UNIVERSITY OF ALBERTA
FACULTY OF ARTS
Department of Economics

Working Paper No. 2024-08

Environmental Regulations and Green Innovation: The Role of Trade and Technology Transfer

Corinne Langinier
University of Alberta

Inmaculada Martínez-Zarzoso
University of Goettingen

Amrita RayChaudhuri
University of Winnipeg

October 2024

Environmental regulations and green innovation: The role of trade and technology transfer*

Corinne Langinier[†], Inmaculada Martínez-Zarzoso[‡], and Amrita RayChaudhuri[§]

October 2023

Abstract

Our theoretical model predicts that green innovation is an inverted U-shaped function of emission tax under free trade, while it is upward sloping under autarky. Our empirical analysis supports this finding by using the Environmental Policy Stringency Index (EPS) as a proxy for environmental regulations. Our theory also determines the conditions under which international technology transfers increase green innovation. The empirical results indicate that technology transfers increase green innovation at any given level of EPS, although the inverted U-shape persists. We observe that OECD and non-OECD countries lie on either side of the turning point. Implementing stricter environmental regulations in non-OECD countries increases green innovation, while the reverse is likely to hold for most OECD countries. Our findings also show that market-based regulations are more effective in non-OECD countries for fostering green innovation, while non-market-based regulations are more effective in OECD countries.

Keywords: Green Innovation, Environmental Policy, International Trade, Technology Transfer

JEL Classification = Q55, Q58, Q56, O34.

*We would like to thank the participants at CEA 2023 for insightful comments. All remaining errors are ours.

[†]Corresponding author. Department of Economics, University of Alberta, Edmonton, Canada. langinie@ualberta.ca

[‡]Department of Economics, University of Goettingen, Platz der Goettinger Sieben 3, Goettingen, 37073, Germany, Department of Economics and Instituto de Economía Internacional Universitat Jaume I, 12080, Castellón, Spain. martinei@uji.es

[§]Department of Economics, University of Winnipeg, Canada and TILEC, Tilburg University, The Netherlands. a.raychaudhuri@uwinnipeg.ca

1 Introduction

Innovation that reduces firms' marginal abatement costs (often referred to as "green innovation") has long been recognized as a key mechanism for mitigating emissions of polluting industries. Such innovation has emerged as particularly important in our fight against climate change (see e.g., Barrett, 2009; Galiana and Green, 2009), given that international cooperation on mitigating greenhouse gases in the absence of sufficient innovation has proven to be very difficult. As per the Porter hypothesis (Porter and van der Linde, 1995), more stringent environmental policies can incentivize regulated firms to develop cleaner (i.e., less polluting) technologies in order to cut compliance costs.[1] However, the evidence surrounding the Porter hypothesis is mixed (see e.g., Ambec *et al.*, 2013; Dechezleprêtre and Sato, 2017). Hence the urgency to determine under what conditions more stringent environmental policies are, in fact, effective in fostering more green innovation. This paper is an attempt to shed more light on this issue by examining the role played by two factors that have not been adequately discussed in the related literature: international trade flows and technology transfers.[2]

Extending the implications of the Porter hypothesis to an international context, countries that regulate pollution sooner than others may generate a first-mover advantage in terms of developing clean technologies that are increasingly in demand globally (Porter and van der Linde, 1995). There is a lack of consensus on the role played by international technology transfers in mitigating emissions. For instance, in the policy debate surrounding climate change, international organizations such as UNCTAD proactively encourage such transfers. Also, international agreements such as Free Trade Agreements increasingly come with technological or environmental clauses (Martínez-Zarzoso and Chelala, 2021). At the same time, it may or may not be the profit-maximizing option for innovating firms to licence their green technologies in oligopolistic markets depending on a number of factors including licensing arrangements. Therefore, it is unclear as to how international technology transfers affect firms' incentives to undertake green innovation. However, most existing studies related to the Porter hypothesis focus on the relationship between the stringency of environmental policies and green innovation without explicitly accounting for technology transfer across countries (e.g., Jaffe et al., 1995).[3]

[1] This is referred to as the weak Porter hypothesis in the related literature while the strong Porter hypothesis argues that more stringent environmental regulation may generate so much innovation that it reduces or completely offsets regulatory costs. This paper analyses the weak Porter hypothesis only. Henceforth in the paper, the term Porter hypothesis is used to refer to the weak Porter hypothesis.

[2] Langinier and RayChaudhuri (2020) and Langinier and RayChaudhuri (2023) also examine firms' incentives to innovate in green technology, focusing on the role of patent policies. They use a closed economy model. Thus, they abstract away from heterogenous environmental policies across jurisdictions in their analysis.

[3] For recent surveys of the Porter hypothesis literature, please refer to Ambec *et al.,* (2013) and Dechezleprêtre and Sato (2017). Papers that find evidence in support of the Porter hypotheses include Jaffe and Palmer (1997), Brunnermeier and Cohen (2003), Newell, Jaffe, and Stavins (1999), and Popp (2002). More recent evidence, using firm-level data, includes Aghion et al., (2016) and Calel and Dechezleprêtre (2016). Aghion et al., (2016) find that firms innovate more in clean technologies (electric, hybrid, and hydrogen cars) in response to higher road fuel prices. Calel and Dechezleprêtre (2016) find that the EU ETS has increased innovation activity in low-carbon technologies among regulated firms by 30% relative to a control group. Martínez-Zarzoso, Bengochea-Morancho and Morales-Lage (2019) find support for the weak and strong versions of the Porter hypothesis using the EPS index as an indicator for the stringency of environmental regulations. While they used total patent applications as a proxy for innovation and did not account explicitly for trade and technology transfers, in this paper, we use green patent applications and include trade and technology transfers.

International trade of polluting goods is also expected to influence firms' incentives to invest in green innovations by changing the profitability of polluting industries. Moreover, increasing the stringency of environmental policies impacts these trade flows. As highlighted by the literature surrounding the pollution haven effect, an increase in the stringency of environmental regulations increases imports of pollution-intensive goods from regions with laxer environmental policies (e.g., McGuire, 1982; Grossman and Krueger, 1995; Antweiler, Copeland and Taylor, 2001; Levinson and Taylor, 2008; Branger, Quirion, and Chevallier, 2016; Sato and Dechezleprêtre, 2015; Copeland, Shapiro and Taylor, 2022). Recent evidence suggests that the pollution haven effect is significant, although generally dominated by other factors in terms of driving international trade patterns (see Dechezleprêtre and Sato, 2017 for a survey). While this set of empirical studies focuses on the relationship between the stringency of environmental policies and trade flows, it does not explicitly account for firms' incentives to invest in green innovation or allow for international technology transfer.

This paper develops an overarching framework which combines the key elements of both the above mentioned streams of the literature (i.e., the Porter hypothesis and the pollution haven effect), and provides empirical evidence in support of the key hypotheses generated by our theoretical model. We consider sectors where pollution is a by-product of the production process, such as manufacturing.[4] Indeed, according to Copeland, Shapiro and Taylor (2022), dirty industries are more exposed to international trade such that international trade accounts for a fourth to a third of global pollution emissions. Shapiro (2016) shows that in most countries, import tariffs and non-tariff barriers are substantially lower on industries with higher carbon dioxide emissions per dollar of output.

Within a setup where countries set different levels of emission taxes and are asymmetric in terms of production costs, we allow countries to trade in a polluting good. At the same time, firms' investment in developing green innovation is endogenized. More specifically, in a two-country model where each country has a single firm, we capture the pollution haven effect since, in equilibrium, the net exports of the polluting good flow from the country with the lower emission tax to the country with the higher emission tax. At the same time, we allow for differences in production costs to also drive trade flows. The firms behave as Cournot oligopolists in the product markets. Crucially, firms endogenously choose how much to invest in green innovation in the face of increasing emission taxes. We further investigate what changes when green technologies can be transferred to other countries through a licensing arrangement.[5]

For our empirical analysis, we use an unbalanced-panel dataset over the period from 1990 to 2019 for OECD and BRIIC countries. The dependent variable is the number of green patent applications at the sectoral level. The WIPO IPC Green Inventory is used to identify patents that have an environmental content, i.e., green patents (see LaBelle et al., 2023). Among the independent variables, EPS (Environmental Policy Stringency Index) denotes the environmental policy stringency index built by the OECD. Data on sectoral imports have been extracted from the International Trade and Produc-

[4] Emission rates vary significantly across industries. Evidence of this is reflected by abatement costs, which are typically higher for pollution-intensive industries such as pulp and paper, steel, mineral mining and refining and oil refining. In the United States, for example, in 2005 each of such sectors spent approximately 1% of their turnover to comply with environmental regulations, while the average for all manufacturing plants was 0.4 percent (Ferris et al., 2014).

[5] According to Andrenelli, Gourdon and Moisie (2019), most non-collaborative technology transfers occur via mandatory licensing.

tion Database for Estimation (ITPD-E). We use two proxies for technology transfer. First, the number of Regional Trade Agreements (RTAs) with technology provisions using the classification provided by Martínez-Zarzoso and Chelala (2021). Second, we use the number of green patent applications of a given country made in patent offices located in other countries, that is, the aggregated number of international patent applications, which are from PATSTAT and LaBelle et al., 2023.

Our theoretical framework generates two key hypotheses regarding the impact of international trade and international technology transfers, respectively. Our first set of theoretical findings on the impact of international trade is as follows. Under autarky, the weak Porter hypothesis holds such that firms increase their investment in green innovation as emission taxes increase. However, a move from autarky to free trade, where the polluting good is traded internationally, makes it less likely that the Porter hypothesis holds. This is due to the pollution haven effect, whereby the country with the stricter environmental regulation imports the polluting good from the country with the laxer environmental regulation, making it less profitable for firms in the country with stricter environmental regulation to invest in green innovation. Specifically, we find that the relationship between investment in green innovation and emission tax takes on an inverted-U shape. This is an important finding since, in practice, the stringency of environmental policies varies widely across countries as we document in our empirical section, and the inverted-U shaped relationship implies that the impact of marginal increases in EPS differs across countries depending on the initial EPS level.[6]

Our second set of theoretical findings on the impact of international technology transfers is as follows. When we allow licensing of the innovation under free trade in our theoretical model in order to examine the impact of international technological transfers on green innovation, our findings are ambiguous. On the one hand, the innovating firm gains a per unit royalty and a fixed fee for selling the technology. On the other hand, it suffers from lost market share since licensing effectively reduces its rival's emission tax bill. We show that international technology transfer only increases green innovation and the likelihood of the weak Porter hypothesis holding, compared to the case with no licensing, as long as the royalty rate is sufficiently high and the inventive step corresponding to the innovation is not too large, i.e., the innovation does not cause too large a reduction in the emission-output ratio of the firms. Given this conditional result, the actual impact of international technological transfers remains an empirical question.

Our empirical findings support our theoretical predictions. Increasing trade flows weaken the effect of EPS on green innovation and we find an inverted U-shaped relationship between EPS and green patent

[6] While several papers have focused on differences of environmental regulations across specific sectors or regions (Dechezleprêtre and Sato, 2017; Pasurka, 2008; Ferris et al., 2014; Iraldo et al, 2011; Goulder and Parry, 2008), we begin our empirical section by documenting the degree to which such differences exist globally, using the EPS data. Such differences are likely to continue into the future, with different regions planning to mitigate carbon emissions to different extents under the United Nations Framework Convention on Climate Change Paris agreement. Moreover, evidence suggests that regulatory differences across jurisdictions do affect the relative production costs of firms. Pasurka (2008) finds that across nine countries in Europe, North America, and Asia, the share of manufacturing capital expenditure assigned to pollution abatement in 2000 ranges from 1 % (Taiwan) to 5% (Canada). These differences are driven by differences in environmental stringency across countries. Chan, Li, and Zhang (2013) show that the European Union Emissions Trading System (EU ETS), across Europe, increased average material costs (including fuel) for regulated firms in the power, cement, and iron and steel sectors from 5% to 8%.

applications, in line with our theoretical predictions. This inverted U-shaped relationship is robust across multiple variations of the basic empirical model, as well as after including measures of international technology transfer. Moreover, we observe that OECD and non-OECD countries lie on either side of the turning point of the inverted-U shape which yields important policy implications. In non-OECD countries, implementing stricter environmental regulations increases green innovation, while the reverse is likely to hold for most OECD countries. The implication of this finding is that it is not sufficient for OECD countries to continue unilaterally tightening their own environmental regulations further, which may even deter innovation in these countries. Rather, global efficiency may be enhanced by facilitating non-OECD countries through transfers to tighten their environmental regulations. Our empirical analysis also shows that tightening market-based regulations may be more effective in non-OECD countries, whereas in OECD countries non-market-based regulations may be more effective in fostering green innovation.

Regarding the role of international technology transfers, our empirical findings show that they increase green innovation at any given level of EPS, although the inverted U-shaped relationship between EPS and green innovation persists. In fact, we find that international technology transfers do not significantly affect the likelihood of the Porter hypothesis holding since the turning point of the inverted-U shaped relationship is hardly affected by the inclusion of technology transfers.[7] Nevertheless, our findings support the stance taken by the UN and other international organizations in terms of facilitating international technology transfers since our empirical results show that such transfers help foster green innovation at any level of environmental regulation.

In section 2, we present our theoretical model and generate testable hypotheses. In section 3, we present our empirical strategy and summarize our results. In section 4, we provide concluding remarks.

2 Theoretical Model

We consider a model with two firms a and b that are located in countries A and B, respectively. Each firm i produces a polluting good at marginal cost c_i where $i = a, b$. Each firm i can invest I_i to reduce its emission output level, γ_i. That is, γ_i is defined as

$$\gamma_i \equiv \frac{e_i}{q_i},$$

where e_i denotes emission and q_i denotes output. We assume that γ_i is a function of I_i, i.e., $\gamma_i(I_i)$, with $\gamma_i'(I_i) < 0$, $\gamma_i''(I_i) \geq 0$. Moreover, $\gamma_i(I_i) \in [\underline{\gamma}, \overline{\gamma}]$ where $\overline{\gamma}$ is the emission-output level of the initial polluting good and $\underline{\gamma}$ is the emission-output ratio associated with the cleaner good. Within this context,

[7] Recent empirical studies find that invention has remained highly concentrated geographically over the past decade, with inventors in Germany, Japan and the United States accounting for more than half of global inventions, and the top ten countries for almost 90%. Most middle-income economies have not caught up and remain less specialized in low-carbon technologies than high-income economies (Probst et al., 2021). This may be explained by factors exogenous to our framework such as certain OECD countries developing a first-mover advantage in terms of innovation. Our analysis states that increased international technology transfers from these innovation leaders increases their domestic firms' incentives to innovate further. At the same time, we caution that further increases of EPS in these countries may not generate more innovation, while increasing EPS in non-OECD countries would do so.

we refer to green innovation as a decrease in the value of γ_i.[8]

Each firm i produces in its own country and can also export to the other country when trade is allowed. Therefore, firm a sells q_a^A in its own country A, and exports q_a^B to country B. Firm b sells q_b^B in its own country B, and exports q_b^A to country A.

The markets of the two countries are assumed to be segmented such that the product price may differ across countries in equilibrium. The inverse demand function in each country j, $j = A, B$ is given by:

$$p^j(q_i^j, q_k^j) = \alpha^j - q_i^j - q_k^j \text{ for } i = a, b \text{ and } i \neq k.$$

That is, consumers perceive the goods as being perfect substitutes. Firms pollute at the production stage and, thus, each firm has to pay an emission tax in the country where it produces. The per unit tax rate in country $j = A, B$ is given by τ_j. Each firm i pays a tax bill in country j, given by $\tau_j e_i = \tau_j \gamma_i (q_i^j + q_i^{-j})$. Thus, in our setting, τ_j captures the environmental protection stringency for country j.

In the absence of any technology transfer, firm a's profit is given by:

$$\pi_a = (p^A(q_a^A, q_b^A) - c_a)q_a^A + (p^B(q_a^B, q_b^B) - c_a)q_a^B - \tau_A \gamma_a (q_a^A + q_a^B) - I_a,$$

and firm b's profit is given by:

$$\pi_b = (p^A(q_a^A, q_b^A) - c_b)q_b^A + (p^B(q_a^B, q_b^B) - c_b)q_b^B - \tau_B \gamma_b (q_b^A + q_b^B) - \lambda I_b.$$

We make the following assumptions:

A1. Taxes are such that
$$\tau_B < \tau_A < \frac{\alpha^A - c_a}{2\overline{\gamma}}.$$

A2. Innovation process of firm b is such that $\lambda > \max\{\underline{\lambda}, 1\}$, where $\underline{\lambda}$ is derived in Appendix A.3.[9]

A3. Marginal costs of production are such that $c_a > c_b$.

A4. The emission output function $\gamma_i(I_i)$ for $i, j = a, b$ and $i \neq j$ is such that
$$\gamma_i(I_i) > \frac{(\gamma_i'(I_i))^2}{\gamma_i''(I_i)}.$$

Assumption ($A1$) states that country A has a higher emission tax than country B. Assumption ($A2$) states that the innovation process for firm b is more costly than for firm a. Moreover, the assumption that $\lambda > \underline{\lambda}$ ensures that firm b prefers to obtain the green innovation through technology transfer from firm a rather than investing in green innovation itself. Assumption ($A3$) states that the marginal cost of production is higher for firm a than for firm b. Assumptions ($A1$)-($A3$) reflect two types of countries that we observe in practice. Country A represents developed countries such as U.S. or EU countries whereas

[8] The modelling of the innovation process is similar to that of Langinier and RayChaudhuri (2020). For simplicity, we abstract away from uncertainty in the innovation process. Allowing for such uncertainty would make the analysis more cumbersome without generating additional insights.

[9] We define $\underline{\lambda} \equiv [(q_b^A(I_a^*, I_b^*))^2 - (q_b^A)^2 + (q_b^B(I_a^*, I_b^*))^2 - (q_b^B)^2 + r(q_b^A + q_b^B) + F]/I_b^*$, where I_a^*, and I_b^* denote the equilibrium investment levels of each firm. The complete derivation is available in Appendix A.3.

country B represents developing countries or emerging markets such as China or India. While country A has comparative advantage in R&D, country B has comparative advantage in the production of polluting goods. Assumption $(A4)$ ensures that there exists an interior solution for the optimal investment I_i.[10]

The timing of the game is as follows. In the first period (investment stage), both firms choose their investment in green innovation simultaneously. If only one firm (say firm a) has obtained the green innovation, and if there exists an international agreement or if firm a has patented its innovation in country B, firm a may transfer its technology to firm b for a royalty rate r and a fixed fee F. In the second period (production stage), both firms choose their quantities simultaneously.

As a benchmark, we first consider the case where trade is not allowed, and firms do not transfer their technologies (autarky). In that case, each firm is a monopolist in its own country. We then allow firms to trade, in which case, each firm will sell its product in the other country as well as in its own country. In the presence of trade, we consider three cases: in the first case, technology transfer does not occur, and one firm sells the polluting good while the other sells the cleaner good. In the second case, one firm invests in green innovation and technology transfer occurs such that both firms sell the cleaner good. In the last case, both firms invest in green innovation and both produce the cleaner good.

Note that, throughout this paper, the term "polluting good" refers to the product produced using the more polluting technology, i.e., the one associated with a higher γ_i, and the term "cleaner good" refers to the product produced using the less polluting technology.

2.1 Benchmark Case: Autarky

Consider first the case of autarky such that trade is prohibited and firms only sell in their own countries. Moreover, there is no transfer of technology from one firm to another. The inverse demand function for each country $j = A, B$ is, thus, given by:

$$p_i^j(q_i^j) = \alpha^j - q_i^j. \tag{1}$$

Firm a's profit is given by:

$$\pi_a = (p_a^A(q_a^A) - c_a - \tau_A\gamma_a)q_a^A - I_a, \tag{2}$$

and firm b's profit is given by:

$$\pi_b = (p_b^B(q_b^B) - c_b - \tau_B\gamma_b)q_b^B - \lambda I_b.$$

Both firms are monopolies in their own country. Given (1) and (2) , firm a chooses q_a^A that solves $\max \pi_a$. Substituting the equilibrium quantity and price, which are reported in Appendix A.1, we obtain firm a's equilibrium profit which is denoted by $\pi_a^m(I_a)$ and given by:

$$\pi_a^m(I_a) = (q_a^A(I_a))^2 - I_a. \tag{3}$$

Firm a chooses I_a that maximizes $\pi_a^m(I_a)$, as given by (3), which gives the following first-order condition:

$$-q_a^A(I_a)\gamma_a'(I_a)\tau_A - 1 = 0. \tag{4}$$

[10] For an example of a functional form that satisfies the above assumptions, please refer to Appendix A.4.

Let I_a^m be the optimal investment of firm a. If we totally differentiate (4), we find that

$$\frac{dI_a^m}{d\tau_A} > 0, \tag{5}$$

as long as ($A1$) and ($A4$) are satisfied (see Appendix A.1 for the details). Thus, as the EPS increases, firm a will invest more in green innovation. As τ_A increases, the tax bill increases, and thus firm a has an incentive to invest in order to reduce the emission output level γ_a.

By similar reasoning as that behind (5) , we have the following:

$$\frac{dI_b^m}{d\tau_B} > 0. \tag{6}$$

Proposition 1 *Under autarky, green innovation, as captured by reductions in the emission-output ratio, is increasing in emission tax in country* j*, for* $j = A, B$.

Proposition 1 follows directly from (5) and (6). As emission tax increases in either country, investment by the firm in each country increases. Given our assumption that $\gamma_i'(I_i) < 0$, a higher τ_j induces a lower γ_i for $i = a, b$ and $j = A, B$. Thus, by investing in green innovation each firm reduces its tax bill. This incentive increases as τ_A increases, which explains why firms increase their investment as emission tax increases under autarky, as per Proposition 1. Proposition 1 is a manifestation of the Porter Hypothesis.

We note that if both firms were identical ($c_a = c_b$, and $\gamma_a(I_a) = \gamma_b(I_b)$), demands were symmetric ($\alpha^A = \alpha^B$), taxes were identical ($\tau_A = \tau_B$), and at the same time $\lambda > 1$ (i.e., it is harder for firm b to innovate), firm b would invest less than firm a, $I_b < I_a$. Moreover, we obtain $I_b < I_a$ as long as $\tau_A \geq \tau_B$.

2.2 Trade and Technology Transfer

We now allow for international trade such that firms can export their good to the other country. By backward induction, for given investments, we first determine the quantities that firms will choose. We focus on the scenario where one firm, firm a, invests in green innovation while the other firm does not. This allows us to compare the cases where there is no technology transfer (Case I) and when there is (Case II). The cases where either none or both firms invest, while not directly relevant for our analysis, are available in Appendix A.2 for completeness. In Case I, one of the firms invests and sells the cleaner good while the other firm sells the dirty good, and there is no technology transfer. In Case II, one of the firms invests, there is technology transfer, and thus, both firms sell the cleaner good.

2.2.1 Case I: Trade without Technology Transfer

Consider first Case I, where there is no technology transfer, firm a invests and sells the cleaner good associated with emission-output ratio γ_a, while firm b sells the dirty good associated with $\overline{\gamma}$. The inverse demand function in country A is the same as before. Firm a chooses q_a^A and q_a^B that solve the following:

$$\max\{(\alpha^A - q_a^A - q_b^A - c_a - \tau_A\gamma_a)q_a^A + (\alpha^B - q_a^B - q_b^B - c_a - \tau_A\gamma_a)q_a^B\}, \tag{7}$$

and firm b chooses q_b^A and q_b^B that solve the following:

$$\max\{(\alpha^A - q_b^A - q_a^A - c_b - \tau_B\overline{\gamma})q_b^A + (\alpha^B - q_b^B - q_a^B - c_b - \tau_B\overline{\gamma})q_b^B\}. \tag{8}$$

Substituting the equilibrium quantities and prices, which are derived from (7) and (8) and reported in Appendix A.2, we obtain firm a's equilibrium profit, which is given by:

$$\pi_a^{NT} = (q_a^{A,NT}(I_a))^2 + (q_a^{B,NT}(I_a))^2 - I_a, \tag{9}$$

and firm b's profit is given by:

$$\pi_b^{NT} = (q_b^{A,NT})^2 + (q_b^{B,NT})^2. \tag{10}$$

In the first period, firm a chooses I_a that solves $\max \pi_a^{NT}$, as given by (9), which yields the following first-order condition:

$$-4\frac{\gamma_a'(I_a)\tau_A}{3}(q_a^{A,NT}(I_a) + q_a^{B,NT}(I_a)) - 1 = 0. \tag{11}$$

Let's denote as I_a^{NT} the investment level that solves (11). By totally differentiating (11), we find that $\frac{dI_a^{NT}}{d\tau_A} > 0$ iff $\tau_A < \widehat{\tau}_A^{NT}$, where $\widehat{\tau}_A^{NT}$ is given by:

$$\widehat{\tau}_A^{NT} \equiv \frac{\alpha^A + \alpha^B - 4c_a + 2c_b}{8\gamma_a} + \frac{\overline{\gamma}}{4\gamma_a}\tau_B. \tag{12}$$

Therefore, as long as $\tau_A < \widehat{\tau}_A^{NT}$, when τ_A increases, so does the equilibrium investment I_a^{NT}. However, for $\tau_A > \widehat{\tau}_A^{NT}$, when τ_A increases, the investment I_a decreases. The above discussion is summarized in the following Proposition, which follows directly from (11) and (12).

Proposition 2 *When international trade is allowed, and in the absence of technology transfer,*

(i) for $\tau_A < \widehat{\tau}_A^{NT}$, a marginal increase in country A's emission tax, τ_A, leads to an increase in green innovation;

(ii) for $\tau_A \geq \widehat{\tau}_A^{NT}$, a marginal increase in country A's emission tax, τ_A, leads to a decrease in green innovation.

By contrast to Proposition 1, Proposition 2 implies that, once firms are allowed to export their product, investment in green innovation becomes an inverted U-shaped (rather than a positively sloped) function of emission tax, as shown in Figure 1. For low values of EPS in country A, increasing EPS leads to more green innovation. However, for higher values of EPS, as EPS increases, investment in green innovation is reduced.

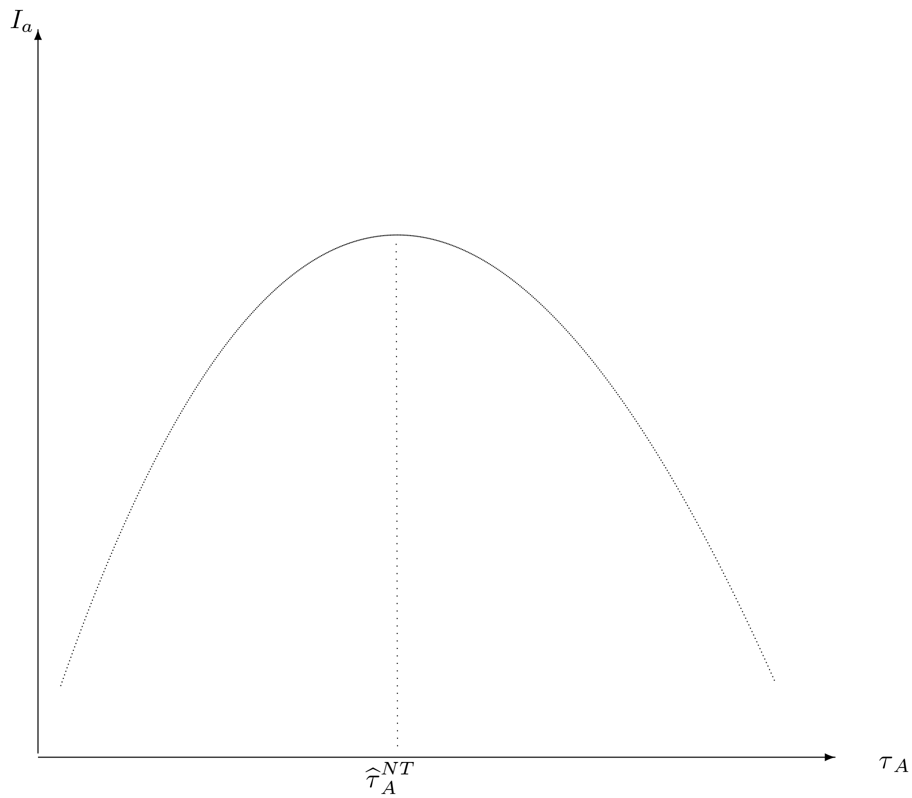


Figure 1: Equilibrium investment as a function of the tax

This occurs because in Case I, firm a obtains duopoly profits in equilibrium in each market rather than monopoly profit in country A as under autarky. As τ_A increases, holding constant τ_B, firm a becomes less competitive in both markets, A and B, such that the duopoly profits in either market are decreasing in τ_A. Thus, as τ_A increases, the marginal returns on investment in green innovation decrease, and eventually outweigh the marginal benefits from a reduced tax bill, causing the equilibrium level of investment to decrease beyond $\widehat{\tau}_A^{NT}$.

Moreover, it follows from (12) that as τ_B increases, so does $\widehat{\tau}_A^{NT}$. If τ_B increases, firm a becomes more competitive in both markets, A and B, increasing the marginal returns on investment in green innovation. Therefore, green innovation is increasing in τ_A for a greater range of τ_A. From (11), it follows that the equilibrium investment I_a^{NT} also increases in τ_B. Therefore, as EPS increases in the other country, firm a invests more.

2.2.2 Case II: Trade with Technology Transfer

Next, we consider Case II, in which firm a invests I_a, transfers its technology to firm b charging a royalty rate r and a fixed fee F, and both firms sell the cleaner good associated with γ_a. We consider that both r and F are exogenous. We note that such technology transfer may occur voluntarily between firms a and b, or may be part of an international treaty (such as part of a regional trade agreement signed between countries A and B with a clause that makes it mandatory for the innovations to be transferred from firms in one country to those in another at pre-specified r and F).[11]

The inverse demand functions in country A are defined as before. Firm a chooses q_a^A and q_a^B that solve the following:

$$\max\{(\alpha^A - q_a^A - q_b^A - c_a - \tau_A\gamma_a)q_a^A + (\alpha^B - q_a^B - q_b^B - c_a - \tau_A\gamma_a)q_a^B + r(q_b^A + q_b^B) + F - I_a\}.$$

Firm b chooses q_b^A and q_b^B that solve the following:

$$\max\{(\alpha^A - q_a^A - q_b^A - c_b - \tau_B\gamma_a)q_b^A + (\alpha^B - q_b^B - q_a^B - c_b - \tau_B\gamma_a)q_b^B - r(q_b^A + q_b^B) - F\}.$$

Substituting the equilibrium quantities and prices, which are derived from (7) and (8) and reported in Appendix A.3, we obtain firm a's equilibrium profit, which is given by:

$$\pi_a^T = (q_a^{A,T}(I_a))^2 + (q_a^{B,T}(I_a))^2 + r(q_b^{A,T}(I_a) + q_b^{B,T}(I_a)) - I_a + F,$$

and firm b's equilibrium payoff is given by:

$$\pi_b^T = (q_b^{A,T})^2 + (q_b^{B,T})^2 - r(q_b^{A,T} + q_b^{B,T}) - F.$$

In the first period, firm a chooses I_a that solves $\max \pi_a^T$, which yields the following first-order condition:

$$-2\gamma_a' \frac{2\tau_A - \tau_B}{3}(q_a^{A,T} + q_a^{B,T}) + 2r\gamma_a' \frac{\tau_A - 2\tau_B}{3} - 1 = 0. \tag{13}$$

Let's denote I_a^T the level of investment that satisfies (13). By totally differentiating (13), we find that $\frac{\partial I_a^T}{\partial \tau_A} > 0$ if $\tau_A < \widehat{\tau}_A^T$, where

$$\widehat{\tau}_A^T \equiv \frac{\alpha^A + \alpha^B - 4c_a + 2c_b}{8\gamma_a} + \frac{\tau_B}{2} + \frac{r}{16\gamma_a}. \tag{14}$$

Thus, as long as $\tau_A < \widehat{\tau}_A^T$, an increase in τ_A will lead to an increase in I_a^T. For $\tau_A > \widehat{\tau}_A^T$, an increase in τ_A will lead to a decrease in I_a^T. This leads to the following proposition, which is qualitatively similar to Case I.

[11] For climate change, we note that international organizations such as the UN advocate for such technology transfer between countries.

Proposition 3 *When international trade is allowed, and firm a licences its green innovation to firm b,*

(i) for $\tau_A < \widehat{\tau}_A^T$*, a marginal increase in country A's emission tax,* τ_A*, leads to an increase in green innovation;*

(ii) for $\tau_A \geq \widehat{\tau}_A^T$*, a marginal increase in country A's emission tax,* τ_A*, leads to a decrease in green innovation.*

Proposition 3 shows that one of our key findings, that investment in green innovation is an inverted U-shaped function of emission tax, can be generalized to scenarios where technology transfer between firms takes place along with international trade.

Moreover, for any I_a, we can rewrite $\widehat{\tau}_A^T$ as follows:

$$\widehat{\tau}_A^T \equiv \widehat{\tau}_A^{NT} - \frac{\overline{\gamma} - 2\gamma_a}{4\gamma_a}\tau_B + \frac{r}{16\gamma_a}. \tag{15}$$

If $\overline{\gamma} < 2\gamma_a$ (i.e., the green innovation is not too drastic), from (15) it follows that $\widehat{\tau}_A^T > \widehat{\tau}_A^{NT}$. On the other hand, if $\overline{\gamma} > 2\gamma_a$ (drastic innovation), $\widehat{\tau}_A^T > \widehat{\tau}_A^{NT}$ iff

$$r > 4(\overline{\gamma} - 2\gamma_a)\tau_B.$$

This leads to the following Proposition.

Proposition 4 *When international trade is allowed, and firm a licences its green innovation to firm b, a marginal increase in country A's emission tax,* τ_A*, leads to an increase in green innovation for a greater range of* τ_A *as long as*

(i) either the innovation does not lower γ_a *below* $\hat{\gamma} \equiv \frac{\overline{\gamma}}{2}$*,*

(ii) or the royalty rate is sufficiently large, i.e. $r > 4(\overline{\gamma} - 2\gamma_a)\tau_B$*.*

The intuition behind Proposition 4 is as follows. Allowing firm a to license its green innovation increases firm a's marginal return on investment since firm a earns the royalty rate, r, per unit of output produced by firm b. We, thus, find that technology transfer increases green innovation, $I_a^{NT} < I_a^T$, if the royalty rate is large enough $r > \underline{r}$ for any given τ_A. This also explains Proposition 4 which states that a marginal increase in country A's emission tax, τ_A, may lead to an increase in green innovation for a greater range of τ_A. Indeed, as stated by Proposition 4(ii), the larger the royalty rate, the more likely that the Porter hypothesis holds.

However, for a given level of r, if the innovation is sufficiently drastic, that is, γ_a decreases sufficiently due to the innovation, the technology transfer allows firm b to benefit from a significant decrease in its tax bill, which decreases firm a's competitiveness in both product markets, A and B. If this effect is sufficiently large, it reduces firm a's incentive to invest in green innovation. This is captured by Proposition 4(i), which highlights that at a given level of r, the positive effect of technology transfer on green innovation can only occur when the innovation is not too drastic.

Propositions 1-4 yield testable hypotheses which we take to the data in the following section.

3 Empirical Analysis

We begin this section by outlining the hypotheses yielded by our theoretical analysis in the previous sections. Propositions 1-4 yield the following testable hypotheses. First, comparing Propositions 1 and 2, we expect to see a negative effect of international trade on the likelihood that the Porter hypothesis holds. Second, since in practice countries are engaged in international trade, we expect to see an inverted U-shaped relationship between emission tax and green innovation rather than an upward sloping relationship as per Propositions 2 and 3. Third, the relationships between technology transfer and either green innovation or the likelihood that the Porter hypothesis holds are ambiguous since they depend on the royalty rates in the licensing agreements and the degree of innovation. Our empirical results shed light on whether the role of international technology transfer is positive or negative in fostering green innovation. In this section we present our empirical strategy to test the above hypotheses and our findings.

3.1 Data and Variables

We use an unbalanced-panel dataset over the period from 1990 to 2019 for OECD and BRIIC countries, namely, Australia, Austria, Belgium, Brazil, Canada, China, Czech Republic, Denmark, Finland, France, Germany, Greece, Hungary, India, Indonesia, Ireland, Italy, Japan, Korea, Netherlands, Norway, Poland, Portugal, Russia, Slovak Republic, Slovenia, South Africa, Spain, Sweden, Switzerland, Turkey, the United Kingdom (UK) and the United States of America (USA). The dependent variable is the number of green patent applications at the sectoral level.[12] We use disaggregated PATSTAT data to identify green patents according to the WIPO IPC Green Inventory,[13] which list patents that have an environmental content. The method to identify patent applications by origin country of the applicant is a fractional method (see LaBelle et al., 2023). This is important because an application may cite a technology class considered "green" by WIPO, however, that does not necessarily mean it is a fully "green" patent. Since each patent can have many technology classes associated with it, rather than assuming the entirety of a patent is green if it cites a single green technology class, we assume a fraction of the patent is green equal to the fraction of its technology classes cited that are green. For instance, if an application cites B60K 6/28 and B60K 6/20, both green classifications according to WIPO, and B60K 1/00, a non-green classification, then only two-third of this patent should be considered as green.

Among the independent variables, EPS denotes the environmental policy stringency index built by the OECD. We offer a more detailed explanation of the EPS below. Data on sectoral imports have been extracted from the International Trade and Production Database for Estimation (ITPD-E). The database contains international and domestic trade data at the industry level for several activities including agriculture, mining, energy, manufacturing, and services. The ITPD-E is originally constructed using reported administrative data and does not include information estimated by statistical techniques. This fact makes the ITPD-E well suited for estimation of economic models, according to the information on

[12] The sectoral classification is shown in Table A1 in the Appendix. A concordance table from Goldschlag, Lybbert and Zolas (2016) has been used to link the WIPO patent classification (IPC codes) to the industry codes from the International Standard Industrial Classification (ISIC Revision 3 at 2 digits).

[13] See: https://www.wipo.int/classifications/ipc/green-inventory/home.

the website.[14] Data for manufacturing is used in our estimations, which is available for the period 1988 to 2019.

Finally, we use two proxies for technology transfer. First, the number of RTAs with technology provisions using the classification provided by Martínez-Zarzoso and Chelala (2021). Second, we use the number of green patent applications of a given country made in patent offices located in other countries, that is, the aggregated number of international patent applications, which are also from PATSTAT and LaBelle et al., 2023. Definitions and units of the variables are given in Table A.2 and summary statistics of the main variables are provided in Table A.3 provided in the Appendix.

Environmental Policy Stringency Index

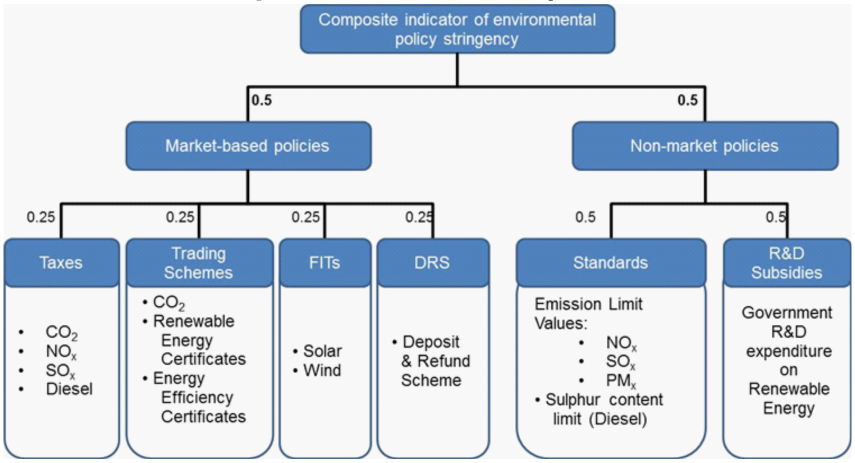
The EPS provided by the OECD combines quantitative and qualitative information related to environmental policy (laws and regulations) and is comparable across countries (Botta and Koźlak, 2014).[15] Hence, it overcomes the issues related to other indicators, such as the pollution abatement cost and expenditures (PACE), which has been used as a proxy for EPS stringency in many empirical studies, especially for the US.[16] EPS accounts for the multi-dimensional nature of environmental stringency and is based on environmental indicators corresponding to several policy instruments. Fifteen environmental policy instruments are used, primarily related to climate and air pollution. Stringency is defined as the degree to which environmental policies put an explicit or implicit price on polluting or environmentally harmful behaviour. EPS ranges from 0 (not stringent) to 6 (highest degree of stringency). Figure 2 shows the detailed instruments used to build the EPS by policy and indicator with their corresponding weights. There are two main subsets of instruments. In the market-based subset of instruments, we find taxes on emissions, a group of trading schemes (like the European carbon allowances or the green certificates), systems of deposit and refund and FITs (feed in tariffs) applied to promote renewable energies such as solar and wind energy. The Non-market subset includes the norms concerning emissions ceilings of some compounds, as well as the limit of sulphur content in diesel, and governmental subsidies for renewable energy.

[14] See: https://www.usitc.gov/data/gravity/itpde.htm.

[15] Barbieri, Marzucchi and Rizzo (2023) is another recent paper to use EPS data.

[16] Several shortcomings of PACE have been mentioned (Brunel and Levison, 2016): Variations in PACE could be caused by technological innovation, and not only by the adaptation of environmental regulations. Moreover, companies can reduce the effects of environmental regulations through decisions that do not require expenditures, for example, by outsourcing or using offshoring agreements and economies with an important heavy industry most likely have a higher level of expenditures than services economies. PACE also presents endogeneity concerns connected with other economic indicators and comparability over time and across countries is not always possible (Koźluk and Zipperer, 2015).

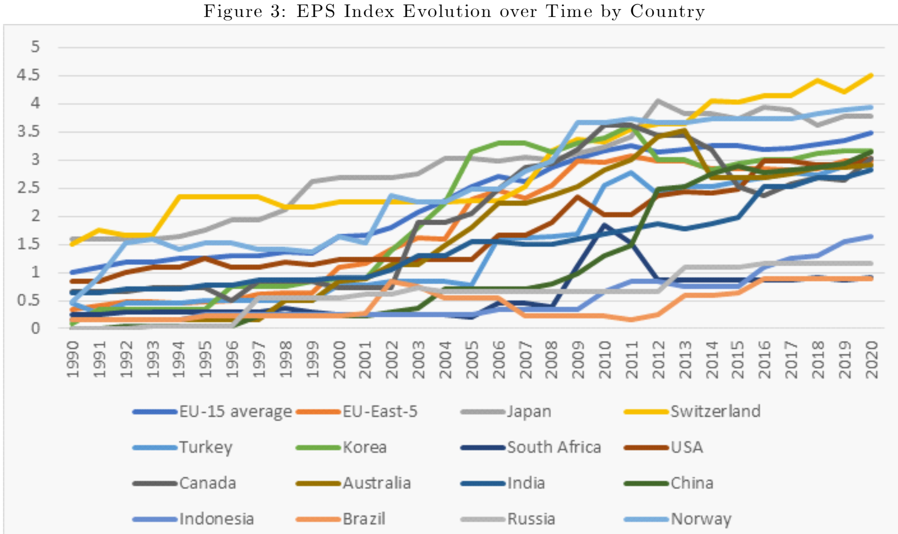
Figure 2: EPS Index and its Components



Source: OECD

Figure 3 illustrates the EPS evolution by EU-groups and countries over time. Most of the countries have increased their index values, especially from 2002 onwards. The highest values over the period are for Switzerland, Japan and the EU-15 (around 3.5-4-5 points). A slight reduction of the EPS is observed after the 2009 crisis (e.g. US, South Africa, EU-15, and 2012 crisis (Australia, Canada, Russia) for some countries.

Figure 3: EPS Index Evolution over Time by Country



Note: The score of the EPS index is on the y-axis.
The most recent EPS data was made available in 2020.

Table 1 presents the EPS summary statistics, including the variation over the sample period. Whereas the average EPS in the EU-15 is 2.5 times the initial level at the end of the period; in China, Korea, Norway and Switzerland the EPS is around 3 times higher; and in the US and Japan around 2 times. The lowest values and also the smaller changes are observed for Brazil, Russia and South Africa.

Table 1: Variation of the EPS Index (1990-2020)

	EU-15 average	EU-East-5	Japan	Switzerland	Turkey	Korea	South Africa	United States	Canada	Australia	India	China	Indonesia	Brazil	Russia	Norway
Average	2.1	1.4	2.7	2.7	1.1	1.4	0.5	1.6	1.6	1.0	1.3	0.6	0.4	0.3	0.5	2.3
Max	3.5	3.1	4.1	4.5	2.9	3.6	1.8	3.0	3.6	3.5	2.8	3.1	1.6	0.9	1.2	3.9
Min	1.0	0.3	1.6	1.5	0.3	0.1	0.2	0.8	0.5	0.2	0.6	0.0	0.2	0.2	0.0	0.5
% Change	248	265	219	300	244	308	67	219	236	275	219	314	147	72	117	347

3.2 Model Specification and Estimation Issues

The econometric model used to test the theoretical prediction is based on a fixed effects Poisson (FEP) estimation framework, as described in Wooldridge (2002, page 675). This framework is suitable for count data, which is the case for our dependent variable, green patent applications (GP). The FEP estimator has very strong robustness properties and allows for deviations from the Poisson distribution and for arbitrary time dependency under weak assumptions (Wooldrigde, 2002). In addition, variables that do not vary over time do not contribute to the estimation, meaning that factors that are inherent to the applicant countries but hardly vary over time, such as institutional quality or innovation capacity are controlled for.

The estimated models use GP as dependent variable and the EPS variable as the main proxy for environmental policy stringency. The first model is used to test the prediction that more environmental stringency increases the number of GP, but considering that the relationship is non-linear a squared EPS term is added to test for the existence of an inverted U-shaped relationship. The model specification includes sector-and-time fixed effects in a panel data setting (FEP) and it is estimated with a Poisson quasi-maximum likelihood estimator (PQML) for panel data[17] with the dependent variable in levels:

$$GP_{jkt} = exp\{\beta_1 EPS_{jt} + \beta_2 [EPS_{jt}]^2 + \beta_3 ln(Imports_{jkt}) + \beta_4 TT_{jt} + \alpha_{kt}\} * \mu_{jkt}, \tag{16}$$

where GP_{jkt} denotes the number of green patent applications of country j in sector k at year t. EPS_{jt} denotes the EPS index for country j and year t, which is introduced in a non-linear form (in levels and its squared term).[18] $Imports_{jkt}$, introduced in natural logarithms, denote imports of country j of goods in sector k at time t. TT_{jt} denotes technology transfer of country j at year t, and it is proxied with two variables: first, the number of regional trade agreements (RTA) ratified by country j at year t that contain technology provisions (RTA_tech_{jt}); and second, $Crosspatgr_{jt}$, the total number of green patent applications made by country j in other countries (international patents or cross-patenting) at year t.

[17] Similar linear models have also been estimated, the results are available on request:

$$GP_{jkt} = \beta_0 + \beta_1 EPS_{jt} + \beta_2 [EPS_{jt}]^2 + \beta_3 ln(Imports_{jkt}) + \beta_4 TT_{jt} + \alpha_{kt} + \mu_{jkt}.$$

[18] See Wooldridge (1999) for the interpretation of variables with a squared term in non-linear models.

Fixed effects are included to account for unobserved heterogeneity that is specific for each sector-year (α_{kt}) and the multiplicative error term is given by μ_{jkt}. Standard errors are clustered at the country-sector level.

The second specification models potential non-linearities using an interaction term between the natural log of imports and the EPS:

$$GP_{jkt} = exp\{\gamma_1 EPS_{jt} + \gamma_2 ln(Imports_{jkt}) + \gamma_3 [ln(Imports_{jkt}) * EPS_{jt}] + \gamma_4 TT_{jt} + \alpha_{kt}\} * \mu_{jkt}, \quad (17)$$

where the variables are described below equation (16).[19]

Finally, in model (18) interactions between the two proxies for technology transfer and the EPS are introduced. First, to test for the existence of non-linearities between the EPS and the RTAs with technology provisions and second with the number of green cross-patent applications:

$$GP_{jkt} = exp\{\delta_1 EPS_{jt} + \delta_2 TT_{jt} + \delta_3 [TT_{jt} * EPS_{jt}] + \alpha_{kt}\} * \mu_{jkt}, \quad (18)$$

where the variables are described below equation (16).

3.3 Empirical Results

In this section, we present the main results from estimating the above mentioned empirical models. We start with several versions of model (16), for which estimation outcomes are shown in Table 2.

The results in column (1) indicate a positive correlation between environmental regulations and green patent applications, as expected by the theory. Nevertheless, this positive correlation is only valid for low values of the EPS, given that the coefficient of the squared EPS is negative and significant at the one percent level (column 2). This result indicates the existence of an inverted U-shaped relationship between environmental regulations and green patent applications, which is in accordance with the theoretical predictions. The marginal effect of an increase in the EPS at the mean indicates that an increase in the EPS from 1.88 to 2.88 (53% increase from the sample mean), that is, moving from the EPS in South Africa to that in India in 2020, will increase the number of green patent applications by a multiplicative factor of 2.35 ($exp(2.267 - 2 * 0.3754 * 1.88) = exp(0.855)$). The turning points, out of which the effect of environmental regulations on green patent applications change from positive to negative are shown at the bottom of Table 2.[20] For instance, in column (2), this turning point indicates an EPS around 3. As shown in Table 1, all BRIICS countries plus Turkey have a maximum EPS below this level, with a high potential for an increase in green innovations if their level of environmental regulations increases. The turning point remains fairly stable when adding imports as control variable in column (3) and also when controlling for technology transfer with the number of RTA with technology provisions in column (4), and with the number of international patent applications in column (5). It is worth noticing that an increase in imports (added in column (3)) reduces the number of green patent applications, but its coefficient becomes non-significant when adding the second proxy for technology transfer.

[19] The squared of EPS is omitted because it is no longer significant when the interaction is added.

[20] For column (2) the turning point is calculated by taking the partial derivative of GP with respect to EPS and equating it to zero: $\beta_1 - 2 * \beta_2 EPS = 0 \Rightarrow EPS = 2.2670/(2 * 0.37\ 54) = 3.0194$.

Table 2: Estimation Results: Green Patents and Environmental Regulations

Variables	(1) Gpatents	(2) Gpatents	(3) Gpatents	(4) Gpatents	(5) Gpatents
EPS	0.9104***	2.2670***	2.3939***	2.3901***	2.4561***
	(0.133)	(0.177)	(0.207)	(0.211)	(0.174)
EPS^2		-0.3754***	-0.4076***	-0.3960***	-0.4117***
		(0.035)	(0.041)	(0.042)	(0.036)
lnImports			-0.0534***	-0.0494**	-0.0171
			(0.026)	(0.025)	(0.020)
RTA_tech				0.0136***	0.0130***
				(0.005)	(0.005)
Crosspatgr					0.0009***
					(0.000)
Turning point		3.0194	2.9366	3.0178	2.9829
Observations	17,824	17,824	17,824	17,824	17,824
Number of id	610	610	610	610	610

Note: The dependent variable is the number of Green patent applications (Gpatents) by country and sector. Among the explanatory variables: EPS denotes the Environmental Policy Stringency Index. lnImports is the natural logarithm of sectoral imports. RTA_tech denotes the number of free trade agreements with technology and IPR provisions by country. Crosspatgr denotes the number of green patent applications made abroad (cross-patent applications) by country and sector. The models in all columns are estimated with a Poisson quasi-maximum likelihood estimator. Sectoral-time fixed effects are included, but not reported to save space. Mean value of EPS=1.88.
Robust Standard errors are in parentheses. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

A second set of results is presented in Table 3, including estimations for equation (17), which considers the interaction between imports and the EPS with and without technology transfer. In this way, we are able to test for the second hypothesis. The results in columns (2)-(4) show that the effect of environmental regulations on green patent applications decreases with increasing imports (the coefficient of the interaction term is negatively signed). The results stay similar when the two proxies for technology transfer are added in columns (3) and (4).

Table 4 includes interactions between the EPS variable and the two technology transfer proxies. It can be seen that the effect of the EPS decreases with the increase in technology transfers, both for the number of RTAs and for the number of cross-patenting. The marginal effects are shown at the bottom of Table 4 for the average, maximum and minimum levels of the corresponding variable.

Table 5 presents results when the coefficients of the explanatory variables are allowed to differ by OECD and non-OECD countries. The full model is estimated with all coefficients interacted with an OECD dummy variable, so that we keep all the observations allowing for heterogeneity in the coefficients. The main results show that the Porter hypothesis holds more strictly for non-OECD countries, as shown

Table 3: Green Patents and Interactions between Environmental Regulations and Imports

Variables	(1) Gpatents	(2) Gpatents	(3) Gpatents	(4) Gpatents
EPS	0.8519***	1.4882***	1.6428***	1.9101***
	(0.116)	(0.485)	(0.493)	(0.477)
lnImports	0.1985***	0.3164***	0.3233***	0.4151***
	(0.029)	(0.078)	(0.079)	(0.081)
lnImports*EPS		-0.0544	-0.0593*	-0.0818**
		(0.035)	(0.034)	(0.034)
RTA_tech			0.0335***	0.0338***
			(0.007)	(0.007)
Crosspatgr				0.0009***
				(0.000)
Observations	17,824	17,824	17,824	17,824
Number of id	610	610	610	610

Note: The dependent variable is the number of Green patent applications (Gpatents) by country and sector. Among the explanatory variables: EPS denotes the Environmental Policy Stringency Index. lnImports is the natural logarithm of sectoral imports. RTA_tech denotes the number of free trade agreements with technology and IPR provisions by country. Crosspatgr denotes the number of green patent applications made abroad (cross-patent applications) by country and sector. The models in all columns are estimated with a Poisson quasi-maximum likelihood estimator. Sectoral-time fixed effects are included, but not reported to save space.
Robust Standard errors are in parentheses. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

in the right-hand-side of the table. It can be seen in columns (5)-(8) that the coefficient for the EPS variable is always positive and significant for the non-OECD sample, with a turning point in column (4) for $EPS = 2.9$ (the max EPS for BRIICS is below this number). Instead, for the OECD sample the positive sign is only found in column (1) and for low values of EPS, that is, below the turning point at $EPS = 2.41$ (notice that even Turkey has an $EPS = 2.9$), whereas in columns (2)-(4) is it either negative or non-significant at conventional levels.

Moreover, when the proxies for technology transfer are added to the model, the effect remains positive and significant for the OECD sample, but it is negative for RTA_tech in the non-OECD sample.

Finally, we also estimated the model for different sectors and for the two main components of the EPS (see Figure 2), namely, market-based and non-market policies. The results, shown in Table 6, indicate that the EPS turning point increases for products that are more sophisticated (column (3) versus columns (1) and (2)) and for which innovation is more crucial. Moreover, the Porter hypothesis holds more strictly for non-market in comparison to market-based policies, since in column (5) the positive effect of EPS on green patent applications holds for all countries (turning point is out of sample, at a level not reached yet for any country).

Table 4: Green Patents and Interactions between Environmental Regulations and Technology Transfer

	(1)	(2)		(3)	(4)
Variables	Gpatents	Gpatents		Gpatents	Gpatents
EPS	1.0061***	1.0683***		0.9221***	0.9232***
	(0.136)	(0.140)		(0.126)	(0.081)
RTA_tech	0.0327***	0.1235***			
	(0.008)	(0.026)			
EPS*RTA_tech		-0.0281***			
		(0.007)			
Crosspatgr				0.0005**	0.0052**
				(0.000)	(0.001)
Crosspatgr*EPS					-0.0013**
					(0.000)
Marginal effect of EPS				**Marginal effect of EPS**	
Av RTA_tech		-0.536		Av Crosspatgr	0.905
Min RTA_tech		1.0683		Min Crosspatgr	0.923
Max RTA_tech		-2.143		Max Crosspatgr	-1.287
Observations	18,360	18,360		18,360	18,360
Number of id	612	612		612	612

Note: The dependent variable is the number of Green patent applications (Gpatents) by country and sector. Among the explanatory variables: EPS denotes the Environmental Policy Stringency Index. lnImports is the natural logarithm of sectoral imports. RTA_tech denotes the number of free trade agreements with technology and IPR provisions by country. Crosspatgr denotes the number of green patent applications made abroad (cross-patent applications) by country and sector. The models in all columns are estimated with a Poisson quasi-maximum likelihood estimator. Sectoral-time fixed effects are included, but not reported to save space.
Robust Standard errors are in parentheses. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

Overall, our empirical findings support our theoretical predictions. Increasing trade flows weaken the effect of EPS on green innovation, in line with the comparison between Propositions 1 and 2. As expected, we find an inverted U-shaped relationship between emission tax and green innovation rather than an upward sloping relationship in the data in line with Propositions 2 and 3. This inverted U-shaped relationship is robust across multiple variations of the basic empirical model, as well as after including measures of international technology transfer. Moreover, the level of EPS at which the turning point of the green innovation measure occurs is stable and remains similar when estimating alternative models. The positive and negative effects of international technology transfer on the turning point, as presented in Proposition 4, seem to balance each other such that the turning point remains unchanged after including measures of international technology transfer. At the same time, increasing technological transfer (as measured by two different variables) is found to increase green innovation at any given level of EPS. Recall that as per our theoretical predictions this case occurs (i.e., $I_a^{NT} < I_a^T$) as long as the royalty rate is sufficiently high.

Table 5: Results for OECD and BRIICS

Variables	(1) OECD	(2) OECD	(3) OECD	(4) OECD	(5) BRIICS	(6) BRIICS	(7) BRIICS	(8) BRIICS
EPS	0.7327***	-0.5936*	-0.2440***	0.0710	1.6817***	2.6497***	0.7076***	0.4955***
	(0.206)	(0.320)	(0.091)	(0.070)	(0.298)	(0.569)	(0.167)	(0.136)
EPS^2	-0.1514***				-0.2901***			
	(0.043)				(0.070)			
lnImports	0.1136***	0.0546			-0.1427***	0.2816***		
	(0.030)	(0.076)			(0.038)	(0.124)		
RTA_tech	0.0378**	0.0439***	-0.0405***		-0.0428**	-0.0554***	-0.0353	-0.0738***
	(0.018)	(0.016)	(0.011)		(0.020)	(0.020)	(0.071)	(0.022)
Crosspatgr	0.0008***	0.0008***	0.0008***	0.0027***	0.0017***	0.0013***	0.0012***	0.0088***
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.002)
EPS*lnImports		0.0500*	0.7076***	0.4955***		-0.1691***		
		(0.028)	(0.167)	(0.136)		(0.048)		
EPS*RTA_tech			0.0189***				-0.0023	
			(0.005)				(0.024)	
EPS*Crosspatgr				-0.0006***				-0.0023***
				(0.000)				(0.001)
EPS turning point	2.410				2.898			
Observations	17,824	17,824	18,360	18,360	17,824	17,824	18,360	18,360
Number of id	610	610	612	612	610	610	612	612

Note: The dependent variable is the number of Green patent applications (Gpatents) by country and sector. Among the explanatory variables: EPS denotes the Environmental Policy Stringency Index. lnImports is the natural logarithm of sectoral imports. RTA_tech denotes the number of free trade agreements with technology and IPR provisions by country. Crosspatgr denotes the number of green patent applications made abroad (cross-patent applications) by country and sector. The models in all columns are estimated with a Poisson quasi-maximum likelihood estimator. Sectoral-time fixed effects are included, but not reported to save space.
Robust Standard errors are in parentheses. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

Table 6: Results for different sectors and for the two components of the EPS

	(1)	(2)	(3)	(4)	(5)
Variables	ISIC 10-19	ISIC 20-29	ISIC 30-35	Market based	Non-Market
EPS	2.1285***	2.3896***	2.6654***	2.5493***	1.3339***
	(0.296)	(0.151)	(0.271)	(0.512)	(0.225)
EPS^2	-0.4091***	-0.4156***	-0.4296***	-0.7759***	-0.1266***
	(0.079)	(0.033)	(0.053)	(0.187)	(0.028)
lnImports	0.0410	-0.0022	-0.0678*	0.1763***	0.0731**
	(0.034)	(0.023)	(0.037)	(0.033)	(0.033)
RTA_tech	-0.0022	0.0073	0.0215***	0.0137	0.0270***
	(0.009)	(0.005)	(0.008)	(0.010)	(0.006)
Crosspatgr	0.0024**	0.0005	0.0005***	0.0005***	0.0008***
	(0.001)	(0.000)	(0.000)	(0.000)	(0.000)
Turning point	2.601	2.857	3.106	1.643	5.2682
Observations	3,050	8,440	6,334	17,824	17,824
Number of id	104	289	217	610	610

Note: The dependent variable is the number of Green patent applications (Gpatents) by country and sector. Among the explanatory variables: EPS denotes the Environmental Policy Stringency Index. lnImports is the natural logarithm of sectoral imports. RTA_tech denotes the number of free trade agreements with technology and IPR provisions by country. Crosspatgr denotes the number of green patent applications made abroad (cross-patent applications) by country and sector. The models in all columns are estimated with a Poisson quasi-maximum likelihood estimator. Sectoral-time fixed effects are included, but not reported to save space.
Robust Standard errors are in parentheses. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

The empirical analysis also goes beyond the theoretical model in two directions and finds important policy implications. First, by identifying which countries lie on either side of the turning point, we obtain a clear pattern. As per our results, in non-OECD countries, implementing stricter environmental regulations will increase green innovation, while the reverse is likely to hold for most OECD countries. That is, in countries where EPS is already high (OECD countries), increasing EPS further may be detrimental to green innovation. This is because firms in countries with high EPS invest less in the face of higher EPS since a higher EPS hurts their competitiveness in global markets, making investment less profitable. On the other hand, more strict environmental regulations in non-OECD countries will increase green innovations, as well as contributing directly to mitigate emissions, hence providing a double dividend.

Second, an interesting comparison is made in the data across market-based and non-market-based environmental regulations. Whereas previous empirical studies have concluded that non-market-based regulations are more effective at fostering green innovation (Hassan and Rousselière, 2022), our results are more nuanced. We find that a monotonic positive relationship between EPS and green innovation is more likely with non-market-based regulations, similar to previous studies. At the same time, we note that at low levels of EPS (i.e., below the turning point), the magnitude of the positive effect of environmental regulations on green innovation is greater with market-based regulations. Together with our previous result, this implies that tightening market-based regulations may be more effective in non-OECD countries, whereas in OECD countries non-market-based regulations may be more effective in fostering green innovation.

3.4 Robustness Checks

In order to validate the results presented in the previous section, a number of specifications that introduce changes of the main model have been estimated. A first set of robustness checks presented in Table 7 consists of estimating the model with past values of the explanatory variables. By lagging the variables one period, the results remain practically unchanged (column 1). Next, we estimate the main model for two different periods in columns (2) and (3), namely, before and after 2005, that is, the year in which the Paris agreement was signed. The results hold, with the only particularity that the turning point is much higher after 2005, indicating that the positive effect of environmental regulation is in place for higher levels of the EPS after the Paris agreement. The same is the case when similar regressions are estimated for the market-based and non-market-based regulatory instruments in columns (4)-(7). Interestingly, the turning point for the non-market-based environmental regulations is out of sample, meaning that for any level of the EPS the relationship between non-market-based environmental regulations and green patents is positive, and this holds only after 2015.

A second set of estimations consists of sector-specific estimates for each 2-digit ISIC code in our data, as presented in Table A.4. (in the Appendix). The results indicate that the inversed U-shaped empirical relationship holds for all sectors (15-36), but one, which is leather and footwear (sector 19). There are some sectors, such as Tobacco and Printing & Publishing for which green patents are non-existent and hence there are no observations in the dependent variable.

A third set of robustness checks, as presented in Table 8 consists of variations in the dependent variable or the estimation technique. First, we estimate the model assigning the patents to the country where the inventor is a national instead of considering the nationality of the owner of the patent. The results remain very similar, as shown in column (1). Next, we estimate the model adding total patents by sector as a regressor and the results still remain similar, as shown in column (2). In column (3), exports are added as a control variable and the main conclusions remain the same. Next, we use a linear probability model (LPM) instead of a PPML estimator, with country, sector and time fixed effects in column (4) and random effects in (5). The interpretation of the magnitude of the coefficients changes, For each 1 point increase in the EPS, the number of green patents increase by $110.4 - 15.3 * avEPS = 81$. However, the results remain similar, except for imports that now positively affect green patents. Finally, to account for the potential endogeneity of environmental regulations (EPS), the model is estimated in first differences using the Generalized Method of Moments (GMM) and instrumenting the EPS in model (6) with the lagged values of EPS-market and EPS-non-market subindices and adding $EPS2$ in model (7) with the same instruments. The results remain similar.

Finally, the results also hold when using technology subsidies as a proxy for environmental regulations, as seen in the Table 9.

Table 7: Table Robustness 1

Dep. Variable: Green Patent Applications	(1) lag var	(2) Before2005	(3) After2005	(4) EPSMarket Before2005	(5) EPSMarket After2005	(6) EPSNoMarket Before2005	(7) EPSNoMarket After2005
Ind. Variables:							
EPS	2.4072***	1.4483***	1.9231***	0.9722***	2.6026***	0.2588*	1.4862***
	(0.178)	(0.248)	(0.127)	(0.280)	(0.300)	(0.137)	(0.202)
EPS^2	-0.4207***	-0.4070***	-0.2601***	-0.5422***	-0.5902***	-0.0700***	-0.1368***
	(0.038)	(0.055)	(0.020)	(0.116)	(0.088)	(0.023)	(0.025)
lnImports	0.0012	-0.0144	-0.0811***	-0.0488*	-0.0700***	-0.0239	-0.1079***
	(0.020)	(0.021)	(0.020)	(0.030)	(0.023)	(0.028)	(0.022)
RTA_tech	0.0064	-0.0217*	0.0290***	-0.0270*	-0.0101	0.0077	0.0262***
	(0.005)	(0.013)	(0.007)	(0.014)	(0.007)	(0.013)	(0.007)
Crosspatgr	0.0008***	0.0012***	0.0011***	0.0010***	0.0011***	0.0009***	0.0012***
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Turning point	2.861	1.779	3.697	0.897	2.205	1.847	5.431
Observations	17,214	8,374	8,625	8,374	8,625	8,374	8,625
Number of id	610	589	575	589	575	589	575

Note: The dependent variable is the number of Green patent applications (Gpatents) by country and sector. Among the explanatory variables: EPS denotes the Environmental Policy Stringency Index. lnImports is the natural logarithm of sectoral imports. RTA_tech denotes the number of free trade agreements with technology and IPR provisions by country. Crosspatgr denotes the number of green patent applications made abroad (cross-patent applications) by country and sector. The models in all columns are estimated with a Poisson quasi-maximum likelihood estimator. In column (1) "lag var" indicates that all explanatory variables are lagged one period.
Robust Standard errors are in parentheses. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

Likewise, results hold when using aggregated environmental patents from the OECD dataset, which are only available for the years 1995, 2000, 2005 and from 2010-2019, as seen in Table 10.

Table 8: Robustness 3

Dep. Variable: Patent Applications	(1) invent	(2) allpat	(3) exports	(4) LPM_FE	(5) LPM_RE	(6) GMM1	(7) GMM2
Ind. Variables							
EPS	2.459***	1.9855***	2.3958***	110.3683***	96.7115***		
	(0.173)	(0.228)	(0.152)	(37.609)	(32.270)		
EPS^2	-0.410***	-0.3407***	-0.3993***	-15.2681***	-14.3890***		
	(0.036)	(0.044)	(0.032)	(5.187)	(4.871)		
lnImports	-0.0152	-0.010	-0.129**	12.7191***	9.8415***		
	(0.019)	(0.020)	(0.057)	(4.253)	(3.262)		
RTA_tech	0.0195***	0.0125***	0.0131***	-2.0050**	-2.1916***		
	(0.004)	(0.004)	(0.005)	(0.885)	(0.849)		
Crosspatgr	0.0009***	0.0008***	0.0009***	1.5819***	1.576***		
	(0.000)	(0.000)	(0.000)	(0.238)	(0.210)		
patenta_all		0.0088***					
		(0.003)					
lnexports			0.138**				
			(0.062)				
D.EPS						2.6463*	3.6241**
						(1.372)	(1.503)
D.lnImports						-1.7792*	-0.2086
						(0.980)	(0.698)
D.RTA_tech						-0.0340	-0.0834
						(0.103)	(0.102)
D.Crosspatgr						0.6471***	0.6669
						(0.132)	(0.131)
D.EPS2							-0.6072*
							(0.355)
Turning points	2.997	2.913	3.000	3.627	3.360	-	2.984
Observations	17,703	17,824	17,823	21,141	21,142	20,416	19,228
R-squared				0.228		0.076	0.075
Number of id	605	610	610	726	726	726	726
Hansen test						1.118	16.46
Hansen Prob						0.290	0.00246

Note: The dependent variable is the number of Green patent applications (Gpatents) by country and sector in all columns except in column (1), where it is Green patent inventors. Among the explanatory variables: EPS denotes the Environmental Policy Stringency Index. lnImports is the natural logarithm of sectoral imports. RTA_tech denotes the number of free trade agreements with technology and IPR provisions by country. Crosspatgr denotes the number of green patent applications made abroad (cross-patent applications) by country and sector. D denotes that the corresponding variable is in the first differences. The models in columns (1)-(3) are estimated with a Poisson quasi-maximum likelihood estimator. Models in columns (4)-(5) are estimated using a linear probability model (LPM) with Fixed Effects (FE) and Random Effects (RE), respectively. Models (6)-(7) use a Generalized Method of Moments (GMM) estimated without and with the squared term of the EPS variable (EPS2), respectively.
The number of observations differs in the linear models (columns (4)-(7)) because using the xtppml 116 groups (3318 obs) are dropped. The results remain when running the linear models with the same number of observations as in columns (1)-(3).
Robust Standard errors are in parentheses. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

Table 9: Robustness 4 with technology subsidies

	(1)	(2)
Variables	TechSubs	TechSubs2
L.EPS_ts	0.3720***	1.2132***
	(0.061)	(0.114)
L.EPS_ts^2		-0.1639***
		(0.015)
L.lnImports	0.3844***	0.1527***
	(0.049)	(0.029)
L.RTA_tech	0.0223***	0.0194***
	(0.006)	(0.007)
L.Crosspatgr	0.0008***	0.0009***
	(0.000)	(0.000)
Turning point	-	3.700
Observations	17,214	17,214
Number of id	610	610

Note: The dependent variable is the number of Green patent applications (Gpatents) by country and sector. Among the explanatory variables: EPS_ts denotes the component of the environmental Policy Index that refers to technology subsidies. lnImports is the natural logarithm of sectoral imports. RTA_tech denotes the number of free trade agreements with technology and IPR provisions by country. Crosspatgr denotes the number of green patent applications made abroad (cross-patent applications) by country and sector. L denotes the value of the corresponding variable lagged one period (t-1). The models in all columns are estimated with a Poisson quasi-maximum likelihood estimator. Sectoral-time fixed effects are included, but not reported to save space.

Robust Standard errors are in parentheses. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

Table 10: Robustness 5 patents from the OECD

Variables	(1) Env_pat_OECD	(2) Green_pat_patstat	(3) Env_pat_OECD
L.EPS	0.9379***	1.4700***	0.7341***
	(0.061)	(0.137)	(0.070)
L.EPS^2	-0.1379***	-0.1777***	-0.1036***
	(0.009)	(0.018)	(0.011)
L.lnImports	-0.0573***	-0.1110***	-0.0880***
	(0.017)	(0.024)	(0.015)
L.RTA_tech	0.0003	0.0242***	0.0003
	(0.001)	(0.001)	(0.001)
L.Crosspatgr	0.0002***	0.0010***	0.0001
	(0.000)	(0.000)	(0.000)
Observations	6,534	5,022	5,022
Number of id	726	558	558

Note: The dependent variable in columns (1) and (2) is environmental patents from the OECD, whereas in column (2) it is Green patents originally from Patstat. Column (3) restricts the regression to the same number of observations as in column (2) for comparability purposes. Among the explanatory variables: EPS denotes the Environmental Policy Stringency Index. lnImports is the natural logarithm of sectoral imports. RTA_tech denotes the number of free trade agreements with technology and IPR provisions by country. Crosspatgr denotes the number of green patent applications made abroad (cross-patent applications) by country and sector. L denotes the value of the corresponding variable lagged one period (t-1). The models in all columns are estimated with a Poisson quasi-maximum likelihood estimator. Sectoral-time fixed effects are included, but not reported to save space.
Robust Standard errors are in parentheses. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

4 Conclusion

This paper theoretically and empirically examined the relationship between environmental regulations and green innovation when international trade and technology transfers are explicitly accounted for. Within a theoretical setup where countries are asymmetric in terms of emission taxes and production costs, we allowed international trade of polluting goods. The firms were assumed to behave as Cournot oligopolists in the product markets, and to endogenously choose how much to invest in green innovation. Under autarky, we found that countries with higher emission taxes generate more green innovation in line with the Porter hypothesis. However, when international trade is allowed, we found that the Porter hypothesis is less likely to hold since with higher emission taxes investment becomes less lucrative. Moreover, we showed that when technologies can be transferred to other countries through licensing arrangements, firms' investment in green innovation depends on the royalty rates. We then tested these hypotheses using EPS data.

Our empirical findings support our theoretical predictions. Increasing trade flows weaken the effect of EPS on green innovation. We found an inverted U-shaped relationship between emission tax and green innovation in the data in line with our theoretical predictions, rather than an upward sloping relationship. The inverted U-shape is robust across multiple variations of the basic empirical model, as well as after including measures of international technology transfer. Moreover, the level of EPS at which the turning point of the green innovation measure occurs was found to be stable and remained similar despite varying the basic empirical model. Increasing technological transfer was found to increase green innovation at any given level of EPS, although it did not affect the turning point significantly.

The empirical analysis also yield important policy implications. In non-OECD countries, implementing stricter environmental regulations increases green innovation, while the reverse is likely to hold for most OECD countries. That is, in countries where EPS is already high (OECD countries), increasing EPS further may be detrimental to green innovation. On the other hand, more strict environmental regulations in non-OECD countries is likely to increase green innovation, as well as contribute directly to mitigate emissions, hence providing a double dividend. Moreover, we found that a monotonic positive relationship between EPS and green innovation is more likely with non-market-based regulations and after 2015. At the same time, at low levels of EPS (i.e., below the turning point), the magnitude of the positive effect of environmental regulations on green innovation is greater with market-based regulations. Together with our previous result, this implies that tightening market-based regulations may be more effective in non-OECD countries, whereas in OECD countries non-market-based regulations may be more effective in fostering green innovation.

Overall, our results yield support for the stance taken by international organizations on two important issues. First, organizations such as the United Nations have been attempting to facilitate international technology transfers in a number of ways. Our findings imply that this could increase the global level of innovation. Second, organizations such as the European Union have been attempting to harmonize environmental regulation stringency, especially those related to climate change, across countries. The European Commission has recently approved setting carbon tariffs (or carbon border adjustments)[21]

[21] Such carbon tariffs involve producers from a country with a lower carbon price paying a tariff when exporting their

towards this end. We showed that it is not sufficient for OECD countries to continue to unilaterally tighten their own environmental regulations further, which may even deter innovation in these countries. Rather, more green innovation may be generated by facilitating non-OECD countries, e.g., through appropriate transfers, to tighten their environmental regulations. Our findings imply that such measures, by incentivizing countries with currently lower EPS to set more stringent policies, could increase the global level of innovation in addition to mitigating carbon leakage.

Our work may be extended in a number of directions. One approach would be to allow for the existence of environmentally friendly or green consumers. The proportion of green consumers vary across regions, and their existence has been shown to change firms' incentives to undertake green innovation. Another avenue for future work would be to incorporate upstream and downstream sectors within our framework and analyze how firms' investment decisions in each sector respond to stricter environmental regulation in open economies. This is a useful exercise in light of recent evidence that upstream industries are typically more polluting and less protected by trade barriers.

good to a country with a higher carbon price, a policy aimed at adjusting for the carbon price differential across countries.

References

Aghion, P., Dechezleprêtre, A., Hemous, D., Martin, R., and Van Reenen, J. (2016). Carbon taxes, path dependency, and directed technical change: Evidence from the auto industry. *Journal of Political Economy*, 124(1):1–51.

Ambec, S., Cohen, M. A., Elgie, S., and Lanoie, P. (2013). The porter hypothesis at 20: can environmental regulation enhance innovation and competitiveness? *Review of Environmental Economics and Policy*, 7(1):2–22.

Andrenelli, A., Gourdon, J., and Moïsé, E. (2019). International technology transfer policies. *OECD*.

Antweiler, W., Copeland, B. R., and Taylor, M. S. (2001). Is free trade good for the environment? *American economic review*, 91(4):877–908.

Barbieri, N., Marzucchi, A., and Rizzo, U. (2023). Green technologies, interdependencies, and policy. *Journal of Environmental Economics and Management*, 118:102791.

Barrett, S. (2009). The coming global climate–technology revolution. *The Journal of Economic Perspectives*, 23(2):53–75.

Botta, E. and Koźluk, T. (2014). Measuring environmental policy stringency in oecd countries: A composite index approach.

Branger, F., Quirion, P., and Chevallier, J. (2016). Carbon leakage and competitiveness of cement and steel industries under the eu ets: much ado about nothing. *The Energy Journal*, 37(3).

Brunel, C. and Levinson, A. (2016). Measuring the stringency of environmental regulations. *Review of Environmental Economics and Policy*.

Brunnermeier, S. B. and Cohen, M. A. (2003). Determinants of environmental innovation in us manufacturing industries. *Journal of environmental economics and management*, 45(2):278–293.

Calel, R. and Dechezleprêtre, A. (2016). Environmental policy and directed technological change: evidence from the european carbon market. *Review of economics and statistics*, 98(1):173–191.

Chan, H. S. R., Li, S., and Zhang, F. (2013). Firm competitiveness and the european union emissions trading scheme. *Energy Policy*, 63:1056–1064.

Copeland, B., Shapiro, J., and Taylor, M. (2022). Globalization and the environment. *Handbook of International Economics, Elsevier Science Publishing*.

Dechezleprêtre, A. and Sato, M. (2017). The impacts of environmental regulations on competitiveness. *Review of environmental economics and policy*.

Ferris, A. E., McGartland, A., Coglianese, C., Finkel, A., and Carrigan, C. (2014). A research agenda for improving the treatment of employment impacts in regulatory impact analysis. *Does Regulation Kill Jobs*, pages 170–189.

Galiana, I. and Green, C. (2009). Let the global technology race begin. *Nature*, 462(7273):570–571.

Goldschlag, N., Lybbert, T. J., and Zolas, N. J. (2016). An algorithmic links with probabilities crosswalk for uspc and cpc patent classifications with an application towards industrial technology composition. *US Census Bureau Center for Economic Studies paper no. CES-WP-16-15*.

Goulder, L. H. and Parry, I. W. (2008). Instrument choice in environmental policy. *Review of environmental economics and policy*.

Grossman, G. M. and Krueger, A. B. (1995). Economic growth and the environment. *The quarterly journal of economics*, 110(2):353–377.

Hassan, M. and Rousselière, D. (2022). Does increasing environmental policy stringency lead to accelerated environmental innovation? a research note. *Applied Economics*, 54(17):1989–1998.

Iraldo, F., Testa, F., Melis, M., and Frey, M. (2011). A literature review on the links between environmental regulation and competitiveness. *Environmental Policy and Governance*, 21(3):210–222.

Jaffe, A. B. and Palmer, K. (1997). Environmental regulation and innovation: a panel data study. *Review of economics and statistics*, 79(4):610–619.

Jaffe, A. B., Peterson, S. R., Portney, P. R., and Stavins, R. N. (1995). Environmental regulation and the competitiveness of us manufacturing: what does the evidence tell us? *Journal of Economic literature*, 33(1):132–163.

Kozluk, T. and Zipperer, V. (2015). Environmental policies and productivity growth: a critical review of empirical findings. *OECD Journal: Economic Studies*, 2014(1):155–185.

LaBelle, J., Martínez-Zarzoso, I., Santacreu, A. M., and Yotov, Y. (2023). Cross-border patenting, globalization and development: a new database. *Mimeo*.

Langinier, C. and RayChaudhuri, A. (2020). Green technology and patents in the presence of green consumers. *Journal of the Association of Environmental and Resource Economists*, 7(1):73–101.

Langinier, C. and RayChaudhuri, A. (2023). Green patents in an oligopolistic market with green consumers. *Working Paper*.

Levinson, A. and Taylor, M. S. (2008). Unmasking the pollution haven effect. *International economic review*, 49(1):223–254.

Martínez-Zarzoso, I., Bengochea-Morancho, A., and Morales-Lage, R. (2019). Does environmental policy stringency foster innovation and productivity in oecd countries? *Energy Policy*, 134:110982.

Martínez-Zarzoso, I. and Chelala, S. (2021). Trade agreements and international technology transfer. *Review of World Economics*, 157(3):631–665.

McGuire, M. C. (1982). Regulation, factor rewards, and international trade. *Journal of public economics*, 17(3):335–354.

Newell, R. G., Jaffe, A. B., and Stavins, R. N. (1999). The induced innovation hypothesis and energy-saving technological change. *The Quarterly Journal of Economics*, 114(3):941–975.

Pasurka, C. (2008). Perspectives on pollution abatement and competitiveness: theory, data, and analyses. *Review of Environmental Economics and Policy*.

Popp, D. (2002). Induced innovation and energy prices. *American economic review*, 92(1):160–180.

Porter, M. E. and Van der Linde, C. (1995). Toward a new conception of the environment-competitiveness relationship. *The journal of Economic Perspectives*, 9(4):97–118.

Probst, B., Touboul, S., Glachant, M., and Dechezleprêtre, A. (2021). Global trends in the invention and diffusion of climate change mitigation technologies. *Nature Energy*, 6(11):1077–1086.

Sato, M. and Dechezleprêtre, A. (2015). Asymmetric industrial energy prices and international trade. *Energy Economics*, 52:S130–S141.

Shapiro, J. (2016). Trade costs, co2, and the environment. *American Economic Journal: Economic Policy*, 8(4):220–54.

Wooldridge, J. M. (1999). Quasi-likelihood methods for count data. *Handbook of applied econometrics volume 2: Microeconomics*, pages 321–368.

Wooldridge, J. M. (2002). Econometric analysis of cross section and panel data mit press. *Cambridge, ma*, 108(2):245–254.

Appendix

Appendix A.1: The Autarky Equilibrium

Under autarky, firm a's equilibrium quantity is given by

$$q_a^{Am} = \frac{\alpha^A - c_a - \tau_A \gamma_a(I_a)}{2}.$$

We note that q_a^{Am} is always positive as long as assumption $(A1)$ is satisfied. The price in country A is given by

$$p_a^A = \frac{\alpha^A + c_a + \tau_A \gamma_a(I_a)}{2}.$$

Firm a chooses I_a that maximizes $\pi_a(I_a) = (q_a^A(I_a))^2 - I_a$, which gives the following first-order condition

$$-q_a^A(I_a)\gamma_a'(I_a)\tau_A - 1 = 0.$$

The second order condition is

$$\frac{\tau_A(\gamma_a'(I_a))^2}{2} - q_a^A(I_a)\gamma_a''(I_a) < 0,$$

if

$$\gamma_a''(I_a) > \frac{\tau_A}{2q_a^A(I_a)}(\gamma_a'(I_a))^2,$$

or, equivalently, if

$$\tau_A < (\alpha^A - c_a)\frac{\gamma_a''(I_a)}{(\gamma_a'(I_a))^2 + \gamma_a(I_a)\gamma_a''(I_a)}. \tag{19}$$

Let us define $H \equiv -q_a^A(I_a)\gamma_a'(I_a)\tau_A - 1$. Totally differentiating H, we have the following

$$\frac{\partial H}{\partial \tau_A}d\tau_A + \frac{\partial H}{\partial I_a}dI_a = 0,$$

which implies that

$$\frac{dI_a}{d\tau_A} = -\frac{\frac{\partial H}{\partial \tau_A}}{\frac{\partial H}{\partial I_a}}.$$

As long as $\frac{\partial H}{\partial I_a} < 0$, we have that $sign\frac{dI_a}{d\tau_A} = sign\frac{\partial H}{\partial \tau_A}$, where

$$\frac{\partial H}{\partial \tau_A} = \gamma_a'(I_a)(\frac{\gamma_a(I_a)}{2}\tau_A - q_a^A(I_a)).$$

Thus, $\frac{\partial H}{\partial \tau_A} > 0$ if

$$\tau_A < \frac{\alpha^A - c_a}{2\gamma_a(I_a)},$$

which is always satisfied by $(A1)$ as $\gamma_a(I_a) < \overline{\gamma}$. We also need to make sure that the second order condition is satisfied. Rewriting (19) , we have the following

$$\tau_A < \frac{(\alpha^A - c_a)}{2\gamma_a(I_a)}\frac{2\gamma_a(I_a)\gamma_a''(I_a)}{(\gamma_a'(I_a))^2 + \gamma_a(I_a)\gamma_a''(I_a)}.$$

Thus, if

$$\frac{2\gamma_a(I_a)\gamma_a''(I_a)}{(\gamma_a'(I_a))^2 + \gamma_a(I_a)\gamma_a''(I_a)} > 1,$$

we have

$$\tau_A < \frac{\alpha^A - c_a}{2\gamma_a(I_a)} < \frac{(\alpha^A - c_a)}{2\gamma_a(I_a)} \frac{2\gamma_a(I_a)\gamma_a''(I_a)}{(\gamma_a'(I_a))^2 + \gamma_a(I_a)\gamma_a''(I_a)}.$$

Therefore,

$$\frac{2\gamma_a(I_a)\gamma_a''(I_a)}{(\gamma_a'(I_a))^2 + \gamma_a(I_a)\gamma_a''(I_a)} > 1$$

if

$$\gamma_a(I_a) > \frac{(\gamma_a'(I_a))^2}{\gamma_a''(I_a)},$$

which is satisfied as per assumption $(A4)$.

Symmetrically for firm b, we obtain that firm b chooses its quantity as follows

$$q_b^{Bm} = \frac{\alpha^B - c_b - \tau_B \gamma_b(I_b)}{2}.$$

As long as $\alpha^B \geq \alpha^A$, and under assumption $(A1)$, q_b^{Bm} is always positive. Country B's price is given by

$$p_B = \frac{\alpha^B + c_b + \tau_B \gamma_b(I_b)}{2}.$$

Thus, firm b's profit is given by

$$\pi_b^m(I_b) = (q_b^B(I_b))^2 - \lambda I_b.$$

Firm b chooses I_b^m as the solution to $\max \pi_b(I_b)$, such that the first order condition is given by

$$-q_b^B(I_b)\gamma_b'(I_b)\tau_B - \lambda = 0.$$

By similar reasoning as that behind (5), we have the following

$$\frac{dI_b^m}{d\tau_B} > 0.$$

Appendix A.2: The Equilibrium with International Trade but no Technological Transfer

Case A(i)

Let's start with Case $A(i)$, where both firms sell the polluting good associated with the emission-output ratio $\overline{\gamma}$. The inverse demand function faced by both firms in country j for $j = A, B$, is given by

$$p^j(q_a^j, q_b^j) = \alpha^j - q_a^j - q_b^j.$$

Firm a chooses q_a^A and q_a^B that solve the following

$$\max\{(\alpha^A - q_a^A - q_b^A - c_a - \tau_A\overline{\gamma})q_a^A + (\alpha^B - q_a^B - q_b^B - c_a - \tau_A\overline{\gamma})q_a^B\}.$$

Firm b chooses q_b^A and q_b^B that solve the following

$$\max\{(\alpha^A - q_a^A - q_b^A - c_b - \tau_B\overline{\gamma})q_b^A + (\alpha^B - q_b^B - q_a^B - c_b - \tau_B\overline{\gamma})q_b^B\}.$$

We find that firm a chooses the following quantities in countries A and B, respectively

$$q_a^A = \frac{\alpha^A - 2(c_a + \tau_A \overline{\gamma}) + c_b + \tau_B \overline{\gamma}}{3},$$

and

$$q_a^B = \frac{\alpha^B - 2(c_a + \tau_A \overline{\gamma}) + c_b + \tau_B \overline{\gamma}}{3}.$$

Firm b chooses the following quantities in countries A and B, respectively

$$q_b^A = \frac{\alpha^A - 2(c_b + \tau_B \overline{\gamma}) + c_a + \tau_A \overline{\gamma}}{3},$$

and

$$q_b^B = \frac{\alpha^B - 2(c_b + \tau_B \overline{\gamma}) + c_a + \tau_A \overline{\gamma}}{3}.$$

The equilibrium prices in countries A and B are, respectively

$$p^A(q_a^A, q_b^A) = \frac{\alpha^A + c_a + \tau_A \overline{\gamma} + c_b + \tau_B \overline{\gamma}}{3},$$

and

$$p^B(q_a^B, q_b^B) = \frac{\alpha^B + c_a + \tau_A \overline{\gamma} + c_b + \tau_B \overline{\gamma}}{3}.$$

Firm a's equilibrium payoff is given by

$$\overline{\pi}_a = (q_a^A)^2 + (q_a^B)^2,$$

and firm b's equilibrium payoff is given by

$$\overline{\pi}_b = (q_b^A)^2 + (q_b^B)^2.$$

Case A(ii) (referred to as Case I in the main text)

Consider Case $A(ii)$ where firm a produces the cleaner product, γ_a, and firm b produces the dirty product $\overline{\gamma}$, in which case the inverse demand function of firms a and b in country A are

$$p_a^A(q_a^A, q_b^A) = \alpha^A - q_a^A - q_b^A,$$

$$p_b^A(q_a^A, q_b^A) = \alpha^A - q_b^A - q_a^A,$$

and in country B, there are

$$p_a^B(q_a^B, q_b^B) = \alpha^B - q_a^B - q_b^B,$$

$$p_b^B(q_a^B, q_b^B) = \alpha^B - q_b^B - q_a^B,$$

where $0 < \beta_b < \beta_a < 1$. Firm a chooses q_a^A and q_a^B that solve

$$Max\{(\alpha^A - q_a^A - q_b^A - c_a - \tau_A \gamma_a) q_a^A + (\alpha^B - q_a^B - q_b^B - c_a - \tau_A \gamma_a) q_a^B\}.$$

The first order conditions give

$$q_a^A = \frac{\alpha^A - q_b^A - c_a - \tau_A \gamma_a}{2},$$

$$q_a^B = \frac{\alpha^B - q_b^B - c_a - \tau_A \gamma_a}{2}.$$

Symmetrically for firm b

$$q_b^A = \frac{\alpha^A - q_a^A - c_b - \tau_B \overline{\gamma}}{2},$$

$$q_b^B = \frac{\alpha^B - q_a^B - c_b - \tau_B \overline{\gamma}}{2}.$$

Thus, we have the following

$$q_a^A = \frac{\alpha^A - 2(c_a + \tau_A \gamma_a) + c_b + \tau_B \overline{\gamma}}{3},$$

$$q_b^A = \frac{\alpha^A - 2(c_b + \tau_B \overline{\gamma}) + c_a + \tau_A \gamma_a}{3},$$

$$q_a^B = \frac{\alpha^B - 2(c_a + \tau_A \gamma_a) + c_b + \tau_B \overline{\gamma}}{3},$$

$$q_b^B = \frac{\alpha^B - 2(c_b + \tau_B \overline{\gamma}) + c_a + \tau_A \gamma_a}{3}.$$

Equilibrium prices are given by

$$p_a^A(q_a^A, q_b^A) = \frac{\alpha^A + c_a + \tau_A \gamma_a + c_b + \tau_B \overline{\gamma}}{3},$$

$$p_b^A(q_a^A, q_b^A) = \frac{\alpha^A + c_b + \tau_B \overline{\gamma} + c_a + \tau_A \gamma_a}{3},$$

$$p_a^B(q_a^B, q_b^B) = \frac{\alpha^B + c_a + \tau_A \gamma_a + c_b + \tau_B \overline{\gamma}}{3},$$

$$p_b^B(q_a^B, q_b^B) = \frac{\alpha^B + c_b + \tau_B \overline{\gamma} + c_a + \tau_A \gamma_a}{3}.$$

In the first period firm a's profit is given by:

$$\pi_a(\gamma_a(I_a), I_a) = (q_a^A(I_a))^2 + (q_a^B(I_a))^2 - I_a.$$

Firm a chooses I_a that solves $Max \pi_a(\gamma_a(I_a), I_a)$. The first order condition yields the following:

$$2\frac{\partial q_a^A(I_a)}{\partial I_a} q_a^A(I_a) + 2\frac{\partial q_a^B(I_a)}{\partial I_a} q_a^B(I_a) - 1 = 0,$$

where

$$\frac{\partial q_a^A(I_a)}{\partial I_a} = \frac{\partial q_a^B(I_a)}{\partial I_a} = \frac{-2\tau_A \gamma_a'(I_a)}{3}.$$

Thus, firm a will invest I_a^{NT} that satisfies the following

$$-4\frac{\gamma_a'(I_a)\tau_A}{3}(q_a^A(I_a) + q_a^B(I_a)) - 1 = 0.$$

The second order condition,

$$-4\frac{\gamma_a''(I_a)}{3}\tau_A(q_a^A(I_a) + q_a^B(I_a)) + (\frac{4\tau_A \gamma_a'(I_a)}{3})^2 < 0,$$

is satisfied as long as

$$\gamma_a''(I_a) > \frac{4\tau_A(\gamma_a'(I_a))^2}{3(q_a^A(I_a) + q_a^B(I_a))}.$$

Let us define H_{NT} as follows

$$H_{NT} \equiv -4\frac{\gamma_a'(I_a)\tau_A}{3^2}((\alpha^A+\alpha^B)-4(c_a+\tau_A\gamma_a)+2(c_b+\tau_B\overline{\gamma}))-1.$$

Totally differentiating H_{NT}, we have the following

$$\frac{\partial H_{NT}}{\partial \tau_A}d\tau_A+\frac{\partial H_{NT}}{\partial I_a}dI_a=0.$$

Rearranging the terms, we find that

$$\frac{dI_a}{d\tau_A}=-\frac{\frac{\partial H_{NT}}{\partial \tau_A}}{\frac{\partial H_{NT}}{\partial I_a}},$$

where as long as $\frac{\partial H_{NT}}{\partial I_a}<0$, we have that $sign\frac{dI_a}{d\tau_A}=sign\frac{\partial H_{NT}}{\partial \tau_A}$, where

$$\frac{\partial H_{NT}}{\partial \tau_A}=-4\frac{\gamma_a'(I_a)}{3^2}((\alpha^A+\alpha^B)-4c_a-8\tau_A\gamma_a+2(c_b+\tau_B\overline{\gamma})).$$

Therefore, we have that $\frac{\partial H}{\partial \tau_A}>0$ if $\tau_A<\widehat{\tau}_A^{NT}$ where

$$\widehat{\tau}_A^{NT}\equiv\frac{(\alpha^A+\alpha^B)-4c_a+2(c_b+\tau_B\overline{\gamma})}{8\gamma_a}.$$

Thus, for $\tau_A<\widehat{\tau}_A^{NT}$, as τ_A increases, so does I_a. For $\tau_A>\widehat{\tau}_A^{NT}$, as τ_A increases, I_a decreases. Therefore, we have an inverted U-shaped function.

We need to check that the second order condition is satisfied. Let us rewrite the second order condition as

$$\tau_A<\frac{2\gamma_a\gamma_a''(I_a)}{(\gamma_a'(I_a))^2+\gamma_a''(I_a)\gamma_a}\widehat{\tau}_A^{NT}.$$

Thus, as long as $(A4)$ is satisfied we have

$$\frac{2\gamma_a(I_a)\gamma_a''(I_a)}{(\gamma_a'(I_a))^2+\gamma_a(I_a)\gamma_a''(I_a)}>1,$$

and thus

$$\tau_A<\widehat{\tau}_A^{NT}<\frac{2\gamma_a\gamma_a''(I_a)}{(\gamma_a'(I_a))^2+\gamma_a''(I_a)\gamma_a}\widehat{\tau}_A^{NT}.$$

If $\tau_A<\widehat{\tau}_A^{NT}$, then the second order condition is always satisfied. On the other hand, if $\tau_A>\widehat{\tau}_A^{NT}$, we need to make sure that

$$\tau_A<\frac{2\gamma_a''(I_a)\gamma_a}{(\gamma_a'(I_a))^2+\gamma_a''(I_a)\gamma_a}\widehat{\tau}_A^{NT},$$

to have the second order satisfied.

Lastly, we analyze how I_a is affected by a change in τ_B. By totally differentiating H_{NT}, we have that

$$\frac{dI_a}{d\tau_B}=-\frac{\frac{\partial H_{NT}}{\partial \tau_B}}{\frac{\partial H_{NT}}{\partial I_a}}.$$

As long as $\frac{\partial H_{NT}}{\partial I_a}<0$, we have that $sign\frac{dI_a}{d\tau_B}=sign\frac{\partial H_{NT}}{\partial \tau_B}$, where

$$\frac{\partial H}{\partial \tau_B}=-4\frac{\gamma_a'(I_a)\tau_A}{3^2}2\overline{\gamma}>0.$$

Thus, $\frac{dI_a}{d\tau_B} > 0$. We also show that

$$\frac{\partial \widehat{\tau}_A^{NT}}{\partial \tau_B} = \frac{\overline{\gamma}}{4\gamma_a} > 0.$$

Therefore, if τ_B increases, so does $\widehat{\tau}_A^{NT}$ and the optimal investment I_a^{NT}.

Case A(iii)

Finally, we consider the case in which both firms invest and both sell a cleaner good, in which case the demands for firms a and b in country j are

$$p_a^j(q_a^j, q_b^j) = \alpha^j - q_a^j - q_b^j,$$

and

$$p_b^j(q_a^j, q_b^j) = \alpha^j - q_b^j - q_a^j.$$

Firm a chooses q_a^A and q_a^B that solve

$$Max\{(\alpha^A - q_a^A - q_b^A - c_a - \tau_A\gamma_a)q_a^A + (\alpha^B - q_a^B - q_b^B - c_a - \tau_A\gamma_a)q_a^B\},$$

and firm b chooses q_b^A and q_b^B that solve

$$Max\{(\alpha^A - q_a^A - q_b^A - c_b - \tau_B\gamma_b)q_b^A + (\alpha^B - q_b^B - q_a^B - c_b - \tau_B\gamma_b)q_b^B\}.$$

We find that firm a chooses the following quantities in countries A and B, respectively

$$q_a^A = \frac{\alpha^A - 2(c_a + \tau_A\gamma_a) + c_b + \tau_B\gamma_b}{3},$$

$$q_a^B = \frac{\alpha^B - 2(c_a + \tau_A\gamma_a) + c_b + \tau_B\gamma_b}{3},$$

and firm b chooses the following quantities in countries A and B, respectively

$$q_b^A = \frac{\alpha^A - 2(c_b + \tau_B\gamma_b) + c_a + \tau_A\gamma_a}{3},$$

$$q_b^B = \frac{\alpha^B - 2(c_b + \tau_B\gamma_b) + c_a + \tau_A\gamma_a}{3}.$$

The prices of firms a and b in country A are

$$p_a^A(q_a^A, q_b^A) = \frac{\alpha^A + c_a + \tau_A\gamma_a + c_b + \tau_B\gamma_b}{3},$$

$$p_b^A(q_a^A, q_b^A) = \frac{\alpha^A + (c_b + \tau_B\gamma_b) + c_a + \tau_A\gamma_a}{3},$$

and in country B, the prices are

$$p_a^B(q_a^B, q_b^B) = \frac{\alpha^B + c_a + \tau_A\gamma_a + c_b + \tau_B\gamma_b}{3},$$

$$p_b^B(q_a^B, q_b^B) = \frac{\alpha^B + c_b + \tau_B\gamma_b + c_a + \tau_A\gamma_a}{3}.$$

Firm a's payoff is

$$\pi_a = (q_a^A(I_a, I_b))^2 + (q_a^B(I_a, I_b))^2 - I_a,$$

and firm b's payoff is

$$\pi_b = (q_b^A(I_a, I_b))^2 + (q_b^B(I_a, I_b))^2 - \lambda I_b.$$

In the first period, firm a chooses I_a that solves $\max \pi_a$ which yields

$$-4\frac{\tau_A \gamma_a'}{3}(q_a^A + q_a^B) - 1 = 0.$$

Denote $I_a(I_b)$ the best response function of firm a to any investment by firm b, which is a decreasing function of I_b. In the first period, firm b chooses I_b that solves $\max \pi_b$ which yields

$$-\frac{4\tau_B \gamma_b'}{3}(q_b^A + q_b^B) - \lambda = 0.$$

Denote $I_b(I_a)$ the best response function of firm b to any investment by firm a, which is a decreasing function of I_a. Let denote the solution (I_a^*, I_b^*).

Thus, firm a's equilibrium payoff is

$$\pi_a^* = (q_a^A(I_a^*, I_b^*))^2 + (q_a^B(I_a^*, I_b^*))^2 - I_a^*,$$

and firm b's payoff is

$$\pi_b^* = (q_b^A(I_a^*, I_b^*))^2 + (q_b^B(I_a^*, I_b^*))^2 - \lambda I_b^*.$$

Appendix A.3: The Equilibrium with International Trade and Technological Transfer (Case II)

Consider the case (referred to as Case II in the main text) where there is trade and technological transfer. Firm a offers a license (r, F) where r is the royalty rate paid for all the production of firm b and F the fixed fee. The payoff of firm a is given by:

$$\pi_a + r(q_b^A + q_b^B) - I_a + F,$$

and the payoff of firm b is given by:

$$\pi_b - r(q_b^A + q_b^B) - I_b - F.$$

We consider that both r and F are exogenous. Firm a chooses q_a^A and q_a^B that solve

$$Max\{(\alpha^A - q_a^A - q_b^A - c_a - \tau_A\gamma_a)q_a^A + (\alpha^B - q_a^B - q_b^B - c_a - \tau_A\gamma_a)q_a^B + r(q_b^A + q_b^B) + F - I_a\}.$$

The first order conditions are

$$q_a^A = \frac{\alpha^A - q_b^A - c_a - \tau_A\gamma_a}{2},$$

$$q_a^B = \frac{\alpha^B - q_b^B - c_a - \tau_A\gamma_a}{2}.$$

Firm b chooses q_b^A and q_b^B that solve

$$\max\{(\alpha^A - q_b^A - q_a^A - c_b - \tau_B\gamma_a)q_b^A + (\alpha^B - q_b^B - q_a^B - c_b - \tau_B\gamma_a)q_b^B - r(q_b^A + q_b^B) - F\}.$$

The first order conditions are given by

$$q_b^A = \frac{\alpha^A - q_a^A - c_b - \tau_B\gamma_a - r}{2},$$

$$q_b^B = \frac{\alpha^B - q_a^B - c_b - \tau_B\gamma_a - r}{2}.$$

Therefore, the solutions are given by

$$q_a^A = \frac{\alpha^A - 2(c_a + \tau_A\gamma_a) + c_b + \tau_B\gamma_a + r}{3},$$

$$q_b^A = \frac{\alpha^A - 2(c_b + \tau_B\gamma_a + r) + c_a + \tau_A\gamma_a}{3},$$

$$q_a^B = \frac{\alpha^B - 2(c_a + \tau_A\gamma_a) + c_b + \tau_B\gamma_a + r}{3},$$

$$q_b^B = \frac{\alpha^B - 2(c_b + \tau_B\gamma_a + r) + c_a + \tau_A\gamma_a}{3}.$$

Thus, firm a's equilibrium payoff is given by

$$\pi_a^T = (q_a^A)^2 + (q_a^B)^2 + r(q_b^A + q_b^B) - I_a + F,$$

and firm b's equilibrium payoff is given by

$$\pi_b^T = (q_b^A)^2 + (q_b^B)^2 - r(q_b^A + q_b^B) - F.$$

Firm a chooses I_a that solves the following

$$Max(q_a^A)^2 + (q_a^B)^2 + r(q_b^A + q_b^B) - I_a + F.$$

The first order condition is given by

$$2\frac{\partial q_a^A}{\partial I_a}q_a^A + 2\frac{\partial q_a^B}{\partial I_a}q_a^B + r(\frac{\partial q_b^A}{\partial I_a} + \frac{\partial q_b^B}{\partial I_a}) - 1 = 0,$$

with

$$\frac{\partial q_a^A}{\partial I_a} = \frac{\partial q_a^B}{\partial I_a} = \gamma_a'(I_a)\frac{-2\tau_A + \beta\tau_B}{3},$$

$$\frac{\partial q_b^A}{\partial I_a} = \frac{\partial q_b^B}{\partial I_a} = \gamma_a'(I_a)\frac{-2\tau_B + \beta\tau_A}{3}.$$

Thus, the first order condition is given by

$$-2\gamma_a'(I_a)\frac{2\tau_A - \tau_B}{3}(q_a^A + q_a^B) + 2r\gamma_a'(I_a)\frac{\tau_A - 2\tau_B}{3} - 1 = 0.$$

The second order condition is given by

$$-2\gamma_a''(I_a)(\frac{2\tau_A - \tau_B}{3}(q_a^A + q_a^B) - r\frac{\tau_A - 2\tau_B}{3}) + (2\gamma_a'(I_a)\frac{2\tau_A - \tau_B}{3})^2 < 0.$$

This implies the following

$$(2\tau_A - \tau_B)((\alpha^A + \alpha^B) - 4(c_a + \tau_A\gamma_a) + 2(c_b + \tau_B\gamma_a)) + r(4\tau_B + \tau_A) > 2\frac{(\gamma_a'(I_a))^2}{\gamma_a''(I_a)}(2\tau_A - \tau_B)^2$$

Let us denote I_a^T as the solution. Define

$$H_T \equiv 2\gamma_a'(I_a)\frac{-2\tau_A+\tau_B}{3}(q_a^A+q_a^B)+2r\gamma_a'(I_a)\frac{-2\tau_B+\tau_A}{3}-1.$$

Totally differentiating H_T, we have the following:

$$\frac{\partial H_T}{\partial \tau_A}d\tau_A+\frac{\partial H_T}{\partial I_a}dI_a=0.$$

We thus have

$$\frac{dI_a}{d\tau_A}=-\frac{\frac{\partial H_T}{\partial \tau_A}}{\frac{\partial H_T}{\partial I_a}}.$$

Since $\frac{\partial H_T}{\partial I_a}<0$, as long as the second order condition holds, we have that $sign\frac{dI_a}{d\tau_A}=sign\frac{\partial H_T}{\partial \tau_A}$, where

$$\frac{\partial H_T}{\partial \tau_A}=-\gamma_a'(I_a)\frac{2}{3}[2(q_a^A+q_a^B)+(-2\tau_A+\tau_B)(\frac{4\gamma_a}{3})-r].$$

Therefore, $\frac{\partial H_T}{\partial \tau_A}>0$ if $\tau_A<\widehat{\tau}_A^T$ where

$$\widehat{\tau}_A^T\equiv\frac{\alpha^A+\alpha^B-4c_a+2c_b}{8\gamma_a}+\frac{\tau_B}{2}+r\frac{1}{16\gamma_a}.$$

If $\tau_A<\widehat{\tau}_A^T$, we have that as τ_A increases so does I_a^T.

We need to check that the second order condition is satisfied. Let us rewrite the second order condition as follows:

$$((\alpha^A+\alpha^B)-4(c_a+\tau_A\gamma_a)+2(c_b+\tau_B\gamma_a))+r\frac{(4\tau_B+\tau_A)}{(2\tau_A-\tau_B)}>2\frac{(\gamma_a'(I_a))^2}{\gamma_a''(I_a)}(2\tau_A-\tau_B).$$

If $r=0$, we have

$$\tau_A<\frac{(\alpha^A+\alpha^B)-4c_a+2c_b}{8\gamma_a}(\frac{2\gamma_a''(I_a)\gamma_a}{(\gamma_a'(I_a))^2+\gamma_a\gamma_a''(I_a)}-1)+\widehat{\tau}_A^T.$$

If $(A4)$ is satisfied we have

$$\frac{2\gamma_a''(I_a)\gamma_a}{(\gamma_a'(I_a))^2+\gamma_a\gamma_a''(I_a)}>1,$$

and, thus,

$$\tau_A<\widehat{\tau}_A^T<\frac{(\alpha^A+\alpha^B)-4c_a+2c_b}{8\gamma_a}(\frac{2\gamma_a''(I_a)\gamma_a}{(\gamma_a'(I_a))^2+\gamma_a\gamma_a''(I_a)}-1)+\widehat{\tau}_A^T.$$

However, if $\tau_A>\widehat{\tau}_A^T$, we need to have

$$\tau_A<\frac{(\alpha^A+\alpha^B)-4c_a+2c_b}{8\gamma_a}(\frac{2\gamma_a''(I_a)\gamma_a}{(\gamma_a'(I_a))^2+\gamma_a\gamma_a''(I_a)}-1)+\widehat{\tau}_A^T.$$

If $r>0$,

$$(\alpha^A+\alpha^B)-4c_a+2c_b+r\frac{(4\tau_B+\tau_A)}{(2\tau_A-\tau_B)}>2(2\tau_A-\tau_B)\frac{(\gamma_a'(I_a))^2+\gamma_a\gamma_a''(I_a)}{\gamma_a''(I_a)}$$

Let us compare the thresholds $\widehat{\tau}_A^T$ and $\widehat{\tau}_A^{NT}$ where

$$\widehat{\tau}_A^{NT}\equiv\frac{(\alpha^A+\alpha^B)-4c_a+2(c_b+\tau_B\overline{\gamma})}{8\gamma_a}.$$

We rewrite

$$\widehat{\tau}_A^T \equiv \widehat{\tau}_A^{NT} - \tau_B \frac{\overline{\gamma} - 2\gamma_a}{4\gamma_a} + \frac{r}{16\gamma_a}.$$

If $\overline{\gamma} < 2\gamma_a$ (i.e., innovation not too drastic), we have that $\widehat{\tau}_A^T > \widehat{\tau}_A^{NT}$. However, if $\overline{\gamma} > 2\gamma_a$ (drastic innovation), we have $\widehat{\tau}_A^T > \widehat{\tau}_A^{NT}$ if

$$r > 4\tau_B(\overline{\gamma} - 2\gamma_a).$$

We also show that $\widehat{\tau}_A^T$ increases with τ_B and that I_a^T increases with τ_B if

$$\tau_B < \frac{-((\alpha^A + \alpha^B) - 2(c_a + \tau_A\gamma_a) + c_b) + 2c_a - c_b + 4r + 6\tau_A\gamma_a}{4\gamma_a}$$

Comparison of quantities for a given level of investment shows that $q_a^{ANT} > q_a^{AT}$ if $r > \tau_B(\overline{\gamma} - \gamma_a)$.

We note that firm b prefers to obtain the cleaner innovation through technology transfer rather than investing if $\pi_b^T > \pi_b^*$, or if $\lambda > \underline{\lambda}$ with

$$\underline{\lambda} = \frac{(q_b^A(I_a^*, I_b^*))^2 - (q_b^A)^2 + (q_b^B(I_a^*, I_b^*))^2 - (q_b^B)^2 + r(q_b^A + q_b^B) + F}{I_b^*}.$$

If $\lambda > \underline{\lambda}$, the equilibrium is such that firm b does not invest, and firm a invests and transfers its technology to firm b at with a license (r, F).

Appendix A.4: An Example

Consider the following function

$$\gamma_a(I_a) = 1 + (\overline{\gamma} - 1)e^{-I_a},$$

with $\gamma_a(I_a) > \frac{(\gamma_a'(I_a))^2}{\gamma_a''(I_a)}$, where

$$\gamma_a'(I_a) = -(\overline{\gamma} - 1)e^{-I_a},$$

and

$$\gamma_a''(I_a) = (\overline{\gamma} - 1)e^{-I_a}.$$

The first order condition is given by

$$-e^{-I_a}(\alpha^A - c_a) + \tau_A e^{-I_a} + \tau_A(\overline{\gamma} - 1)(e^{-I_a})^2 - \frac{2}{\tau_A(\overline{\gamma} - 1)} = 0. \quad (20)$$

Let $X \equiv e^{-I_a}$. We can rewrite (20) as follows

$$\tau_A(\overline{\gamma} - 1)X^2 - X(\alpha^A - c_a) + \tau_A e^{-I_a} - \frac{2}{\tau_A(\overline{\gamma} - 1)} = 0.$$

The second order condition is given by

$$\frac{\tau_A(\gamma_a'(I_a))^2}{2} - q_a^A(I_a)\gamma_a''(I_a) < 0,$$

with

$$\tau_A < \frac{\alpha^A - c_a}{2(\overline{\gamma} - 1)e^{-I_a} + 1}.$$

Table A1: Sectoral Classification

D. Manufacturing	
15	Manufacture of food products and beverages
16	Manufacture of tobacco products
17	Manufacture of textiles
18	Manufacture of wearing apparel; dressing and dyeing of fur
19	Tanning and dressing of leather; manufacture of luggage, handbags, saddlery, harness and footwear
20	Manufacture of wood and products of wood and cork, except furniture; manufacture of articles of straw and plaiting materials
21	Manufacture of paper and paper products
22	Publishing, printing and reproductions of recorded media
23	Manufacture of coal, refined petroleum products and nuclear fuel
24	Manufacture of chemical and chemical products
25	Manufacture of rubber and plastic products
26	Manufacture of other non-metallic mineral products
27	Manufacture of basic metals
28	Manufacture of fabricated metal products, except machinery and equipment
29	Manufacture of machinery and equipment n.e.c.
30	Manufacture of office, accounting and computing machinery
31	Manufacture of electrical machinery and apparatus n.e.c.
32	Manufacture of radio, television and communication equipment and apparatus
33	Manufacture of medical, precision and optical instruments, watches and clocks
34	Manufacture of motor vehicles, trailers and semi-trailers
35	Manufacture of other transport equipment
36	Manufacture of furniture; manufacturing n.e.c.
37	Recycling

Table A2: Variable Definitions and Sources

Variable	**Definition**	**Source**
GPT	Number of green patent applications in country i at year t	WIPO
EPS	Environmental Stringency Policy index in country i at year t	OECD
Imports	Sectoral imports in country i sector k at year t	ITDP-E
RTA_tech	Regional Trade Agreements with technology	WTO
Crosspatgr	Number of green patent applications made in foreign offices	WIPO

Note: ITPD-E: International Trade and Production Database for Estimation.

Table A3: Summary Statistics

Variable	**Obs.**	**Mean**	**Std. dev.**	**Min**	**Max**
GP	17,824	32.743	213.064	0	7915.064
EPS	17,824	1.952	1.122	0	4.722
lnimports	17,824	8.774	1.697	0.778	14.451
Imports	17,824	26675.350	83910.250	2.178	1887229
RTA_tech	17,824	12.995	10.129	0	26
Crosspatgr	17,824	13.940	75.133	0	700.547

Note: GP denotes Green Patent applications by country and sector. Among the explanatory variables: EPS denotes the Environmental Policy Stringency Index. lnImports is the natural logarithm of sectoral imports. RTA_tech denotes the number of free trade agreements with technology and IPR provisions by country. Crosspatgr denotes the number of green patent applications made abroad (cross-patent applications).

Table A4: Robustness 2

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
	S15	S17	S18	S19	S20	S21	S23
	Food&Bev	Textiles	Apparel	Leather	Wood&Cork	Paper	Coal&Petrol
Variables							
EPS	2.1227***	2.5655***	1.0564*	-0.2231	2.5464***	1.5639***	2.1278***
	(0.307)	(0.340)	(0.548)	(0.775)	(0.335)	(0.389)	(0.215)
EPS^2	-0.4076***	-0.5196***	-0.2876**	0.0373	-0.4319***	-0.3159***	-0.3693***
	(0.082)	(0.091)	(0.127)	(0.164)	(0.066)	(0.083)	(0.058)
lnImports	0.0410	0.0667	-0.0755	0.5125**	0.0940*	0.0322	0.0127
	(0.035)	(0.059)	(0.057)	(0.201)	(0.049)	(0.037)	(0.024)
RTA_tech	-0.0016	-0.0224	0.0035	-0.0082	0.0360***	-0.0031	0.0089
	(0.009)	(0.015)	(0.026)	(0.053)	(0.005)	(0.027)	(0.007)
Crosspatgr	0.0024**	0.5704***	9.5388***	1.1706	0.0873**	0.0510***	0.0061***
	(0.001)	(0.138)	(2.100)	(0.763)	(0.036)	(0.009)	(0.002)
Turning point	2.604	2.468	1.836	2.987	2.947	2.475	2.88
Observations	961	911	793	385	911	832	961
Number of id	33	31	27	13	31	28	33

Note: The dependent variable is the number of Green patent applications (Gpatents) by country and sector. Among the explanatory variables: EPS denotes the Environmental Policy Stringency Index. lnImports is the natural logarithm of sectoral imports. RTA_tech denotes the number of free trade agreements with technology and IPR provisions by country. Crosspatgr denotes the number of green patent applications made abroad (cross-patent applications) by country and sector. The models in all columns are estimated with a Poisson quasi-maximum likelihood estimator. Sectoral-time fixed effects are included, but not reported to save space.

Robust Standard errors are in parentheses. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

Table A4: Robustness 2 (cont'd)

	(8)	(9)	(10)	(11)	(12)	(13)	(14)
	S24	S25	S26	S27	S28	S29	S30
	Chemical	Rubber &Plastic	Minerals	Basic Metals	Metal Products	Machinery	Office &CompMachinery
Variables							
EPS	2.1204***	2.8172***	2.7294***	2.6201***	2.5998***	2.3772***	3.2406***
	(0.246)	(0.558)	(0.287)	(0.328)	(0.238)	(0.440)	(0.467)
EPS^2	-0.3639***	-0.5439***	-0.4728**	-0.4706***	-0.3943***	-0.4243***	-0.5492***
	(0.058)	(0.108)	(0.070)	(0.083)	(0.060)	(0.088)	(0.114)
lnImports	0.1241**	-0.0303	-0.0192	-0.0114	-0.0403	-0.0548	0.0693*
	(0.055)	(0.033)	(0.023)	(0.037)	(0.043)	(0.043)	(0.042)
RTA_tech	0.0050	-0.0338	0.0155**	0.0112	0.0220***	0.0054	0.0441***
	(0.007)	(0.022)	(0.007)	(0.009)	(0.008)	(0.012)	(0.011)
Crosspatgr	0.0011***	0.0776***	0.0004	0.0003	0.0004	-0.0003	0.5021
	(0.000)	(0.027)	(0.001)	(0.005)	(0.000)	(0.000)	(0.347)
Turning point	2.914	2.59	2.887	2.784	3.296	2.801	2.95
Observations	961	931	961	961	961	961	705
Number of id	33	32	33	33	33	33	24

Note: The dependent variable is the number of Green patent applications (Gpatents) by country and sector. Among the explanatory variables: EPS denotes the Environmental Policy Stringency Index. lnImports is the natural logarithm of sectoral imports. RTA_tech denotes the number of free trade agreements with technology and IPR provisions by country. Crosspatgr denotes the number of green patent applications made abroad (cross-patent applications) by country and sector. The models in all columns are estimated with a Poisson quasi-maximum likelihood estimator. Sectoral-time fixed effects are included, but not reported to save space.

Robust Standard errors are in parentheses. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

Table A4: Robustness 2 (cont'd)

	(15)	(16)	(17)	(18)	(19)	(20)
	S31	S32	S33	S34	S35	S36
	Electr Machinery	CommunicEq	Medical &Optical	Vehicles	Other Transport	Furniture Other
Variables						
EPS	2.6335***	2.5853***	2.5999***	2.2328***	2.2607***	1.9112***
	(0.390)	(0.174)	(0.247)	(0.586)	(0.369)	(0.167)
EPS^2	-0.4330***	-0.3797***	-0.4148***	-0.3656***	-0.3754***	-0.2745***
	(0.075)	(0.042)	(0.057)	(0.096)	(0.071)	(0.041)
lnImports	-0.0722**	-0.0170	0.0467	-0.0548	-0.0450	0.3174***
	(0.036)	(0.035)	(0.060)	(0.053)	(0.056)	(0.065)
RTA_tech	0.00267**	0.0244***	0.0133	0.0265*	0.0233***	0.0292***
	(0.013)	(0.009)	(0.010)	(0.014)	(0.008)	(0.008)
Crosspatgr	0.0003***	0.0002**	0.0039	-0.0007	-0.0122*	0.0215
	(0.000)	(0.000)	(0.003)	(0.001)	(0.007)	(0.032)
Turning point	3.041	3.404	3.134	3.053	3.011	3.481
Observations	961	961	961	931	931	884
Number of id	33	33	33	32	32	30

Note: The dependent variable is the number of Green patent applications (Gpatents) by country and sector. Among the explanatory variables: EPS denotes the Environmental Policy Stringency Index. lnImports is the natural logarithm of sectoral imports. RTA_tech denotes the number of free trade agreements with technology and IPR provisions by country. Crosspatgr denotes the number of green patent applications made abroad (cross-patent applications) by country and sector. The models in all columns are estimated with a Poisson quasi-maximum likelihood estimator. Sectoral-time fixed effects are included, but not reported to save space.

Robust Standard errors are in parentheses. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

Department of Economics, University of Alberta
Working Paper Series

2024-07: Green Patents in an Oligopolistic Market with Green Consumers– **Langinier, C.,** RayChaudhuriz, A.

2024-06: The Effect of Patent Continuation on the Patenting Process – **Langinier, C.**

2024-05: Applying Indigenous Approaches to Economics Instruction – Chavis, L., **Wheeler, L.**

2024-04: Electric Vehicles and the Energy Transition: Unintended Consequences of a Common Retail Rate Design – Bailey, M., **Brown, D.,** Myers, E., Shaffer, B., Wolak, F.

2024-03: Electricity Market Design with Increasing Renewable Generation: Lessons From Alberta – **Brown, D.,** Olmstead, D., Shaffer, B.

2024-02: Evaluating the Role of Information Disclosure on Bidding Behavior in Wholesale Electricity Markets – **Brown, D.,** Cajueiro, D., **Eckert, A., Silveira, D.**

2024-01: Medical Ethics and Physician Motivations – **Andrews, B.**

2023-14: Employers' Demand for Personality Traits and Provision of Incentives – **Brencic, V., McGee, A.**

2023-13: Demand for Personality Traits, Tasks, and Sorting – **Brencic, V., McGee, A.**

2023-12: Whoever You Want Me to Be: Personality and Incentives – **McGee, A.,** McGee, P.

2023-11: Gender Differences in Reservation Wages in Search Experiments – **McGee, A.,** McGee, P.

2023-10: Designing Incentive Regulation in the Electricity Sector – **Brown, D.,** Sappington, D.

2023-09: Economic Evaluation under Ambiguity and Structural Uncertainties – **Andrews, B.**

2023-08: Show Me the Money! Incentives and Nudges to Shift Electric Vehicle Charge Timing – Bailey, M., **Brown, D.,** Shaffer, B., Wolak, F.

2023-07: Screening for Collusion in Wholesale Electricity Markets: A Review of the Literature – **Brown, D., Eckert, A., Silveira, D.**

2023-06: Information and Transparency: Using Machine Learning to Detect Communication – **Brown, D.,** Cajueiro, D., **Eckert, A., Silveira, D.**

2023-05: The Value of Electricity Reliability: Evidence from Battery Adoption – **Brown, D.,** Muehlenbachs, L.

2023-04: Expectation-Driven Boom-Bust Cycles – **Brianti, M.,** Cormun, V.

2023-03: Fat Tailed DSGE Models: A Survey and New Results – **Dave, C.,** Sorge, M.

2023-02: Evaluating the Impact of Divestitures on Competition: Evidence from Alberta's Wholesale Electricity Market – **Brown, D., Eckert, A.,** Shaffer, B.

2023-01: Gender Specific Distortions, Entrepreneurship and Misallocation – **Ranasinghe, A.**

2022-12: The Impact of Wholesale Price Caps on Forward Contracting – **Brown, D.,** Sappington, D.

2022-11: Strategic Interaction Between Wholesale and Ancillary Service Markets – **Brown, D., Eckert, A., Silveira, D.**

2022-10: Employing Gain-Sharing Regulation to Promote Forward Contracting in the Electricity Sector – **Brown, D.,** Sappington, D.

2022-09: Enhanced Intergenerational Occupational Mobility through Trade Expansion: Evidence from Vietnam – Mitra, D., Pham, H., **Ural Marchand, B.**