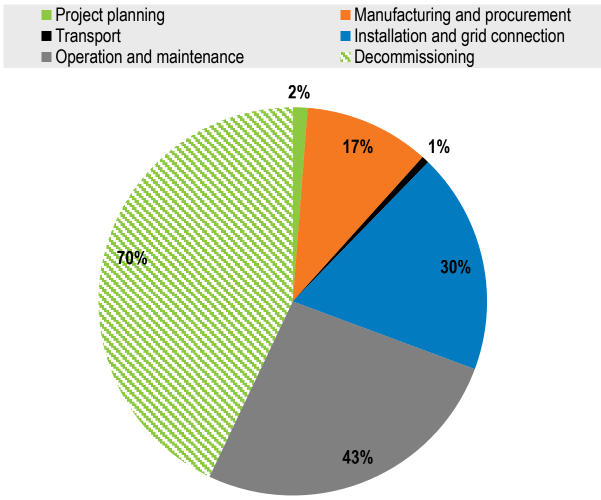
Second, these results shed light on the seeming tension between the political economy of domestic support for renewable energy and the basic principles of global trade regimes (Lewis, 2014[85]). Over the last decades, policy makers have pursued the dual objective of reducing carbon emissions through the deployment of renewable energy and creating local jobs associated with the expansion of a local manufacturing industry to supply renewables projects. Their policy approach has often times been based on discriminatory trade measures.

For example, local content requirements (LCRs) – which often come with government support like feed-in tariffs – require a minimum percentage of locally manufactured inputs in renewable energy projects. The increasing use of these industrial policies in the renewable energy sector has led to a rise in trade-related disputes, both via the WTO and domestic trade remedy channels (Asmelash, 2015[86]; Lewis, 2014[85]). In addition, evidence suggests that LCRs are associated with a decline in trade – even in those regions not implementing an LCR – and a loss in international competitiveness in the countries imposing the measure. This undermines the growth and innovation opportunities that come from a diverse economy (Stone, Messent and Flaig, 2015[87]).

However, achieving both renewable energy expansion and job creation does not need to be based on such measures. On a typical wind farm project, only 17% of the jobs are associated with manufacturing, while the rest is accounted for by services such as operation and maintenance, and installation and grid connection (Figure 11 from IRENA (2019[88])).[17] As a result, non-manufacturing job creation hinges on the continuous deployment of wind energy, which is only possible if wind farms can compete with older power generation technologies. As this study shows, the competitiveness of wind energy depends on access to international markets where high quality wind turbines are found.

Figure 11. More jobs in the wind farm value chain lie in operations, rather than in manufacturing turbines

Distribution of human resources required along the value chain for the development of a 50 MW wind farm, by occupation



Source: IRENA (2019[88])

Therefore, the viability of ambitious climate policies – which depends, among other things, on their (perceived) economic benefits that foster public acceptability (Klenert et al., 2018[7]) and support across the political spectrum (Schmidt, Schmid and Sewerin, 2019[89]) – can be strengthened by a more open trade regime for renewable energy equipment. In addition, these results should also alleviate concerns about the so-called “green dilemma”, whereby policy-makers would have to choose between protecting

[17] Similar results are found for solar photovoltaic installations from IRENA (2017[133]).

domestic manufacturing capacities and supporting renewable energy project operators who benefit from open trade and access to top-notch equipment (Hughes and Meckling, 2017[90]).

Third, the implications of this study are not that potential new firms should not try to enter the wind turbine manufacturing market. Rather, they suggest that the opportunity cost of developing complex wind technologies in a reasonable time period is large. This cost should be weighed against other alternatives to participate in the value chain of the wind industry, which has now become global as wind turbine manufacturers outsource the production of components such as blades, towers, gearboxes and generators (Lawson, 2013[91]).

Evidence shows that firms have engaged with the emergence of solar and wind power industries by building on their existing industrial capabilities and their application in these sectors rather than vertically-integrating the full range of skills required to commercialize new technologies (Nahm, 2017[81]). Consequently, countries with the industrial capacity to produce components for aircrafts, automobiles, or other such products may have a competitive edge to manufacture components for wind turbines (Jha, 2017[92]). The latter have a wide difference in their technology complexity and countries without an existing wind industry have been able to supply low-technology components only (Surana et al., 2020[93]). Thus, the challenge may not be to design industrial policies for the creation of national champions but rather to ensure that domestic firms can apply their specific capabilities to new opportunities in global industries (Nahm, 2017[81]).

As noted above, innovation in wind technologies is enabled by strong networks of producers, suppliers, government actors and research institutions. Trust and reliability are key facilitators for the creation of such networks and can be achieved via well-designed innovation and trade policies. Domestic ecosystems can be integrated with their foreign counterparts thanks to measures aiming at international cooperation and collaboration – for instance the promotion of renewable energy partnerships through joint ventures and long-term capacity building programmes (GEA, 2012[94]; Fidelman et al., 2019[95]). In addition, a dialogue between renewable energy suppliers, regulators and local communities would allow for a mutual understanding of the benefits associated with renewable energy and contribute to higher social acceptance, a condition needed for a large-scale diffusion of environmental technology solutions (Ellis and Ferraro, 2016[96]; Delicado, 2018[97]).

6. Concluding remarks

This paper provides empirical evidence on the role of trade as a channel for the diffusion of environmental technologies that are key for a low-carbon transition. It has focussed on one type of technology – i.e. wind technologies – where dissemination processes are highly technology-dependent.

Other environmental technologies could warrant further study insofar as they have different characteristics raising different issues. For example, solar photovoltaic (PV) technologies are manufacturing-intensive technologies, which require the manipulation of high-tech assembly lines. In contrast to the tacit knowledge embodied in finished or semi-finished wind turbines, PV technologies require specific production equipment enabling state-of-art manufacturing (Schmidt and Huenteler, 2016[6]). In addition, diffusion processes also depend on the maturity of technologies and whether they have already become price-competitive vis-à-vis older technologies they aim to displace (Popp, 2019[24]; IRENA, 2019[88]).

The study of the dissemination of other environmental technologies is a promising area for future research. This paper should be seen as the first of a series that would build knowledge on various types of technology diffusion processes taking place through trade.

Annex A. Gravity model estimation strategy

The gravity model is often referred as the workhorse of international trade analysis. Introduced by Tinbergen (1962[98]) and Anderson (1979[99]), it provides trade researchers and practitioners with a powerful tool to understand the determinants of bilateral trade flows including trade policies and border effects (Eaton and Kortum, 2002[46]; Anderson et al., 2003[100]; Head and Mayer, 2014[101]; Yotov et al., 2016[69]).[18]

In this study, the gravity model is used to investigate the extent to which wind technologies drive trade in wind turbines. The approach examines the relationship between an exporter's degree of expertise in a technological field and the exports of products made with this technology. A country's degree of technological expertise can be proxied by the accumulation of related patent applications filed by its residents, which defines its "knowledge stock" in this technological field (Griliches, 1990[71]; Grafström and Lindman, 2017[102]) (see Annex C for a complete methodological discussion).

Therefore, the variable of interest is the exporter's knowledge stock in wind technologies. Because it is expected that technology drives exports in general (Wolff, 1995[70]; Fagerberg, 1996[10]), the effect of an exporter's knowledge stock in wind technologies is compared against a benchmark – i.e. the effect of an exporter's knowledge stock in technologies on exports in other products comparable to wind turbines.[19] If such an effect is more pronounced for wind technologies, the latter would play a larger role (on exports in wind turbines) than benchmark technologies (on exports in similar products).

In a gravity equation, such a comparison can be made by introducing an interaction variable that estimates whether the effect of knowledge stock is significantly differentiated for wind turbines exports. Formally, the following equation is estimated:

$$X_{ijst} = exp\{a + \beta_1 Log(KS_{ist}) + \beta_2 (Log(KS_{ist}) * I_{s=wind\ turbines}) + \rho_{it} + \mu_{jt} + \delta_{ijt} + \lambda_s + \varepsilon_{ijst}\} \qquad (1)$$

where the dependent variable X_{ijst} is the volume of exports in products s from exporter i to importer j in year t, KS_{ist} is exporter i's knowledge stock in the technological field of which product s is an industrial output in year t, and $I_{s=wind\ turbines}$ is a dummy variable that takes value 1 if product s is wind turbines. Therefore, β_1 captures the effect of a knowledge stock increase on exports for all products on average, and β_2 captures the extent to which this effect is differentiated for wind turbines. The total marginal effect of an increase in wind technologies knowledge stocks on exports in wind turbines is given by $(\beta_1 + \beta_2)$. Next, ρ_{it}, μ_{jt} , δ_{ijt} and λ_s are exporter-time, importer-time, directional exporter-importer-time, and products fixed effects respectively. This very robust fixed-effect structure allows to control for potential confounding factors that may explain both exports volumes and knowledge stocks levels. The exporter-time, importer-time, directional exporter-importer-time fixed effects will absorb all observable and unobservable country-specific and bilateral characteristics that vary over time. They therefore include all relevant national policies and institutional settings such as government support for renewable energy (e.g. feed-in tariffs) or specific trade barriers (e.g. local-content requirements or tariffs on wind turbines), exchange rates, and bilateral treaties (free trade agreements and others) between an exporter and an importer – see Feenstra (2016[103]) and Yotov et al. (2016[69]) for discussions.

[18] Eaton and Kortum (2002[46]) and Anderson et al. (2003[100]) can be considered the two most influential contributions as they added micro-foundations and multilateral trade costs (multilateral resistances) to the gravity equations. Additional important extensions of the gravity model were the introduction of heterogeneous firms (Chaney, 2008[134]; Helpman, Melitz and Rubinstein, 2008[135]), and its applicability for sectoral analysis (Chor, 2010[136]; Costinot, Donaldson and Komunjer, 2012[137]) as well as for aggregate data (Head and Mayer, 2014[101]).

[19] The benchmark products are steam turbines, combustion engines, and pumps. See Annex D for a discussion on the selection of benchmark products.

Alternatively, the difference in knowledge stocks between exporter i and importer j, $KS_{ist} - KS_{jst}$ can be used as a predictor of X_{ijst}:

$$X_{ijst} = \exp\{a + \beta_1(Log(KS_{ist}) - Log(KS_{jst})) + \beta_2[(Log(KS_{ist}) - Log(KS_{jst})) * I_{s=wind\ turbines}] + \rho_{it} + \mu_{jt} + \delta_{ijt} + \lambda_s + \varepsilon_{ijst}\} \quad (2)$$

where β_1 captures the effect the exporter-importer technological gap on exports and β_2 captures the extent to which this effect is differentiated for wind turbines. Again, the total marginal effect of an increase in the exporter-importer gap in wind technologies on exports in wind turbines is given by $(\beta_1 + \beta_2)$.

All equations are estimated via the Poisson pseudo-maximum likelihood method (PPML). Since its introduction by Silva and Tenreyro (2006[104]), the PPML approach has become widely used in gravity model estimations. Better at handling the presence (and often high frequency) of zeros in bilateral trade data, it outperforms the Ordinary Least Squares (OLS) technique. Following standard practices, Equations 1 and 2 are estimated with the absolute values of exports and the natural logarithm of knowledge stocks.[20] Therefore, point estimates of knowledge stocks and difference in knowledge stocks report full elasticities – see Silva and Tenreyro (2006[104]) for mathematical derivations. Finally, following recommendations in Yotov et al. (2016[69]), standard errors are clustered at exporter and importer levels in order to account for any intra-cluster correlations at the trading pair level.

[20] Because knowledge stocks are proxied by patent counts with some countries having no patent at all for some of the technological fields considered in this study, the logarithmic transformation is applied on $KS_{ist} + 1$.

Annex B. Fixed effects model estimation strategy

To explore the relationship between imports and efficiency of wind turbines, the following equation is estimated:

$$ln\ Wpower_{it} = a + \beta\ Log(Capacity_{it}) + \gamma\ Share_{it} + X_{it} + \mu_i + \lambda_t + \varepsilon_{it} \quad (3)$$

where the dependent variable $Wpower_{it}$ is the amount of wind electricity produced in country i in year t, $Capacity_{it}$ is country i's installed wind power capacity in year t, $Share_{it}$ is the share of imported wind turbines in $Capacity_{it}$, and X_{it} is a vector of co-variates including GDP per capita to capture the development stage of country i in year t, and the total amount of electricity generated in country i in year t to account for the size of national power network and the extent to which the economy relies on it. Further, μ_i and λ_t are country and time fixed-effects.

Alternatively, the ratio of wind electricity to total power generation can be used as a dependent variable:

$$\mathrm{Log}(\frac{Wpower}{Tpower})_{it} = a + \beta\ Log(Capacity_{it}) + \gamma\ Share_{it} + X_{it} + \mu_i + \lambda_t + \varepsilon_{it} \quad (4)$$

where $Tpower_{it}$ is the total amount of electricity generated in country i in year t – a variable that is included in the vector of control co-variates X_{it} in Equation 3.

In Equation 3, the parameter of interest is γ, which captures the effect of an increase in the share of imported wind turbines on wind electricity output, for a given installed wind power generation capacity. In Equation 4, parameter γ captures the effect of an increase in the share of imported wind turbines on wind electricity output relative to the total amount of electricity generated – i.e. the share of wind electricity in the energy matrix.

Because $Share_{it}$ is a ratio, it is expressed in absolute value – i.e. percentage points – in Equations 3 and 4. Point estimates of γ therefore report semi-elasticities – i.e. the percentage change in the dependent variable for a 1-unit (i.e. a 1 percentage point) increase in the share of imported wind turbines.

All equations are estimated using the within estimator. All estimations account for the other above-mentioned control variables, all time-invariant country characteristics – captured by country fixed-effects – and the common global trend in wind energy generation – captured by years fixed-effects. Finally, standard errors are clustered at the country level to account for potential within-group correlation.

Annex C. Construction of knowledge stocks in technological fields

Patent data and statistics have proven to be very useful for tracking, measuring and comparing innovation activities within and across countries (Griliches, 1990[71]; Nagaoka, Motohashi and Goto, 2010[105]; Haščič and Migotto, 2015[72]; Haščič, Silva and Johnstone, 2015[73]). Patent data contain information on firms' innovation activities at a country level, disclosing technical details and providing relevant information such as the identities of applicants and inventors, the timeline of inventions – i.e. dates the patents were filed, reviewed, and accepted – and their technological field.

In addition, patent data provide a number of advantages over alternative measures of innovation such as R&D expenditures and personnel, new product sales, licensing data or innovation surveys of firms and inventors.[21] First, patent documentation provides continuous and readily available data, starting back as far as the 19th century. Second, patent data provide a quantitative metric based on objective and well-defined criteria. Whether an invention is patentable relies on three essential conditions: the invention must i) be novel; ii) include an inventive step (non-obvious to experts in the field), and; iii) industrially applicable. Third, the finely detailed patent classification systems – the International Patent Classification (IPC) and Cooperative Patent Classification (CPC) – provides granular data of innovation activities in precisely defined technological fields. Furthermore, additional information can be used to infer the quality and value of patents. In particular, citations received from subsequent patents (forward citations), patents' renewal, and the number of patent offices where protection is sought give indications of the quality and value of the patented inventions (Squicciarini, Dernis and Criscuolo, 2013[106]). Such important information allows to factor the heterogeneity of patent filing procedures and examination across national patent offices in analyses and allows to work with quality-adjusted samples of patents.[22]

However, the usage of patent data as indicators and measures for innovation also comes with some limitations. First, not all inventions are patented by firms nor they fulfil the three key criteria of patentability listed above. Second, firms might use other types of intellectual property such as copyrights, trademarks and industrial designs to protect their inventions. They might also rely on complex design, secrecy or lead time as a way to protect and rent appropriation from their inventions (Cohen et al., 2002[107]; Hall et al., 2014[108]). Finally, the tacit knowledge embedded in managerial practices and engineering skills of innovative firms is difficult to quantify and not entirely captured by patent data.

Notwithstanding these limitations, patent data remain the best readily available metric to conduct empirical analyses that address international comparisons of innovation activities in specific technological fields as no other measure captures as much relevant information. Such an approach has long been adopted both at the OECD and in the academic literature – see for instance Griliches (1990[71]), OECD (2009[109]), Nagaoka, Motohashi and Goto (2010[105]), Haščič and Migotto (2015[72]), and Haščič, Silva and Johnstone (2015[73]).

Thus, the empirical analysis in this study relies on patent data to measure the degree of expertise in specific technological fields. Conceptually, such a degree of technological expertise is the accumulation of knowledge that have industrial applications, thereby being likely to be patented (Griliches, 1990[71]; Grafström and Lindman, 2017[102]). Therefore, a country's degree of expertise in a technological field is proxied by the accumulation of patent applications in this field over time. In addition, as it is generally assumed that the value of an invention depreciates with time, a depreciation rate of 15% is imposed – which follows common practices (Griliches, 1990[71]; Braun, Schmidt-Ehmcke and Petra, 2010[110]; Grafström and Lindman, 2017[102]). Formally, exporter i's knowledge stock in the technological field of which product s is an industrial output in year t is given by:

[21] For an extensive discussion on the use, advantages and limitations of patent data as a proxy for innovation, see Griliches (1990[71]) and Nagaoka, Motohashi and Goto (2010[105]). For environmental innovations in particular, see Haščič and Migotto (2015[72]) and Haščič, Silva and Johnstone (2015[73]).

[22] It also allows for the development of quality indicators. See for instance the OECD patent quality and citations databases (link).

$$KS_{ist} = (1 - 0.15)KS_{is,t-1} + PA_{ist}$$

where PA_{ist} is the counts of patent applications in country i in the technological field of which product s is an industrial output at time t.

Next, the concept of patent families is used to ensure a minimum quality threshold (Squicciarini, Dernis and Criscuolo, 2013[106]; Haščič and Migotto, 2015[72]). A patent family is a "set of patents (or applications) filed in several countries, which are related to each other by one or several common priority filings" (OECD, 2009, p. 71[109]), where priority filing means the first application of the patent worldwide.[23] In this study, it is only considered patents that have been registered in at least two patent offices – i.e. the patent family is at least of size 2. In addition, at least one patent office must be one of the five major intellectual property patent offices of the world (IP5), namely China National Intellectual Property Administration (CNIPA), European Patent Office (EPO), Japan Patent Office, Korean Intellectual Property Office (KIPO) and United States Patent and Trademark Office (USPTO). This approach excludes priority applications that have not been claimed at another patent office (singletons) and which are prone to low-value and strategic patenting (Dernis et al., 2015[111]; Haščič and Migotto, 2015[72]; Dechezleprêtre, Ménière and Mohnen, 2017[112]).

Finally, the patent data information exploited in this study is the applicant's country of residence and the priority year – i.e. the year the invention was first filed worldwide. The fractional counts' approach was applied to patents with multiple applicants residing in different countries. Fractional counts merely divide the patent between applicants' countries of origin. For instance, if one patent has four different applicants, from Denmark, the United States, and Germany with two different applicants from the latter, the patent count would be 0.25 for Denmark, 0.25 for the United States and 0.5 for Germany. Fractional counts provide an accurate measure of the cross-country distribution of patent applications and patent classes. They are commonly used to compile patent statistics (Guellec and Van Pottelsberghe De La Potterie, 2001[113]; OECD, 2009[109]; Squicciarini, Dernis and Criscuolo, 2013[106]; Dernis et al., 2015[111]).

[23] The counts of distinct patent families also allows to avoid double-counting of the same patent when simultaneously or subsequently filed at multiple patent offices (Nagaoka, Motohashi and Goto, 2010[105]; De Rassenfosse et al., 2013[138]; Dechezleprêtre, Ménière and Mohnen, 2017[112]).

Annex D. Mapping between International Patent Classifications and Harmonized System codes

The gravity approach of this study – detailed in Annex A – requires to establish a correspondence between exports in product s (X_{ijst}) and knowledge stock in the technological field of which product s is an industrial output (KS_{ist}). That is, for given exports classified in the Harmonized System (HS) by the World Customs Organization (United Nations Statistics Division, 2017[114]), the class of patents defining the technological field associated with these products has to be identified in the International Patent Classification (IPC) established by the World Intellectual Property Organization (WIPO). With no direct link between the HS and the IPC, a mapping between the two classification systems is developed for the purpose of this study.

Exports in wind turbines are measured with the HS code 850231, which is defined as "Electric generating sets; wind-powered, (excluding those with spark-ignition or compression-ignition internal combustion piston engines)".[24] This HS code covers sets of finished or semi-finished wind turbines – i.e. their most important components such as gearboxes and generators presented together at the customs, whether or not assembled (Wind, 2008[115]).[25] It has been used to measure trade in wind turbines in various other studies (Sugathan, 2013[116]; Dechezleprêtre and Glachant, 2014[56]; Pegels and Lütkenhorst, 2014[117]; Schleich, Walz and Ragwitz, 2017[118]). Patents in wind technologies fall under the IPC code F03D, which covers inventions related to "wind motors, i.e. mechanisms for converting the energy of wind into useful mechanical power, and the transmission of such power to its point of use".[26] Other studies on wind technologies have also relied on this IPC code to conduct their empirical analyses (Dubarić et al., 2011[119]; Haščič and Johnstone, 2011[50]; Dechezleprêtre and Glachant, 2014[56]; Schleich, Walz and Ragwitz, 2017[118]).

Benchmark products and associated technologies were selected as follows. First, as wind turbines, benchmark products must be manufactured goods that can be improved by technical innovations. That is, patents of associated technologies must protect inventions that have an industrial output in the manufacturing industry. Therefore, the large group of patents – to which F03D belongs – defined as category 27 *Engines, pumps, turbines* in Schmoch (2008[120]) was considered.[27] Second, within this group, IPC codes, like F03D, that can unambiguously be matched with one or many HS codes were selected.

Through careful inspection of descriptions of IPC codes and 6-digit HS codes – i.e. by comparing key words in definitions in both classification systems – three IPC codes could be identified: combustion engines (IPC code F02#), pumps (IPC code F04#), and steam turbines (IPC code F01D). Table A D.1 provides their corresponding HS codes, as well as all relevant definitions.

[24] See UN Trade Statistics website for reference (link).

[25] Wind turbines blades, towers, electronic equipment, and bearings will fall under the same HS code if these components are presented with the gearbox and generator. See Wind (2008[115]) for a discussion.

[26] See WIPO website for reference (link).

[27] Schmoch (2008[120]) provides a methodology to group IPC codes by areas of technology. This classification is has been widely used in the academic literature and by international organisations such as the WIPO and the OECD. It is also found in PATSTAT.

Table A D.1. IPC – HS code matching

IPC code	Definition IPC code	HS code	Definition HS code
F03D	Wind motors	850231	Electric generating sets; wind-powered, (excluding those with spark-ignition or compression-ignition internal combustion piston engines)
F01D	Non-positive-displacement machines or engines, e.g. steam turbines	840610	Turbines; steam and other vapour turbines, for marine propulsion
		840681	Turbines; steam and other vapour turbines, (for other than marine propulsion), of an output exceeding 40MW
		840682	Turbines; steam and other vapour turbines, (for other than marine propulsion), of an output not exceeding 40MW
		840690	Turbines; parts of steam and other vapour turbines
F02#	Combustion engines; hot-gas or combustion-product engine plants	840710	Engines; for aircraft, spark-ignition reciprocating or rotary internal combustion piston engines
		840721	Engines; outboard motors for marine propulsion, spark-ignition reciprocating or rotary internal combustion piston engines
		840729	Engines; for marine propulsion, (other than outboard motors), spark-ignition reciprocating or rotary internal combustion piston engines
		840731	Engines; reciprocating piston engines, of a kind used for the propulsion of vehicles of chapter 87, of a cylinder capacity not exceeding 50cc
		840732	Engines; reciprocating piston engines, of a kind used for the propulsion of vehicles of chapter 87, of a cylinder capacity exceeding 50cc but not exceeding 250cc
		840733	Engines; reciprocating piston engines, of a kind used for the propulsion of vehicles of chapter 87, of a cylinder capacity exceeding 250cc but not exceeding 1000cc
		840734	Engines; reciprocating piston engines, of a kind used for the propulsion of vehicles of chapter 87, of a cylinder capacity exceeding 1000cc
		840790	Engines; rotary internal combustion piston engines, for other than aircraft or marine propulsion
		840810	Engines; for marine propulsion, compression-ignition internal combustion piston engines (diesel or semi-diesel engines)
		840820	Engines; compression-ignition internal combustion piston engines (diesel or semi-diesel engines), of a kind used for the propulsion of vehicles of chapter 87
		840890	Engines; compression-ignition internal combustion piston engines (diesel or semi-diesel engines), of a kind used for other than marine propulsion or the vehicles of chapter 87
		840910	Engines; parts of aircraft engines (spark-ignition reciprocating or rotary internal combustion piston engines)
		840991	Engines; parts, suitable for use solely or principally with spark-ignition internal combustion piston engines (for other than aircraft)
		840999	Engines; parts for internal combustion piston engines (excluding spark-ignition)
F04#	Positive-displacement machines for liquids; Pumps for liquids or elastic fluids	841311	Pumps; fitted or designed to be fitted with a measuring device, for dispensing fuel or lubricants, of the type used in filling-stations or in garages
		841319	Pumps; for liquids, fitted or designed to be fitted with a measuring device, other than pumps for dispensing fuel or lubricants
		841320	Pumps; hand, fitted or designed to be fitted with a measuring device, for liquids, other than those of item no. 8413.11 or 8413.19
		841330	Pumps; fuel, lubricating or cooling medium pumps for internal combustion piston engines
		841340	Pumps; concrete pumps
		841350	Pumps; reciprocating positive displacement pumps, n.e.s. in heading no. 8413, for liquids
		841360	Pumps; rotary positive displacement pumps, n.e.s. in heading no. 8413, for liquids
		841370	Pumps; centrifugal, n.e.s. in heading no. 8413, for liquids
		841381	Pumps and liquid elevators; n.e.s. in heading no. 8413
		841382	Liquid elevators
		841391	Pumps; parts thereof
		841392	Liquid elevators; parts thereof

Note: For details and respective sub-classes and descriptions, see IPC classification (link) and HS system classification (link).
Source: International Patent Classification (IPC) by World Intellectual Property Organization (WIPO), HS - Harmonized System / UN Comtrade Commodity Classifications.

Annex E. Data sources

Countries' exports volume come from the *Base pour l'analyse du commerce international* (BACI) database from *Centre d'études prospectives et d'informations internationales* (CEPII), which relies on the United Nations COMTRADE database. This database provides trade volume data at the six digit product class level of the HS.

Patent data were extracted from the OECD, STI Micro-data Lab: Intellectual Property Database (link), which is based on the PATSTAT database. PATSTAT stands for Worldwide Patent Statistical Database, compiled by the European Patent Office. PATSTAT was jointly developed by leading patent offices, research and statistical institutions and the OECD in the 2000s. It covers patent data from over 90 countries and is biannually updated. All extractions were carried out with the PATSTAT version of spring 2020.

The share of imported wind turbines in installed wind power capacity is estimated based on a global wind farms database from the wind energy market intelligence The Wind Power.[28] For each (observed) wind farm, this database provides information on installed capacity, types of turbines and manufacturers, commissioning and decommissioning dates of the farm.

Data on wind electricity and total electricity generated – in Equations 3 and 4 – come from the International Energy Agency's (IEA) World Energy Statistics and Balances database. The IEA also provides a more complete coverage on wind power installed capacity at the country level than the global wind farms database, although these data do not distinguish between local and foreign manufacturers. Therefore, while they cannot be used to estimate the share of imported wind turbines in installed capacity, they can be used as a control variable for wind power installed capacity in estimating Equations 3 and 4.

Countries' GDP per capita (in US dollars at constant 2010 prices) data come from the World Bank World Development Indicators (WDI) database.

The final datasets cover 124 countries over the period 1996-2016 (Table A E.1.). An overview of the databases and their sources used in this study is provided in Table A E.2.

[28] Available at www.thewindpower.net.

Table A E.1. List of countries

Albania*	Germany	Norway
Algeria**	Ghana*	Oman*
Angola*	Gibraltar*	Pakistan
Argentina	Greece	Panama
Armenia	Guatemala	Paraguay*
Australia	Honduras	Peru
Austria	Hong Kong (China)*	Philippines
Azerbaijan**	Hungary	Poland
Bahrain*	Iceland	Portugal
Bangladesh**	India	Qatar*
Belarus	Indonesia*	Romania
Belgium	Iran	Russia
Bolivia	Ireland	Saudi Arabia*
Bosnia and Herzegovina*	Israel	Senegal*
Brazil	Italy	Serbia
Brunei Darussalam*	Jamaica	Singapore*
Bulgaria	Japan	Slovakia
Cambodia*	Jordan	Slovenia
Cameroon*	Kazakhstan	South Africa
Canada	Kenya	Spain
Chile	Korea	Sri Lanka
China	Kuwait*	Sweden
Colombia	Kyrgyzstan*	Switzerland
Congo*	Latvia	Syrian Arab Republic*
Costa Rica	Lebanon*	Tanzania*
Côte d'Ivoire*	Lithuania	Thailand
Croatia	Luxembourg**	Togo*
Cuba	Malaysia*	Trinidad and Tobago*
Cyprus	Malta*	Tunisia
Czech Republic	Mauritius*	Turkey
Democratic People's Republic of Korea*	Mexico	Ukraine
Denmark	Moldova*	United Arab Emirates*
Dominican Republic	Mongolia**	United Kingdom
Ecuador	Montenegro*	United States
Egypt	Morocco	Uruguay
El Salvador*	Mozambique*	Venezuela
Estonia	Netherlands	Viet Nam
Ethiopia	New Zealand	Yemen*
Finland	Nicaragua	Zambia*
France	Niger*	Zimbabwe*
Gabon*	Nigeria*	
Georgia	North Macedonia*	

Note: * Countries included in gravity approach only, ** Countries included in the fixed-effect approach only.
Note by Turkey:
The information in this document with reference to "Cyprus" relates to the southern part of the Island. There is no single authority representing both Turkish and Greek Cypriot people on the Island. Turkey recognises the Turkish Republic of Northern Cyprus (TRNC). Until a lasting and equitable solution is found within the context of the United Nations, Turkey shall preserve its position concerning the "Cyprus issue".
Note by all the European Union Member States of the OECD and the European Union:
The Republic of Cyprus is recognised by all members of the United Nations with the exception of Turkey. The information in this document relates to the area under the effective control of the Government of the Republic of Cyprus.

Table A E.2. Summary table data sources

Variable	Database	Source
Exports	BACI	Centre d'Études prospectives et d'Informations Internationales (CEPII)
Patent applications	STI Micro-data Lab: Intellectual Property Database - based on PATSTAT database	OECD European Patent Office (EPO)
Share of imported wind turbines in installed wind power capacity	Global wind farms database	The Wind Power - Wind Energy Market Intelligence
Electricity output (total and wind)	World Energy Statistics and Balances	International Energy Agency (IEA)
Installed wind power capacity	Internally provided	International Energy Agency (IEA)

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