Climate Policy and Trade in Polluting Technologies

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DISCUSSION PAPER

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Climate Policy and Trade in Polluting Technologies *

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Abstract

This paper studies international trade in equipment used in the combustion of fossil fuels. Informed by a theoretical analysis, we identify a type of *technology leakage* hitherto unexplored in the literature: a country's export of combustion equipment tends to increase, all else equal, in the stringency of its climate policy. We test this prediction by estimating the impact of carbon pricing on international trade in combustion equipment using detailed data on bilateral trade and domestic carbon prices for the period 1995–2021. Our estimates reveal a robust positive association between the stringency of climate policies and exports of combustion equipment, providing clear evidence for the existence of technology leakage. We argue that standard policies to mitigate carbon leakage are unlikely to prevent technology leakage, raising novel policy questions.

JEL codes: F14, F18, Q37, Q58, Q54

Keywords: emissions pricing, cap-and-trade, carbon leakage, international trade in technologies

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1 Introduction

Fossil fuel combustion holds the dubious distinction as principal source of global greenhouse gas emissions. In industrial processes, combustion is typically done using specialized technologies. The production and sales of these technologies hence facilitate greenhouse gas emissions and, in so doing, fuel global warming. This paper studies how climate policy affects international trade in combustion equipment.

We first present a theoretical analysis, which predicts that domestic climate policies tend to increase a country's exports of combustion equipment. The intuition is simple. By increasing the effective cost of emissions, climate policy creates incentives to substitute away from fossil fuels toward less emissions-intensive sources of energy.[1] Facing a fallout in domestic demand, a producer of combustion technologies becomes more inclined to export its output in response. Our theoretical analysis formalizes this intuition. We consider two vertically integrated markets: a downstream market that uses combustion technologies and an upstream market that supplies them. Firms in the downstream market choose which technology to use in response to the climate policy in place; their problem is similar to that facing firms in Huebler and Schwerhoff (2023). Our model predicts that domestic climate policy unambiguously facilitates the export of emissions-intensive technologies. To our knowledge, this paper is the first to study the effect of climate policy on the trade in emissions-facilitating technologies.

Ultimately, the validity and relevance of our model and its predictions is an empirical question. Our second contribution is to take our theoretical predictions to the data.

In the empirical analysis, we find evidence suggesting that domestic climate policies indeed stimulate the export of fossil fuel combustion technologies. We focus on international trade in furnace equipment used in the combustion of fossil fuels, which we henceforth refer to simply as *burners*. We measure climate policy stringency using both emissions trading system (ETS) permit prices and carbon taxes. According to all these measures, more stringent climate policy stimulates exports of burners. We document this effect both at the extensive and at the intensive margin of trade, using an exhaustive dataset covering bilateral trade flows for the entire world for this equipment during the period 1995–2021.

Overall, we find that carbon pricing in origin countries exhibits a robust positive relationship with exports of combustion-facilitating equipment. For example, a one dollar increase in the carbon price in a country with an ETS is associated with a 0.1 percentage point increase in the probability that it exports burners, depending on the specification. Along the intensive

[1]These incentives work: Bayer and Aklin (2020) and Dechezleprêtre et al. (2023) document a clear decrease in European carbon emissions due to its emissions trading system (the EU ETS). In addition, climate policy stimulates domestic low-carbon innovation patenting (Calel and Dechezleprêtre, 2016), arguably facilitating emissions reductions in the future.

margin, our baseline specification suggests that an additional one dollar increase in the ETS price in an exporting country is associated with a 0.4 percent increase in the value of exports, depending on the specification.

The result that domestic climate policy stimulates exports of polluting technologies is related to carbon leakage or the pollution haven hypothesis. The latter states that environmental regulations will move polluting activities for tradeable products to countries where policy is less strict (Eskeland and Harrison, 2003). The similarity is clear: all else equal, stricter domestic climate policies tend to stimulate exports of polluting technologies and therefore facilitate emissions abroad. The empirical evidence on carbon leakage points in different directions. Aichele and Felbermayr (2015) find evidence that participation in the Kyoto protocol led to an increase in embodied carbon imports from non-committed countries. Prete et al. (2024) document substantial shifts in energy generation away from plants covered under California's cap-and-trade scheme. Fell and Maniloff (2018) show that the Regional Greenhouse Gas Initiative (RGGI) reduced coal-fired electricity generation in participating U.S. states, yet increased dirty electricity generation in surrounding states that do not participate in RGGI. On the other side of the Atlantic, however, Naegele and Zaklan (2019) and Dechezleprêtre et al. (2022) do not find evidence that the EU ETS caused carbon leakage. In a related strand of the literature, evidence also suggests that exports are adversely affected by domestic energy prices (Sato and Dechezleprêtre, 2015) and other types of environmental regulations (Ederington et al., 2005; Levinson and Taylor, 2008; Cherniwchan and Najjar, 2022).

Despite the similarities, our findings are conceptually distinct from studies of carbon leakage for several reasons. First, higher carbon taxes would imply a decrease in exports of emissions-intensive goods, while we posit that those same carbon taxes would imply an increase in exports of emissions-facilitating technologies. We exploit this critical difference in the empirical analysis, using trade in products unrelated to combustion or the energy sector as a control group.

Second, carbon leakage means that national climate policies shift the production of emissions-intensive goods abroad yet cause a less-than-proportionate reduction in consumption-based emissions due to changes in a country's imports and exports. In contrast, combustion technologies can be used for the production of both traded and non-traded commodities. If the technology is used to produce goods that are not traded internationally, such as electricity, then domestic climate policies should be expected to decrease national production- and consumption-based emissions at a roughly equal rate.

Third, our results raise novel policy questions. While domestic climate regulations may reduce national emissions (even at the level of consumption), the induced export of combustion technologies facilitates emissions abroad. This creates new policy challenges compared to traditional carbon leakage: while carbon border adjustment mechanisms (Fischer and Fox, 2012), carbon tariffs (Böhringer et al., 2015), output-based tax rebates (Fowlie and Reguant, 2022; Böhringer et al., 2023), or intensity-based emissions rebates (Böhringer et al., 2023) may be able attenuate emissions leakage, these measures do not prevent the export of combustion technologies in response to environmental regulation. Taking as given the climate policies of the importing country, there are only two obvious ways to avoid the kind of technology leakage identified here: a direct ban on exports of polluting technologies, or a price on potential emissions embedded in exports. Neither would seem an ideal solution to the problem, if a solution at all.

Although the scope for diffusion of clean technology across international borders is often discussed (Copeland et al., 2022), there is a dearth of studies on trade in dirty technologies that facilitate emissions abroad. Beyond the context of climate change, a related paper is Ferguson (2023), who shows that an increase in the stringency of regional animal welfare regulation stimulates the exports of regionally banned poultry-keeping equipment.

An important industry to which our results apply is the energy sector, which relies on combustion technologies to generate electricity from fossil fuels. This sector matters. According to the United States Environmental Protection Agency, electric power generation alone was responsible for 25% of U.S. greenhouse gas emissions in 2020 (EPA, 2022). To mitigate global warming it is hence critical to decarbonize the energy sector, not just in an individual country but also globally. Our results suggest that existing climate policies may fail to do so and thus contribute less to global emissions reductions than aimed and hoped for.

The paper proceeds as follows. Section 2 develops a simple model of trade in combustion technologies that formalizes our main hypothesis. Section 3 discusses our empirical methodology and identification strategy. Section 4 describes our data. Section 5 presents our main results, robustness checks and analysis of heterogeneous effects. Section 6 discusses and concludes.

2 Theory

This section develops a very simple model to describe the impact of domestic climate policy stringency on international trade in polluting technologies. Our model consists of two, vertically connected markets. The upstream market describes the domestic demand for burners, which we will use as an umbrella term for all sorts of polluting-facilitating equipment. This market is populated by heterogeneous producers (utilities) with endogenous technology choice, see also Huebler and Schwerhoff (2023). Utilities choose whether to generate electricity using either fossil fuels or renewables. Burners are needed only for the combustion of fossil fuels, which leads to emissions. More stringent climate policy increases the cost of using fossil fuels for electricity generation relative to the cost of (emissions-free) renewables. Ceteris paribus, an increase in climate policy stringency is hence associated with a decrease in the demand for burners.

The downstream market describes the international market for burners. Burner manufacturers can sell their product either domestically or abroad. When confronted with an increase in the stringency of domestic climate policy, the manufacturer faces a fallout of domestic demand. Domestic policies do not affect the foreign demand for burners, however. For any given market price of burners, an increase in domestic climate policy stringency thus increases foreign relative to domestic demand. This, then, is our main hypothesis: all else equal, domestic climate policies tend to stimulate exports of burners.

2.1 The demand for burners

In some country, there is a continuum of utilities $i \in [0, 1]$ who can generate electricity using either of two technologies. One technology, "burners," generates electricity through combustion of fossil fuels which causes pollution. The other technology, "renewables," generates electricity in some other way and is associated with (substantially) less emissions. Each utility chooses which technology to operate. We write T for the stringency of domestic climate policy. Note that the the decision problem described here implicitly assumes perfect sustainability between technologies; at least for the energy sector, there is strong evidence in support of this assumption (Papageorgiou et al., 2017; Stöckl and Zerrahn, 2023). That said, while the assumption of perfect substitution between technologies simplifies the exposition, it is not crucial for our results.

Let P denote the market price of a burner (e.g. per unit of electricity generated over the course of the burner's lifetime). Let $q_i \in \{0, 1\}$ denote the choice of technology by utility i, where $q_i = 1$ means that i chooses the burner technology. Each utility i has its own profit potential from using either technology, which we summarize by the parameter θ_i. We assume that θ_i is distributed according to a continuously differentiable distribution on a nonempty interval of positive real numbers.[2] Given its parameter θ_i, the price of burners P, and a

[2]Continuous differentiability of the distribution function is not necessary, but convenient: it implies that $D_D(P, T)$ is differentiable in P and T, which allows us to state our main hypotheses concisely in terms of derivatives.

climate policy of stringency T, the payoff U_i to utility i is given by:

$$U_i(q_i \mid P, T, \theta_i) = \begin{cases} 0 & \text{if} \quad q_i = 0, \\ \theta_i - P - T & \text{if} \quad q_i = 1, \end{cases} \tag{1}$$

where we normalize the payoff to using the renewable technology to 0.[3] Let $q_i^*(P, T)$ denote the choice of technology that maximizes $U_i(q_i \mid P, T, \theta_i)$ for utility i. Given P and T, we define

$$D_D(P, T) = \int_0^1 q_i^*(P, T)\, di. \tag{2}$$

That is, $D_D(P, T)$ is the domestic market demand for burners given a price P and an emissions policy with stringency T. Inspection of (1) immediately reveals that

$$\frac{\partial D_D(P, T)}{\partial P} < 0, \quad \frac{\partial D_D(P, T)}{\partial T} < 0. \tag{3}$$

In other words, the demand for burners is decreasing both in the price of burners and the stringency of climate policy. We will use these properties when describing the international market for burners and, more precisely, a burner manufacturer's decision to sell its product domestically or abroad.

2.2 The market for burners

Consider a manufacturer of burners. For simplicity, we will refer to a single manufacturer although one could equally interpret our analysis in terms of a single *representative* manufacturer in some given country. Given a price P, the demand for burners is $D_D(P)$ in the domestic market and $D_X(P)$ abroad. Net revenues from selling S_D burners domestically, given the market price P, are $P \cdot S_D$; revenues from selling S_X units in the foreign market are $(P - \tau) \cdot S_X$, where $\tau \geq 0$ describes additional costs associated with exporting such as shipping fees. The cost of producing a total of $S_D + S_X$ burners for the domestic and foreign market, respectively, is $C(S_D + S_X)$, Where X is an increasing convex function. Combining these elements, profits to the manufacturer are given by:

$$\Pi(S_D, S_X) = P \cdot S_D + (P - \tau) \cdot S_X - C(S_D + S_X). \tag{4}$$

[3] Exactly what goes into the stringency of policy T is left undiscussed here. In our empirical analysis, we will use a country's carbon price as a measure of policy stringency. We note already here, however, that other details of the policy may also influence the investment incentives generated by given carbon price. For example, in an experimental study Cason et al. (2022) find that the presence of a price floor in a cap-and-trade scheme stimulates investments in abatement technologies.

We maintain the natural assumption that the manufacturer is small relative to world demand for burners and takes the world price $\bar{P}$ as given. Conditional on the climate policy T and the going world price, the problem of the manufacturer is to choose the domestic and foreign supply of production of burners, S_D and S_X, that maximizes profits. Formally, the manufacturer solves

$$\begin{aligned} \max_{S_D, S_X} \quad & \bar{P} \cdot S_D + (\bar{P} - \tau) \cdot S_X - C(S_D + S_X) \\ \text{s.t.} \quad & D_D(\bar{P}, T) \geq S_D \\ & S_D, S_X \geq 0 \end{aligned} \tag{5}$$

where the constraint $D_D(\bar{P}, T) \geq S_D$ says that the manufacturer cannot sell more burners domestically than are demanded at the going market price. Given a world price of burners $\bar{P}$ we let $S_D(\bar{P}, T)$ and $S_X(\bar{P}, T)$ denote the solutions to this problem. The first order conditions to this problem are $\bar{P} \geq C'(S_D(\bar{P}, T) + S_X(\bar{P}, T))$, with a strict inequality if the constraint $D_D(\bar{P}, T) \geq S$ is binding, and $\bar{P} - \tau \leq C'(D_D(\bar{P}, T) + S_X(\bar{P}, T))$, with equality if $S_X(\bar{P}, T) > 0$. We observe that a profit-maximizing manufacturer supplies all domestic demand for burners before exporting any excess supply to the global market should that be profitable. This makes sense: shipping costs reduce the revenues from a burner exported relative to one sold domestically so the manufacturer saturates all domestic demand before it starts exporting. To avoid corner solutions and simplify notation, we henceforth assume that $S_D(\bar{P}, T) + S_X(\bar{P}, T) > D_D(\bar{P}, T)$. We obtain the following implicit solution for $S_X(\bar{P}, T)$:

$$\bar{P} - \tau = C'(D_D(\bar{P}, T) + S_X(\bar{P}, T)). \tag{6}$$

Equation (6) allows us to state our first main result.

Proposition 1 (Technology leakage: intensive margin)**.** *Let $\bar{P}$ be given and assume that $S_D(\bar{P}, T) + S_X(\bar{P}, T) \geq D_D(\bar{P}, T)$. We have*

$$\frac{\partial S_X(\bar{P}, T)}{\partial T} > 0. \tag{7}$$

Proposition 1 says that, all else equal, a country's exports of burners are increasing in the stringency of its domestic climate policy. We dub this effect *technology leakage*. Technology leakage should not be confused with the related but fundamentally distinct concept of carbon leakage, the latter an issue that is well studied in the literature.[4]

[4]See Aichele and Felbermayr (2015), Fell and Maniloff (2018), Naegele and Zaklan (2019), Dechezleprêtre et al. (2022), and Prete et al. (2024) for empirical evidence regarding the existence of carbon leakage. In a

Note that the technology leakage effect in Proposition 1 describes the intensive margin of trade. The proposition assumes (through the condition that $S_D(\bar{P}, T) + S_X(\bar{P}, T) > D_D(\bar{P}, T)$) that the country is already exporting burners; the stringency of domestic climate policy T then affects the size of these exports. The intensive margin technology leakage hypothesis is graphically illustrated in Figure 1.

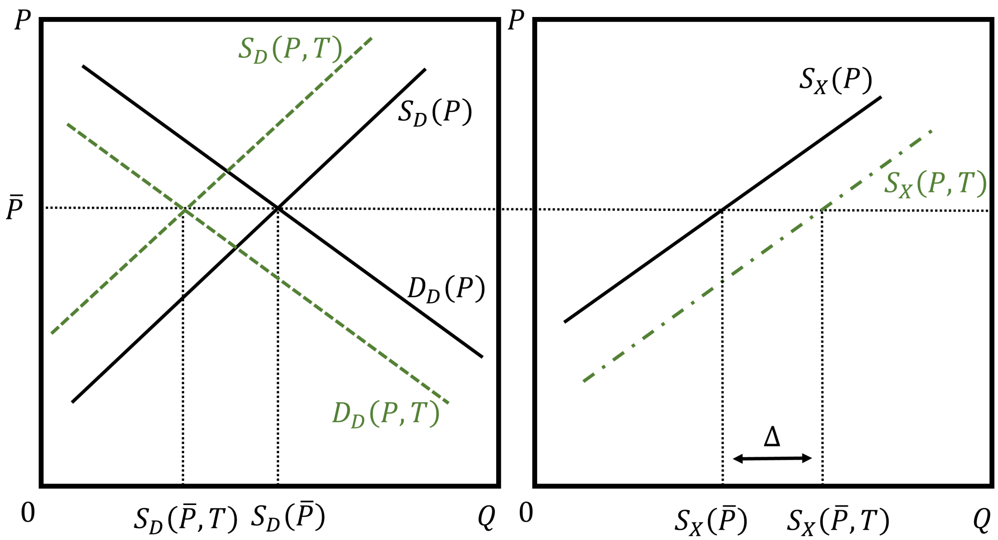

Figure 1: Equilibrium effects due to a change in domestic climate policy stringency on exports. The left panel describes the domestic market for burners, the right panel the international market. Our base case assumes the absence of domestic climate policies. The associated equilibrium is given by the intersection of the (solid black) domestic market supply and demand curves; given the world price $\bar{P}$, exports are $S_X(\bar{P})$. When the country introduces a domestic climate policy, the domestic demand for burners shifts down to the dashed green curve $D_D(P, T)$, while domestic market supply shifts up to $S_D(P, T)$. Meanwhile, supply on the international market shifts down to the green dashed-dotted curve $S_X(P, T)$. The amount of technology leakage is given by Δ.

Proposition 1 rules out technology leakage at the extensive margin as exports, by assumption, are positive even before the stringency of domestic climate policy is increased. Nevertheless, it is easy to imagine scenarios in which a country does *not* export burners when the stringency of its domestic climate policy is low but starts exporting burners once the policy becomes more stringent. We formalize this intuition in Proposition 2. To state the result, define $\bar{T} := \max\{T : S_X(\bar{P}, T) = 0\}$.[5]

related branch of literature, authors assume that carbon leakage exists and study possible ways to prevent it; see for example Fischer and Fox (2012), Böhringer et al. (2015, 2023), and Fowlie and Reguant (2022).

[5]Clearly, the value of $\bar{T}$ also depends upon parameters such as τ and $\bar{P}$; we leave this dependence out of the notation for expositional clarity.

Proposition 2 (Technology leakage: extensive margin)**.** *Let $\bar{P}$ be given. For all (T_0, T_1) such that $T_0 < \bar{T} < T_1$, we have $S_X(\bar{P}, T_0) = 0$ and $S_X(\bar{P}, T_1) > 0$.*

If a country starts out with climate policy of stringency $T_0 < \bar{T}$, it does not export burners. When the stringency of climate policy is increased to $T_1 > \bar{T}$, however, the reduction in domestic demand for burners is so substantial that the burner manufacturers start to supply burners on the global market. The country thus becomes an exporter. A direct implication of Proposition 2 that is more suitable for empirical testing is that the *probability* that a country exports burners is increasing in the stringency of its climate policy.

Finally, we observe that a country may well be an *importer* or burners. This happens when the domestic demand for burners exceeds domestic supply (i.e. if $D_D(\bar{P}, T) > S_D(\bar{P}, T)$). Note that in our simple model, a country either exports or imports burners; because, to save on trade costs, burner manufacturers sell their production to the domestic market first, exports and imports cannot coexist within the same country. Let $M_D(P, T)$ denote burner imports by the country given a world price of burners P and a domestic climate policy of stringency T; clearly, equilibrium imports are equal to $M_D(\bar{P}, T) = \max\{0, D_D(\bar{P}, T) - S_D(\bar{P}, T)\}$. It seems intuitive that a country's imports of burners – if it imports at all – are decreasing in the stringency of its domestic climate policy: a stricter climate policy tends to reduce the domestic demand for burners which, all else equal, should translate in fewer imports of burners as well. Our final result confirms this intuition.

Proposition 3. *Let $\bar{P}$ be given and assume that $D_D(\bar{P}, T) > S_D(\bar{P}, T)$. We have*

$$\frac{\partial M_D(\bar{P}, T)}{\partial T} < 0. \tag{8}$$

In conclusion, our theoretical analysis yields three testable predictions. We predict that: (i) a country's exports of burners are increasing in the stringency of its climate policy, which we call technology leakage at the intensive margin; (ii) the probability that a country exports burners is increasing in the stringency of its climate policy, which we call technology leakage at the extensive margin; and (iii) a country's imports of burners are decreasing in the stringency of its climate policy. In the remainder of the paper, we test these predictions using detailed data on bilateral trade and domestic carbon prices for the period 1995–2021.

3 Empirical methodology

The empirical analysis employs an OLS panel regression model with multiple levels of fixed effects (Correia, 2014). Using data on bilateral trade flows at the product-origin-destination-year level, we first estimate the relationship between a carbon price and the intensive margin of trade for products embodying polluting technologies:

$$\ln\left(Y_{odkt}\right) = \alpha^{o}\theta_{okt} + \alpha^{d}\theta_{dkt} + \beta X_{okt} + \gamma X_{dkt} + \delta_{odk} + \delta_{odt} + \delta_{kt} + \epsilon_{odkt}, \tag{9}$$

where Y_{odkt} is the value of trade from origin country o to destination country d of product k in year t. Two products are included in each estimation, burners and a control product. θ_{okt} and θ_{dkt} are vectors of carbon price measures in the origin and destination countries, respectively, while X_{okt} and X_{dkt} are vectors of country-product-year covariates, such as tariffs. δ_{odk} denote panel fixed effects, while δ_{odt} and δ_{kt} are origin-destination-year and product-year fixed effects.

The point estimates of most interest are α^o and α^d, which represent the percentage change in the value of trade for each 1 USD per tonne increase in the ETS or carbon tax. Our theoretical analysis predicts that a price on carbon in a country will increase its exports of products that embody dirty technologies ($\alpha^o > 0$) and will decrease its imports of such goods ($\alpha^d < 0$). Since climate policy in the origin and destination country may be correlated (for example, intra-EU trade and the EU-ETS), it is crucial to control for climate policy in the destination country. Separately estimating the impact of climate policy in the origin and destination country follows Naegele and Zaklan (2019).

The fixed effects are saturated in equation (9). Panel fixed effects control for all time-constant factors that explain trade patterns. Origin-destination-year fixed effects control for changes in trade over time for each country-pair that affect trade in the polluting good and the control good in the same way. This specification controls for country-year price indices that are typically included in gravity models of trade, as well as GDP and GDP per capita. Any changes in a country's trade policies that affect both goods symmetrically will also be captured by the origin-destination-year fixed effects. Finally, the product-year fixed effects control for any changes in trade over time that are specific to a particular good, but not specific to a particular origin or destination country. The need to control for destination country climate policy as well as the fixed effects make the panel regression the ideal methodology, as opposed to an event study methodology.[6]

A potential threat to identification is unobserved origin-product-year and destination-product-year covariates that are correlated with the carbon policy variables. One example of such variables is changes in tariffs over time differ for burners versus the control products. As it is difficult to find tariff data with sufficient coverage, we will use data on free trade agreements as well as additional destination-product-year fixed effects as a robustness check.

Our analysis of the extensive margin of trade also uses an OLS model, which permits

[6]In the robustness section we control for non-contemporaneous effects of carbon pricing.

the full set of fixed effects used in equation (9). We estimate the following linear probability model:

$$\Pr\left(Y_{odkt} > 0 \,|\ldots\right) \;=\; \alpha^{o}\theta_{okt} + \alpha^{d}\theta_{dkt} + \beta X_{okt} + \gamma X_{dkt} + \delta_{odk} + \delta_{odt} + \delta_{kt} + \epsilon_{odkt}, \qquad (10)$$

where $\Pr\left(Y_{odkt} > 0 \,|\ldots\right)$ is the probability that country o exports product k to country d in year t. All control variables and fixed effects are the same as in equation (9). In equation (9), the point estimates for α^{o} and α^{d} represent the increase in the probability of exporting or importing due to a 1 USD per tonne increase in the price of carbon in the origin or destination country.

4 Data and descriptives

4.1 Measures of carbon prices

We use data from the World Carbon Pricing Database (WCPD), compiled by Dolphin (2022), as our measure of carbon prices. These data cover the period 1990–2021, include both national and subnational policies, and include both carbon taxes and cap-and-trade schemes. We convert the price data at the national and subnational levels from the local currency units to constant 2015 USD. We use the ETS carbon tax levied on coal in electricity and heat production (IPCC category 1A1A) because it is a major source of emissions. The evolution of ETS permit prices are illustrated in Figure 2. Carbon tax levels in EU ETS and non-EU ETS countries are illustrated in Figures 3 and 4, respectively. Note that the WCPD reports carbon taxes levied within the scope of an ETS in cases where a jurisdiction has both an ETS and a carbon tax a given year.

As a rule, cap-and-trade schemes are more common than carbon taxes, regulating a total of 18% and 6% of global greenhouse gas emissions, respectively (World Bank, 2023). A number of countries nevertheless had carbon taxes prior to entering an ETS, most notably several European countries prior to the onset of the EU ETS or joining the EU. In addition, several countries have implemented carbon taxes but have not implemented an ETS. That said, the vast majority of countries with a carbon tax but not emissions trading have relatively low carbon taxes.

4.2 Bilateral trade flow data

The analysis uses bilateral trade flow data at the 6-digit Harmonized System (HS) level. The source of the international trade data is CEPII's BACI database (Gaulier and Zignago, 2010).

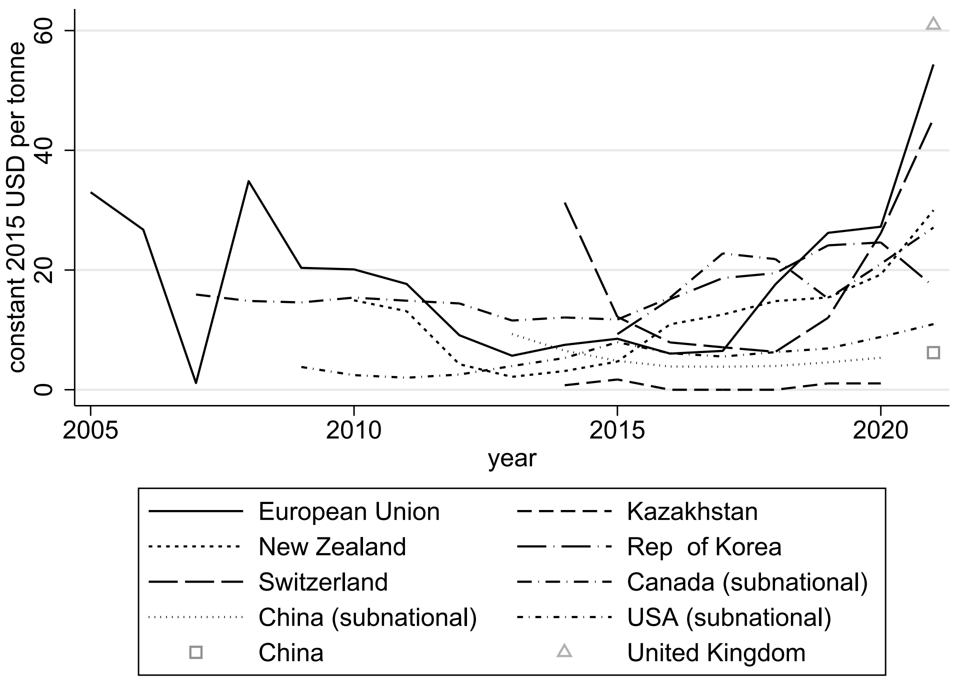

Figure 2: ETS permit prices by jurisdiction in the World Carbon Pricing Database, 1995–2021. Note: Average subnational ETS prices are reported in cases where a country had multiple subnational policies a given year.

The trade data is available for the period 1995–2021. Belgium and Luxembourg are treated as a single country in the analysis. We include all trade zeros in the data. We use data on the value of bilateral trade in constant 2015 USD.

Our main product of interest is "Furnace burners for liquid fuel, for pulverised solid fuel or for gas; mechanical grates, mechanical ash dischargers and similar appliances." These products are captured in the trade data by HS heading 8416.[7] We refer to this group of products as "burners" for the rest of the analysis.

We use two different product groups as the control group in our analysis. The main control product is other products included in HS chapter 84 ("Nuclear reactors, boilers, machinery and mechanical appliances; parts thereof") unrelated to combustion or the energy sector, which includes headings 8407–8409, 8412–8415, plus 8418 and higher. We argue that these other products included in Chapter 84 are the most similar in nature to our treatment product. The alternative control group is trade in the entire HS chapter 85 (Electrical machinery and equipment and parts). Products in Chapter 85 is clearly not as similar as the Chapter 84 alternative, but have the beneficial characteristic of not being deemed sensitive

[7]See `https://www.wcotradetools.org/en/harmonized-system` for a full description of the Harmonized System Nomenclature.

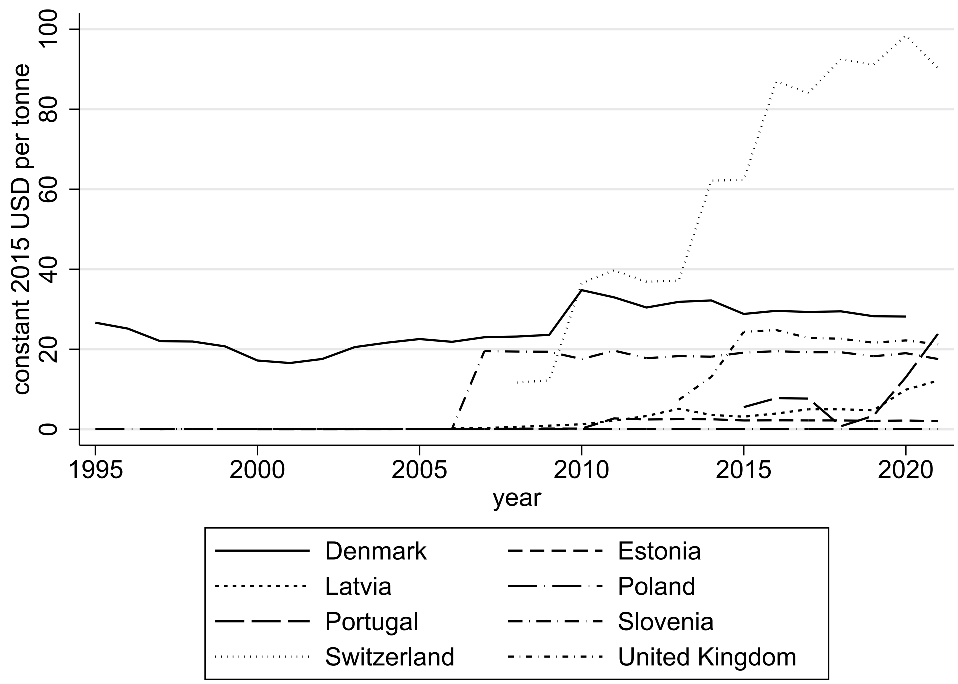

Figure 3: Carbon taxes in EU ETS countries according to the World Carbon Pricing Database, 1995–2021. Note: Data based on carbon tax for coal in electricity and heat production (IPCC category 1A1A) within the scope of the EU ETS.

to carbon leakage (*cf.* Aichele and Felbermayr, 2015).

An illustration of the top nine exporting and importing countries of burners is given in Figures 5 and 6, respectively. Several EU member states feature prominently among the largest exporters of burners, and a sharp increase in exports from EU members states can be seen during the 2000's. China is historically the largest importer of burners.

4.3 Other data

In some specifications, we include data on whether or not the country pair have a free trade agreement (FTA), as well as the GDP per capita in the origin and destination country. These data are derived from CEPII's Gravity database (Conte et al., 2022).

In some specifications we include an indicator for if a destination belongs to the United Nations Committee for Development Policy's list of Least Developed Countries (LDCs).[8] We include all 46 current LDCs, plus the 6 countries that have graduated from the LDC list, for a total of 52 countries.

[8] The complete list of least developed countries and graduated countries is available at https://www.un.org/development/desa/dpad/least-developed-country-category/ldcs-at-a-glance.html

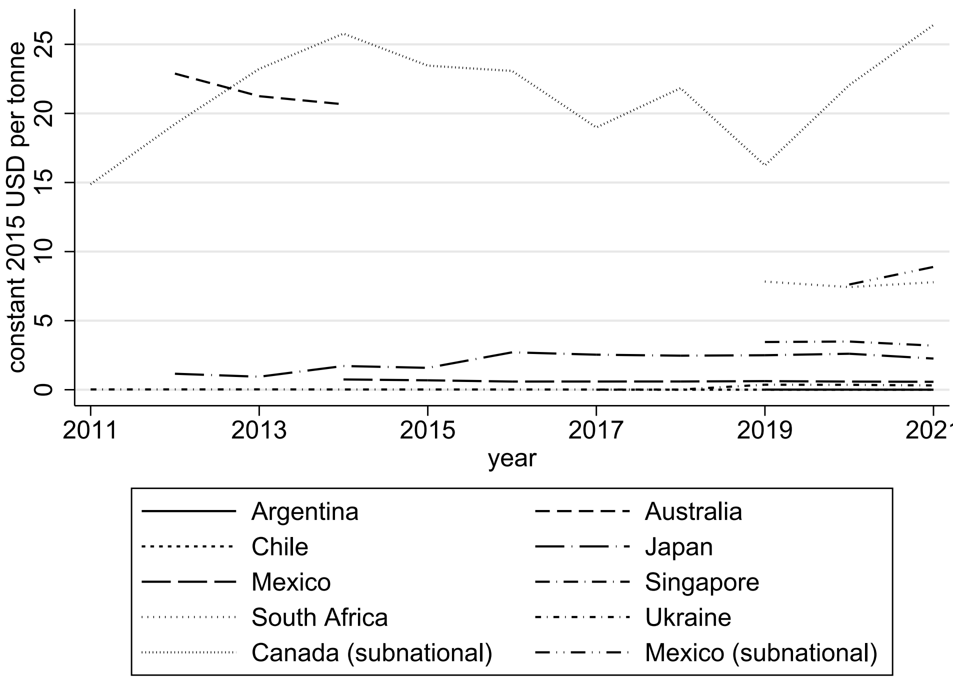

Figure 4: Carbon taxes in non-EU countries according to the World Carbon Pricing Database, other countries, 2011–2021. Note: Data based on carbon tax for coal in electricity and heat production (IPCC category 1A1A) within the scope of an ETS if applicable. Average subnational carbon prices are reported in cases where a country had multiple subnational policies a given year. No non-EU country had a carbon tax prior to 2011.

We convert from local currency units to USD using exchange rate data from the World Bank World Development Indicators. We deflate carbon prices and bilateral trade values to constant 2015 USD using the OECD's Domestic Producer Prices Index for Manufacturing for the United States. Descriptive statistics for the data, restricted to observations for trade in burners, are given in Table 1.

5 Results

5.1 Main results

The main results are presented in Table 2. Estimation results for the intensive margin of trade are reported in columns (1) and (2), while results for extensive margin of trade are reported in columns (3) and (4). Panel, origin-destination-year and product-year fixed effects are included in all specifications. Standard errors are clustered at the origin country and destination country level.

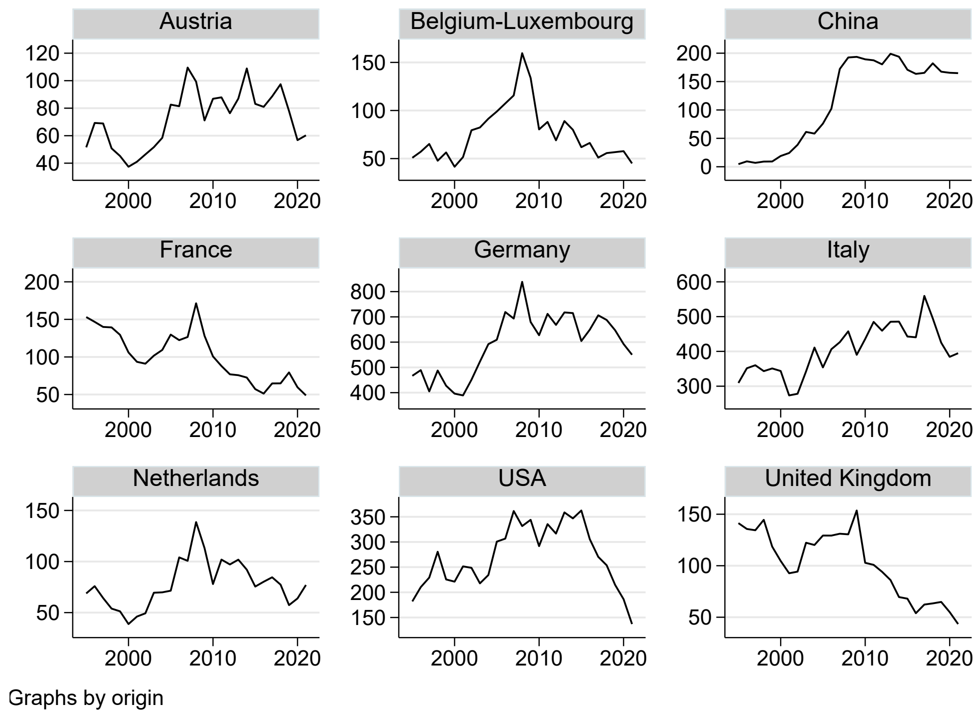

Figure 5: Exports of "Furnace burners for liquid fuel, for pulverised solid fuel or for gas; mechanical grates, mechanical ash dischargers and similar appliances" (HS heading 8416), by top nine origins, 1995–2021

We first discuss the results for the intensive margin of trade. The independent variables in column (1) are the national ETS prices in the origin and destination country. The point estimate for $ETSprice_o$ in column (1) suggests that a 1 USD/tonne increase in the ETS price in the origin country is associated with a 0.39 percent increase in exports of burners relative to the control product (other non-energy Chapter 84 goods). In contrast, the point estimate for $ETSprice_d$ in column (1) suggest that there is no statistically significant effect of an ETS in the destination country on its imports of burners compared to the control product.

In column (2) of Table 2 we include both ETS prices and carbon taxes, also in USD/tonne, in the origin and destination countries. The point estimate for $ETSprice_o$ suggests that a 1 USD/tonne increase in the ETS price in the origin country is associated with a 0.40 percent increase in exports of burners relative to the control product. In column (2) the point estimate for tax_o does not indicate a statistically significant relationship between ETS permit prices in the destination country and imports of burners.

Turning to the results for the extensive margin of trade, the point estimates from the linear probability model reported in column (3) of Table 2 suggest that a 1 USD higher ETS permit price in the origin country raises the probability of exports by 0.10 percent, relative to the control product. Adding carbon taxes in column (4) changes the results with respect

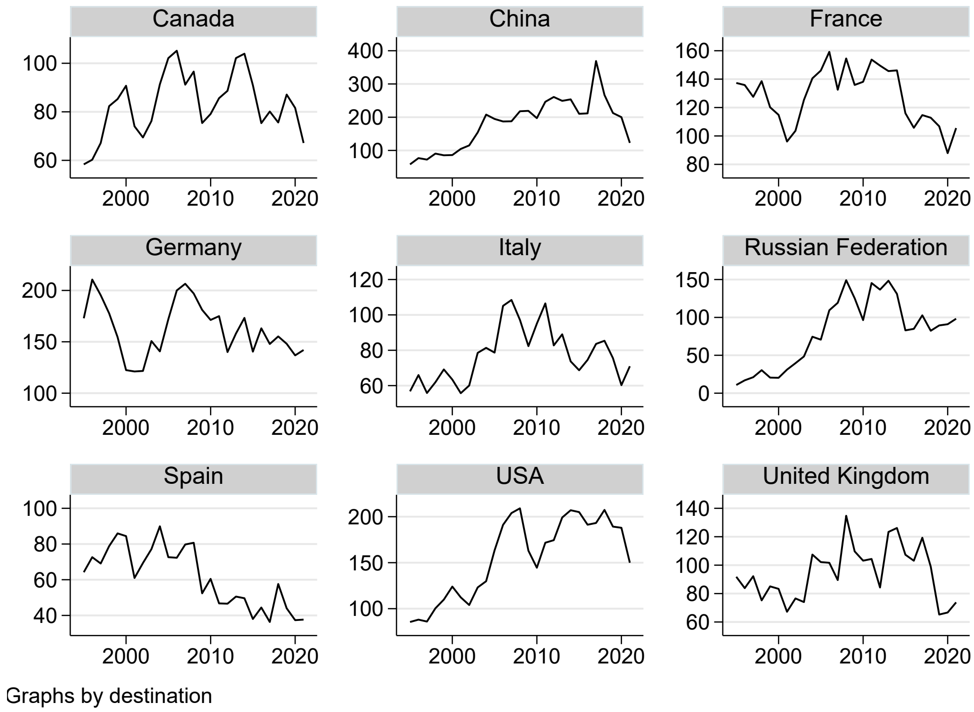

Figure 6: Imports of "Furnace burners for liquid fuel, for pulverised solid fuel or for gas; mechanical grates, mechanical ash dischargers and similar appliances" (HS heading 8416), by top nine destinations, 1995–2021

to ETS prices to 0.095 percent.

The point estimates for tax_o in columns (2) and (4) suggest that national carbon taxes increase the probability of trade, but not necessarily the value of trade. The point estimate for tax_o suggests that a 1 USD higher carbon tax in the origin country leads to a 0.08 percent increase in the probability of exporting.

5.2 Alternative control products

As a robustness check we use an alternative control group, trade in products included in HS Chapter 85 (Electrical machinery and equipment and parts). The result for the intensive and extensive margins of trade are reported in Table 3. The results suggest that carbon pricing policies in the origin country are associated with a higher value of export and a higher probability of export relative to trade in the alternative control product. The point estimates for $ETSprice_o$ in columns (1) and (2) of Table 3 suggests that a 1 USD/tonne increase in the ETS price in the origin country is associated with a 0.43 percent and 0.45 percent increase in exports of burners relative to the control product. The results using this alternative control group support the main results in Table 2 suggesting that carbon pricing in the origin country

Table 1: Summary statistics

VARIABLES	(1) N	(2) mean	(3) sd	(4) min	(5) max
Bilateral trade, real 2015 USD, millions	1,409,724	0.046	0.91	0	295
ETS price, real 2015 USD ($ETSprice_o$, $ETSprice_d$)	1,409,724	1.35	6.01	0	60.9
CO2 tax, real 2015 USD (tax_o, tax_d)	1,409,724	0.36	3.85	0	98.5
Bilateral trade indicator	1,409,724	0.061	0.24	0	1
CO2 pricing indicator ($CO2pricedum_o$, $CO2pricedum_d$)	1,409,724	0.093	0.29	0	1
Free trade agreement indicator (FTA_{od})	1,346,514	0.087	0.28	0	1
Least Developed Country indicator (LDC_d)	1,409,724	0.23	0.42	0	1
GDP per capita, real 2015 USD, thousands ($GDPpc_d$)	1,150,033	12.4	17.6	0.097	110

Notes: Summary statistics for the main variables for our analysis, restricted to trade flow observations for "Furnace burners for liquid fuel, for pulverised solid fuel or for gas; mechanical grates, mechanical ash dischargers and similar appliances".

Table 2: Regression of bilateral trade in burners on carbon pricing.

VARIABLES	(1) Intensive	(2) Intensive	(3) Extensive	(4) Extensive
$ETSprice_o$	0.0039**	0.0040**	0.0010**	0.00095**
	(0.0017)	(0.0018)	(0.00044)	(0.00044)
$ETSprice_d$	-0.0017	-0.0013	-0.000070	-0.00011
	(0.0023)	(0.0023)	(0.00041)	(0.00041)
tax_o		-0.0012		0.00080***
		(0.00099)		(0.00026)
tax_d		-0.0045**		0.00046**
		(0.0021)		(0.00022)
Constant	0.089***	0.091***	0.20***	0.20***
	(0.0064)	(0.0063)	(0.00036)	(0.00037)
Observations	168,288	168,288	2,819,448	2,819,448
R-squared	0.966	0.966	0.859	0.859

Notes: OLS regression of outcome on different measures of carbon pricing stringency. The dependent variable in columns (1) and (2) is the value of exports of burners. The dependent variable in columns (3) and (4) is the probability that a country pair trades in burners. All regressions include panel, origin-destination-year, and product-year fixed effects. Robust standard errors are clustered at the origin and destination levels. *** p<0.01, ** p<0.05, * p<0.1.

have a positive significant impact on the intensive and extensive margins of trade in burners.

Table 3: Robustness to alternative control product

VARIABLES	(1) Intensive	(2) Intensive	(3) Extensive	(4) Extensive
$ETSprice_o$	0.0043**	0.0045**	0.00083*	0.00077*
	(0.0021)	(0.0021)	(0.00046)	(0.00046)
$ETSprice_d$	-0.0031	-0.0029	-0.00011	-0.00018
	(0.0026)	(0.0026)	(0.00042)	(0.00042)
tax_o		-0.0029**		0.00069**
		(0.0013)		(0.00030)
tax_d		-0.0031		0.00085***
		(0.0023)		(0.00029)
Constant	-0.10***	-0.10***	0.20***	0.20***
	(0.0069)	(0.0069)	(0.00037)	(0.00038)
Observations	168,196	168,196	2,819,448	2,819,448
R-squared	0.962	0.962	0.858	0.858

Notes: OLS regression of outcome on different measures of carbon pricing stringency. The control product in this table is HS chapter 85 (Electrical machinery and equipment and parts). The dependent variable in columns (1) and (2) is the value of exports of burners. The dependent variable in columns (3) and (4) is the probability that a country pair trades in burners. All regressions include panel, origin-destination-year, and product-year fixed effects. Robust standard errors are clustered at the origin and destination levels. *** p<0.01, ** p<0.05, * p<0.1.

5.3 Lagged effects

We thus far studied the instantaneous association between carbon prices and international trade in burners. It is conceivable that carbon prices also have lagged effects, for example because it takes time to adjust trade flows. Table 4 reports estimates when we control for lagged carbon prices. At the intensive margin, the instantaneous effect of origin country ETS prices on trade remains statistically significant with estimates similar in magnitude to those reported in our baseline regressions. At the extensive margin, the results in Table 4 suggest that carbon prices have a lagged effect on trade in burners. One possible explanation is that it takes time to establish new trade relationships. When burner manufacturers face more stringent domestic climate policy and, in response, seek to increase their exports, the easiest solution is to export more to countries that are already importing; this might explain why only instantaneous trade is affected by carbon prices in our intensive margin estimates. In contrast, finding a new trade partner and setting up the details of a new export-import relationship likely requires substantial amounts of time; this might explain why carbon prices only have a lagged effect on the extensive margin according to our estimates.

5.4 Trade policies

As another robustness check we attempt to control for changes in trade policies that could affect burners and the control product differently. We first check whether the intensive and extensive margins of trade are more sensitive to carbon pricing policies for country pairs with a free trade agreement (FTA). We include this as an interaction of the carbon pricing policy in the origin country with the FTA indicator variable. In this specification, the uninteracted point estimates for $ETSprice_o$ represent the impact on country pairs that do not have a FTA. The uninteracted effects of an FTA on trade are subsumed by the origin-destination-year fixed effects. The results in column (1) of Table 5 suggest that the intensive margin of trade is more sensitive to origin country ETS prices for country pairs that do not have an FTA. In contrast, the results in column (4) of Table 5 suggest that the extensive margin of trade is more sensitive to origin country ETS prices for country pairs that have an FTA.

In columns (2) and (5) of Table 5 we employ additional destination-product-year fixed effects, which control for any unobserved trade policy changes in the importing country, such as import tariffs and quotas. This additional set of fixed effects controls for the vast majority of trade policies, as most trade policies are administered by importers. Our results are robust to including this additional set of fixed effects. Finally, in columns (3) and (6) we include the FTA interaction and the destination-product-year fixed effects at the same time, yielding similar results to compared to columns (1) and (4) respectively.

5.5 Subnational carbon pricing policies

Our main analysis focused on national carbon pricing policies. In Table 6 we include controls for subnational carbon policies in our estimates for the intensive and extensive margins of trade. In columns (1) and (4) we include the subnational ETS prices, then in columns (2) and (5) we include subnational carbon taxes. Our main results with respect to national carbon pricing are robust to controlling for subnational carbon pricing. The results with respect to subnational carbon pricing are mixed.

Finally, in columns (3) and (6) of Table 6 we use composite indicators for carbon pricing through either an ETS or carbon tax in the origin or destination countries, at either the

Table 4: Lagged effects of climate policy on trade in burners

VARIABLES	(1) Intensive	(2) Intensive	(3) Extensive	(4) Extensive
$ETSprice_{o,t-2}$	-0.0012	-0.0012	0.00081***	0.00077***
	(0.0016)	(0.0016)	(0.00028)	(0.00028)
$ETSprice_{o,t-1}$	0.0021	0.0022	0.00056**	0.00054**
	(0.0016)	(0.0016)	(0.00022)	(0.00022)
$ETSprice_{o,t}$	0.0030**	0.0032***	0.00034	0.00031
	(0.0012)	(0.0012)	(0.00024)	(0.00024)
$ETSprice_{d,t-2}$	0.0011	0.0015	0.00049*	0.00048*
	(0.0025)	(0.0024)	(0.00027)	(0.00027)
$ETSprice_{d,t-1}$	0.00032	0.00042	0.00027	0.00025
	(0.0017)	(0.0017)	(0.00021)	(0.00021)
$ETSprice_{d,t}$	-0.0019	-0.0018	-0.00038	-0.00042*
	(0.0018)	(0.0018)	(0.00025)	(0.00024)
$tax_{o,t-2}$		-0.0057**		-0.00083
		(0.0024)		(0.00064)
$tax_{o,t-1}$		-0.0028		0.00079***
		(0.0046)		(0.00017)
$tax_{o,t}$		0.0062		0.00061
		(0.0041)		(0.00050)
$tax_{d,t-2}$		0.0038		0.0016**
		(0.0044)		(0.00065)
$tax_{d,t-1}$		0.0029		-0.00074
		(0.0050)		(0.00052)
$tax_{d,t}$		-0.010		-0.000071
		(0.0072)		(0.00074)
Constant	0.061***	0.063***	0.21***	0.21***
	(0.0092)	(0.0090)	(0.00047)	(0.00047)
Observations	160,570	160,570	2,610,600	2,610,600
R-squared	0.967	0.967	0.863	0.863

Notes: OLS regression of outcome on different measures of (instantaneous and lagged) carbon pricing stringency. The dependent variable in columns (1) and (2) is the value of exports of burners in year t. The dependent variable in columns (3) and (4) is the probability that a country pair trades in burners, also in year t. All regressions include panel, origin-destination-year, and product-year fixed effects. Two lags are included. Robust standard errors are clustered at the origin and destination levels. *** p<0.01, ** p<0.05, * p<0.1.

Table 5: Robustness to trade policy controls

VARIABLES	(1) Intensive	(2) Intensive	(3) Intensive	(4) Extensive	(5) Extensive	(6) Extensive
$ETSprice_o$	0.0058***	0.0047***	0.0064***	0.00053	0.00095**	0.00051
	(0.0021)	(0.0017)	(0.0020)	(0.00049)	(0.00044)	(0.00049)
$ETSprice_o \times FTA_{od}$	-0.0033*		-0.0032	0.0015***		0.0016***
	(0.0019)		(0.0022)	(0.00045)		(0.00049)
$ETSprice_d$	-0.00026			-0.00017		
	(0.0024)			(0.00040)		
tax_o	0.0026**	-0.0014	0.0025*	0.00085*	0.00080***	0.00085**
	(0.0012)	(0.0012)	(0.0015)	(0.00044)	(0.00026)	(0.00042)
$tax_o \times FTA_{od}$	-0.0065***		-0.0067***	0.00042		0.00044
	(0.0018)		(0.0019)	(0.00098)		(0.00087)
tax_d	-0.0044**			0.00048**		
	(0.0022)			(0.00022)		
product-destination-year FE	NO	YES	YES	NO	- YES	YES
Constant	0.089***	0.099***	0.099***	0.21***	0.20***	0.21***
	(0.0065)	(0.0049)	(0.0048)	(0.00037)	(0.00031)	(0.00031)
Observations	168,266	167,224	167,220	2,693,016	2,819,448	2,693,016
R-squared	0.966	0.969	0.969	0.861	0.864	0.866

Notes: OLS regression of outcome on different measures of carbon pricing stringency. The dependent variable in columns (1)–(3) is the value of exports of burners. The dependent variable in columns (4)–(6) is the probability that a country pair trades in burners. All regressions include panel, origin-destination-year, and product-year fixed effects. Robust standard errors are clustered at the origin and destination levels. *** p<0.01, ** p<0.05, * p<0.1.

national or sub-national level. We thus construct an indicator variable equal to one each year that a country had either a national or subnational price on carbon. The point estimate for $CO2pricedum_o$ in column (3) suggests that carbon pricing in the origin country is positively associated with exports of burners, with 14 percent higher exports when carbon pricing is in place. The results for $CO2pricedum_d$ suggest that carbon pricing in the destination country is not associated with a change in imports of burners. The results in column (6) suggest that the presence of carbon pricing in the origin country raises the probability of exports by 5.6 percent.

Table 6: Effects of subnational carbon pricing policies

VARIABLES	(1) Intensive	(2) Intensive	(3) Intensive	(4) Extensive	(5) Extensive	(6) Extensive
$ETSprice_o$	0.0041**	0.0040**		0.00098**	0.00096**	
	(0.0017)	(0.0018)		(0.00044)	(0.00044)	
$ETSprice_d$	-0.0011	-0.0012		-0.00010	-0.00010	
	(0.0024)	(0.0023)		(0.00041)	(0.00041)	
tax_o	-0.0012	-0.0012		0.00081***	0.00080***	
	(0.0010)	(0.0010)		(0.00026)	(0.00026)	
tax_d	-0.0043**	-0.0044**		0.00046**	0.00046**	
	(0.0022)	(0.0022)		(0.00022)	(0.00022)	
$SubNatETSprice_o$	0.0026			0.0089**		
	(0.0095)			(0.0043)		
$SubNatETSprice_d$	0.022***			0.0012		
	(0.0043)			(0.0013)		
$SubNatTax_o$		-0.0020			0.0034***	
		(0.0026)			(0.00095)	
$SubNatTax_d$		0.018***			0.0022*	
		(0.0017)			(0.0013)	
$CO2pricedum_o$			0.14**			0.056***
			(0.057)			(0.017)
$CO2pricedum_d$			0.069			0.019
			(0.069)			(0.015)
Constant	0.088***	0.090***	0.059***	0.20***	0.20***	0.20***
	(0.0059)	(0.0064)	(0.013)	(0.00040)	(0.00037)	(0.00092)
Observations	168,288	168,288	168,288	2,819,448	2,819,448	2,819,448
R-squared	0.966	0.966	0.966	0.859	0.859	0.859

Notes: OLS regression of outcome on different measures of carbon pricing stringency. The dependent variable in columns (1)–(3) is the value of exports of burners. The dependent variable in columns (4)–(6) is the probability that a country pair trades in burners. All regressions include panel, origin-destination-year, and product-year fixed effects. Robust standard errors are clustered at the origin and destination levels. *** p<0.01, ** p<0.05, * p<0.1.

5.6 Heterogeneous effects by destination country economic development

Table 7 reports our results when we control for the economic development of importing countries, using either the destination LDC status or destination GDP per capita. These results support our main conclusions. In columns (1) and (3), the uninteracted point estimates for $ETSprice_o$ represent the impact of ETS prices on exports to countries that are not LDCs.

Since GDP per capita is given in thousands and is logged, the uninteracted point estimates for $ETSprice_o$ in columns (2) and (4) represent the impact on exports to destinations with a real GDP per capita of 1000 USD.

Overall, the results in Table 7 suggest that exports of burners to less developed countries respond to ETS prices more along the intensive margin of trade, while developed countries respond more along the extensive margin of trade. The interaction between carbon taxes and the destinations' level of development are less conclusive. The coefficient for $ETSprice_o$ in column (1) suggests that a 1 USD/tonne increase in the ETS price in the origin country is associated with a 0.36 percent increase in exports of burners to non-LDCs relative to the control product. If the destination has least-developed country status, the associated increase in exports of burners more than doubles to 0.85 percent. The estimates in column (2) suggest that a 1 USD/tonne increase in the ETS price in the origin country is associated with a 0.57 percent increase in exports of burners relative to the control product. The interaction term $ETSprice_o \times \ln(GDPpc)$ in column (2) suggests that this intensive margin effect does not vary with destination GDP per capita.

Moving to extensive margin effects in Table 7, in column (3) an increase in the ETS price in the origin country is found to be associated with increased exports of burners to non-LDCs, but not for least-developed countries whose likelihood of exporting burners in fact decreases. An increase in carbon taxes is associated with an increase in exports of burners for all countries, developed or not. Finally, the point estimates with respect to ETS prices in column (4) are consistent with those in column (3). The extensive margin does not respond to ETS prices when exporting to countries with a GDP per capita of 1000 USD, but becomes more responsive as GDP per capita increases. In column (4), we do not detect an interactive effect of destination country GDP per capita and domestic carbon taxes on the probability of a country exporting burners.

5.7 Discussion

Overall, we find that carbon prices in origin countries display a robust positive relationship with exports of combustion-facilitating equipment. In general, our findings are most robust with respect to the impact of ETS prices and also with respect to the extensive margin. Our results are robust to using alternative control products, controlling for FTA status and differential importer policies for burners versus the control product, and controlling for subnational carbon pricing policies. Results with respect to the impact of carbon taxes on the intensive margin are less robust. This makes sense given that carbon taxes in our data are generally much lower compared to ETS schemes and cover a substantially smaller share

Table 7: Heterogeneous effects by destination country economic development

VARIABLES	(1) Intensive	(2) Intensive	(3) Extensive	(4) Extensive
$ETSprice_o$	0.0036**	0.0057**	0.0015***	0.00016
	(0.0018)	(0.0025)	(0.00044)	(0.00065)
$ETSprice_o \times LDC_d$	0.0049*		-0.0021***	
	(0.0027)		(0.00067)	
$ETSprice_o \times \ln(GDPpc_d)$		-0.00087		0.00087***
		(0.00081)		(0.00019)
$ETSprice_d$	-0.0010	-0.00060	-0.00017	-0.000029
	(0.0023)	(0.0025)	(0.00040)	(0.00040)
tax_o	-0.0012	-0.0036*	0.00093***	0.00047
	(0.0010)	(0.0020)	(0.00025)	(0.0010)
$tax_o \times LDC_d$	-0.00050		-0.00058	
	(0.00078)		(0.00087)	
$tax_o \times \ln(GDPpc_d)$		0.0010*		0.00038
		(0.00059)		(0.00050)
tax_d	-0.0045**	-0.0044**	0.00046**	0.00059***
	(0.0021)	(0.0021)	(0.00022)	(0.00020)
Constant	0.090***	0.12***	0.20***	0.24***
	(0.0063)	(0.0067)	(0.00036)	(0.00042)
Observations	168,288	163,832	2,819,448	2,300,058
R-squared	0.966	0.966	0.859	0.862

Notes: OLS regression of outcome on different measures of carbon pricing stringency. The dependent variable in columns (1) and (2) is the value of exports of burners. The dependent variable in columns (3) and (4) is the probability that a country pair trades in burners. All regressions include panel, origin-destination-year, and product-year fixed effects. Robust standard errors are clustered at the origin and destination levels. *** p<0.01, ** p<0.05, * p<0.1.

of emissions.

Note that the effects reported here are econometric estimates. In contrast, most of the evidence on the impacts of carbon policies where general equilibrium effects arise through international trade comes from applied general equilibrium (GE) models (Carbone et al., 2020). It would be interesting to see how robust our estimates are to a GE analysis.[9]

As we do not exploit a natural experiment or IV approach, we cannot make causal

[9] In an interesting case study, Carbone et al. (2020) compare econometric and GE estimates of the effect of the British Columbia carbon tax on employment, and find that both estimates are very similar in both sign and magnitude.

claims from our analysis. The finding that exports of combustion-facilitating equipment systematically increase when a country imposes more stringent carbon pricing, compared to exports of similar products, indicates at the very least an interesting correlation that deserves further study. Our theoretical model offers one possible interpretation of this pattern of trade, namely that firms shift sales of equipment used in the combustion of fossil fuels to export markets in response to decreased domestic demand.

6 Conclusion

In this study, we evaluate the impact of carbon pricing on international trade in equipment used in the combustion of fossil fuels. Using detailed data on bilateral trade, we find that carbon pricing policies are associated with greater exports of this equipment. Our work is conceptually distinct from the carbon leakage literature, and suggest that the diffusion of technology can occur in dirty production methods. Our results provide new evidence for this unexplored form of leakage due to more stringent climate policies.

Overall, we find that carbon prices in origin countries exhibit a robust positive relationship with exports of combustion-facilitating equipment. Our results are robust to a variety of specifications. Our findings agree with the predictions of a simple model of international trade in polluting technologies.

The facilitation of emissions abroad is a difficult policy issue for which there are no simple solutions. A ban on polluting technologies would be difficult to enforce and easy to circumvent by importing equipment from less regulated countries. We hope that our work has brought this issue to the forefront and encourages further work in this area.

A Proofs

PROOF OF PROPOSITION 1

Proof. Observe that (6) should hold for all T. As $\partial(\bar{P}-\tau)/\partial T = 0$, this implies that $\partial C'(D_D(\bar{P},T) + S_X(\bar{P},T))/\partial T = 0$. Because C is convex, we hence have $\partial D_D(\bar{P},T)/\partial T + \partial S_X(\bar{P},T)/\partial T = 0$. From (3) we know that $\partial D_D(\bar{P},T)/\partial T < 0$, so it must be that $\partial S_X(\bar{P},T)/\partial T > 0$, as claimed. □

PROOF OF PROPOSITION 2

Proof. Note that, if $S_X(\bar{P},T) = 0$, then $\bar{P} - \tau \leq C'(D_D(\bar{P},T))$ (as otherwise the burner manufacturer, after supplying $D_D(\bar{P},T)$ burners to the domestic market, would be able to increase its profits by exporting burners; as the country does not export burners, it must be that $\bar{P} - \tau \leq C'(D_D(\bar{P}, T)))$. Because C is convex while $D_D(\bar{P}, T)$ is decreasing in T, note that

$$\frac{\partial C'(D_D(\bar{P}, T))}{\partial T} = \frac{\partial C'(D_D(\bar{P}, T))}{\partial D_D(\bar{P}, T)} \frac{\partial D_D(\bar{P}, T)}{\partial T} < 0.$$

Hence, if we keep on increasing the stringency of climate policy T, eventually we reach some (unique) stringency $\bar{T}$ such that:

$$\bar{P} - \tau = C'(D_D(\bar{P}, \bar{T})).$$

For all $T > \bar{T}$, we have $\bar{P} - \tau > C'(D_D(\bar{P}, T))$ (again by strict convexity of C combined with $\partial D_D(\bar{P}, T)/\partial T < 0$). But if $\bar{P} - \tau > C'(D_D(\bar{P}, T))$, a profit-maximizing manufacturer will export $S_X(\bar{P}, T) > 0$ burners to the global market, where $S_X(\bar{P}, T)$ is found by solving $\bar{P} - \tau = C'(D_D(\bar{P}, T) + S_X(\bar{P}, T))$. Hence, for all $T < \bar{T}$ the country does not export burners and $S_X(\bar{P}, T) = 0$; for all $T > \bar{T}$, the country does exports burners and $S_X(\bar{P}, T) > 0$. □

PROOF OF PROPOSITION 3

Proof. Because $D_D(\bar{P}, T) > S_D(\bar{P}, T)$ by assumption, we have $M_D(\bar{P}, T) = D_D(\bar{P}, T) - S_D(\bar{P}, T) > 0$. Furthermore, it follows from the manufacturer's problem that $\partial S_D(\bar{P}, T)/\partial T = 0$. To see this, note that $S_D(\bar{P}, T)$ is implicitly defined by the equality $\bar{P} = C'(S_D(\bar{P}, T))$ when the country is an importer. Because $\partial \bar{P}/\partial T = 0$, so it must be that $C'(S_D(\bar{P}, T))$ is constant in T, or:

$$\frac{\partial C'(S_D(\bar{P}, T))}{\partial T} = \frac{\partial C'(S_D(\bar{P}, T))}{\partial S_D(\bar{P}, T)} \frac{\partial S_D(\bar{P}, T)}{\partial T} = 0.$$

Now recall that C is a strictly convex function, so $\frac{\partial C'(S_D(\bar{P}, T))}{\partial S_D(\bar{P}, T)} > 0$ and therefore $\frac{\partial S_D(\bar{P}, T)}{\partial T} = 0$. Finally, since $M_D(\bar{P}, T) = D_D(\bar{P}, T) - S_D(\bar{P}, T)$, we know that

$$\frac{\partial M_D(\bar{P}, T)}{\partial T} = \frac{\partial D_D(\bar{P}, T)}{\partial T} - \frac{\partial S_D(\bar{P}, T)}{\partial T} = \frac{\partial D_D(\bar{P}, T)}{\partial T} < 0,$$

where the inequality follows from (3). □

B The large country case

The analysis assumed that burner manufacturers take the world price of burners as given. While customarily maintained in the context of global trade, one could imagine this assumption being violated if the exporting country is a large economy such as the U.S. or China. An explicit analysis of the large-country case, with downward-sloping international demand for burners, is beyond the scope of this paper. A graphical illustration is provided in Figure 7. The key takeaway is that in the large-country case, too, domestic climate policies stimulate the exports of burners. The same note on extensive margin effects discussed for Figure 1 applies.

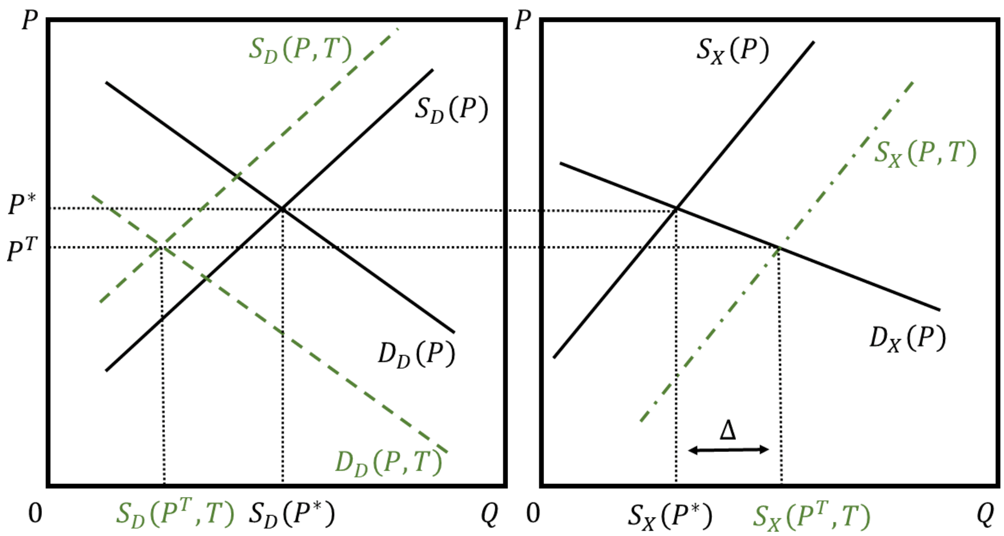

Figure 7: Graphical illustration of the equilibrium effects of domestic climate policy on burner exports when the world demand for burners is downward-sloping. Upon the introduction of a domestic climate policy, exports increase by Δ.

References

Aichele, R. and Felbermayr, G. (2015). Kyoto and carbon leakage: An empirical analysis of the carbon content of bilateral trade. *Review of Economics and Statistics*, 97(1):104–115.

Bayer, P. and Aklin, M. (2020). The european union emissions trading system reduced co2 emissions despite low prices. *Proceedings of the National Academy of Sciences*, 117(16):8804–8812.

Böhringer, C., Fischer, C., and Rivers, N. (2023). Intensity-based rebating of emission pricing revenues. *Journal of the Association of Environmental and Resource Economists*, 10(4):1059–1089.

Böhringer, C., Müller, A., and Schneider, J. (2015). Carbon tariffs revisited. *Journal of the Association of Environmental and Resource Economists*, 2(4):629–672.

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.

Carbone, J. C., Rivers, N., Yamazaki, A., and Yonezawa, H. (2020). Comparing applied general equilibrium and econometric estimates of the effect of an environmental policy shock. *Journal of the Association of Environmental and Resource Economists*, 7(4):687–719.

Cason, T., Stranlund, J., and Vries, F. d. (2022). Investment incentives in tradable emissions markets with price floors. *Journal of the Association of Environmental and Resource Economists*.

Cherniwchan, J. and Najjar, N. (2022). Do environmental regulations affect the decision to export? *American Economic Journal: Economic Policy*, 14(2):125–160.

Conte, M., Cotterlaz, P., and Mayer, T. (2022). The CEPII gravity database highlights.

Copeland, B. R., Shapiro, J. S., and Scott Taylor, M. (2022). Chapter 2 - globalization and the environment. In Gopinath, G., Helpman, E., and Rogoff, K., editors, *Handbook of International Economics: International Trade, Volume 5*, volume 5 of *Handbook of International Economics*, pages 61–146. Elsevier.

Correia, S. (2014). REGHDFE: Stata module to perform linear or instrumental-variable regression absorbing any number of high-dimensional fixed effects. Statistical Software Components, Boston College Department of Economics.

Dechezleprêtre, A., Gennaioli, C., Martin, R., Muûls, M., and Stoerk, T. (2022). Searching for carbon leaks in multinational companies. *Journal of Environmental Economics and Management*, 112:102601.

Dechezleprêtre, A., Nachtigall, D., and Venmans, F. (2023). The joint impact of the European Union emissions trading system on carbon emissions and economic performance. *Journal of Environmental Economics and Management*, 118:102758.

Dolphin, G. (2022). Evaluating national and subnational carbon prices: A harmonized approach. *Washington, DC: Resources for the Future Working Paper 22-4*.

Ederington, J., Levinson, A., and Minier, J. (2005). Footloose and pollution-free. *Review of Economics and Statistics*, 87(1):92–99.

Eskeland, G. S. and Harrison, A. E. (2003). Moving to greener pastures? multinationals and the pollution haven hypothesis. *Journal of development economics*, 70(1):1–23.

Fell, H. and Maniloff, P. (2018). Leakage in regional environmental policy: The case of the regional greenhouse gas initiative. *Journal of Environmental Economics and Management*, 87:1–23.

Ferguson, S. M. (2023). Unconstrained trade: The impact of EU cage bans on exports of poultry-keeping equipment. *Journal of Agricultural Economics*, 74(2):435–449.

Fischer, C. and Fox, A. K. (2012). Comparing policies to combat emissions leakage: Border carbon adjustments versus rebates. *Journal of Environmental Economics and management*, 64(2):199–216.

Fowlie, M. L. and Reguant, M. (2022). Mitigating emissions leakage in incomplete carbon markets. *Journal of the Association of Environmental and Resource Economists*, 9(2):307–343.

Gaulier, G. and Zignago, S. (2010). Baci: international trade database at the product-level (the 1994-2007 version).

Huebler, M. and Schwerhoff, G. (2023). Economic policy and technology choice of heterogeneous producers. *Journal of the Association of Environmental and Resource Economists*, 10(5):1369–1404.

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

Naegele, H. and Zaklan, A. (2019). Does the EU ETS cause carbon leakage in european manufacturing? *Journal of Environmental Economics and Management*, 93:125–147.

Papageorgiou, C., Saam, M., and Schulte, P. (2017). Substitution between clean and dirty energy inputs: A macroeconomic perspective. *Review of Economics and Statistics*, 99(2):281–290.

Prete, C. L., Tyagi, A., and Xu, Q. (2024). California's cap-and-trade program and emission leakage in the western interconnection: comparing econometric and partial equilibrium model estimates. *Journal of the Association of Environmental and Resource Economists*, 11(2):359–402.

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

Stöckl, F. and Zerrahn, A. (2023). Substituting clean for dirty energy: A bottom-up analysis. *Journal of the Association of Environmental and Resource Economists*, 10(3):819–863.

U.S. Environmental Protection Agency (2022). Inventory of U.S. greenhouse gas emissions and sinks: 1990-2020. *EPA 430-R-22-003*.

World Bank (2023). *State and trends of carbon pricing 2023*. The World Bank.

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