

Carbon Pricing and Cross-Border Innovation Spillovers

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Abstract

We examine whether carbon pricing and emission taxes induce investments in innovation. We predict the innovation-enhancing response to carbon pricing need not occur in the country implementing the policy but can materialize abroad through product-market linkages, creating cross-border spillover effects. Using patent data from 45 countries between 2008 and 2019 and a shift-share design that exploits country-level variation in the bilateral exposure to trading partners' carbon pricing mechanisms, we show that increases in carbon prices in connected countries significantly raise innovation output in focal countries. A 1 percent increase in connected countries' carbon prices is associated with a 1.15 percent increase in forward-looking patent citations. The effect is stronger in countries with patent boxes, lower corporate taxes, and more researchers. Our results highlight how environmental regulation can generate international innovation spillovers beyond domestic policy boundaries.

Keywords: Carbon pricing, innovation investment, spillover effects, carbon taxes.

JEL-Classifications: Q58, Q55, H23, O31

1. Introduction

This paper examines whether carbon pricing and emission taxes can enhance innovation activities. Many countries worldwide have set ambitious targets to address climate change and to foster a cleaner environment by substantially reducing greenhouse gas emissions and other forms of pollution. The European Union, for example, set the objective to reduce greenhouse gases by 55% in 2030. Many other countries have committed to becoming climate-neutral by 2050 (IMF 2023). Central to reaching these objectives are policy tools such as emission taxes and carbon pricing systems. In addition to the European Union and its Emission Trading System (ETS), many other jurisdictions have implemented carbon pricing systems or carbon taxes (e.g., California, Canada, China, Japan, Mexico, or New Zealand), generating substantial revenues. In 2023, for instance, EU member states collected over €340 billion from environmental taxes and from carbon allowances, which represents 2% of total GDP (Eurostat, 2025).

By putting a price on carbon emissions, firms are incentivized to develop new “green”, i.e., clean technologies and products, which are critical part of the transition to climate-neutrality and reduced greenhouse gas emissions (e.g., Aghion et al. 2016). In a world with global trade and markets, we argue that the innovation response to carbon pricing may not necessarily take place in the jurisdiction that implements or increases carbon pricing. Firms that are innovating in clean technologies have a global market for their products. Accordingly, if there is an increase in the demand for green technologies, e.g., in countries where policymakers increase carbon pricing, innovators in other countries can also respond to these demand shocks by investing in innovation. In fact, firms in other countries may be better equipped to respond to these carbon pricing-induced demand shocks, for example, because they may enjoy more innovation support through tax incentives or because they have access to necessary resources (e.g., highly educated researchers) that may not be available in the country increasing carbon pricing. Taken together, we argue that

carbon pricing can induce innovation, but that this carbon-pricing induced innovation may not only place in the country with carbon pricing, but also in other countries. In this, we thus examine whether carbon pricing and emission taxes spurs innovation across borders.

Understanding such spillover effects is important because whether and to what extent carbon pricing and emission taxes can foster innovation and the development of clean technologies and products is still an open empirical question.¹ While there is theory (Krass, Nedorezov, and Ovchinnikov 2013) and empirical evidence that carbon taxes can induce more R&D investment (Brown, Martinsson, and Thomann 2022 for Sweden), there is also evidence that carbon taxes reduce corporate investment, not only by polluting firms, but also by cleaner firms that do not pay emission taxes (Jacob and Zerwer 2024 and the case of Spain).² However, single country studies can arguably not account for any potential cross-border spillover effect of carbon pricing. Hence, the overall effects of carbon prices on innovation may not be fully understood. For policy evaluation and also for the society at large, it is, however, critical to account for any effect of carbon pricing on innovation across borders and to understand when a spillover effect is stronger.

Testing this cross-border effect empirically faces at least two challenges. First, one requires data on innovation across many countries. To overcome the first challenge, we use data on innovation output from the Orbis Intellectual Property (IP) data which provides detailed insights into the number of registered patents and number of forward-looking citations. One of the advantages of Orbis IP data is that it links patents applicants to their large sample of companies, thereby compiling extensive patent portfolio data for companies and their corporate groups. Orbis

¹ See also Lilliestam, Patt and Bersali (2021, 2022) who have documented that the existing literature until date had only triggered few, and at best rather weak, innovation increases.

² Moreover, the incentives for high-polluting firms to invest in innovation and the development of green technologies in response to carbon pricing and emission taxes might be mitigated by the possibility that firms may relocate their production to countries without carbon pricing (e.g., Naegele and Zaklan 2019; Borghesi, Franco, and Zaldokas 2020; Dechezleprêtre et al. 2022; Colmer et al. 2024; Kanzig et al. 2025). Such “carbon leakage” undermines policies that create financial pressure on high-polluting firms to innovate and to engage in investments into new technologies.

IP data provides an ownership timeline for all live patents. The data include transactions for affiliates and unrelated companies, patent citations, original patent owners, and information on whether purchase transactions were intragroup or with third parties. Following prior literature, we use forward-looking patent citations as our primary measure of innovation (see, also, Acharya and Subramanian 2009; Hsu, Tian, and Xu 2014; He et al. 2022). Our final sample explores innovation output from 45 countries over the period 2008–2019.

The second empirical challenge is to identify cross-border effects of carbon pricing on innovation in a compelling way. To overcome this challenge, we use a shift-share design (e.g., Bartik 1991; Goldsmith-Pinkham, Sorkin, and Swift 2020; Breuer 2022) as applied in various settings in the literature (e.g., Autor, Dorn, and Hanson 2013; Breuer and Breuer 2022; Brühne, Jacob, and Schütt 2025; Gallemore and Jacob 2025; Bonetti, Jacob, and Ormazabal 2025). The idea of our approach is that we measure the exposure of one focal country to other countries' carbon pricing and emission taxes. To measure this exposure, we use bilateral trade flows between countries. The underlying assumption is that bilateral trade intensity proxies for the strength of product-market linkages. That is, the bilateral trade there is between two countries, the more the focal country is exposed to the partner's carbon pricing policies, which makes innovators in the focal country more responsive to the foreign carbon pricing mechanisms. To address the potential endogeneity issue that changes in carbon pricing affect trade flows, we fix the trade flows prior to our final sample period. This way, any variation in our measure of connected countries' carbon pricing only stems from changes in carbon pricing and emission taxes in other countries. We collect annual data on carbon pricing and carbon taxes from the World Bank Carbon Pricing Dashboard, the International Carbon Action Partnership (ICAP), and the World Carbon Pricing Database by Dolphin and Xiahou (2022). For our final sample of 45 countries over the period 2008–2019, we have information on aggregate forward-looking patent citations and carbon pricing and emission

taxes of connected countries and the focal country.

In our main country-level tests, we find evidence consistent with carbon pricing and emission taxes leading to more innovation in other countries. Our results show that carbon pricing and emission taxes (hereafter, ETS) in connected countries lead to more innovation output in a focal country. We estimate an elasticity of forward-looking citations to connected countries' carbon pricing and ETS between 1.15 and 1.16. That is, a 1% increase in carbon trading prices and ETS in connected countries is associated with a 1.15% to 1.16% increase in patent citations in the focal country. We obtain this finding from specifications with country fixed effects for the focal country, year fixed effects, and several control variables absorbing economic characteristics, tax policy variables, and country-level governance in the focal country. This finding also holds across a battery of robustness tests. For example, our results are robust to excluding control variables or using a first-difference model. Results also persist whether the focal country itself has a carbon trading price mechanism or not. More importantly, we observe a parallel pre-trend in response to connected countries' carbon prices. Once connected countries increase carbon prices, innovation output in focal countries starts to gradually increase, a finding consistent with the notion that innovation processes require sufficient time.

In the next step, we test the heterogeneity in the cross-country spillover effect of carbon pricing in two ways. First, we test whether there are other tax costs affecting foreign firms' incentives to innovate. For example, corporate tax incentives such as low corporate tax rates or patent boxes that offer very low tax rates on profits from innovation have a positive impact on firms' innovation activity (e.g., Klassen et al. 2004, Brown and Krull 2008, Rao, 2016, Alstadsæter et al. 2018, Guceri and Liu 2019, Agrawal, Rosell, and Simcoe 2020, Akcigit and Stantcheva 2022, Knoll et al. 2021). Hence, we argue that, when a focal country also has a patent box or a low corporate tax rate, the spillover effect of connected countries' carbon pricing on innovation output in a country

is stronger. Put differently, when firms operate in a favorable tax environment, it is more likely that they respond to the increased demand in foreign countries for green technologies induced by carbon pricing. We find empirical evidence consistent with this notion. When a country has low corporate tax rates or patent boxes, innovation output responds more strongly to connected countries' carbon pricing. This shows that innovation output induced by other countries' carbon pricing is more likely to take place in focal countries where any potential benefit from such innovation output is taxed at lower corporate tax rates.

In our second cross-sectional test, we explore the availability of resources to innovate. The prediction is that one potential impediment to innovation in response to carbon pricing is a lack of financial resources, researchers, or innovation culture. The idea is that innovators are more likely to respond to the increased global demand for green technologies when they operate in countries with the necessary resources. We test for this notion using i) GDP per capita to proxy for the availability of financial resources, ii) the number of PhD graduates to proxy for the availability of human capital to innovate, and iii) a country's long-term orientation to proxy for an innovation culture. We find that the positive spillover effect of carbon pricing is stronger when i) the focal country has a higher GDP per capita, ii) there are more PhD graduates in the focal country, and iii) when the focal country's culture is characterized by more long-term orientation. Collectively, these findings are consistent with the availability of resources—financial capacity or in terms of available staff—driving the innovation response to carbon pricing across borders. Our results imply that innovation in response to carbon pricing takes place in countries where the business environment is more innovation-friendly, for example, because of low corporate taxes, available researchers, and long-term thinking that is necessary for innovation projects.

Next, we explore the nature of innovation that is triggered by carbon pricing. Specifically, we explore whether carbon pricing induces more radical innovation or rather incremental, i.e.,

exploitative innovation. We expect that in response to carbon pricing and emission taxes, more radical innovation is better able to meet the demand for green technologies than incremental, i.e., more exploitative innovation. Hence, cross-border spillover effect of carbon pricing and emission taxes on innovation are expected to be more prevalent for radical vis-à-vis exploitative innovation. Following the approach in He et al. (2022) to distinguish between exploitative versus radical innovation, we find that evidence of a spillover effect of carbon pricing and emission taxes on other countries' innovation activities for both, radical innovation and exploitative innovation, but that the cross-border spillover effect is stronger for more radical innovations. As a final step, we also explore whether our results hold at the company level. The results using firm-level data on granted patents support our main findings. We find that foreign countries' carbon pricing increases the number of granted patents of a firm. The increase in patenting activity at the firm level can explain the country-level increase in forward-looking citations in response to carbon pricing.

With these findings, our paper contributes to two streams in the literature. First, our paper is related to the literature on the effects of carbon pricing and emission taxes on innovation and investment (e.g., Aghion et al. 2016, Brown et al. 2022, Jacob and Zerwer 2024) and emissions (e.g., Naegele and Zaklan 2019, Borghesi et al. 2020, Li et al. 2021, Dechezleprêtre et al. 2022, Pretis 2022, Metcalf and Stock 2023, Martinsson et al. 2024, Erbertseder et al. 2025). Our findings of cross-border spillover effects of carbon pricing and taxes on innovation can bridge the gap between more innovation and R&D investments in Brown et al. (2022) and reduced investments in Jacob and Zerwer (2024) in response to emission taxes. Our evidence of cross-border spillover effects implies that the innovation does not necessarily take place in the country implementing carbon pricing. Instead, carbon pricing-induced innovation can take place in other countries.³

³ Our paper also augments earlier argumentations about potential foreign technological spillover effects of CO₂ abatement effects obtained via simulation models (e.g; Garlich and Kuik, 2014). More precisely, we are among the

Second, our paper is also related the literature on the effect of tax incentives on innovation (e.g., Klassen et al. 2004, Brown and Krull 2008, Rao, 2016, Alstadsæter et al. 2018, Guceri and Liu 2019, Agrawal, Rosell, and Simcoe 2020, Akcigit and Stantcheva 2022, Knoll et al. 2021) as well as the broader literature on investment effects of taxation (e.g., Djankov et al. 2010, Giroud and Rauh 2019, Gallemore et al. 2025 and the reviews by Jacob 2022 and Lester and Olbert 2025). The papers closest to ours are Knoll et al. (2021) on R&D spillovers of tax incentives and Bonetti, Jacob, and Ormazabal (2025) on cross-border spillovers of corporate taxes on investment. Knoll et al. (2021) provide evidence of *negative* spillover effects of R&D tax incentives as one country aims to attract R&D investments from other countries. Bonetti, Jacob, and Ormazabal (2025) provide evidence of *negative* investment spillover effect of corporate taxes if firms are connected via their supply chain. In this study, we provide evidence of *positive* innovation spillover effects of carbon pricing policies across countries. Our results imply that firms in one country respond to the carbon pricing-induced demand for green technologies in other countries by expanding their innovation activities. The expansion in innovation activities in response to other countries' carbon pricing is stronger when firms benefit from corporate tax incentives and an innovation-friendly business environment in their home country.

Our findings also have important policy implications. Because carbon pricing in one country can stimulate innovation abroad, the overall effectiveness of such policies depends on their global rather than their purely domestic impact. Moreover, corporate tax regimes, the availability of human capital, and institutional differences appear to shape where innovation in response to carbon pricing takes place. This suggests that carbon pricing and emission taxes interact with international tax competition and the allocation of innovation outcomes, underscoring the value of cross-border

first to provide direct evidence that domestic CO2 abatements impact foreign innovation activity directly, thereby uncovering both the channels of cross-border spillovers as well as the local conditions that shape its magnitude.

coordination and complementary policies such as corporate tax incentives to foster innovation and support the green transition.

2. Hypothesis Development: Carbon pricing and Innovation

The idea of taxing polluters for their actions dates back to Pigou (1932) and the notion of federal governments imposing taxes on polluters. The premise of a Pigouvian tax is that when an externality causes marginal social costs to diverge from private marginal costs, the market outcome is unlikely to produce an efficient level of output. According to Pigou (1932), a tax-efficient mechanism can be proposed to equal the difference between marginal social costs and private marginal cost. As such, tax internalizes the externality into private costs and according to the Pigouvian tradition, the optimal tax on environmental damage caused should equal the marginal cost of pollution. An alternative way of reducing pollution and greenhouse gas emission is through emission pricing mechanisms such as the European Trading System (ETS) in the EU.

In principle, a well-designed Pigouvian tax or carbon pricing system can lead to more innovation and investments in clean technologies as higher carbon prices foster competitiveness by forcing firms to adopt innovative, environmental-friendly technologies (Porter and van der Linde 1995). The underlying idea is that adding a carbon price on greenhouse gas emissions encourages firms to invest in new technologies so that dirty firms become cleaner (e.g., Acemoglu et al. 2016). Consequently, firms targeting such new technologies in response to carbon taxes or emission are expected to decrease unit costs which in turn can boost further investments (see, for example, Brown et al. 2022).

However, there are also reasons why carbon pricing may not affect innovative outputs of polluting firms. First, polluting firms may be able to pass on the burden created by carbon pricing mechanisms to consumers or other stakeholders (Marron and Toder 2014). Consistent with this notion, Jacob and Zerwer (2024) show that in response to an emission tax, investment decreases

not only for high polluting firms, but also for cleaner firms because they also bear part of the emission tax burden. Likewise, in case of carbon pricing mechanisms, polluters may pass on the costs to their customers (e.g., Alonso et al. 2025 and the case of the carbon border adjustment mechanism). Second, firms can respond to carbon pricing by relocating their production to countries without carbon pricing or taxes (e.g., Naegele and Zaklan 2019, Borghesi et al. 2020, Dechezleprêtre et al. 2022, Colmer et al. 2024, Kanzig et al. 2025). However, policymakers in the EU have responded to such “carbon leakage” by introducing cross-border carbon pricing.

Collectively, carbon pricing increase the demand for green technologies. This likely holds even if polluting firms avoid the burden of carbon pricing by passing it onto consumers in the form of higher prices. This is because firms competing with polluters may engage in innovation or may invest in green technologies to make their production cleaner and to gain market share from polluting companies passing on the carbon costs to consumers via higher prices. Cleaner competitors or market entrants may offer their products at a lower price. Taken together, we expect higher demand for green technologies and innovation in response to carbon pricing.

Importantly, we argue that innovation may not necessarily take place in the country implementing carbon pricing, but that it can occur in other countries, given international trade and technology exchange. Consider the following simple example of two countries A and B that are economically tied. Country A introduces carbon pricing, Country B does not. In response to Country A’s carbon pricing, innovators in Country B observe the increasing demand for green technologies in Country A. This induces firms in Country B to respond to the carbon pricing in Country A by engaging in innovation. While spillover effects are typically weaker than direct effects, in case of innovation in response to foreign countries’ carbon pricing, this may be different. For example, in our simple illustration, it is possible that firms in Country B may be better equipped to engage in innovation than firms in Country A following the carbon pricing increase in

Country A. This may be the case if firms in Country B may have better resources to engage in innovation (e.g., due to greater availability of human capital) or if they may have better financial incentives to foster innovation (e.g., if R&D tax incentives exist in Country B). Put differently, high corporate taxes and a lack of an innovation-friendly environment in Country A may mute innovation effects of carbon pricing within the country. This void can potentially be filled by firms located in other countries, where the regulatory framework, the economic conditions, and the infrastructure are more favorable to innovate and to cater to the demand for cleaner products and technologies. In sum, we expect that there are spillover effects of carbon pricing and emission taxes on innovation to other countries. We thus formulate the following hypothesis:

H1: Carbon Pricing and emission taxes trigger innovation activities in other countries.

3. Model and Data

3.1 Data

We obtain data on patents across countries from Orbis Intellectual Property (IP) data from Bureau Van Dijk. Orbis IP data covers the location of firms' intellectual property (IP) as well as detailed insights on the number of registered patents and forward-looking citations, linking patent applicants to their vast universe of companies and compiling extensive patent portfolios for companies. Patents granted are linked to the applicant's country. We acknowledge that a single patent application are typically filed with multiple patent offices (e.g., in the US as well as in the EU). However, these filings are all associated with the same applicant and rather illustrate the international nature of innovation.⁴

We use forward-looking citations as our measure of innovation output. This helps us to overcome several issues associated with innovation input data. For example, relying on R&D

⁴ For this reason, we do not collect data on the location of the patent office. What matters for our research question is the location of the applicant.

expense data to proxy for innovation comes with substantial issues of data coverage for listed firms (Koh and Reeb 2015). Moreover, for non-listed firms, common databases such as Bureau Van Dijk Orbis do not cover R&D expenses in most cases. Finally, R&D expenses are not a mandatory reporting item under common accounting principles. For these reasons, we focus on the innovation output of private firms as well as of publicly listed firms.

We compile annual information on carbon pricing and carbon taxes from the World Bank Carbon Pricing Dashboard, the International Carbon Action Partnership (ICAP), and the World Carbon Pricing Database (Dolphin and Xiahou 2022).⁵ We merge these data with country-level indicators to construct our final sample, which covers 45 countries over the period 2008–2019. We compile countries' trade flow imports and GDP data from the World Bank, corporate tax rates from The Tax Foundation, IP boxes data from Chen, De Simone, Hanlon, and Lester (2023), IP rights from the international property rights index website, the number of Ph.D. graduates from the OECD database and countries' long-term orientation data from Hofstede (1984).

3.2 Measuring exposure to other countries' carbon pricing and emission taxes

To explore the cross-border spillover effect of carbon pricing on innovation output, we apply a shift-share design (e.g., Bartik 1991, Goldsmith-Pinkham, Sorkin, and Swift 2020, Breuer 2022). This design has been applied in several different contexts, for example, when exploring the role of foreign imports (e.g., Autor et al. 2013) or the cross-border spillover effect of corporate taxes on investments (Bonetti et al. 2025). The idea of this approach is to measure country's c exposure to other countries d . Different focal countries c have different exposure to all other countries. We measure cross-country exposure by the bilateral trade flows between two countries. The idea is that a focal country is more likely to react to other countries' increased demand for green

⁵ For the US, we use state-level GDP data from the Bureau of Economic Analysis – BEA- to create a GDP-weighted ETS, since it is implemented at the state level.

technologies following their higher carbon pricing if this focal country is economically more tied to these foreign countries via bilateral trade.

In the next step, we account for the fact that carbon prices in other countries change over time. Because we fix the exposure to—i.e., the bilateral trade with—other countries in 2006 (to avoid that carbon prices endogenously change the bilateral trade of country c to the other countries d), the variation of our key independent variable stems only from changes in carbon prices in other countries, but not from changes in bilateral trade. The resulting carbon price of other connected countries in year t for country c , denoted *Connected Countries ETS* $_{c,t}$, is thus defined as:

$$\text{Connected Countries ETS}_{c,t} = \sum_{d=1}^D \frac{\text{Trade}_{c,d,2006}}{\text{Trade}_{c,2006}} \times \text{ETS Price}_{d,t} \quad (1)$$

where $\text{Trade}_{c,d,2006}$ represents the USD value of total bilateral trade country c has with the foreign country d in the year 2006. In turn, $\text{Trade}_{c,2006}$ is the total trade of country c with all foreign countries. There are D foreign countries. The variable *ETS Price* is the average carbon trading price in the foreign country d in year t . Effectively, *Connected Countries ETS* is the trade-value weighted average carbon trading price of all countries connected via bilateral trade. Because our baseline measure only uses the carbon price from trading systems, we also expand the definition from Equation (1) to capture carbon taxes $\text{Tax}_{d,t}$ in country d in year t . The definition of the other countries' carbon pricing and taxes *Other Countries ETS & Tax* $_{c,t}$ is thus as follows:

$$\text{Connected Countries ETS \& Tax}_{c,t} = \sum_{d=1}^D \frac{\text{Trade}_{c,d,2006}}{\text{Trade}_{c,2006}} \times (\text{ETS Price}_{d,t} + \text{Tax}_{d,t}) \quad (2)$$

3.3 Variation in carbon pricing and emission taxes

Table 1 presents descriptive statistics for our sample of 45 host countries c . For each country, we report the sample average carbon trading price in its own ETS (*ETS Price*) as well as the carbon trading price of the connected countries (*Connected Countries ETS*). Because the countries in the

European Union have the same carbon emission trading system, the EU ETS, the values for EU countries are similar.⁶ Other countries (e.g., Canada, Chile, China, or Mexico) have their own carbon emission trading system. The sample average carbon trading price per ton is USD 10.91 per ton of carbon dioxide. Important of our purpose is the variation in the carbon trading price in connected countries. We find that even within the European Union with its ETS, there is variation in the connected countries' carbon trading price. This variation stems from different bilateral trade exposure to different non-EU countries.

Figure 1 provides a visual representation of the within-country variation in *Connected Countries ETS*. Specifically, we plot a histogram that shows the distribution of *Connected Countries ETS*, which we demean by the country average value of *Connected Countries ETS* from Table 1. The resulting variation is what we explore in our empirical approach, which includes country fixed effects. We find that there is considerable variation in the connected countries' carbon trading prices. In some sample years and countries, the carbon trading price in connected countries increases (decreases) by more than USD 10 per ton (USD 5 per ton). Taken together, even though we use pre-determined exposure to other countries from 2006, our approach explores considerable variation in carbon emission trading prices in connected countries.

3.4 Estimation equation

Our empirical analysis assesses the impact of connected countries' carbon emission trading prices on innovation in a focal country c . To this end, we estimate the following OLS model:

$$Innovation_{c,t+2} = \beta_0 + \beta_1 \times Connected\ Countries\ ETS_{c,t} + X_{i,t} + \alpha_c + \alpha_t + \varepsilon \quad (3)$$

where the dependent variable *Innovation* is our measure of innovation output in country c in year $t+2$. We measure innovation using the natural logarithm of forward-looking citations of patents

⁶ Deviations in the average *ETS Price* of European Union countries occur because we sometimes lose some sample years for some countries due to missing control variables.

following prior studies (e.g., Aghion et al. 2013; Fang, Tian, and Tice 2014; Balsmeier, Fleming, and Manso 2017; Kim and Valentine 2021). In our main model, we allow the innovation to materialize within the three years t , $t+1$, and $t+2$. This approach follows prior literature which shows that such a time horizon is sufficient to detect innovation output responses (e.g., Aghion et al. 2013, Acharya Baghai, and Subramanian 2014, Fang et al. 2014, Mukherjee, Singh, and Zaldokas 2017). The key independent variable of interest is the connected countries carbon trading price *Connected Countries ETS* $_{c,t}$ of country c in year t as defined in equation (1). As an alternative measure, we include carbon taxes as well (*Connected Countries ETS & Tax* $_{c,t}$) following equation (2). The coefficient β_l captures the cross-country spillover effect of carbon trading prices on innovation output. Consistent with H1, we expect the coefficient to be positive ($\beta_l > 0$).

In our model, we also control for several country-level characteristics of the host country c (vector $X_{c,t}$). These variables include the natural logarithm of the gross domestic product (*GDP*) and *GDP Growth* from $t-1$ to t . Moreover, we control for the host country's carbon trading price (*ETS Price* $_{c,t}$) as well as the carbon tax (*Carbon Tax* $_{c,t}$) in year t . To account for the general tax environment, we control for the statutory corporate tax rates (*Corporate Tax*) and whether the country has an *IP Box* regime. As institutional and governance variables, we include the intellectual property rights score (*IPR Score*) as well as the World Governance Indicators *Control for Corruption*, *Rule of Law*, and *Regulatory Quality*. We also include country fixed effects (α_c) and year fixed effects (α_t) in our main model to absorb not only time-invariant country characteristics, but also any general time trend.⁷ With these fixed effects, our identification of cross-country spillover effects stems only from changes in carbon prices and emission taxes in foreign countries. By including country fixed effects as well as year fixed effects, we note that most of the variation

⁷ We cluster standard errors at the country level in all tests.

in the focal country's carbon pricing is absorbed. Hence, one limitation of our approach is that we cannot reliably estimate the direct effects of carbon pricing in the focal country. The focus of equation (3) is on the cross-border spillover effects of carbon pricing on innovation output.

3.5 Descriptive statistics

Table 2 presents descriptive statistics. The average number of forward-looking citations is highly skewed as indicated by the large difference in median citations (123) and average citations (88,131). For this reason, we use the natural logarithm of Forward Citations in our empirical tests. The sample average *Connected Countries ETS* (*Connected Countries ETS & Tax*) is USD 10.55 per ton (USD 18.50). About 19% of our country-year observations stem from jurisdictions with an IP box. The sample average corporate tax rate is 25%. GDP growth averages about 2% during our sample period for our sample of 45 countries.

4. Empirical Results: Country-level evidence

4.1 Main Findings: Country-level evidence

In Table 3, we present the results from estimating our main regression model from equation (3). We start with a version of this model without control variables in column 1, but with country as well as year fixed effects. In column 2, we add control variables to arrive at equation (3). In column 3, we use a first-difference model, where the dependent variable is defined as the change in the natural logarithm of forward-looking citations from $t-1$ to $t+2$. Control variables are in first differences from $t-1$ to t . Across all three columns, the coefficient on *Connected Countries ETS* is positive and statistically significant. In columns 4 to 6, we repeat these three tests using the measure of connected countries' carbon pricing including taxes (*Connected Countries ETS & Tax*) as our main independent variable of interest. Across the three columns, we find positive and significant coefficient estimates for *Connected Countries ETS & Tax*.

The findings in columns 1 to 6 of Table 3 are consistent with our hypothesis H1 and suggest a

significant cross-country spillover effect on innovation. These findings are also economically significant. Using the estimate from column 2, we obtain an elasticity of forward-looking citations with respect to connected firms' carbon pricing of 1.15.⁸ That is, a 1% increase in carbon prices in connected countries leads to a 1.15% increase in patent citations two years later. When using a combined measure of carbon prices and carbon taxes in column 5, we obtain an elasticity of 1.16.⁹ That is, a 1% increase in carbon prices and taxes in connected countries is associated with a 1.16% increase in patent citations. This is consistent in magnitude with findings from other studies, such as Akcigit, Grigsby, and Stantcheva (2022), which show that the elasticity of patent citations with respect to the personal income tax rate is about 1. Relative to the corporate tax rates and the estimate of 0.46 in Moretti and Wilson (2017), our estimates are somewhat larger, but this can be explained by the fact that carbon pricing is directly tied to emissions.

To further corroborate our findings, we next explore the timing of the innovation output responses to connected countries' carbon pricing by varying the timing of the dependent variable. That is, we run equation (3) separately for each of the three years before and after measuring our independent variables (Aobdia and Shroff 2017, Mukherjee, Singh, and Zaldokas 2017, and He et al. 2022 for a similar approach). The resulting coefficient estimates for *Connected Countries ETS* are reported in Figure 2.¹⁰ Consistent with the parallel trends assumption implicitly underlying our approach as innovation should not respond to future changes in other countries' carbon pricing, we find statistically insignificant coefficients on *Connected Countries ETS* for the years $t-3$, $t-2$,

⁸ This elasticity is calculated as follows: We calculate a 1% increase in carbon prices (=1% of the sample average *Connected Countries ETS* of 10.55, or 0.1055). We then multiply the coefficient estimate of 0.109 with this 1% increase. To obtain the effect on citations, we calculate $\exp(0.109 \times 0.1055) - 1$ to obtain an increase in citations of 1.15% in response to a 1% increase in carbon prices. Hence, the elasticity is $1.15 = 1.15\%/1\%$. Alternatively, looking at semi-elasticities a one-dollar increase in the connected countries' carbon price is associated with an 11.5% increase in forward-looking citations $100 \times (\exp(0.109) - 1)$.

⁹ This elasticity is calculated as $(\exp(0.065 \times 0.1850) - 1) / 1\%$. In case of *Connected Countries ETS*, a 1% increase in the carbon price and tax is equal to 1.16% increase in patent citations.

¹⁰ We repeat this test using *Connected Countries ETS & Tax* in Figure OA.1 of the Online Appendix.

and $t-1$. The effect on forward-looking citations starts to kick in contemporaneously with the change in other countries' carbon pricing and fully materializes in year $t+2$. This is consistent with prior literature showing that innovation output responses come with a certain delay (e.g., Aghion et al. 2013, Acharya et al. 2014, Fang et al. 2014, Mukherjee et al. 2017, He et al. 2022).

Table 3 also provides further robustness tests. In column 7, we replicate our main result from column 2, but use the natural logarithm of forward-looking citations of patents that are directly related to the environment as dependent variable. We continue to find a positive coefficient on *Connected Countries ETS*, although with a lower statistical significance (t-stat = 1.93). One potential explanation for this lower significance is that the Orbis IP data can only measure patents related to the environment with some level of imprecision. For example, a patent related to a new filter technology is not necessarily classified as an environmental patent because it is linked to production technologies as well. Hence, we use all patents as our main measure.

We also address concerns about the definition of our dependent variable. Because we use the natural logarithm of the forward-looking citations plus one, we may run into the issue outlined in Chen and Roth (2024). We thus apply two of their suggested solutions. In column 8, we do not add one to the number of citations so that we exclude observations with zero forward-looking citations. In column 9, we use a negative binomial model for count data, which does not require the log transformation as in our main test. Across the two tests, we continue to find a positive and significant coefficient on *Connected Countries ETS*. Finally, we show in the Online Appendix that our main findings on *Connected Countries ETS* from column 2 are robust to excluding any single country (Figure OA.2) or any single sample year (Figure OA.3). Taken together these findings suggest that there is a positive spillover effect of carbon pricing on innovation across countries.

4.2 Heterogeneity: Country-level evidence

This section presents three heterogeneity tests of the cross-country spillover effect of carbon

pricing. First, we examine whether the spillover effect hinges on the focal country also having implemented its own carbon trading pricing mechanism and a carbon tax in Section 4.2.1. Second, Section 4.2.2 assesses the role of corporate taxes in shaping the innovation spillover effect of carbon pricing. Third, we explore how the availability of resources in the focal country affects the spillover effect in Section 4.2.3.

4.2.1 Role of Own Carbon Trading Price Systems

In our first heterogeneity test, we examine whether the cross-country spillover effect hinges on the focal country having their own carbon trading price mechanism. One potential concern about our main finding is that the evidence of a cross-border effect of carbon pricing might be driven, for example, by European countries who are all part of the EU ETS. To this end, we create an indicator variable *No own ETS* which equals one if the focal country c does not have its own carbon trading price mechanism. In the same vein, we define a variable *No own Carbon Tax* which equals one if the focal country c does not have its own carbon tax. We then expand equation (3) and additionally include *No own ETS* as well as its interaction with *Connected Countries ETS*.

As shown in Table 4, column 1, we find that there is a positive spillover effect on innovative output for countries with their own ETS as well as for those without their own ETS. The innovation spillover effect is even stronger in countries without its own ETS. We obtain qualitatively similar findings when we use the non-existence of a carbon tax (*No own Carbon Tax*) or of an ETS and a carbon tax (*No own ETS & No own Carbon Tax*). Collectively, these results indicate that the finding of a spillover effect of carbon pricing does not hinge on the existence of carbon pricing mechanisms in the focal country. In fact, the spillover effect appears to be stronger if the focal country does not have its own carbon pricing mechanism.

4.2.2 Role of Corporate Tax Incentives

Next, we test whether there are corporate tax costs affecting firms' incentives to innovate. As

shown by prior literature, corporate tax incentives such as low corporate tax rates or patent boxes that offer very low tax rates on profits from patents can increase firms' innovation (e.g., Klassen et al. 2004, Brown and Krull 2008, Rao, 2016, Alstadsæter et al. 2018, Guceri and Liu 2019, Agrawal, Rosell, and Simcoe 2020, Akcigit and Stantcheva 2022, Knoll et al. 2021). Building on these studies, we argue that when a focal country has implemented a patent box or a has a low corporate tax rate, firms in such countries are more likely to engage in R&D when the demand for green technologies increases in connected countries. Hence, we expect the spillover effect of connected countries' carbon trading prices on innovation output to be stronger when the corporate tax rate in the focal country is low. This is because in such low-tax countries, innovators receive higher net-of-tax returns from their innovations relative to high tax countries.

To test this notion, we use two different variables, which we include as main variables and as interactions with *Connected Countries ETS*. First, we use an indicator variable if the focal country c has implemented an IP box (*IP Box*). These IP boxes provide low corporate tax rates on profits generated from patents developed in the focal countries. Several countries such as Belgium, France, the Netherlands, and Spain have implemented such tax incentives. Second, we define an indicator variable *Low Tax* if the corporate tax rate is 15% or lower (which is equals the threshold of the Global Minimum Tax) or if the country has implemented an IP box as the IP box allows firms to pay a corporate tax below 15%. The latter condition is important because we would falsely classify a country (e.g., Belgium or the Netherlands) as a high tax country ($Low Tax = 0$) even though the tax rate on profits earned with innovation output is taxed at a rate below 15%.

The results are reported in Table 5. We find similar results across the two measures. While we find a positive cross-country innovation spillover effect of carbon emission prices as suggested by the positive and significant coefficients on *Connected Countries ETS*, the cross-country spillover effect of carbon pricing is stronger when the focal country c is a low tax country. This is shown by

the significant and positive interactions *Connected Countries ETS* \times *IP Box* and *Connected Countries ETS* \times *Low Tax*, respectively. This shows that innovation output induced by other countries' carbon pricing is more likely to take place in focal countries where the profits from such innovation output is taxed at lower corporate tax rates.¹¹

4.2.3 Role of Country-Level Institutions and Economic Conditions

In our final cross-sectional test, we explore the availability of resources to innovate. One potential hurdle for innovation in response to carbon trading prices mechanisms is that a lack of financial resources, researchers, or innovation culture. Hence, we expect that if a focal country c offers financial resources, has sufficient researchers, and has a long-term oriented culture, the innovation spillover effect of carbon trading prices should be stronger. To test this notion, we use the following three country characteristics: i) level of GDP, ii) the number of PhD graduates, and iii) a country's long-term orientation. We source the number of PhD graduates from the OECD database. The measure of long-term orientation is taken from Geert Hofstede. For each of the three characteristics, we define indicator variables *High GDP*, *Many PhDs*, *Long-Term Oriented*, respectively which equal 1 if GDP, the number of graduates with a PhD, and the long-term orientation score, respectively are above the median.

The results are shown in Table 6.¹² We continue to find statistically significant innovation spillover effects of carbon pricing across borders for the group of countries that are not in the high GDP group, that have many PhD graduates, or that are very long-term oriented. Importantly, we find that the cross-border innovation spillover effect of carbon pricing is stronger when i) the focal country has a higher GDP, ii) there are more PhD graduates in the focal country, and iii) when the focal country's culture is characterized by more long-term orientation. These findings are

¹¹ Note that the negative coefficient on *Low Tax* is identified only from few cases where the statutory tax rate declined from above to below 15%. Hence, this coefficient is not credibly identified. Our focus is on the interaction term.

¹² As the long-term orientation is a static measure, *Long-Term Oriented* is absorbed by country fixed effects.

consistent with the availability of resources and an innovation-friendly environment—financial capacity, in terms of available staff, or in terms of long-term orientation—enabling firms in one country to respond to increased demand for green technologies. Put differently, our results imply that innovation in response to carbon pricing may not necessarily take place in the country imposing the carbon price. Our results suggest that innovation rather takes place in countries where the business environment is more innovation-friendly, for example, because of low corporate taxes, more financial resources, available researchers, and long-term thinking that is necessary for risky and costly projects such as innovation in green technologies.

4.3 Additional Analysis

4.3.1 Variation in the Nature of the Innovation

To assess whether the spillover effect manifests in more product-company-related outcomes, we examine whether the estimated cross-border spillover effects are concentrated in more radical versus more exploitative innovations. Relative to incremental improvements, radical innovations typically involve greater technological uncertainty and longer horizons before commercial payoffs are realized. Carbon pricing may shift expectations about which low-carbon technologies are likely to be valuable and may stimulate experimentation and adoption in early-moving markets. By raising the cost of emissions, a higher carbon price increases the demand for emissions-saving technologies, and thus provides a market signal about demand and commercial opportunities for the innovators. Thus, innovators may update their beliefs about which technologies are worth pursuing. We thus argue that when carbon pricing increases, more radical, i.e., explorative innovation will more likely meet the increased demand for green technologies than incremental, more exploitative innovation. Hence, we expect that the cross-border spillover effect of carbon pricing on innovation is more prevalent for radical vis-à-vis exploitative innovation.

To test this idea, we follow He et al. (2022) and distinguish between exploitative versus radical innovation. Because our main outcome are forward-looking citations, we classify patents based on forward citation impact. Exploitative patents are those that include at least one forward citation to a patent assigned to the same assignee (i.e., at least one self-citation) while radical patents are those that do not have at least one self-citation. We then re-estimate our baseline specification. Results are presented in Table 7. We find that the spillover effect of carbon pricing on other countries' innovation activities is present for both, radical innovation and exploitative innovation. However, consistent with our expectations, we also find that the cross-border spillover effect is stronger for more radical innovations (t-stat = 2.36).

4.3.2 Company-level Analysis

Data & Empirical Approach

In the final step, we explore the link between foreign countries' carbon pricing and emission taxes and innovation activity using firm-level data. To test our predictions at the firm level, we exploit data that link granted patents and patent ownership changes with worldwide multinational corporation (MNC) financials, using ORBIS and ORBIS Intellectual Property. Our granular company-level patent ownership and financial data allow us to examine company-level variation in the location of granted patents as a function of variation in carbon and emission taxes across partner countries. We download all information by companies classified as very large, large, and medium-sized in ORBIS and link patent applicants to this sample of firms, thereby compiling extensive patent portfolios at the company level. Granted patents are linked to the applicant's country. We require firms to have available data on industry codes, global ultimate ownership, total assets, net income, and the full set of control variables used in the analysis.

We then run a version of Equation (3) at the firm level. The dependent variable is the growth in the number of granted patents over the next two years. Our main independent variable of interest

is *Connected Countries' ETS* (and *Connected Countries' ETS & Tax*, respectively). As control variables, we include the natural logarithm of total assets, the natural logarithm of gross domestic product (*GDP*) and *GDP Growth* from $t-1$ to t , statutory corporate tax rates and whether the country has an *IP Box* regime. Moreover, we control for the host country's carbon trading price as well as the carbon tax (*ETS Price_{c,t}* & *Carbon Tax_{c,t}*) in year t . As institutional and governance variables, we include the intellectual property rights score (*IPR Score*) as well as the World Governance Indicators *Control for Corruption*, *Rule of Law*, and *Regulatory Quality*. We also include firm and year fixed effects in our main model and cluster errors by country. The final sample consists of 7,860,978 company-year observations. Descriptives statistics are presented in Table 8, Panel A.

Empirical Results

The main results at the company level are presented in Table 8, Panel B. Columns (1) and (2) focus on total patent grants in year $t+2$ as dependent variable, while columns (3) and (4) restrict the outcome to patents related to environmental technologies in year $t+2$. Columns (1) and (3) use *Connected Countries' ETS* as the main explanatory variable, whereas columns (2) and (4) use this measure with *Connected Countries' ETS & Tax*. Across both specifications, the coefficient estimates on *Connected Countries' ETS* and *Connected Countries' ETS & Tax*, respectively are positive and statistically significant, indicating that higher carbon pricing and emission taxes in connected countries lead to an increase in firms' future patenting activity. Columns (3) and (4) show that carbon pricing spillovers are also relevant for innovation in environmental technologies.

These findings—although modest—are economically significant. Using the estimate from column (1), we find that an increase in the connected countries' carbon price by \$1 is associated with an increase in granted patents by 0.39%. The effect is similar when incorporating carbon taxes. Moreover, we note that the effect is smaller in Columns 3 and 4, but one has to consider that only very few firms have patents and even less firms have granted environmental patents. Overall, the

results in Panel B complement the evidence shown at the country level analysis. We find that connected countries' carbon pricing leads to more patenting activity at the firm-level, which can explain a higher innovation output at the country-level.

5. Conclusions

This paper shows that carbon pricing generates cross-border spillovers in innovation. While existing studies have emphasized the direct effects of emission taxes on polluting firms' investment (e.g., Brown et al. 2022), our results show that the innovation effect of carbon pricing can extend beyond the countries implementing carbon pricing mechanisms. Using a shift-share design that exploits variation in the bilateral exposure to trading partners' carbon pricing mechanisms, we find that connected countries' carbon pricing spurs innovation in other countries. In economics terms, we find that a 1% increase in connected countries' carbon prices is associated with a 1.15–1.16% increase in forward-looking patent citations. The cross-border innovation spillover effect is stronger in countries with low corporate taxes, more financial resources, more researchers, or greater long-term orientation.

These findings have potential policy implications, for example, for the design of carbon pricing and emission tax policy. When carbon pricing in one jurisdiction fosters innovation abroad, the aggregate effectiveness of such policies depends not only on the domestic effects but also on the global effect on innovation activity. Our results imply that countries with weaker institutional frameworks, limited human capital, or high corporate tax rates are less likely to attract innovation activity in response to carbon pricing. Favorable corporate taxes and an innovation-friendly business environment spur more innovation in response to carbon pricing. As a result, carbon pricing appears to interact closely with international tax competition and the migration of innovation activities. Policymakers seeking to accelerate the green transition may want to consider coordinate policy actions across borders, for example, by ensuring that carbon pricing mechanisms

are accompanied by complementary policies such as corporate tax incentives to foster innovation and, thereby facilitate the green transition towards the policy goals.

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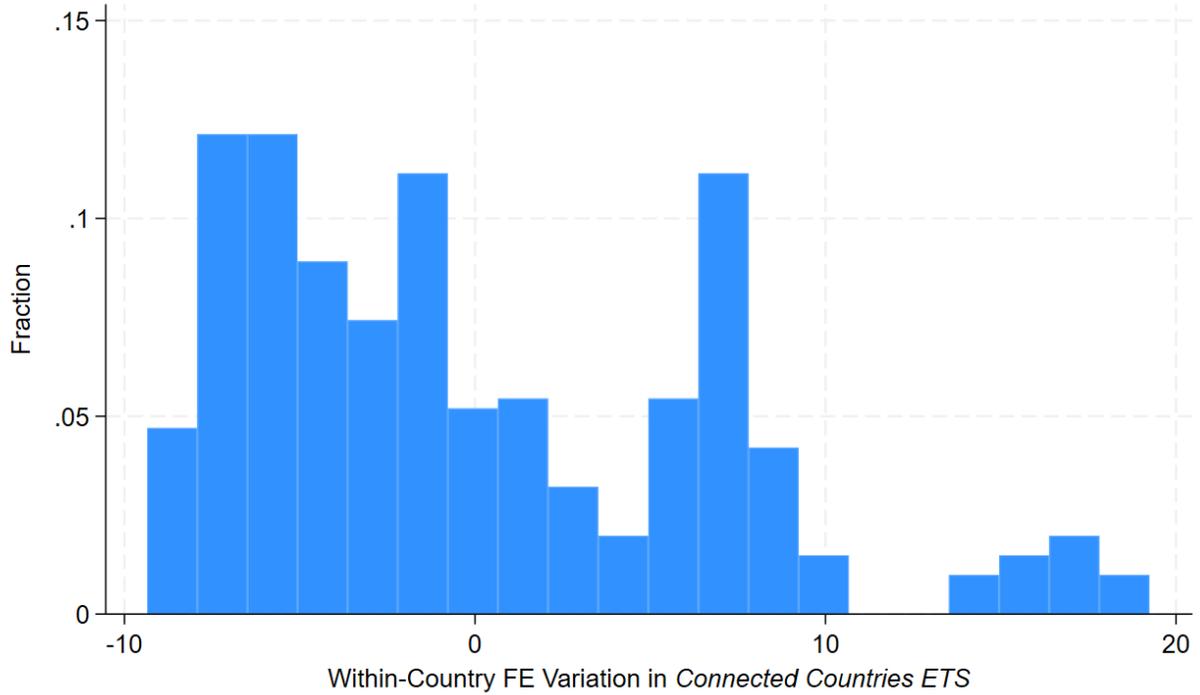
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Appendix A: Variable Definitions

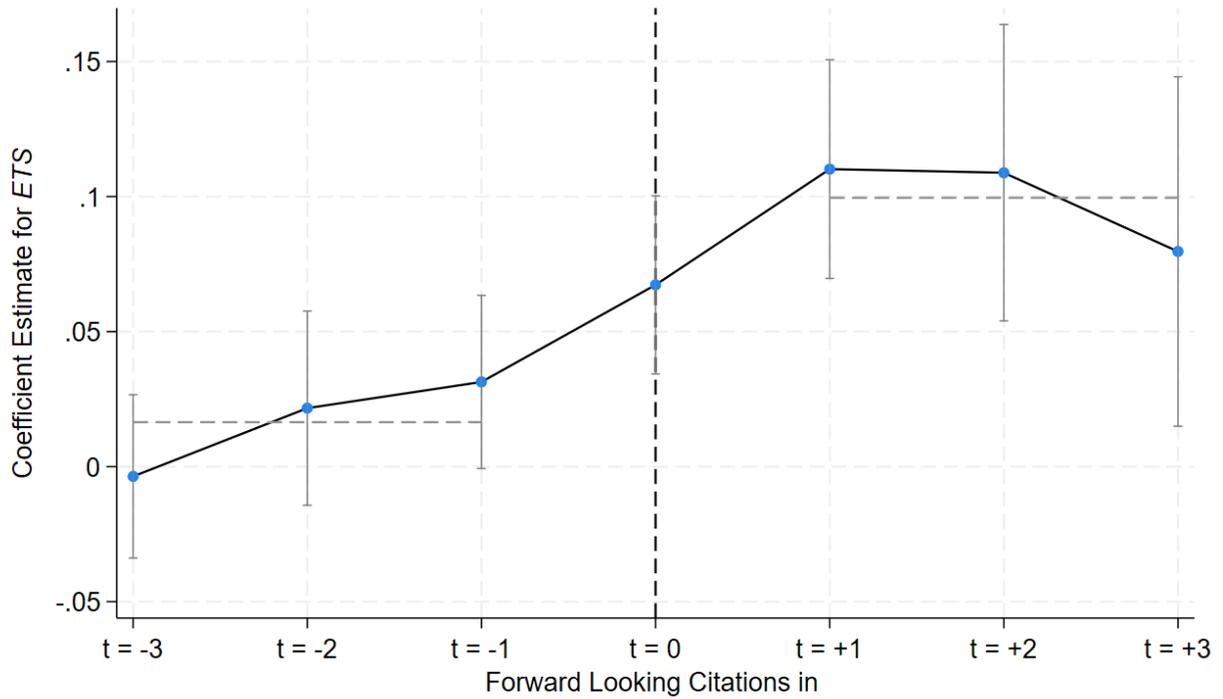
Variable Name	Definition
<i>Forward Citations</i>	Logarithm of one plus the number of forward-looking citations to patents in country c and year t . Source: Orbis – Intellectual Property Section.
<i>Forward Citations Environment</i>	Logarithm of one plus the number of forward-looking citations to patents classified in environment-related technology (corresponding to wipotech technology field code 24) in country c and year t . Source: Orbis – Intellectual Property Section.
<i>Connected Country ETS</i>	is the trade-value weighted average carbon price (<i>Own ETS</i>) of connected countries. Source: World Bank, World Carbon Pricing Database (Dolphin and Xiahou 2022) and the International Carbon Action Partnership (ICAP) Website: https://icapcarbonaction.com/es/ets
<i>Connected Country ETS & Tax</i>	is the trade-value weighted average carbon price plus the Average carbon price of country c in year t under an emission trading system (ETS) (i.e., <i>Own ETS</i> + <i>Own Carbon Tax</i>) of connected countries. Source: World Bank, World Carbon Pricing Database (Dolphin and Xiahou 2022) and the International Carbon Action Partnership (ICAP) Website: https://icapcarbonaction.com/es/ets
<i>Own ETS</i>	Average carbon price of country c in year t under an emission trading system (ETS). Source: World Bank, World Carbon Pricing Database (Dolphin and Xiahou 2022) and the International Carbon Action Partnership (ICAP) Website: https://icapcarbonaction.com/es/ets
<i>Own Carbon Tax</i>	Carbon price of country i in year t . Source: World Bank, World Carbon Pricing Database (Dolphin and Xiahou 2022) and the International Carbon Action Partnership (ICAP) Website: https://icapcarbonaction.com/es/ets
<i>Log GDP</i>	Logarithm of GDP. Source: World Bank Database.
<i>Property Rights</i>	IP rights score. Source: https://internationalpropertyrightsindex.org
<i>IP Box</i>	Indicator equal to 1 for countries with an IP box regime in place following De Simone et al. (2023).
<i>Corporate Tax</i>	Statutory tax rate of country i in year t . Source: Tax Foundation.
<i>Low Tax Indicator</i>	Indicator equal to 1 if corporate tax rate is lower than 15%.
<i>GDP Growth</i>	Source: World Bank Database
<i>High GDP</i>	Indicator equal to 1 if <i>Log GDP</i> is greater than the sample median. Source: World Bank Database.
<i>Many PhDs</i>	Indicator equal to 1 if the number of Ph.D. graduates is greater than the sample median. Source: OECD.
<i>Long-term oriented</i>	Indicator equal to 1 long-term orientation proxy is greater than the sample median. It captures the degree to which a country prioritizes future preparedness, adaptability, and pragmatic problem-solving over adherence to past traditions and immediate outcomes. Source: Hofstede Insights. https://www.hofstede-insights.com/country-comparison/
<i>Exploitative Patents</i>	Patents that include at least one forward citation to a patent assigned to the same assignee (i.e., at least one self-citation) as in He et al. (2022).
<i>Radical Patents</i>	Patents that do not have at least one self-citation as in He et al. (2022).

Figure 1: Variation in *Connected Countries ETS*



Notes: This figure shows the within-country variation in emission taxes of connected countries. For this purpose, we first demean *Connected Countries ETS* by the country specific average. The figure is a histogram of the demeaned *Connected Countries ETS*.

Figure 2: Connected Countries' Carbon Pricing (ETS) and Innovation Output, Dynamic Analysis



Notes: This figure plots coefficient estimates for *Connected Countries ETS* from separate year-by-year regressions on innovation output. The dependent variable is forward-looking patent citations measured in year $t + k$ where $k \in \{-3, -2, -1, 0, +1, +2, +3\}$. Year 0 is the year in which the independent variables are measured. Estimates for $k < 0$ capture lead effects (pre-trends) and estimates for $k > 0$ capture lagged responses.

Table 1: Sample Countries

Country	Own ETS	Connected Country ETS	Country	Own ETS	Connected Country ETS
Argentina	0.00	5.65	Japan	0.00	3.23
Australia	5.28	4.47	Kazakhstan	0.00	13.34
Austria	16.77	13.98	Latvia	14.92	13.82
Belgium	16.77	13.78	Lithuania	16.77	15.07
Bulgaria	17.80	13.62	Malta	25.41	19.67
Canada	0.00	2.81	Mexico	0.00	2.36
Chile	0.00	3.70	Netherlands	16.77	11.75
China	0.00	3.81	New Zealand	0.00	6.05
Colombia	0.00	4.22	Norway	16.77	12.96
Croatia	14.92	12.61	Poland	16.77	13.38
Cyprus	14.42	12.17	Portugal	16.77	15.32
Czech Republic	16.77	13.70	Romania	16.77	13.37
Denmark	16.77	14.23	Slovak Republic	14.42	11.75
Estonia	14.92	11.85	Slovenia	14.92	13.01
Finland	16.77	12.48	South Africa	0.00	8.59
France	16.77	12.61	South Korea	0.00	2.94
Germany	16.77	11.78	Spain	16.77	12.81
Greece	16.77	13.10	Sweden	16.77	14.56
Hungary	16.77	13.89	Switzerland	0.00	13.80
Iceland	14.42	10.01	Ukraine	0.00	12.81
Indonesia	0.00	3.44	UK	16.77	11.29
Ireland	13.02	8.80	USA	0.34	4.05
Italy	19.21	14.69	Sample Average	10.91	10.55

Notes: This table reports the sample distribution of the average values of countries' own emission taxes and connected countries' emission taxes. Countries are sorted alphabetically.

Table 2: Descriptive Statistics

Variable	Mean	Std. Deviation	P25	Median	P75
<i>Forward Citations</i>	88,131.15	44,9721.80	18.00	123.00	726.00
<i>Forward Citations Environment</i>	880.05	3,543.62	0.00	2.00	13.00
<i>Connected Country ETS</i>	10.55	7.88	5.29	7.28	17.94
<i>Connected Country ETS & Tax</i>	18.50	10.71	10.10	16.06	24.38
<i>Own ETS</i>	10.91	11.09	0.00	7.83	25.15
<i>Own Carbon Tax</i>	9.40	26.18	0.00	0.00	2.57
<i>Log GDP</i>	26.69	1.63	25.82	26.67	27.85
<i>Property Rights</i>	6.66	1.30	5.60	6.70	7.88
<i>IP Box</i>	0.19	0.39	0.00	0.00	0.00
<i>Corporate Tax</i>	0.25	0.07	0.20	0.25	0.30
<i>Low Tax Indicator</i>	0.23	0.42	0.00	0.00	0.00
<i>GDP Growth</i>	0.02	0.11	-0.05	0.03	0.09
<i>Control for Corruption</i>	0.91	0.96	0.10	1.01	1.78
<i>Rule of Law</i>	0.98	0.83	0.44	1.11	1.73
<i>Regulatory Quality</i>	1.04	0.67	0.68	1.12	1.60
<i>High GDP</i>	0.29	0.45	0.00	0.00	1.00
<i>Many PhDs</i>	0.25	0.43	0.00	0.00	0.00
<i>Long-Term Oriented</i>	0.24	0.43	0.00	0.00	0.00

Notes: This table presents descriptive statistics. All variables are defined in Appendix A.

Table 3: Connected Countries' Carbon Pricing and Innovation Output, Regression Results

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
	$\ln(\text{Forward Citations}_{t+2})$	$\ln(\text{Forward Citations}_{t+2})$	$\Delta \ln(\text{Forward Citations})_{t,t+2}$	$\ln(\text{Forward Citations}_{t+2})$	$\ln(\text{Forward Citations}_{t+2})$	$\Delta \ln(\text{Forward Citations})_{t,t+2}$	$\ln(\text{Forward Citations Environ.}_{t,t+2})$	$\ln(\text{Forward Citations}_{t+2})$ no zeros	$\text{Forward Citations}_{t+2}$
<i>Connected Countries ETS</i>	0.066*** (0.019)	0.109*** (0.033)					0.113* (0.058)	0.138*** (0.030)	0.062** (0.028)
<i>ΔConnected Countries ETS</i>			0.111*** (0.026)						
<i>Connected Countries ETS & Tax</i>				0.065*** (0.018)	0.062** (0.030)				
<i>ΔConnected Countries ETS & Tax</i>						0.062** (0.027)			
Controls	No	Yes	No	No	Yes	No	Yes	Yes	Yes
Controls in First Diff.	No	No	Yes	No	No	Yes	No	No	No
Model	OLS	OLS	OLS	OLS	OLS	OLS	OLS	OLS	Negative Binomial
Country FE	Yes	Yes	No	Yes	Yes	No	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No
Observations	404	404	351	404	404	351	607	331	384
Adjusted R2	0.956	0.959	0.349	0.955	0.958	0.343	0.736	0.966	--

Notes: This table estimates equation (3). $\ln(\text{Forward Citations}_{t+2})$ is the natural logarithm of forward patent citations in year $t+2$. $\Delta \ln(\text{Forward Citations})_{t,t+2}$ is the change in the natural logarithm of forward patent citations from year t to year $t+2$. $\ln(\text{Forward Citations Environ.}_{t,t+2})$ is the natural logarithm of the number of forward-looking citations to patents classified in environment-related technology. $\ln(\text{Forward Citations}_{t+2})$ no zeros is the logarithm of the number of forward-looking citations by excluding observations with zero forward-looking citations. The remaining variables and control variables are defined in Appendix A. Standard errors are reported in parentheses. ***, ** and * indicate statistical significance at the 1% 5% and 10% levels, respectively.

**Table 4: Connected Countries' Carbon Pricing and Innovation Output,
Role of Own ETS and Carbon Tax Regimes**

Dependent Variable	(1) <i>Ln(Forward Citations_{t+2})</i>	(2) <i>Ln(Forward Citations_{t+2})</i>	(3) <i>Ln(Forward Citations_{t+2})</i>
<i>Connected Countries ETS</i>	0.069*** (0.025)	0.023 (0.025)	0.055** (0.021)
<i>No own ETS</i>	0.0457 (0.295)		
<i>Connected Countries ETS × No own ETS</i>	0.072*** (0.019)		
<i>No own Carbon Tax</i>		-0.666** (0.260)	
<i>Connected Countries ETS × No own Carbon Tax</i>		0.058*** (0.017)	
<i>No own Carbon Tax & No own ETS</i>			-0.822*** (0.275)
<i>Countries Country ETS × No own Carbon Tax & No own ETS</i>			0.076*** (0.015)
<i>Joint Significance [t-stat]</i>	0.141*** [4.26]	0.081*** [3.76]	0.131*** [4.65]
Controls	Yes	Yes	Yes
Country FE	Yes	Yes	Yes
Year FE	Yes	Yes	Yes
Observations	404	404	404
Adjusted R-squared	0.960	0.961	0.960

Notes: This table estimates equation (3). $\ln(\text{Forward Citations}_{t+2})$ is the natural logarithm of forward patent citations in year $t+2$. *No own ETS* is a dummy variable equal to one if the focal country does not have an ETS. *No own Carbon Tax* is a dummy variable equal to one if the focal country does not have a carbon tax. The remaining variables and control variables are defined in Appendix A. Standard errors are reported in parentheses. ***, **, and * indicate statistical significance at the 1%, 5%, and 10% levels, respectively.

**Table 5: Connected Countries' Carbon Pricing and Innovation Output,
Role of Corporate Tax Incentives**

Dependent Variable	(1) <i>Ln(Forward Citations_{t+2})</i>	(2) <i>Ln(Forward Citations_{t+2})</i>
<i>Connected Countries ETS</i>	0.108*** (0.033)	0.104*** (0.031)
<i>IP Box</i>	-0.244 (0.379)	
<i>Connected Countries ETS × IP Box</i>	0.044** (0.018)	
<i>Low Tax</i>		-2.407*** (0.628)
<i>Connected Countries ETS × Low Tax</i>		0.040** (0.017)
<i>Joint Significance</i>	0.152***	0.144***
<i>[t-stat]</i>	<i>[3.91]</i>	<i>[3.91]</i>
Controls	Yes	Yes
Country FE	Yes	Yes
Year FE	Yes	Yes
Observations	404	404
Adjusted R-squared	0.960	0.961

Notes: This table estimates equation (3). $\ln(\text{Forward Citations}_{t+2})$ is the natural logarithm of forward patent citations in year $t+2$. The remaining variables and control variables are defined in Appendix A. Standard errors are reported in parentheses. ***, **, and * indicate statistical significance at the 1%, 5%, and 10% levels, respectively.

**Table 6: Connected Countries' Carbon Pricing and Innovation Output,
Country-Level Resources and Culture**

Dependent Variable	(1) <i>Ln(Forward Citations_{t+2})</i>	(2) <i>Ln(Forward Citations_{t+2})</i>	(3) <i>Ln(Forward Citations_{t+2})</i>
<i>Connected Countries ETS</i>	0.095** (0.035)	0.058* (0.029)	0.082** (0.034)
<i>High GDP</i>	-0.915** (0.397)		
<i>Connected Countries ETS × High GDP</i>	0.051*** (0.017)		
<i>Many PhDs</i>		-1.288*** (0.327)	
<i>Connected Countries ETS × Many PhDs</i>		0.063*** (0.011)	
<i>Connected Countries ETS × Long-Term Oriented</i>			0.027* (0.014)
<i>Joint Significance [t-stat]</i>	0.146*** [4.01]	0.122** [4.09]	0.108*** [3.59]
Controls	Yes	Yes	Yes
Country FE	Yes	Yes	Yes
Year FE	Yes	Yes	Yes
Observations	404	305	392
Adjusted R-squared	0.961	0.962	0.961

Notes: This table estimates equation (3). $\text{Ln}(\text{Forward Citations}_{t+2})$ is the natural logarithm of forward patent citations in year $t+2$. The remaining variables and control variables are defined in Appendix A. Standard errors are reported in parentheses. ***, **, and * indicate statistical significance at the 1%, 5%, and 10% levels, respectively.

Table 7: Connected Countries' Carbon Pricing and Innovation Output, Radical vs. Exploitative Innovation

	(1)	(2)
	$\ln(\text{Radical patents}_{t+2})$	$\ln(\text{Exploitative Patents}_{t+2})$
<i>Connected Countries ETS</i>	0.176** (0.072)	0.145** (0.065)
<i>Difference in coefficients</i>		0.031**
<i>[t-stat]</i>		[2.36]
Controls	Yes	Yes
Controls in First Diff.	No	No
Model	OLS	OLS
Country FE	Yes	Yes
Year FE	Yes	Yes
Observations	607	607
Adjusted R2	0.793	0.786

Notes: This table estimates equation (3). $\ln(\text{Radical patents}_{t+2})$ is the natural logarithm of the number of radical patents in year $t+2$. $\ln(\text{Exploitative patents}_{t+2})$ is the natural logarithm of the number of exploitative patents in year $t+2$. The remaining variables and control variables are defined in Appendix A. Standard errors are reported in parentheses. ***, **, and * indicate statistical significance at the 1%, 5%, and 10% levels, respectively.

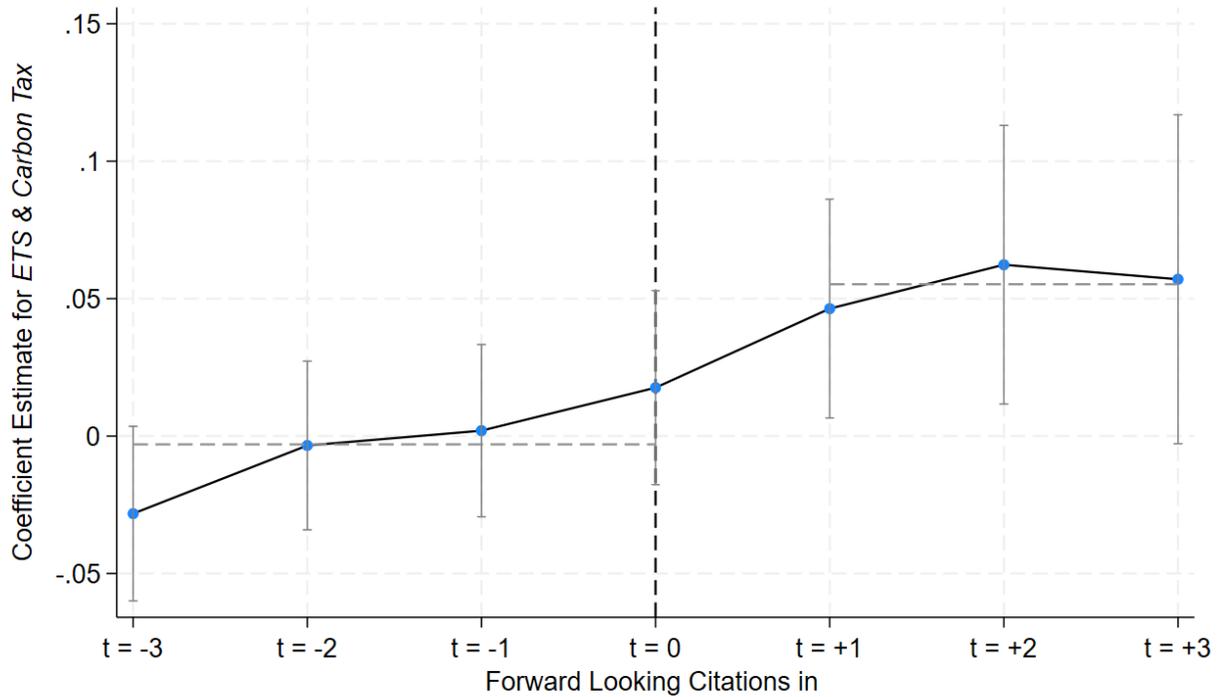
Table 8: Company Level Analysis

Panel A: Descriptive Statistics Company Level Analysis					
Variable	Mean	Std. Deviation	P25	Median	P75
<i>Forward Patents granted</i>	0.86	53.386	0.00	0.00	0.00
<i>Forward Patents granted Environment</i>	0.01	0.119	0.00	0.00	0.00
<i>Connected Country ETS</i>	8.40	6.22	4.99	6.19	9.11
<i>Connected Country ETS & Tax</i>	17.73	9.80	11.51	16.75	23.20
<i>Own ETS</i>	9.62	8.85	0.00	7.47	10.432
<i>Own Carbon Tax</i>	10.74	26.26	1.00	1.00	9.85
<i>Log GDP</i>	27.70	1.31	26.88	28.03	28.54
<i>Property Rights</i>	6.55	1.12	5.83	6.42	7.45
<i>IP Box</i>	0.44	0.50	1.00	1.00	1.00
<i>Corporate Tax</i>	0.27	0.06	0.24	0.28	0.31
<i>GDP Growth</i>	0.02	0.09	-0.02	0.03	0.08
<i>Control for Corruption</i>	0.74	0.80	0.11	0.58	1.44
<i>Rule of Law</i>	0.90	0.70	0.37	1.02	1.44
<i>Regulatory Quality</i>	0.95	0.54	0.70	0.98	1.24
<i>Stand-alone company</i>	0.76	0.43	1.00	1.00	1.00
Panel B: Connected Countries' Carbon Pricing and Innovation Output, Regression					
	(1)	(2)	(3)	(4)	
	<i>Ln(Patents Granted_{t+2})</i>	<i>Ln(Patents Granted_{t+2})</i>	<i>Ln(Patents Granted Environ._{t+2})</i>	<i>Ln(Patents Granted Environ._{t+2})</i>	
<i>Connected Countries ETS</i>	0.0039*** (0.0013)		0.0001*** (0.0010)		
<i>Connected Countries ETS & Tax</i>		0.0039*** (0.0010)		0.0001*** (0.0010)	
Controls	Yes	Yes	Yes	Yes	
Model	OLS	OLS	OLS	OLS	
Country FE	Yes	Yes	Yes	Yes	
Industry FE	Yes	Yes	Yes	Yes	
Company FE	Yes	Yes	Yes	Yes	
Year FE	Yes	Yes	Yes	Yes	
Observations	7,860,978	7,860,978	7,860,978	7,860,978	
Adjusted R2	0.711	0.711	0.182	0.182	

Notes: This table estimates equation (3) at the company level. $\ln(\text{Patents Granted}_{t+2})$ is the natural logarithm of forward patents granted in year $t+2$. $\ln(\text{Patents Granted Environ.}_{t+2})$ is the natural logarithm of patents granted in year $t+2$ classified in environment-related technology. The remaining variables and control variables are defined in Appendix A. Standard errors are reported in parentheses. ***, **, and * indicate statistical significance at the 1%, 5%, and 10% levels, respectively.

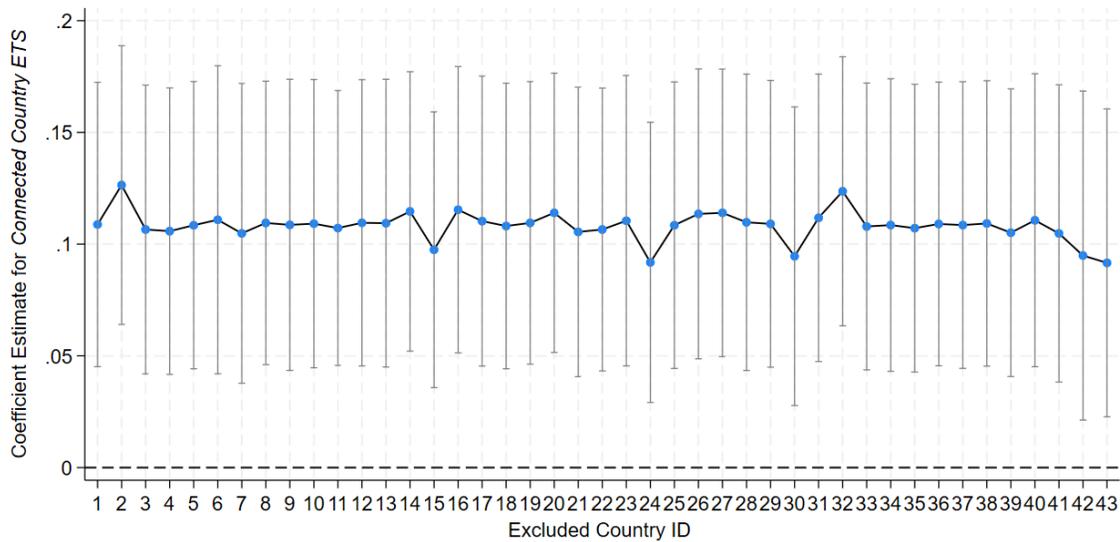
Online Appendix

Figure OA.1: Connected Countries' Carbon Pricing and Carbon Taxes and Innovation Output, Dynamic Analysis



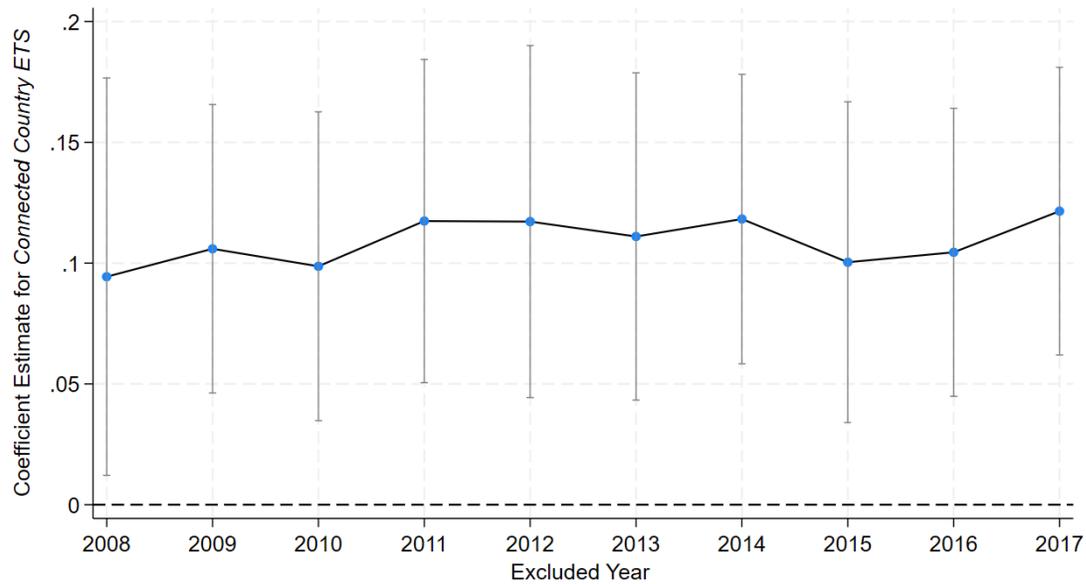
Notes: This figure plots coefficient estimates for *Connected Countries ETS & Carbon Tax* from separate year-by-year regressions on innovation output. The dependent variable is forward-looking patent citations measured in year $t + k$ where $k \in \{-3, -2, -1, 0, +1, +2, +3\}$. Year 0 is the year in which the independent variables are measured. Estimates for $k < 0$ capture lead effects (pre-trends) and estimates for $k > 0$ capture lagged responses.

Figure OA.2: Connected Countries' Carbon Pricing and Innovation Output, Robustness to Exclusion of Single Countries



Notes: This figure assesses whether the estimated effect of *Connected Countries ETS* on innovation output is driven by any single country. Each point reports the coefficient estimate obtained after re-estimating the baseline specification while excluding the country indicated on the x-axis.

Figure OA.3: Connected Countries' Carbon Pricing and Innovation Output, Robustness to Exclusion of Single Years



Notes: This figure assesses whether the estimated effect of *Connected Countries ETS* on innovation output is driven by any single year. Each point reports the coefficient estimate obtained after re-estimating the baseline specification while excluding the year indicated on the x-axis.