The Global Effects of Carbon Border Adjustment Mechanisms

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We study carbon border adjustment mechanism (CBAM) policies, as currently being implemented by the EU and UK. Policy discussions have cited three motivations and one concern. CBAMs can improve domestic competitiveness in regulated markets, reduce emissions leakage to unregulated markets, and encourage other countries to tax carbon. But CBAMs may particularly disadvantage lower-income trading partners. We evaluate these forces with a quantitative equilibrium model and plant-level data on aluminum and steel production worldwide. Our data cover the most emissions-intensive and heavily traded sectors targeted in the first phase of EU and UK implementation. We find that CBAMs can effectively boost competitiveness, curb leakage, and encourage regulation, while also avoiding disproportionate impacts on lower-income countries.

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1 Introduction

As the European Union and United Kingdom implement the first carbon border adjustment mechanisms (CBAMs), the world is experiencing a new climate policy tool. Domestic carbon taxes are important steps toward a global carbon tax, but they are subject to competitiveness, leakage, and free-riding concerns. Competitiveness is an issue because regulation can hinder domestic producers who must compete in global markets. Leakage arises because domestic consumers can shift toward importing from unregulated foreign producers. Free-riding occurs because foreign markets benefit from global emissions reductions. CBAMs aim to address these concerns by applying domestic carbon taxes to imports at the border, with credits for foreign carbon taxes already paid. The border tax levels the playing field and reduces leakage toward imports, while the border credit encourages foreign markets to regulate. At the same time, the EU itself has raised concerns that the CBAM may disproportionately harm its lower-income trading partners (European Commission 2021).

This paper assesses the global welfare implications of CBAM policies. We do so in the context of two key industries targeted by the EU CBAM in the first phase of its implementation: aluminum and steel. These industries are both emissions-intensive and highly traded, together accounting for 14% of world emissions and more than $1 trillion in international trade. We compile detailed plant-level data that record production quantities, costs, capacities, and emissions for the near-universe of aluminum and steel producers globally. Data for aluminum come from Wood Mackenzie, a leading data provider for the energy sector. Data for steel come from Climate TRACE, which uses satellite data to construct monthly measures for plants included in the Global Steel Plant Tracker database.

The data show that production in lower-income countries is not systematically more emissions-intensive than production in higher-income countries. For both aluminum and steel, lower- and higher-income countries emit similar levels of CO_2 per unit of production. We consider differences in the mode and scale of production, state and foreign ownership, and plant age, and we find that this result holds even when accounting for compositional differences in production across countries. Moreover, clean producers in lower-income countries stand to benefit from a CBAM, as low emissions intensity becomes a source of comparative advantage.

We build a quantitative equilibrium model of global trade to evaluate how CBAM policies affect markets worldwide. On the demand side, we model consumption as a simple log-linear function of prices. Assuming a common elasticity across markets allows us to estimate demand with global data. As is typical, price endogeneity arises because positive demand shocks raise prices in equilibrium. We instrument for world aluminum and steel prices with the Australian shares of bauxite and iron ore extraction. These shares act as supply shifters because Australia accounts for one quarter of ore extraction globally, and ore is a key input for metal production. These shares are also plausibly excluded from world demand because Australia is less than 1% of global consumption. We obtain a demand elasticity of -0.93 with instruments, relative to an OLS estimate of -0.73 that is modestly biased toward zero.

On the supply side, we model production as a function of profits, which depend on prices and costs. Assuming constant marginal costs allows us to read costs from our plant-level data in the spirit of Asker et al. (2019). Without these data, the typical approach would need to specify a cost structure and estimate cost parameters. We need only to estimate the elasticity of production with respect to profits, which change as we apply carbon regulation in counterfactuals. Our plant-level data have two further advantages for estimating supply. First, we compare plants within markets to eliminate prices, which are endogenous but fixed within markets. Second, we compare plants within narrowly defined groups, which mitigate potential cost endogeneity. If high-cost plants have access to better technology, which allows them to produce at scale despite high observed costs, then they are a poor comparison for low-cost plants with worse technology. We minimize these differences by grouping plants in the same countries with the same modes of production, the same status of state and foreign ownership, and the same quartile of plant age. We obtain a supply elasticity of 0.60 with group fixed effects, relative to an OLS estimate of -0.36 that is biased to the point of suggesting downward-sloping supply.

We use the estimated model to simulate regulated markets that implement carbon taxation, both with and without border adjustment, and we compute impacts across markets on consumers, producers, government revenue, and emissions. In the model, plants respond to regulation by reallocating their sales across markets. When Europe imposes a CBAM, it taxes imported emissions. This tax pushes emissions-intensive products to foreign markets, raising foreign supply and placing downward pressure on foreign prices. At the same time, Europe pays for its green preference with European prices that rise as European supply falls. These equilibrium forces operate at larger scale when Europe and China regulate in coalition, which we highlight given China's dominance in the aluminum and steel markets. Counterfactuals deliver six results.

First, CBAMs improve domestic competitiveness in regulated markets. When Europe imposes a \$100 carbon tax without a CBAM, European producers become less competitive because regulation adds to production costs. Producer surplus falls by \$23.07B. When Europe taxes carbon with a CBAM, it shields its domestic producers from foreign competition, at least within its domestic market. Higher European prices reflect increased competitiveness, which translates into higher producer profits. European producers must still bear the burden of regulation, but producer surplus falls by a smaller \$22.07B – a reduction of 4%.

Second, CBAMs reduce emissions leakage to unregulated markets. When Europe imposes a \$100 carbon tax without a CBAM, foreign emissions rise even as European emissions fall because European regulation raises world prices. On net, global emissions fall by 17.12 Mt. When Europe taxes carbon with a CBAM, the CBAM reduces the rise in foreign emissions by reducing the rise in foreign prices. Global emissions fall by a larger 18.45 Mt. This reduction in leakage improves the cost-effectiveness of European regulation, and marginal abatement costs fall from \$144 without a CBAM to \$131 with a CBAM – a reduction of 9%.

Third, CBAMs encourage other countries to tax carbon. We focus on China's incentives to join Europe in imposing a \$100 carbon tax, relative to a world in which Europe taxes carbon alone. Chinese regulation is valuable: when Europe and China regulate in coalition, global emissions fall by more than 330 Mt. But regulation is costly for China. When China joins Europe in regulating without a CBAM, China incurs \$19.69B in domestic welfare losses. While China may value global emissions reductions and thus be willing to shoulder these losses, CBAM policy also helps to narrow the gap. First, European regulation without a CBAM creates free-riding incentives that discourage Chinese regulation. A European CBAM reduces free-riding incentives. Second, Chinese regulation without a CBAM disadvantages domestic producers relative to their foreign competitors. A Chinese CBAM offsets that disadvantage. Taken together, when China joins Europe in regulating with a CBAM, China incurs a smaller \$18.22B in domestic welfare losses – a reduction of 7%.

Fourth, CBAMs avoid disproportionate impacts on lower-income trading partners. A European CBAM places a double burden on production in unregulated markets: it taxes emissions-intensive producers that export to Europe, and it lowers prices for those that do not. The first burden is income-neutral because producers in lower-income countries are not more emissions-intensive than producers in higher-income countries. The second burden is income-neutral because it affects all unregulated producers equally. Nonetheless, a CBAM may still be damaging for producers in particular lower-income countries. When Europe imposes a \$100 carbon tax, adding a CBAM reduces Indian producer surplus by \$79M because Indian production is relatively emissions-intensive.

Fifth, CBAMs face potential implementation challenges. While our baseline analysis makes full use of our plant-level emissions data, regulators may find it difficult to measure the emissions intensity of imported goods at this level of granularity. We simulate CBAM regulation that instead taxes imports based on country-level average emissions. We find that this coarser form of regulation is as effective as plant-specific regulation. On one hand, coarse regulation suffers because it targets emissions imprecisely. On the other hand, coarse regulation under-penalizes emissions-intensive producers and thus reduces incentives to avoid the CBAM by reallocating sales. Reduced reallocation increases the impact of the CBAM, offsetting the losses from imprecise targeting. Country-level regulation is an effective and feasible approach for implementing CBAM policy.

Sixth, CBAMs encourage green investment. We simulate a future in which world demand and production capacity both grow by 50%, roughly aligning with industry projections by 2050. We hold the emissions intensity of existing capacity fixed, given the sunk nature of capital investment, but we allow the emissions intensity of new capacity to fall as plants respond to carbon regulation by investing in abatement technology. We show that a modest amount of green investment has large benefits. When a \$100 carbon tax prompts new capacity to reduce its emissions intensity by 10%, a European CBAM at \$100 achieves 40% more in global abatement at a 30% lower marginal abatement cost. The green transition calls for more of this green investment at global scale.

We build on a growing body of work that studies international environmental policy coordination (Nordhaus 2015, Böhringer et al. 2016, Kortum and Weisbach 2023, Bourany 2024, Farrokhi and Lashkaripour 2024, Hsiao 2025) and the environmental effects of trade policy (Copeland and Taylor 2003, Larch and Wanner 2017, Shapiro and Walker 2018, Harstad 2023, Abuin 2024, Caliendo et al. 2024, Harstad 2024, Brunel and Levinson 2025, Casey et al. 2025, Farrokhi et al. 2025, Garcia-Lembergman et al. 2025). Issues of leakage and free-riding are of central concern in this literature, particularly as they relate to unilateral climate policy. CBAMs have emerged as a leading proposal for minimizing leakage (Markusen 1975, Copeland and Taylor 1994, 1995, Hoel 1996, Rauscher 1997, Fowlie 2009, Elliott et al. 2010, Böhringer et al. 2012, Fowlie et al. 2016, Kortum and Weisbach 2017, Fowlie and Reguant 2022, Coster et al. 2024) and for encouraging broader climate cooperation (Clausing and Wolfram 2023). This proposal has now been adopted by policymakers.

Our main contribution is to provide a quantitative global analysis of CBAM policies, as currently being implemented throughout Europe. We present an empirical framework that highlights the role of global equilibrium effects, including as producers respond to border adjustment by redirecting sales elsewhere. We combine this framework with detailed microdata on the two most important industries being targeted in the early phases of EU implementation. We are guided by our novel focus on the distributional implications of CBAM policies for lower-income countries. CBAMs are a landmark development for green trade policy and a crucial new tool in our fight against climate change. This paper evaluates their impacts and mechanisms.

2 Background

We describe recent CBAM policy in the European Union (EU), as well as two key industries targeted in the initial phases of implementation.

2.1 CBAM policies

The EU is implementing the world's first CBAM. The policy gained momentum in 2019 with the announcement of the European Green Deal, a comprehensive plan to make the EU climate neutral by 2050. A major challenge was ensuring that stringent climate policies did not drive production to countries with weaker carbon regulation. European policymakers debated several alternatives before formally proposing the CBAM in July 2021. Under the EU CBAM, importers must purchase certificates at the EU Emissions Trading System (ETS) carbon price to cover the emissions of imported goods. Crucially, these imported goods are credited for any foreign carbon price that has already been paid.[1] Thus, goods produced within the EU and those imported into the EU face the same total carbon tax.

The CBAM began with a phase-in period in October 2023. Importers must report the emissions of imported goods, but without financial obligation until January 2026. The policy covers six initial industries – aluminum, iron and steel, cement, electricity, fertilizer, and hydrogen – with the potential to expand to others over time. For aluminum, iron and steel, and hydrogen, the CBAM currently focuses on Scope 1 emissions (from production itself), excluding Scope 2 emissions (from electricity inputs). Our analysis will measure and include Scope 2 emissions. In January 2026, the CBAM will phase in as the allocation of free allowances – the existing trade competitiveness measure – is phased out.[2]

CBAM policy is also being implemented in Europe more broadly. In the United Kingdom (UK), the government announced its intention in December 2023 to implement a CBAM by 2027. While the UK CBAM is not yet law, the government has specified its plans to cover the same sectors as the EU, except for electricity (HMRC 2024). In the European Free Trade Association (EFTA), which includes Iceland, Liechtenstein, Norway, and Switzerland, producers are exempt from the EU CBAM because carbon is already priced at EU levels. Iceland, Liechtenstein, and Norway participate directly in the EU ETS, and the Swiss ETS is linked to the EU ETS. In October 2024, Norway announced plans to implement a parallel CBAM by 2027. We will use "Europe" in collective reference to EU, UK, and EFTA policy.

Other countries are also discussing CBAMs. Canadian officials have argued that a CBAM will level the playing field for industrial producers, which are subject to

[1] EU regulations suggest that credits will apply for "explicit" carbon prices paid. But what qualifies as an explicit price, including whether the carbon price must apply to all production or only production for export, has not yet been finalized. The same is true for reporting requirements for importers, including default values for those who do not report.

[2] Producers in CBAM sectors are currently allocated free ETS allowances in proportion to historical production levels and the carbon intensity of a plant with 10th-percentile emissions levels. These free allocations will be phased out by 2035.

Canada's federal backstop for carbon pricing, and the governments of Australia, Brazil, and Taiwan are also currently considering CBAMs. Clausing et al. (2024) document the coincidence of EU CBAM discussion with the expansion of carbon pricing around the world. China announced the expansion of its tradable performance standard in March 2025 to cover the CBAM-targeted sectors of aluminum, cement, and steel, and other countries have cited the EU CBAM as motivation for considering and enacting carbon pricing.

At the same time, policymakers have expressed concerns that CBAM policies may particularly disadvantage lower-income countries. The World Bank has developed an index of country-level exposure to the EU CBAM, although it uses coarser data than we use for our analysis (World Bank 2023). The index is constructed as the share of GDP from CBAM-targeted goods exported to the EU, multiplied by the carbon tax per dollar of exports relative to an average EU producer. By this measure, the most exposed countries are Zimbabwe, Ukraine, Georgia, Mozambique, and India.

We analyze European CBAM policy, focusing on the aluminum and steel industries. We use "steel" in reference to "iron and steel." Table 1 highlights that these industries are both heavily traded and emissions-intensive. Aluminum and steel represent a larger share of global trade than other CBAM-targeted industries, and much of aluminum and steel production is traded. Furthermore, aluminum and steel are emissions-intensive and account for 14% of total global CO_2 emissions, relative to only 4% of global GDP. Other target industries have more limited exposure to CBAM policies. Electricity and cement are a large share of global emissions but not heavily traded. Fertilizers are heavily traded but only a small share of global emissions. Hydrogen is neither heavily traded nor a large share of global emissions.

2.2 Aluminum

Aluminum is a globally traded commodity used in the transportation, construction, packaging, and energy sectors. It accounts for 3% of global carbon emissions (table 1). There are two production technologies: primary and secondary.

Primary production involves extracting aluminum from alumina, a compound of aluminum and oxygen. During the smelting process, carbon molecules combine with the oxygen of alumina to yield pure aluminum. CO_2 is released as a byproduct of this

Table 1: Trade and emissions for CBAM-targeted industries

	Global trade (%)	Trade value ($1B)	Trade intensity (%)	Global emissions (%)
Steel	3.5	839	23	11
Aluminum	1.0	253	41	3
Electricity	0.6	136	2	33
Fertilizer	0.5	131	60	1
Cement	0.1	17	2	6
Hydrogen	0.001	0.3	0.1	2

Trade intensity is the share of production exported. Production data come from Climate TRACE for steel, WoodMac for primary aluminum, the World Bureau of Metal Statistics for secondary aluminum, the US Energy Information Administration for electricity, the US Geological Survey for cement, the FAO for fertilizer, and the International Energy Agency (IEA) for hydrogen. Export data come from UN Comtrade, and emissions data from Bataille (2020) and the IEA.

chemical reaction.[3] Moreover, the electricity used in the smelting process can itself generate substantial CO_2 emissions, particularly when power is drawn from coal or other fossil fuels. Smelters that rely on low- or zero-emissions electricity sources, such as hydroelectric power, can produce aluminum with lower emissions.

Secondary production involves the recycling of aluminum scrap, which requires only 5 to 10% of the energy required for primary production. In our data, primary and secondary aluminum emissions average 9.8 and 1.0 tons of CO_2, respectively, per ton of production.

2.3 Steel

Steel is a crucial component for global manufacturing, construction, infrastructure, transportation, and energy. It is also among the most energy-intensive industries in the world, relying largely on coal. It accounts for 11% of global carbon emissions (table 1). There are two production technologies: blast furnace/basic oxygen furnace (BF-BOF) and electric arc furnace (EAF).

BF-BOF steel is also known as primary steel. The raw materials are iron ore

[3] The chemical properties of this reaction imply that the production of 1 ton of aluminum cannot emit less than 1.22 tons of CO_2, even with the most efficient processes. Carbon-free aluminum production with inert-anode technology is not yet commercially viable.

and metallurgical coal, and the process involves two energy-intensive steps. First, pig iron is produced by reducing iron ore in a blast furnace fired by coke, which is a fuel made from coal. Second, molten pig iron is transformed into steel by blowing oxygen in a basic oxygen furnace to remove carbon, which is released as CO_2.

EAF steel is also known as secondary steel. Typically, production involves the recycling of steel scrap, which is melted in an electric arc furnace with electricity as the main input. A smaller portion is produced from direct reduced iron, which is iron ore converted to metallic iron using syngas made from natural gas or gasified coal. The direct reduced iron is then transformed into steel in an electric arc furnace.[4] In our data, BF-BOF and EAF steel emissions average 2.4 and 0.9 tons of CO_2, respectively, per ton of production.

3 Data

We compile global data on aluminum and steel, covering production, consumption, prices, regulation, and ownership. Appendix A details data construction.

3.1 Production and consumption

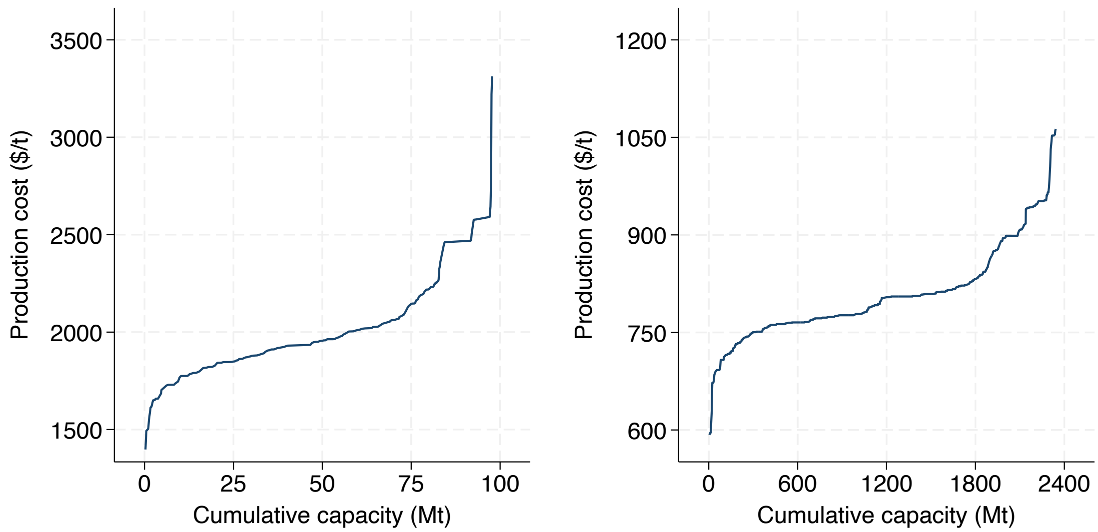
We measure primary aluminum production at the plant level with detailed data from Wood Mackenzie (WoodMac), a leading data provider focused on energy industries and related sectors. These data include 153 plants, covering the global universe of primary aluminum smelters in 2023. The data combine public information with periodic site visits to each plant.[5] We observe detailed information on plant capacity, annual production, and operating and capital costs, along with estimates of both Scope 1 and Scope 2 carbon emissions. Costs include those from electricity, alumina, other raw materials, consumables, labor, maintenance, and freight. We measure secondary aluminum production and total aluminum consumption at the country level with data from the World Bureau of Metal Statistics (WBMS). We observe production for the top 10 secondary producers, which account for 90% of global secondary

[4] This process releases more emissions than EAF steel from scrap, but less than BF-BOF steel. Newer methods produce direct reduced iron through electrolysis using green hydrogen and zero-emission electricity, but these methods are not yet commercially feasible.

[5] Some Chinese smelters are grouped together because of limited data availability.

Figure 1: Production costs and capacity

(a) Aluminum (b) Steel



Production costs are in USD per ton of production. These costs include material, labor, energy, maintenance, and depreciation costs. Cumulative capacity is in megatons of production per year, and it sums over plants in ascending order of production costs.

production in 2023. We obtain historical world and country-specific production of aluminum and bauxite from US Geological Survey reports (USGS 2025).

We observe 84 Mt of aluminum produced and consumed globally in 2023. This production accounts for 691 Mt of CO_2 emissions, consisting of 160 Mt of Scope 1 emissions and 531 Mt of Scope 2. Primary aluminum is 69 Mt (82%) of global production and 676 Mt (98%) of global emissions, while secondary aluminum is 15 Mt of production and 15 Mt of emissions. Figure 1 plots the production costs of primary and secondary aluminum against cumulative capacity, and table 2 lists the top producing and consuming countries. China is dominant at 60% of the market.

We obtain steel data at the plant level from Climate TRACE (Tracking Real-time Atmospheric Carbon Emissions), an independent non-profit that monitors and reports global greenhouse gas emissions. Climate TRACE publishes monthly estimates of steel production, capacity, and emissions for plants in the Global Steel Plant Tracker (GSPT) database from Global Energy Monitor (GEM). These data include 892 plants across 77 countries, covering the global universe of steel mills with a capacity of more than 500 thousand tons. Emissions data include both Scope 1 and Scope 2

Table 2: Aluminum

(a) Top producers

	Mt	%
China	49	58
India	5	6
Europe	5	5
USA	4	5
Russia	4	5
Rest of world	18	21

(b) Top consumers

	Mt	%
China	49	58
Europe	9	11
USA	8	9
Japan	3	4
India	3	4
Rest of world	12	15

Europe includes the EU, UK, and EFTA. We measure quantities for 2023 in megatons.

emissions. Scope 1 emissions derive from more than 300 satellites and 11,000 sensors that capture plant-level activity, covering more than 660 million individual sources of emissions.[6] Scope 2 emissions are based on regional estimates of the emissions intensity of electricity production from Ember, a global energy think tank, as well as plant-level estimates of electricity use from the Mission Possible Partnership's 2024 Steel Transition Strategy. We measure steel consumption at the country level with WBMS data, and we obtain historical world and country-specific production of steel and iron ore from US Geological Survey reports (USGS 2025).

We observe 1,673 Mt of steel produced and consumed globally in 2023. This production accounts for 3,163 Mt of CO_2 emissions, consisting of 2,876 Mt of Scope 1 emissions and 287 Mt of Scope 2. Primary steel is 1,114 Mt (67%) of global production and 2,646 Mt (84%) of global emissions, while secondary steel is 558 Mt of production and 517 Mt of emissions. Figure 1 plots the production costs of primary and secondary steel against cumulative capacity, and table 3 lists the top producing and consuming countries. China is again dominant at 50% of the market.

3.2 Prices, ownership, and regulation

We observe world prices for aluminum and steel. Aluminum prices come from World Bank commodity price data, which derive from the London Metal Exchange

[6] Climate TRACE uses multispectral satellite imagery from the European Space Agency Copernicus Sentinel missions and the NASA/USGS Landsat missions. Infrared sensors capture heat signatures that correlate with production at the plant level.

Table 3: Steel

(a) Top producers

	Mt	%
China	860	51
Europe	153	9
Japan	88	5
USA	86	5
India	76	5
Rest of world	409	24

(b) Top consumers

	Mt	%
China	835	50
Europe	140	8
India	124	7
USA	90	5
Russia	56	3
Rest of world	429	26

Europe includes the EU, UK, and EFTA. We measure quantities for 2023 in megatons.

price for unalloyed primary ingots. The average aluminum price was $2,256 per ton in 2023. Crude steel is not widely traded on exchanges, and so we compute the weighted average of export prices for CBAM-targeted steel products. We obtain an average steel price of $1,011 per ton in 2023.

We construct state and foreign ownership for each plant, with ownership defined by the majority-stakeholder parent company. Appendix table A3 presents country-level statistics for the top aluminum and steel producers globally. State and foreign ownership are more common for aluminum, although not differentially so across lower- and higher-income countries. Much of Indian production is by foreign-owned firms, but the same holds for Europe, as well as globally. Chinese production is 33% state-owned and 0% foreign-owned. Both state and foreign ownership are less common for steel. Chinese production is 10% state-owned and 0% foreign-owned.

We construct global data on carbon pricing. We collect carbon prices as of April 2023 from the World Bank's Carbon Pricing Dashboard, which covers exchange-traded, auction, and government-set prices. We supplement these data by compiling official regulatory documents for each country. Our aluminum and steel plants are spread across jurisdictions with 27 different carbon pricing schemes that cover aluminum and steel production; 14 are regional, 12 are national, and one – the EU ETS – is supranational. Nine are carbon taxes, and 18 are emission trading systems. Tax exemptions and free allowances are common, resulting in lower average prices paid than the reported tax rates or allowance trading prices. We account for exemptions and allowances to construct the adjusted carbon prices that apply to each plant. Plants pay these lower, adjusted prices on average. Appendix tables A5 and A6 present both sets of prices for aluminum and steel in jurisdictions with nonzero carbon prices.

4 Stylized Facts

We document three facts about emissions intensity in aluminum and steel production, and we discuss their implications for carbon regulation.

4.1 Emissions intensity and cost competitiveness

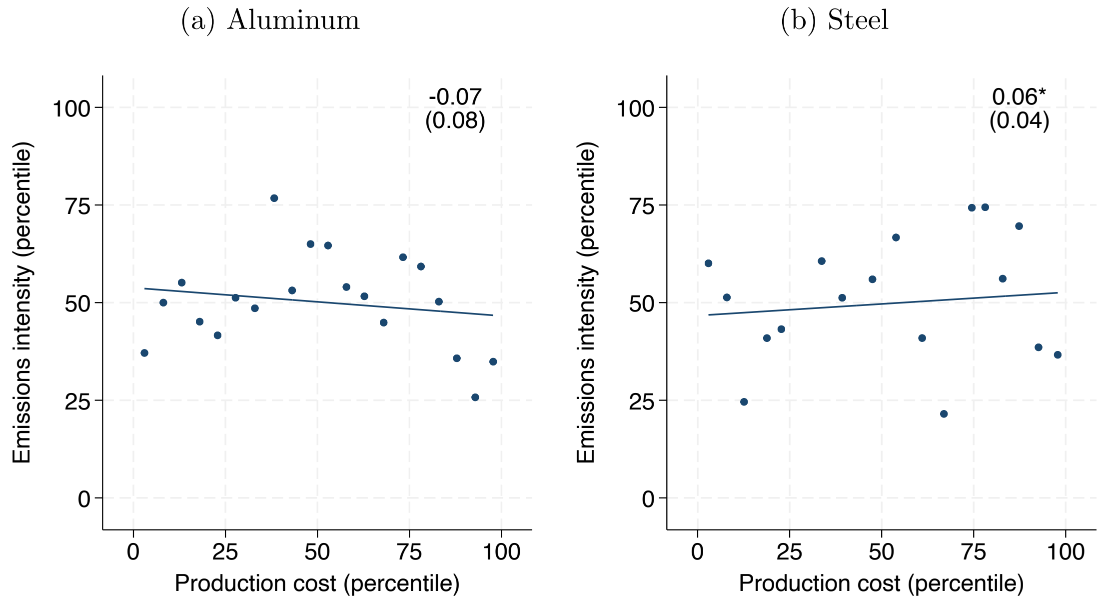
How does carbon pricing affect competitiveness? When carbon is unpriced, the most competitive plants are those with low production costs. When carbon is priced, low emissions intensity becomes an additional source of comparative advantage. Figure 2 plots plant-level emissions intensity against production costs, with each in percentiles to highlight competitiveness in relative terms. We measure emissions intensity as emissions generated per unit of production. If emissions intensity and production costs were perfectly positively correlated, then plants would lie on the 45° line. That is, plants would align in their emissions and cost rankings, and so carbon pricing would have no impact on relative competitiveness.

By contrast, we find that carbon pricing induces a significant shift in the competitive landscape. The emissions-cost gradient is flat, rather than upward-sloping, for both aluminum and steel. A change in production costs of one percentile corresponds to a change in emissions intensity of only 0.07 percentiles for aluminum and 0.06 percentiles for steel. We see that green plants exist not only among the most cost-competitive plants, but also among the least cost-competitive plants. The corollary is that costs are poor predictors of emissions. We must measure plant-level emissions intensity to understand how carbon pricing affects plant profits and production.

4.2 Emissions intensity across countries

Does carbon pricing disadvantage producers in lower-income countries? If low-emission producers are concentrated in higher-income countries, then it is primarily producers in lower-income countries with high emissions intensity and large profit losses under carbon pricing. Figure 3 plots log emissions intensity against log GDP per

Figure 2: Green competitiveness

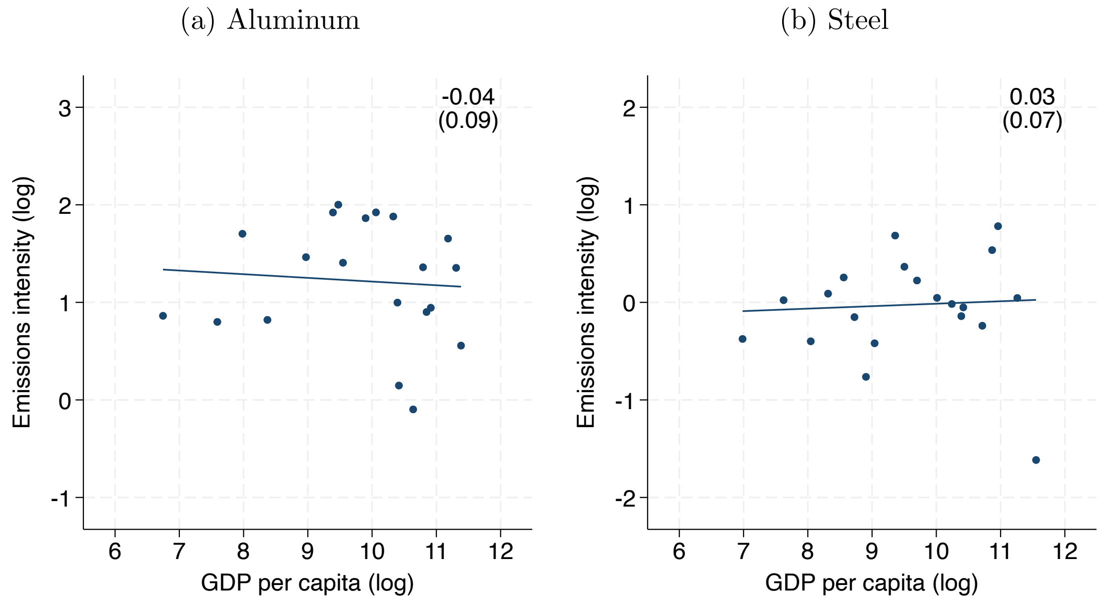


Each figure is a binned scatter plot, and each observation is a plant. Emissions intensity is in tons of CO_2 emitted per ton of production. Production costs are in USD per ton of production. We plot each in percentile terms. We report the slope and standard error of the fitted line in the top-right corner of each figure. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

capita across countries. We find that the emissions-income gradient is flat, rather than downward-sloping, for both aluminum and steel. The slightly negative correlation for aluminum and the slightly positive correlation for steel are weak and not statistically significant. A change in GDP per capita of 1% corresponds to a change in emissions intensity of only 0.04% for aluminum and 0.03% for steel. Production in lower-income countries is not systematically more emissions-intensive than production in higher-income countries.

We probe explanations in appendix B. Appendix table B1 shows that this flat relationship is not explained by compositional differences in production across countries. We obtain similar results when we control for the proportion of primary production, state ownership, and foreign ownership, as well as the average scale of production and plant age. Appendix table B2 and figure B1 highlight electricity emissions as an explanation for aluminum. We calculate that 77% of total emissions derive from the electricity used in production (Scope 2), and we draw on four independent global datasets to show that the emissions-income gradient is also quite flat for electricity

Figure 3: Emissions intensity by income



Each figure is a binned scatter plot, and each observation is a country. Emissions intensity is in tons of CO_2 emitted per ton of production. GDP data are from the World Bank. We plot each in log terms. We report the slope and standard error of the fitted line in the top-right corner of each figure. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

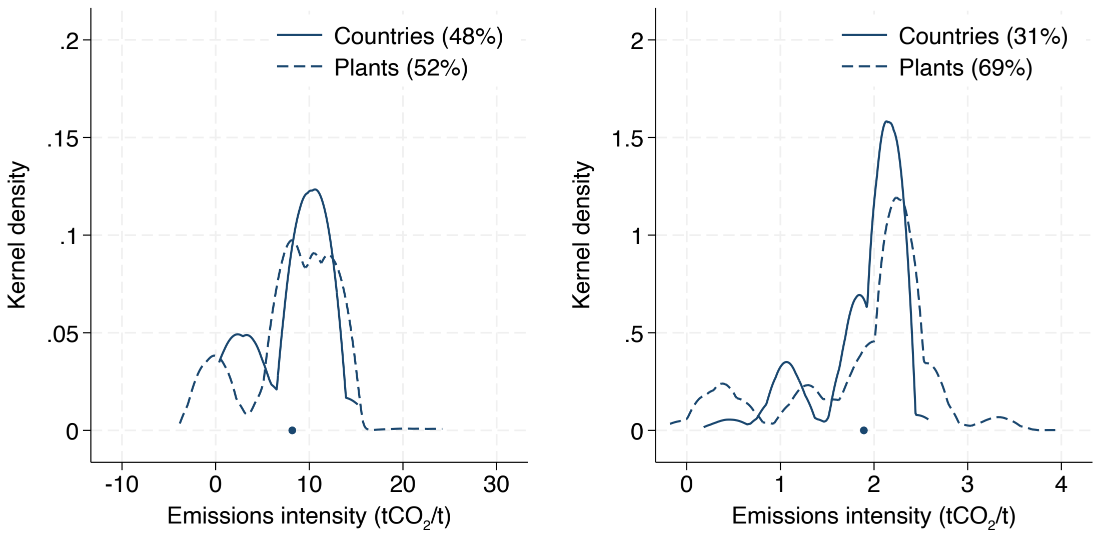
(Ang and Su 2016, EEA 2025, Electricity Maps 2025, Ember 2025). Appendix table B3 points to a compressed emissions distribution as an explanation for steel. The most emissions-intensive producer is 37% more emissions-intensive than the global mean, relative to 85% for aluminum. For both aluminum and steel, we note a mix of higher- and lower-income countries among the most emissions-intensive producers. Kazakhstan is an upper-middle-income country that tops both lists.

4.3 Emissions intensity across plants

Does carbon regulation require plant-level emissions measures? If plants are homogeneous within countries, then country-level measures and regulation are sufficient. If plants are highly heterogeneous within countries, then country-level regulation fails to target the most emissions-intensive plants. Figure 4 decomposes the variation in emissions intensity across countries and across plants within countries. The solid lines capture variation across countries by plotting country averages. The dashed lines capture variation across plants within countries by plotting plants' deviations

Figure 4: Emissions within and across countries

(a) Aluminum (b) Steel



Each figure is a kernel density plot. Emissions intensity is in tons of CO_2 emitted per ton of production. The dot marks the world average. The solid line plots country averages, and the legend shows R^2 when regressing plant-level emissions intensity on country fixed effects. The dashed line plots plant-level emissions intensity, demeaned by the country averages and centered at the world average. The legend shows $1 - R^2$.

from their country averages, which we recenter at the world average.

We highlight considerable heterogeneity in the data. That is, the flat relationships that we document between emissions intensity and production costs (figure 2) and between emissions intensity and GDP per capita (figure 3) are not indicative of a lack of heterogeneity in general. This heterogeneity arises both across and within countries. For aluminum, country fixed effects explain 48% of observed variation in emissions intensity, while the remaining 52% is attributable to variation across plants within countries. For steel, there is less variation across countries (31%) and more variation within countries (69%).[7] In both cases, plant-level measures are necessary for capturing the full range of heterogeneity in the data.[8]

[7] The more limited variation across countries is therefore consistent with the compressed distribution of emissions intensity across countries in appendix table B3. The dashed line crosses below zero because it plots plant deviations from country averages (recentered at the world average). It is negative deviations from high country averages that allow the line to cross zero.

[8] Appendix figure B2 considers heterogeneity in production costs. First, we note that the cost-income gradient is also rather flat. Second, relative to emissions intensity, production costs are better predicted by their country-level averages. The heterogeneity across plants within countries

5 Model

We model carbon taxation and a carbon border adjustment mechanism (CBAM) in a world commodity market. We distinguish between two markets $m \in \mathcal{M}$, where the set of markets $\mathcal{M} = \{R, U\}$ includes those that are regulated (R) and unregulated (U). Regulators in R consider a CBAM on imports from U.

5.1 Demand

We specify log-linear demand in each market. For intercepts δ^m, elasticities $\varepsilon^m < 0$, and prices P^m, demand for a given commodity is

$$\log D^m = \delta^m + \varepsilon^m \log P^m. \tag{1}$$

High prices P^m reduce demand D^m. Consumer surplus follows from integrating equation 1.[9]

$$\log CS^m = \delta^m + (1 + \varepsilon^m) \log P^m - \log(-1 - \varepsilon^m)$$

Our baseline analysis treats primary and secondary products as perfect substitutes in consumption, and we will test this assumption in counterfactuals.

5.2 Supply

Plants $i \in \mathcal{I}^m$ in market m choose production s_i as a function of capacity $\bar{s}_i$, cost c_i, and price p_i^m. We observe capacity and costs, and we assume constant marginal costs. We take capacity and costs as given, noting that adjustment requires substantial capital investment that is difficult in the short run. We also observe production and prices, which we will allow to respond endogenously to regulation. Each plant has a collection of production lines $\mathcal{L}$, and we model choices at the level of the production line. The utility of operating a production line is

$$u_{il}^m = v_i^m + \epsilon_{il}, \quad v_i^m = \beta(p_i^m - c_i) + \epsilon_i.$$

is more muted, particularly for steel.

[9] As is typical, we evaluate consumer surplus only in changes. In levels, the integral from the market price to an infinite choke price does not converge for $\varepsilon^m > -1$.

For a given plant, production lines have common observed costs c_i, common unobserved costs ϵ_i, and idiosyncratic unobserved costs ϵ_{il}, which we assume are logit-distributed. We will estimate parameter β, which captures how changes in prices and costs translate into changes in production.[10] Unobserved costs rationalize observed production in spite of high observed costs.

Production is given in closed form. Logit shocks imply that the probability of operating a production line is

$$o_i^m = \frac{\exp(v_i^m)}{1 + \exp(v_i^m)}. \tag{2}$$

For a given plant, this probability corresponds to capacity utilization. We aggregate across production lines, as given by capacity, to obtain production by plant.

$$s_i^m = \bar{s}_i o_i^m$$

High prices p_i^m raise production s_i^m by raising capacity utilization o_i^m. Producer surplus follows from the log-sum formula for logit expected utility, and emissions are given by emissions intensity and production.

$$PS_i^m = \frac{\bar{s}_i}{\beta} \log\left(1 + \exp(v_i^m)\right), \quad E_i^m = e_i s_i^m.$$

5.3 Regulation

Plants operate under varying levels of carbon regulation. We study domestic carbon taxation and a carbon border adjustment mechanism.

Carbon taxation

Prices p_i^m are net of regulation. Production involves emissions intensity e_i, which we treat as constant, subject to domestic carbon taxes τ^m. We observe emissions intensity across plants, and we observe carbon taxes across markets. Plants receive

[10] As is typical, β is a profit coefficient that captures how plants value profits in utility terms. Equivalently, we can directly take per-unit profits $(p_i^m - c_i)$ as the numeraire, setting $\beta = 1$, then estimate the variance of the logit shocks.

net prices

$$p_i^m = P^m - \tau^m e_i,$$

taking market prices P^m and regulation τ^m as given. Government revenue derives from domestic taxation τ^m of domestic emissions E_i^m.

$$G^m = \sum_{i \in \mathcal{I}^m} \tau^m E_i^m$$

Carbon border adjustment mechanism

Market R has higher carbon taxation than market U, such that $\tau^R > \tau^U$. When R pairs carbon taxation with a CBAM, it introduces a price wedge in the form of adjustment α^R.

$$\alpha^R = \tau^R - \tau^U > 0$$

The adjustment is such that all consumption in R is subject to total tax τ^R. If U is entirely unregulated, then $\tau^U = 0$ and $\alpha^R = \tau^R$. Goods produced in R face carbon tax τ^R during production, and goods imported from U face τ^U during production and $\tau^R - \tau^U$ at the border.[11] The CBAM imposes a price wedge: we distinguish between prices (P^R, P^U), as prices no longer equalize across markets.

Plants choose which market to serve. For plants in R, the comparison is simply between market prices. These plants face domestic tax τ^R on both home sales and exports because they do not receive a negative border adjustment – a tax refund – when exporting to U. For sales from R to R (RR) and from R to U (RU), net prices are

$$p_i^{RR} = P^R - \tau^R e_i, \quad p_i^{RU} = P^U - \tau^R e_i.$$

For plants in U, the comparison is between both prices and regulation. These plants face domestic tax τ^U on home sales and foreign tax $\tau^R = \tau^U + \alpha^R$ on exports, as the CBAM imposes adjustment α^R on exports. Net prices are

$$p_i^{UR} = P^R - \tau^R e_i, \quad p_i^{UU} = P^U - \tau^U e_i.$$

[11] While we levy the CBAM on plants in U that export to R, it is equivalent to levy the CBAM on consumers in R that import from U. Appendix C proves this standard equivalence result for completeness.

In both markets, plants choose their highest net price.

$$p_i^m = \max\{p_i^{mR}, p_i^{mU}\}$$

Plants serve R when net prices in R dominate, and they serve U otherwise.

$$r_i^m = \mathbb{1}(p_i^{mR} > p_i^{mU})$$

For market R, government revenue derives from domestic taxation τ^R, as well as border adjustments α^R on imports from U. For market U, it derives solely from domestic taxation τ^U of domestic emissions E_i^U.

$$G^R = \sum_{i \in \mathcal{I}^R} \tau^R E_i^R + \sum_{i \in \mathcal{I}^U} \alpha^R r_i^U E_i^U, \quad G^U = \sum_{i \in \mathcal{I}^U} \tau^U E_i^U$$

5.4 Equilibrium

Equilibrium prices clear global markets. Without a CBAM, a common price P^* equalizes world demand and world supply.

$$D(P^*) = S(P^*) \tag{3}$$

Demand aggregates across markets, and supply aggregates across plants.

$$D = \sum_m D^m, \quad S = \sum_m \sum_{i \in \mathcal{I}^m} s_i^m$$

With a CBAM, adjustment α^R imposes a price wedge, such that prices (P^{R*}, P^{U*}) clear each market separately.

$$D^R(P^{R*}) = S^R(P^{R*}, P^{U*}; \alpha^R), \quad D^U(P^{U*}) = S^U(P^{R*}, P^{U*}; \alpha^R) \tag{4}$$

Total supply to R and total supply to U each aggregate across plants in both markets.

$$S^R = \sum_m \sum_{i \in \mathcal{I}^m} r_i^m s_i^m, \quad S^U = \sum_m \sum_{i \in \mathcal{I}^m} (1 - r_i^m) s_i^m$$

5.5 CBAM motivations

A major goal of European CBAM policy is to increase domestic competitiveness. Conditional on taxing carbon, a CBAM boosts domestic competitiveness by raising prices and producer surplus in R, while placing downward pressure on prices and producer surplus in U. In particular, a CBAM reallocates trade flows and creates price divergence with $P^R > P^U$, as we prove in appendix C. Intuitively, when R imposes border adjustment α^R, it discourages emissions-intensive imports and thus restricts supply. Lower supply in R raises prices in R. Low-emission exporters enjoy access to these higher prices, and so they redirect sales to R. High-emission exporters cannot access the higher prices in R because of the CBAM, and so they redirect sales to U. Higher supply in U reduces prices in U.

A second major goal is to address leakage concerns, which apply to both demand and supply. On the demand side, carbon taxation without a CBAM in R encourages imports from U, where carbon is untaxed. These additional imports bypass carbon taxes in R. Indeed, Coster et al. (2024) document this import response empirically with data on firm imports in France at the product level. Carbon taxation with a CBAM addresses this concern by directly taxing imports from U. On the supply side, carbon taxation without a CBAM in R raises prices in U, encouraging increased production in U. This additional production undercuts emissions reductions in R. Carbon taxation with a CBAM addresses this concern through the reallocation effect, which limits the extent to which prices rise in U. In both cases, the CBAM reduces leakage to U.

A third goal is to encourage carbon regulation abroad. In particular, a CBAM in R creates revenue incentives for carbon taxation in U. The reason is that plants in U that export to R are indifferent to domestic tax τ^U. Given adjustment $\alpha^R = \tau^R - \tau^U$, these plants face the same total tax τ^R for all $\tau^U \leq \tau^R$ because the adjustment changes one-for-one with τ^U. Consider the extremes. When $\tau^U = 0$, exporters pay $\alpha^R = \tau^R$ and all revenue goes to R. When $\tau^U = \tau^R$, exporters pay $\alpha^R = 0$ and all revenue goes to U. In both cases, exporters pay $\tau^U + \alpha^R = \tau^R$ in total. Thus, imposing $\tau^U = \tau^R$ raises revenue for U without affecting production for export, although it still affects production for domestic consumption.

6 Estimation

We construct empirical demand and supply curves for aluminum and steel. Our estimates allow us to model demand responses at the country level and supply responses at the plant level.

6.1 Demand

We use annual world consumption data to construct demand. Assuming a common demand elasticity across markets, along with a common world price, allows us to estimate demand with global data.[12] Unlike country-specific consumption, global consumption is straightforward to measure historically. By equation 1, world demand for metal j in year t is given by

$$\log D_{jt} = \delta_{jt} + \varepsilon_{jt} \log P_{jt}.$$

We further assume that $\varepsilon_{jt} = \varepsilon$ across metals and years. Doing so allows us to leverage panel variation across both margins. Decomposing $\delta_{jt} = \delta_j + \delta_t + \epsilon_{jt}$, we obtain a panel regression specification that we estimate with data on aluminum and steel consumption from 1976 to 2024.

$$\log D_{jt} = \delta_j + \delta_t + \varepsilon \log P_{jt} + \epsilon_{jt} \tag{5}$$

The coefficient of interest is demand elasticity ε. Although metal and year fixed effects δ_j and δ_t are useful in addressing potential endogeneity concerns, prices P_{jt} and demand shocks ϵ_{jt} may still be correlated. In particular, if positive demand shocks raise prices in equilibrium, then estimation will be biased toward concluding that demand is inelastic.

We instrument for prices with Australia's share of global ore production, which we define as bauxite production for aluminum and iron ore production for steel. This

[12] Consider a given metal j and year t. In the absence of an existing CBAM, prices equalize across markets at a single world price, such that $P^m = P$ across markets m. If $\varepsilon^m = \varepsilon$, then equation 1 implies $\log D^m = \delta^m + \varepsilon \log P$. Exponentiating both sides, $D^m = P^\varepsilon \exp(\delta^m)$. Summing across markets m, $D = \sum_m D^m = P^\varepsilon \sum_m \exp(\delta^m)$. Defining $\exp(\delta) = \sum_m \exp(\delta^m)$, it follows that $\log D = \delta + \varepsilon \log P$.

Table 4: Demand elasticities

	Estimate	SE	Obs
1976 to 2024			
OLS	-0.730***	(0.080)	98
IV: Australian share of ore production	-0.930***	(0.098)	98
1998 to 2022			
OLS	-0.462***	(0.053)	50
IV: Australian share of ore production (AU)	-0.733***	(0.134)	50
IV: concentration of ore production (HHI)	-0.743***	(0.152)	50
IV: both AU and HHI	-0.728***	(0.132)	50

Each row is a regression of log world consumption on log world prices, controlling for metal and year fixed effects. Each observation is a metal-year. The top rows are regressions that include the years 1976 to 2024, while the bottom rows are those that include 1998 to 2022. The Australian share measures Australia's share of global ore production, where ore refers to bauxite for aluminum and iron ore for steel. The concentration measures the country-level market concentration of ore production, which we compute as a Herfindahl-Hirschman index. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

instrument acts as a supply shifter to the extent that Australian market power raises prices.[13] The relevance of the instrument derives from Australia's dominance in ore production: it accounts for 30.9% of global bauxite production and 23.4% of global iron ore production from 1976 to 2024. The exclusion restriction is that Australian market power affects world demand only through its impact on world prices. To this end, our focus on ore production is helpful because we isolate the impact of market power upstream on metal prices downstream, rather than appealing to market power within downstream metal markets. Our focus on Australia is also helpful because, despite being a major ore producer, tables 2 and 3 show that Australia is a small consumer (and producer) of both aluminum and steel. Thus, Australia's share of ore production is arguably unlikely to directly affect world metal demand.

Table 4 presents our estimated demand elasticities. Our baseline IV specification gives an estimated demand elasticity of -0.93, suggesting that metal demand is inelastic. The OLS estimate of -0.73 is biased toward being more inelastic, although the metal and year fixed effects help to minimize this bias. In addition to

[13] For example, Chinese antitrust authorities launched a probe in 2010 to investigate BHP, Rio Tinto, and Vale, which together form the "Big Three" of the iron ore market. BHP and Rio Tinto are Australian companies.

Australia's share of ore production, we consider the concentration of ore production more broadly. We compute a Herfindahl-Hirschman index as the sum of each producing country's squared market share, noting that the country-specific production data are digitized only from 1998 to 2022. On this restricted sample, we obtain very similar estimates when using our Australian instrument, the broader concentration instrument, and both in combination. The IV estimates are around -0.73 and again more elastic than the OLS estimate.

Appendix table C1 shows a strong first stage. The Australian share and market concentration of ore production each have positive effects on prices, as market power allows large producers to raise market prices. The Australian share is a strong instrument in both the full and restricted samples. Furthermore, the F-statistic remains high when instrumenting with market concentration alone and when instrumenting with the Australian share and market concentration simultaneously. In the latter case, it is the Australian share that drives the effect on prices.

We use these elasticity estimates to construct empirical demand curves for each country in our data. We take our full-sample IV estimate as our baseline ($\varepsilon = -0.93$), and we apply this elasticity globally. We observe consumption D^k by country k, and we observe world price P. We recover the intercepts by inverting the country-level analogue of equation 1.

$$\delta^k = \log D^k - \varepsilon \log P$$

We thus obtain demand curves that specify demand by country for any given price. We sum over countries within markets to obtain demand D^m by market.

6.2 Supply

We use plant-level production data to construct supply. Applying the typical logit inversion, choice probability equation 2 gives

$$\log\left(\frac{o_i^m}{1-o_i^m}\right) = \beta(p_i^m - c_i) + \epsilon_i.$$

We construct the left-hand side from observed production s_i^m and production capacity $\bar{s}_i$, which we use to compute capacity utilization $o_i^m = s_i^m/\bar{s}_i$. We construct the main regressor from observed prices p_i^m and costs c_i. Prices are given in the data by

$p_i^m = P - \bar{\tau}^m \bar{e}_i$ for world price P, (adjusted) carbon taxation $\bar{\tau}^m$, and emissions intensity $\bar{e}_i$. Our assumption of constant marginal costs allows us to read costs from the data, as in Asker et al. (2019). That is, the average costs that we observe coincide with the costs c_i that we model. Error term ϵ_i represents unobserved costs.

Subscripting to reflect plants i, metals j, and countries k, we decompose the error term into common and idiosyncratic components to obtain a fixed effects regression specification that we estimate with our plant-level data.

$$\log\left(\frac{o_{ijk}}{1 - o_{ijk}}\right) = -\beta(\bar{\tau}_{jk}\bar{e}_{ijk} + c_{ijk}) + \mu_{jk} + \epsilon_{ijk} \tag{6}$$

World prices P_j are absorbed by country-metal fixed effects μ_{jk}. Among other unobservables, these fixed effects accommodate preexisting regulation and trade barriers that are not tied to emissions, including tariffs and shipping costs. We note that carbon taxation remains modest in our data, particularly at its adjusted values, and so it is largely our cost data that provide identifying variation. The coefficient of interest is parameter β, which is a semi-elasticity that captures how strongly production responds to profits. Strong responses imply a large supply elasticity. We use this parameter to construct empirical supply curves for each plant in our data, and we sum over plants by market to obtain supply S^m by market.

Our data have two advantages for estimation. First, we directly observe costs in dollar terms, and so we avoid the need to estimate the full cost structure of production. We need only to estimate parameter β. Second, our plant-level data allow us to control finely for group fixed effects, which help to address potential threats to identification. Prices are endogenous if aggregate cost shocks raise prices in equilibrium. Our data allow us to compare plants within markets, eliminating prices because prices are fixed across plants. Costs are endogenous if they are correlated with unobserved technology. If high-cost plants have better technology, then they can sustain higher levels of capacity utilization by operating more efficiently. Estimation will be biased toward concluding that production is insensitive to costs. More broadly, the concern is that low-cost plants are not a valid comparison group for high-cost plants because these groups have fundamental differences. Our data allow us to group plants that are observably similar.

Table 5 presents our estimated supply elasticities. We proceed from coarser to

Table 5: Supply elasticities

	Estimate	SE	Obs
OLS	-0.358***	0.076	1,055
FE: country-metal	0.241	0.224	1,005
FE: country-metal + controls	0.583**	0.231	987
FE: country-metal-group	0.602**	0.238	833

Each row corresponds to one regression, and we compute elasticities from the estimated β coefficients. Metals include aluminum and steel. Controls include primary production, state ownership, foreign ownership, and plant age. Groups are the interaction of the first three controls, which are binary variables, and quartiles of plant age. Primary production refers to primary aluminum and BF-BOF steel. State ownership is whether the majority-stakeholder parent company is a state-owned enterprise. Foreign is whether the majority-stakeholder parent company is headquartered in a different country from a given plant. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

finer comparison groups. The OLS estimate is biased downward to the point that supply is downward-sloping. When we control for country-metal fixed effects, the supply elasticity becomes positive but not statistically different from zero. When we further control for plant-level characteristics, which include primary production, state ownership, foreign ownership, and plant age, the supply elasticity becomes larger and statistically different from zero. In the last row, we group plants by these characteristics. This finest grouping compares plants with the same mode of production, the same state and foreign ownership status, and within the same quartile of plant age, each within the same metal and country. The number of observations in estimation declines because some groupings contain too few plants for identification. However, this decline is modest in magnitude: we benefit from rich variation, even when defining comparison groups finely, because of our granular, plant-level data. We obtain a supply elasticity of 0.60, which we take as our baseline estimate.[14]

Equation 6 also clarifies the sources of heterogeneity in supply responses. Within a given producer, we have limited heterogeneity across different levels of production. The reason is that we model constant marginal costs, constant marginal emissions, and market prices that we take as given. Thus, as prices fluctuate and regulation

[14] Appendix table C2 lists the corresponding regression estimates, which are similar when we exclude the limited variation from observed carbon regulation. Appendix figure C1 illustrates that capacity utilization is highest for low-cost producers and that finer fixed effects tighten this relationship. Intuitively, low costs raise profits and thus production. Conversely, greater regulation reduces profits and thus production.

is imposed, production responses vary only to the extent allowed by the logit link function. However, we note that this function does reflect diminishing marginal effects at the extremes, such that regulation has smaller impacts on the highest- and lowest-cost producers. We can also accommodate rich heterogeneity across producers. Differences in costs and emissions, which we observe, and in unobserved costs ϵ_{ijk}, which we recover, each generate variation in supply responses. An advantage of our plant-level data is that we observe many plants – 163 aluminum smelters and 892 steel mills – and so we capture substantial heterogeneity in practice.

7 Counterfactuals

We use the estimated model to study the equilibrium welfare impacts of counterfactual policy. We evaluate the impacts of carbon border adjustment, as well as optimal policy, policy spillovers, and global incidence. We then turn to implementation challenges and implications for green investment.

7.1 CBAM impacts

We quantify the impacts of carbon border adjustment. We simulate unilateral carbon taxation τ^R by a regulated market R, both with and without a CBAM, imposing $\tau^U = 0$ in unregulated markets elsewhere.[15] We solve for equilibrium prices, welfare, and emissions, each relative to a zero-regulation benchmark in which $\tau^R = \tau^U = 0$.[16] We isolate the marginal impact of border adjustment, conditional on carbon taxation, by comparing outcomes with and without a CBAM. We also study the role of scope by considering two regulatory coalitions. When market R includes Europe, where CBAMs are slated for full implementation in 2026 and 2027, it covers 9% of global consumption for aluminum and 10% for steel. Expanding the coalition to include China increases coverage to 70% and 60%, respectively.

Table 6 shows the impacts of carbon taxation at $100 per ton of CO_2, which is roughly in line with the carbon prices we observe in our data, and we define carbon

[15] We focus attention on carbon pricing in R by ignoring baseline carbon pricing in U, which appendix tables A5 and A6 show is correct to first order, particularly when weighted by production.

[16] We compute outcomes in differences because our consumer and producer surplus measures are not identified in levels, as is typical.

to include both Scope 1 and Scope 2 emissions.[17] We begin by focusing on European regulation with table 6a. The price effects highlight two forces: regulation and reallocation. Without a CBAM, we isolate the regulation force. European regulation adds to production costs, thereby reducing world supply and raising world prices. European regulation raises prices by only 0.41% because it covers less than 10% of world production (tables 2 and 3). With a CBAM, the reallocation force emerges. High-emission producers outside of Europe avoid the CBAM by reallocating sales away from Europe. The impact of reallocation is to reduce supply and raise prices in Europe, while raising supply and reducing prices elsewhere. In combination with the regulation effect, the total impact is to raise prices in Europe by a larger 1.22%, while prices elsewhere rise by a smaller 0.33%.

These price effects have direct implications for consumers and producers. Worldwide, consumers suffer as prices rise. A CBAM places a particular burden on European consumers, who lose \$2.12B in consumer surplus, because of its impacts on domestic prices. European producers do not fully enjoy the benefit of higher domestic prices because these prices are paired with carbon regulation. However, the higher prices still reduce European producer surplus losses, which fall from \$23.07B without a CBAM to \$22.07B with a CBAM – a reduction of 4%. The CBAM boosts domestic competitiveness by shielding domestic producers from foreign competition, and this increased competitiveness translates into an additional \$1B in profits. To the extent that climate targets call for European regulation, including through the phase-out of free allowances, the CBAM is useful for blunting producer losses.[18]

We evaluate domestic welfare effects by considering consumer and producer surplus alongside government revenue. The CBAM raises government revenue because it taxes emissions-intensive imports, but these CBAM revenues are much smaller

[17] Appendix tables A5 and A6 show unadjusted carbon prices of \$96.29 for the EU and EFTA and \$88.13 for the UK. These unadjusted prices do not account for allowances and exemptions, which are to be phased out over time.

[18] These free allowances effectively reduce carbon pricing from \$100 in unadjusted terms to roughly \$25 per ton of CO_2. In our data, the average adjusted carbon price across European plants is \$22.39 when weighting by emissions intensity and \$31.90 when weighting by production. It is straightforward to evaluate CBAM policy relative to this baseline rather than our zero-regulation benchmark. Appendix table D3 evaluates European regulation at $\tau^R = 100$ relative to $\tau^R = 25$, and it decomposes the total effect of CBAM regulation into the effect of removing allowances and the effect of imposing a CBAM. European producers lose \$17B as allowances are phased out, and the CBAM reduces these losses by \$1B. Ambec et al. (2024) shows that the provision of free allowances is itself a source of policy richness that our simple decomposition abstracts from.

Table 6: CBAM regulation

(a) Europe as R

	With CBAM			No CBAM		
	Europe	China	Rest of world	Europe	China	Rest of world
Price (%)	1.22	0.33	0.33	0.41	0.41	0.41
Consumer surplus ($1B)	-2.12	-3.08	-2.62	-0.67	-3.92	-3.16
Producer surplus ($1B)	-22.07	3.17	2.61	-23.07	4.02	3.04
Government revenue ($1B)	22.87	0.00	0.00	22.48	0.00	0.00
Welfare ($1B)	-1.32	0.10	-0.01	-1.26	0.11	-0.12
Global welfare ($1B)		-1.23			-1.28	
Emissions (Mt)	-24.03	3.34	2.23	-24.81	4.85	2.84
Global emissions (Mt)		-18.45			-17.12	

(b) Europe and China as R

	With CBAM			No CBAM		
	Europe	China	Rest of world	Europe	China	Rest of world
Price (%)	6.27	6.27	4.22	5.54	5.54	5.54
Consumer surplus ($1B)	-10.26	-59.30	-31.00	-9.10	-52.62	-39.58
Producer surplus ($1B)	-14.30	-162.3	31.94	-15.38	-168.6	41.06
Government revenue ($1B)	23.58	203.5	0.00	23.06	201.7	0.00
Welfare ($1B)	-0.98	-18.12	0.94	-1.42	-19.58	1.49
Global welfare ($1B)		-18.16			-19.52	
Emissions (Mt)	-18.20	-344.6	29.40	-18.98	-359.5	38.52
Global emissions (Mt)		-333.4			-340.0	

We simulate carbon taxation at $\tau^R = 100$ USD per ton of CO_2 with and without a CBAM, imposing $\tau^U = 0$ elsewhere. Market R is Europe in the top table, and Europe and China in the bottom table. We compute effects relative to zero regulation ($\tau^R = \tau^U = 0$). Prices are in percentage changes relative to observed prices. Global welfare sums over domestic welfare, which in turn sums over domestic consumer surplus, producer surplus, and government revenue, as measured in billions of USD. Global emissions sum over domestic emissions, as measured in megatons of CO_2. Price effects are revenue-weighted averages of aluminum and steel, while other effects sum over aluminum and steel.

than those from domestic carbon taxation. First, a large proportion of European consumption is produced domestically rather than imported. Second, domestic producers must pay domestic carbon taxes, but foreign producers can reallocate sales to avoid the CBAM. Taken together, European carbon taxation raises \$22.48B in government revenue even without a CBAM. With a CBAM, government revenue rises to \$22.87B. Combining consumer and producer surplus with government revenue, weighing each equally, the domestic welfare losses from European regulation total \$1.32B with a CBAM and \$1.26B without a CBAM. The CBAM slightly exacerbates European welfare losses on net, as gains in producer surplus and government revenue do not offset losses to consumer surplus.

However, the CBAM also increases global emissions reductions. It does so by reducing leakage in China and the rest of the world. Without the CBAM, higher prices encourage additional production in unregulated markets, such that emissions rise by 4.85 Mt in China and 2.84 Mt in the rest of the world. The CBAM dampens prices in these markets, such that emissions rise instead by a smaller 3.34 Mt in China and 2.23 Mt in the rest of the world. Emissions leakage falls by 28%. We note that the CBAM also raises prices in Europe, such that European emissions rise relative to carbon taxation without a CBAM. But this additional production is subject to carbon taxation, and so the resulting emissions are priced. In total, global emissions fall by 18.45 Mt with a CBAM, relative to a smaller 17.12 Mt without a CBAM.[19] A small increase in European welfare losses achieves a large increase in global emissions reductions. The next section will formalize the comparison of our welfare and emissions effects.

Turning to table 6b, we highlight large potential impacts of a climate coalition that includes China. Price effects are stronger because Chinese regulation greatly expands the size of the regulated market. Indeed, price effects of roughly 5% are sizable relative to $\tau^R = 100$, given observed prices of \$2,256 per ton for aluminum and \$1,011 for steel. Consumers suffer worldwide, while unregulated producers benefit in the rest of the world. Government revenue is substantial at more than \$200B for China. The CBAM reduces welfare losses for Europe and China because it amounts to trade policy that – independent of emissions concerns – allows Europe and China

[19] We ignore the impacts of trade reallocation on shipping emissions, which we expect to be minimal. Shapiro (2016) finds that a transition to autarky would affect shipping emissions by only 5%.

to exercise market power and manipulate their terms of trade. In doing so, they raise domestic government revenues from CBAM taxes that are borne in part by foreign producers. European welfare losses fall from \$1.42B without a CBAM to \$0.98B with a CBAM, while Chinese losses fall from \$19.58B to \$18.12B. In total, the 9% reduction amounts to \$1.9B in gains. The CBAM lessens global emissions reductions, as higher prices in Europe and China encourage additional (carbon-priced) production, but smaller welfare losses compensate for lower abatement. Moreover, with or without a CBAM, global emissions reductions are large at more than 330 Mt, which amounts to 9% of the total emissions observed in the data.

Appendix table D1 separates the effects for aluminum and steel. Steel is the larger industry and drives our total effects, which sum over steel and aluminum, but the qualitative results are consistent across metals. Appendix table D2 reruns counterfactuals with primary aluminum and steel alone. Our baseline analysis treats primary and secondary metals as perfect substitutes in consumption, but certain industries like aerospace and automotive manufacturing rely more heavily on higher-grade primary metals. In restricting markets to primary metals, we rule out substitution to secondary metals. The results are quantitatively similar because primary metals are roughly 70% of production and 85% of emissions, but larger price effects reflect the lack of low-emission secondary substitutes. Appendix figures D1 and D2 plot effects for all levels of carbon taxation τ^R from \$0 to \$100 per ton of CO_2. Weaker regulation has smaller but qualitatively similar effects.

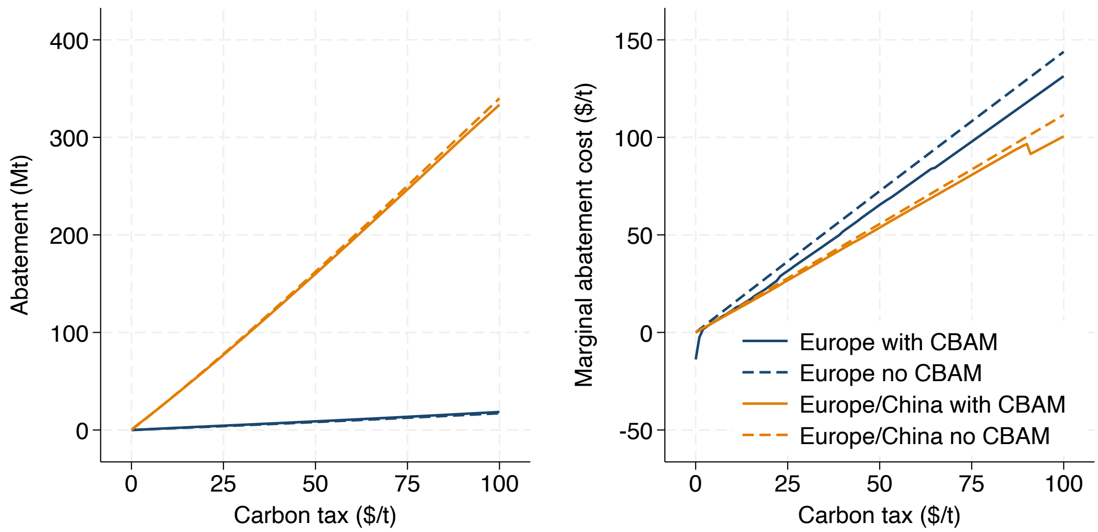
7.2 Optimal policy

We weigh global welfare against global emissions to evaluate impacts on global social welfare, which optimal policy seeks to maximize.[20] Regulation has positive impacts on net if the gains from reducing global emissions, given a social cost of carbon (SCC), exceed the accompanying losses to global welfare. The trade-off is summarized by the marginal abatement cost, which captures the marginal losses to global welfare from additional reductions in global emissions. Regulation maximizes its positive impacts when the marginal abatement cost coincides with the SCC. Figure 5 plots abatement and marginal abatement costs at each level of carbon taxation.

[20] We define welfare $W = CS + PS + G$ for consumer surplus CS, producer surplus PS, and government revenue G and social welfare $W' = W - \sigma E$ for emissions E and SCC σ.

Figure 5: Global emissions

(a) Abatement (b) Marginal abatement costs



We simulate European carbon taxation τ^R of increasing severity, as plotted on the x-axis, imposing $\tau^U = 0$ in non-coalition markets. We compute effects relative to zero regulation ($\tau^R = \tau^U = 0$). The solid lines show impacts with a CBAM, and the dashed lines without a CBAM. The orange lines are in coalition with China. Abatement is reductions in global emissions, which sum over all markets, as measured in megatons of CO_2. Marginal abatement costs are the marginal losses to global welfare from further reductions in global emissions, as measured in USD per ton of CO_2. We sum over aluminum and steel.

On the left, abatement is linear in carbon taxation. It is similar with and without a CBAM, although a European and Chinese coalition has larger effects than a European coalition alone. On the right, CBAMs and larger coalitions both reduce marginal abatement costs.

Thus, while CBAMs may not affect the level of abatement, they do reduce its marginal costs. Without a CBAM, European carbon taxation at $100 per ton of CO_2 has a marginal abatement cost of $144. With a CBAM, this cost falls to $131 – a reduction of 9%. Stated differently, for an SCC of $100 per ton of CO_2, European carbon taxation without a CBAM should not exceed $69. After this point, the marginal abatement cost exceeds the SCC. With a CBAM, Europe can tax carbon up to $76 without exceeding the SCC.[21] Similarly, when Europe and China both tax carbon at $100, the marginal abatement cost is $112 without a CBAM and $101 with a CBAM.

[21] In figure 5b, $144 and $131 are the y-values of the blue lines at $100 on the x-axis, while $69 and $76 are the x-values of the blue lines at $100 on the y-axis.

Given an SCC of \$100, Europe and China can tax up to \$89 without a CBAM and \$99 with a CBAM. CBAMs and larger coalitions allow for stronger taxation and larger emissions reductions, while remaining cost-effective. The intuition is that CBAMs and larger coalitions reduce leakage, which makes for more efficient abatement and lower abatement costs.[22]

European policy implements a border adjustment for the full difference in domestic and foreign carbon pricing, but policymakers could also consider partial border adjustments. Appendix table D6 simulates CBAMs that impose 75%, 50%, and 25% of the difference in carbon pricing. We find that a full border adjustment minimizes marginal abatement costs, although partial adjustments can also be effective.

7.3 Policy spillovers

We study how a European CBAM influences Chinese policy incentives. Indeed, China has already responded to the EU CBAM by expanding Chinese regulation to cover the initial CBAM-targeted sectors. Table 7 shows how Chinese outcomes change when China joins Europe in taxing carbon at \$100 per ton of CO_2. In the first column, Europe taxes carbon with a CBAM, and China joins the CBAM coalition. In the second column, China joins in taxing carbon but not in implementing a CBAM. In the third column, Europe taxes carbon without a CBAM, and China joins in taxing carbon without a CBAM. In each case, domestic Chinese welfare falls by roughly \$20B. Although regulation raises substantial government revenue of more than \$200B, China loses on net because its consumers suffer greatly from higher prices, and its producers must bear the burden of regulation. Whether Europe has a CBAM or not, carbon regulation remains unappealing for a Chinese government focused solely on domestic welfare, without regard for global emissions.

However, CBAM policy helps to close the gap. First, European CBAM policy reduces the Chinese welfare losses from Chinese regulation. Comparing the first and third columns, these losses are \$19.69B when China joins in regulating without a CBAM, and they fall to \$18.22B when China joins in regulating with a CBAM – a

[22] The more nuanced explanation is that leakage creates allocative inefficiency, as high-cost firms gain market share simply because they are unregulated. As a result, leakage raises emissions with only limited welfare gains. That is, to eliminate leakage is to reduce emissions with only limited welfare losses. Thus, efforts to reduce leakage also reduce abatement costs.

Table 7: Policy spillovers for China

Europe:	With CBAM		No CBAM
China / China:	With CBAM	No CBAM	No CBAM
Price (%)	5.94	5.24	5.13
Consumer surplus (\$1B)	-56.23	-49.75	-48.70
Producer surplus (\$1B)	-165.5	-172.0	-172.7
Government revenue (\$1B)	203.5	201.7	201.7
Welfare (\$1B)	-18.22	-20.05	-19.69
Global welfare (\$1B)	-16.93	-18.31	-18.24
Emissions (Mt)	-347.9	-363.0	-364.4
Global emissions (Mt)	-314.9	-321.6	-322.9

We simulate European carbon taxation at $\tau^R = 100$ USD per ton of CO_2 with a CBAM (scenario a) and without a CBAM (scenario b), imposing $\tau^U = 0$ elsewhere. We then simulate China joining in regulation at τ^R with a CBAM (scenario c) and without a CBAM (scenario d), imposing $\tau^U = 0$ elsewhere. We compute effects for China in differences, resulting in three columns. The first and second columns isolate the impacts of Chinese regulation with a CBAM ($c-a$) and without a CBAM ($d-a$), relative to not regulating, when Europe regulates with a CBAM. The third column isolates the impacts of Chinese regulation without a CBAM, relative to not regulating, when Europe regulates without a CBAM ($d - b$). Prices are in percentage changes relative to observed prices. Global welfare sums over domestic welfare, which in turn sums over domestic consumer surplus, producer surplus, and government revenue, as measured in billions of USD. Global emissions sum over domestic emissions, as measured in megatons of CO_2. Price effects are revenue-weighted averages of aluminum and steel, while other effects sum over aluminum and steel.

reduction of 7%. The reason is that the CBAM reduces China's ability to free-ride on the welfare gains that it enjoys when Europe taxes carbon. Smaller free-riding incentives result in smaller welfare losses from regulation. Second, Chinese CBAM policy also reduces the Chinese welfare losses from Chinese regulation. Comparing the first and second columns, the CBAM losses of \$18.22B are 9% smaller than the no-CBAM losses of \$20.05. The reason is that CBAMs advantage domestic governments. Third, we note that China suffers most when Europe regulates with a CBAM but China regulates without a CBAM. In this case, European border adjustment induces unregulated foreign producers to reallocate sales to China, intensifying competition for regulated Chinese producers if China does not itself adopt border adjustment. China should pair regulation with a CBAM.

Moreover, the Chinese government may itself value global emissions reductions.

Chinese regulation reduces global emissions by more than 300 Mt, and the benefits of these emissions reductions may outweigh the domestic welfare losses discussed above. CBAM policy again helps to close the gap. When China joins Europe in regulating without a CBAM, China incurs $19.69B in domestic welfare losses to reduce global emissions by 322.9 Mt. The average domestic welfare cost is $61 per ton of CO_2 averted. When China joins Europe in regulating with a CBAM, China incurs $18.22B in domestic welfare losses to reduce global emissions by 314.9 Mt. Emissions reductions are smaller but more efficient, as the CBAM reduces leakage and brings the average cost down to $58. China benefits on net if it values global emissions reductions by more than $58 per ton.

Appendix table D5 shows that carbon regulation in Europe and China has similar impacts on policy incentives in the rest of the world. When Europe and China tax carbon without a CBAM, the rest of the world incurs $7.89B in domestic welfare losses from imposing its own carbon tax. When Europe and China tax carbon with a CBAM, these domestic welfare losses for the rest of the world fall by 7% to $7.35B. These losses do not depend on the rest of the world's own choice to impose a CBAM because regulation is global when the rest of the world joins Europe and China in taxing carbon. When regulation is global, a CBAM does not bind.

7.4 Global incidence

We assess the incidence of CBAM impacts across countries. We isolate these impacts by computing the differences between outcomes with and without a CBAM. Table 8 shows the countries with the largest gains and losses from European regulation at $100 per ton of CO_2 with a CBAM, relative to European regulation without a CBAM. Figure 6 plots these country-level gains and losses against GDP per capita. We show consumer surplus impacts for all countries that consume aluminum or steel in our baseline data. We show producer surplus effects for all countries that produce.

Outside of Europe, a CBAM places downward pressure on prices. Large consumers gain, while large producers lose. Table 8 shows that Chinese consumers benefit most. The CBAM increases Chinese consumer surplus by $841M. American and Indian consumers also gain $114M and $79M, respectively. For China and India, consumer gains are fully offset by producer losses. Producers in these countries are relatively emissions-intensive (appendix table B3), and so they are directly exposed

Table 8: European CBAM impacts by country

(a) Consumer surplus

Largest gains ($1M)		Largest losses ($1M)	
China	841	Germany	-340
USA	114	Italy	-221
India	79	France	-116
Japan	52	Spain	-109
South Korea	36	Poland	-88

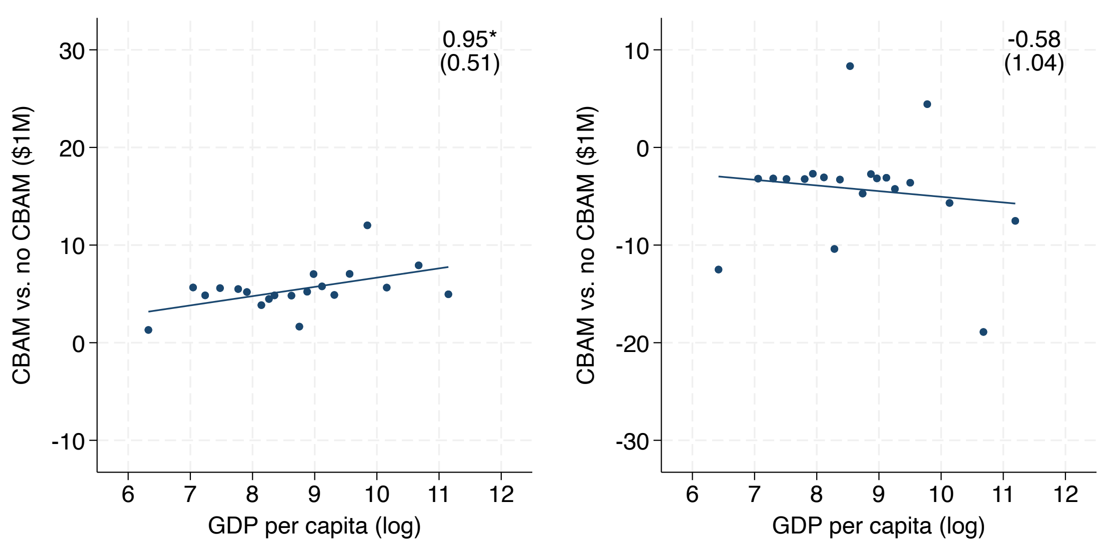
(b) Producer surplus

Largest gains ($1M)		Largest losses ($1M)	
Germany	203	China	-847
Italy	167	India	-79
Norway	156	Russia	-66
France	87	Japan	-42
Iceland	77	Canada	-39

We simulate European carbon taxation at $\tau^R = 100$ USD per ton of CO_2 with and without a CBAM, imposing $\tau^U = 0$ elsewhere. For each country, we compute the difference between CBAM and no-CBAM effects. We sum over aluminum and steel. We show those with the largest gains and losses from the CBAM, as measured in millions of USD.

Figure 6: European CBAM impacts by income

(a) Consumer surplus (b) Producer surplus



We simulate European carbon taxation at $\tau^R = 100$ USD per ton of CO_2 with and without a CBAM, imposing $\tau^U = 0$ elsewhere. For each country, we compute the difference between CBAM and no-CBAM effects. We sum over aluminum and steel. For countries in the rest of the world, we plot these differences in millions of USD against log GDP per capita. GDP data are from the World Bank. We control for observed consumption on the left and for observed production on the right. We report the slope and standard error of the fitted line in the top-right corner of each figure. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

to CBAM regulation. That is, the CBAM imposes a double burden on high-emission producers outside of Europe: taxes on exports to Europe and lower prices outside of Europe. Producers in Russia and Japan are less emissions-intensive in relative terms, but they also suffer large losses. They remain subject to the second burden as equilibrium prices fall for all non-European producers, who all face stronger competition from high-emission products that reallocate away from Europe. Producer losses are minimal for the US, which primarily benefits as a large consumer. The US should favor European border adjustment.

Within Europe, a CBAM places upward pressure on prices. German consumers lose \$340M in consumer surplus, and Italian consumers lose \$221M. Losses also exceed \$100M for France and Spain. However, producers gain from higher prices, which capture the domestic competitive advantages of CBAM policy. Germany gains \$203M in producer surplus, while Italy gains \$167M and Norway gains \$156M. The CBAM helps European producers, regardless of their own emissions intensity, by driving up market-wide prices.

Figure 6 plots the same country-level effects by income. A European CBAM has clear impacts on high-income European countries, and so we focus on the more ambiguous implications for countries in the rest of the world. We control for baseline quantities to avoid capturing larger surplus effects simply because higher-income countries are larger consumers and producers. For both consumer and producer surplus, the CBAM has similar impacts on higher- and lower-income countries in the rest of the world. The flat relationship for consumption suggests that higher- and lower-income countries are similar in their consumption patterns. All benefit from the lower prices induced by the CBAM. The flat relationship for production is consistent with our findings in section 4. Emissions intensity is similar across higher- and lower-income countries, resulting in similar exposure to the CBAM.

Appendix table D4 and figure D3 show the country-level incidence of European and Chinese regulation with a CBAM, relative to regulation without a CBAM. On the consumption side, the US, India, and Japan gain \$1.6B, \$1.3B, and \$0.8B in consumer surplus, respectively, as the CBAM places downward pressure on prices outside of Europe and China. Chinese consumers suffer greatly with a loss of \$6.7B as Chinese prices rise sharply under a CBAM. On the production side, Chinese producers enjoy these higher Chinese prices and gain a total of \$6.3B in producer surplus. Indian, Russian, and American producers lose nearly $3.3B collectively as the CBAM targets their exports, although consumer gains still far outweigh producer losses for the US. CBAM impacts remain income-neutral across the rest of the world.

7.5 Implementation challenges

A challenge in implementing a CBAM is measuring the emissions associated with any particular import. While it is straightforward to identify the country of origin, it is more difficult to trace goods back to their plants of origin. We leverage our plant-level measurement of emissions to assess coarser but more feasible forms of regulation. Rather than imposing the CBAM on plant-specific emissions, as in our baseline analysis, we instead do so on country-level average emissions. We consider country-level averages that distinguish aluminum and steel, and potentially between primary and secondary production. The coarsest regulation taxes aluminum and steel imports based on their global average values.

Table 9 shows that country-level regulation is as effective as plant-specific regulation, if not slightly better, for global welfare, emissions, and marginal abatement costs. The typical intuition might suggest a different result, as coarse regulation suffers from imprecision in targeting carbon emissions. However, our setting features another effect: CBAM regulation prompts emissions-intensive producers to reallocate sales to unregulated markets, and this reallocation undercuts the effectiveness of regulation. Country-level regulation has the benefit of minimizing reallocation, as it pools high- and low-emission imports and thus mutes the incentives to reallocate. For regulation with a CBAM at $100 per ton of CO_2, the gains from reduced reallocation offset the losses from imprecise targeting. At the same time, regulation with global average values leads to higher marginal abatement costs because it is too imprecisely targeted. Country-level regulation is both effective and feasible.

7.6 Green investment

Carbon regulation may encourage green investment over the long run. We incorporate this margin in simple form by allowing emissions intensity e_i to respond counterfactually to carbon taxation τ^m with semi-elasticity γ. For observed emissions intensity $\bar{e}_i$ and carbon taxes $\bar{\tau}^m$, we specify $\log e_i = \log \bar{e}_i - \gamma(\tau^m - \bar{\tau}^m)$, where

Table 9: Coarse regulation

	Europe CBAM			Europe/China CBAM		
	Global welfare ($1B)	Global emissions (Mt)	MAC ($/t)	Global welfare ($1B)	Global emissions (Mt)	MAC ($/t)
Plant-specific measures	-1.23	-18.45	131.3	-18.16	-333.4	100.5
Country-mode averages by metal	-1.23	-18.45	131.3	-18.14	-333.2	100.4
Country averages by metal	-1.26	-19.46	129.1	-18.06	-332.5	100.2
Global averages by metal	-2.01	-23.93	169.7	-18.07	-311.2	104.1

We simulate European carbon taxation at $\tau^R = 100$ USD per ton of CO_2 with a CBAM, alone and with China, imposing $\tau^U = 0$ in non-coalition markets. We compute effects relative to zero regulation ($\tau^R = \tau^U = 0$). The CBAM taxes imported goods based on plant-specific, country-mode average, country average, and global average emissions intensities. Average intensities distinguish between aluminum and steel. Mode refers to primary or secondary production. Global welfare sums over domestic welfare, which in turn sums over domestic consumer surplus, producer surplus, and government revenue, as measured in billions of USD. Global emissions sum over domestic emissions, as measured in megatons of CO_2. Marginal abatement costs are the marginal losses to global welfare from further reductions in global emissions, as measured in USD per ton of CO_2. We sum over aluminum and steel.

$\gamma = -\frac{\partial \log e_i}{\partial \tau^m} = -\frac{\partial e_i}{\partial \tau^m}\frac{1}{e_i}$ captures the percentage decrease in emissions intensity per dollar of carbon regulation.[23] Our baseline analysis treats emissions intensity as fixed, such that $\gamma = 0$ and $e_i = \bar{e}_i$ as observed. If $\gamma > 0$, then higher taxes $\tau^m > \bar{\tau}^m$ induce lower emissions intensity $e_i < \bar{e}_i$, each relative to those observed.

Table 10 simulates future market expansion for aluminum and steel, adding 50% to each country's baseline consumption level and 50% to each plant's production capacity. By comparison, industry projections for 2050 suggest global market growth of 30% to 40% for aluminum and steel (IEA 2020, IAI 2021). We fix the emissions intensity of existing capacity at current levels, given the sunk nature of capital investments, but we allow for the greening of new capacity in response to carbon regulation. For regulation with a CBAM at $100 per ton of CO_2, we find that green expansion amplifies global emissions reductions and decreases abatement costs. When $\gamma = 0.1$, such that the carbon tax prompts a modest 10% reduction in the emissions intensity of new capacity, the marginal abatement cost of regulation falls by nearly 30% for a

[23] Substituting, net prices become $p_i^m = P^m - \frac{\tau^m \bar{e}_i}{\exp[\gamma(\tau^m - \bar{\tau}^m)]}$. The direct effect of taxation τ^m is to lower net prices by taxing each ton of emissions. The indirect effect is to raise net prices by reducing emissions intensity, thereby blunting the impact of carbon taxation on production.

Table 10: Green expansion

	Europe CBAM			Europe/China CBAM		
	Global welfare ($1B)	Global emissions (Mt)	MAC ($/t)	Global welfare ($1B)	Global emissions (Mt)	MAC ($/t)
Expansion ($\gamma = 0$)	-1.84	-27.68	131.3	-27.24	-500.1	100.5
Green expansion ($\gamma = 0.1$)	-1.77	-38.90	95.75	-25.74	-595.4	81.97
Green expansion ($\gamma = 0.2$)	-1.69	-50.37	73.51	-24.60	-686.5	69.47
Green expansion ($\gamma = 0.3$)	-1.62	-61.94	59.00	-23.72	-773.1	61.01

We simulate European carbon taxation at $\tau^R = 100$ USD per ton of CO_2 with a CBAM, alone and with China, imposing $\tau^U = 0$ in non-coalition markets. We compute effects relative to zero regulation ($\tau^R = \tau^U = 0$). Expansion introduces 50% additional production capacity while also increasing metal demand by 50%. Green expansion allows the emissions intensity of new production capacity to respond to carbon regulation with elasticities of 0.1, 0.2, and 0.3. The emissions intensity of existing production capacity remains fixed. Global welfare sums over domestic welfare, which in turn sums over domestic consumer surplus, producer surplus, and government revenue, as measured in billions of USD. Global emissions sum over domestic emissions, as measured in megatons of CO_2. Marginal abatement costs are the marginal losses to global welfare from further reductions in global emissions, as measured in USD per ton of CO_2. We sum over aluminum and steel.

European CBAM and by nearly 20% for a European and Chinese CBAM. Appendix table D7 allows existing plants to adjust by investing in green technology, and this contemporaneous adjustment further amplifies abatement and decreases its costs.

7.7 Discussion

A growing number of papers use quantitative trade models to study trade policy and the environment, while others draw on older computable general equilibrium models.[24] We take a more micro approach. First, we observe production and emissions intensity at the plant level, rather than relying on average measures by country and industry. Second, we specify a relatively detailed model of supply that accommodates plant-specific responses to regulation, rather than abstracting from this heterogeneity. Third, we estimate both demand and supply with identification challenges in mind, rather than calibrating the model or drawing on external estimates. But relative

[24] Costinot and Rodríguez-Clare (2014) provide an overview of quantitative trade models. Caliendo and Parro (2022) and Copeland et al. (2022) survey the use of quantitative trade models to study trade policy and environmental policy, respectively. Bergman (2005) surveys computable general equilibrium modeling of environmental policy.

to more macro approaches, we restrict equilibrium effects to operate through goods prices within our commodity markets of interest. We do not account for spillovers on upstream or downstream products, adjustments in labor or local factor markets, or interactions across sectors or space. Richer equilibrium models capture these margins by imposing additional modeling structure. We stay closer to the data.

We note that our model allows for the frictionless reallocation of trade in response to price differences across countries. However, this reallocation may incur switching costs in practice. Wolfram et al. (2025) compares our baseline model to one with trade frictions. The authors simulate a heavy industry climate coalition that would jointly implement carbon regulation with a CBAM, with qualitatively similar estimates across models. For aluminum and steel, emissions reductions are 15% smaller with trade frictions, while revenues from regulation are nearly identical. Price increases among coalition members are roughly 30% larger with trade frictions, while output changes are somewhat smaller.

We also note the potential for trade retaliation, given that CBAMs impose import tariffs. Our analysis can speak to these concerns, and indeed we find that CBAMs have negative impacts on foreign producers. But first, CBAM policy is nondiscriminatory across trade partners, as it imposes the same carbon tax regardless of origin. Second, foreign producers still gain on net from regulation with a CBAM. European regulation hinders European producers, and so foreign producers face less competition and enjoy higher profits. It is simply that they gain more from regulation without a CBAM. Third, the CBAM enhances profits for low-emission foreign producers, who have access to elevated European prices. Fourth, the CBAM benefits foreign consumers, who appreciate lower prices. Taken together, CBAMs have relatively muted net effects on foreign welfare.

8 Conclusion

CBAMs are a new policy tool for tackling global climate change. We combine a quantitative equilibrium model with detailed plant-level data to evaluate the global impacts of CBAM policies. We show that CBAMs increase domestic competitiveness, which may facilitate establishing carbon regulation in the first place. We also show that CBAMs reduce emissions leakage and encourage carbon regulation abroad.

CBAMs do so without placing disproportionate pressure on lower-income countries, as production in lower-income countries is not systematically more carbon-intensive than it is in higher-income countries.

Future work could extend our analysis in several directions. First, we have examined the most emissions-intensive and highly traded industries targeted by the EU today. Quantifying impacts for other major sectors, including agriculture, chemicals, and energy, will be important for understanding the full potential of CBAM policy. Second, CBAMs create green incentives at global scale. Their long-run, dynamic effects on innovation and technology adoption will shape structural change and facilitate the green transition. Third, as real-world experience with CBAMs evolves, researchers will learn more about how this policy tool operates in practice. Effective CBAM policy will be crucial for meeting global climate targets. Our next steps should be guided by rigorous empirical analysis.

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Online Appendix

A Data Construction

Secondary aluminum production

We obtain country-level data on secondary aluminum production in 2023 from the World Bureau of Metal Statistics (WBMS). We include the top 10 secondary aluminum-producing countries: Brazil, China, Germany, India, Italy, Japan, South Korea, Norway, Taiwan, and the United States. These countries account for 90% of worldwide secondary aluminum production. We estimate secondary aluminum capacity for each country as the maximum production observed over the last 10 years. We set emissions intensity to 10% of that for primary aluminum. We use country-level averages for countries that produce both primary and secondary aluminum and regional averages for countries that only produce secondary.

Production costs include aluminum scrap, labor, energy, maintenance, and depreciation costs. For labor, energy, maintenance, and depreciation costs, we use country-level averages from the WoodMac data where secondary and primary-aluminum producing countries overlap. Out of the top 10 recycled aluminum-producing countries, we do not observe primary aluminum production in 2023 for Italy, Japan, South Korea, or Taiwan. We construct regional cost averages to extrapolate production costs for these countries. According to an independently verified environmental product declaration and life cycle assessment conducted by UL Solutions for the Aluminum Association, the production of an ingot of secondary aluminum requires on average only 8% of the energy required to produce an ingot of primary aluminum. We estimate energy costs for secondary aluminum proportionally as 8% of primary aluminum production. We estimate country-level domestic prices for aluminum scrap, which is the most costly input for secondary production, as the weighted average of the import and export prices reported under the commodity code 7602, "Aluminum; waste and scrap." Appendix table D2 shows robustness to excluding these secondary data.

Steel production

Our steel cost data is based on the Global Steel Cost Tracker (GSCT), a dataset that estimates plant-level raw materials, energy, labor, and overhead costs for 433 plants in 13 of the major steel producing countries (Brazil, China, Germany, India, Italy, Japan, South Korea, Mexico, Russia, Turkey, Ukraine, the United States, and Vietnam). The dataset is produced in collaboration between TransitionZero, a climate data and analytics startup, and Global Efficiency Intelligence, a research and consulting firm focused on industrial decarbonization. We merge plant-level data from Climate TRACE with the plant-level data from GSCT using longitude and latitude.

The set of plants that are in both datasets account for 71% of global production. For plants that are not included in the GSCT but are in one of the 13 countries, we estimate costs using separate country-level averages for BF-BOF and EAF plants. When countries do not overlap, we extrapolate costs using separate regional averages for BF-BOF and EAF steel. We observe 357 BF-BOF plants and 535 EAF plants. Climate TRACE also monitors the primary aluminum market, and appendix table A1 validates that the Climate TRACE and WoodMac measures are consistent.

Metal consumption

The WBMS data also measure consumption of "Primary Aluminium," "Secondary Aluminium," "Aluminium & Alloy," and "Crude Steel Equivalent" in 2023. Each measures "apparent consumption," defined as country-level production net of imports and exports. We take "Aluminium & Alloy" and "Crude Steel Equivalent" as our baseline measures of aluminum and steel consumption, respectively, noting that each combines primary and secondary consumption. Appendix table A2 compares our consumption and production measures, and we find that the data align well: the WBMS data record total consumption that exceeds our measure of total production by only 3% for aluminum and 10% for steel. We adjust the consumption data by scaling consumption in each country to eliminate these differences, as our model imposes market clearing and thus the equalization of world consumption and production. At the global level, we note that apparent consumption is equal to production because imports and exports balance in aggregate. Thus, our USGS data on historical world production also give historical world consumption.

Plant ownership

We define state and foreign ownership based on majority-stakeholder parent companies. For aluminum, we manually code this ownership for 74 unique parent companies. For steel, we draw state ownership from the Climate TRACE data, which code parent companies as fully or partially state-owned. We assume 50% state ownership for those that are partially state-owned. We determine foreign ownership by examining where each parent company produces across its potentially multiple plants. Roughly 90% produce in only one country, and we assume these companies operate in those countries. We otherwise assign parent companies to where they produce the most. There are seven parent companies that produce in multiple countries, but with less than 50% of their production in any given country. We code these companies manually. Appendix table A3 presents ownership by country, production-weighting across plants within each country.

Shipping costs

We obtain 2021 shipping cost estimates for shipping by sea from the UN Trade and Development (UNCTAD) trade and transport dataset. Appendix table A4 presents the data. Aluminum refers to "Aluminium; unwrought," and steel to "Iron or non-alloy steel; semi-finished products thereof." Shipping costs are small, with average rates that are roughly 5% of world goods prices. These average rates aggregate over all country-to-country trade flows globally. We also observe continent-to-continent averages, noting that trade policy may redirect trade – including across continents – and therefore affect shipping costs. However, even freight costs at the 90th percentile of those observed remain small relative to goods prices.

Table A1: Primary aluminum data

	Climate TRACE	WoodMac
Production (Mt)	67	69
Capacity (Mt)	76	81
Scope 1 emissions (Mt)	169	156
Scope 1 and 2 emissions (Mt)	687	676
Number of countries	36	34
Number of smelters	148	153

We use the WoodMac data as our baseline measure of primary aluminum production for 2023. We compare it to similar data on primary aluminum production from Climate TRACE. Emissions are in megatons of CO_2.

Table A2: World quantities

	Production (Mt)	Consumption (Mt)	Difference (%)
Aluminum	84.40	87.20	3.32
Steel	1,672	1,849	10.55

Plant-level production data for 2023 come from WoodMac for aluminum and from Climate TRACE for steel. Country-level consumption data for 2023 come from the World Bureau of Metal Statistics. We report global production and consumption in the unadjusted data in megatons, as well as the differences between the two. We adjust our consumption data by scaling to eliminate these differences.

Table A3: State and foreign ownership

(a) Aluminum

	State (%)	Foreign (%)
China	33	0
India	10	50
Europe	23	32
USA	0	3
Russia	4	0
Rest of world	42	44

(b) Steel

	State (%)	Foreign (%)
China	10	0
Europe	11	9
Japan	0	0
USA	2	17
India	39	10
Rest of world	20	12

Europe includes the EU, UK, and EFTA. State ownership is whether the majority-stakeholder parent company is a state-owned enterprise. Foreign is whether the majority-stakeholder parent company is headquartered in a different country from a given plant. We compute the production-weighted average across plants within each country.

Table A4: Shipping costs

	Freight ($/t)			Price ($/t)
	World	p10	p90	World
Aluminum	124	100	201	2,256
Steel	44	41	73	1,011

Sea shipping costs for 2021 come from the UN Trade and Development (UNCTAD) Trade-and-Transport Dataset. Freight rates average over country-to-country trade flows. We report world averages, as well as the 10th and 90th percentiles of the continent-to-continent averages that we observe in the data. Prices are our baseline world prices for aluminum and steel.

Table A5: Carbon pricing, aluminum

(a) Primary aluminum

	Prices ($/t)	
Country (Region)	Unadjusted	Adjusted
Argentina	3.27	3.27
Canada (British Columbia)	48.03	48.03
Canada (Quebec)	29.84	4.25
China (Chongqing Municipality)	4.66	0.28
China (Guangdong Province)	12.34	0.49
China (Hubei Province)	6.96	0.52
France	96.29	20.26
Germany	96.29	74.30
Greece	96.29	71.28
Iceland	96.29	17.24
Kazakhstan	1.12	0.98
New Zealand	34.20	7.59
Norway	96.29	16.20
Romania	96.29	70.04
Slovenia	96.29	69.34
South Africa	8.93	2.23
Sweden	96.29	25.31
United Kingdom	88.13	35.59

(b) Secondary aluminum

	Prices ($/t)	
Country	Unadjusted	Adjusted
Germany	96.29	30.92
Italy	96.29	0.00
Japan	2.17	2.17
Norway	96.29	0.00
South Korea	11.24	0.00

Prices in USD per ton of CO_2. Adjusted prices deduct regional emissions allowances based on 2023 emissions estimates and production volumes.

Table A6: Carbon pricing, steel

	Prices ($/t)	
Country (Region)	Unadjusted	Adjusted
Argentina	3.27	3.27
Austria	96.29	43.29
Belgium	96.29	11.23
Bulgaria	96.29	33.60
Canada (Ontario)	48.03	26.56
Canada (Quebec)	29.84	1.34
Canada (Saskatchewan)	48.03	3.00
Chile	5.00	5.00
China (Chongqing Municipality)	4.66	0.23
China (Fujian Province)	4.66	0.64
China (Guangdong Province)	12.34	4.42
China (Hubei Province)	6.96	0.30
China (Shanghai Municipality)	8.72	0.52
China (Tianjin Municipality)	4.60	0.09
Czechia	96.29	20.85
Finland	96.29	14.43
France	96.29	7.83
Germany	96.29	35.78
Greece	96.29	21.79
Hungary	96.29	27.47
Italy	96.29	28.85
Japan	2.17	2.17
Kazakhstan	1.12	0.49
Luxembourg	96.29	0.00
Mexico	1.15	1.15
Mexico (México)	3.53	3.53
Netherlands	96.29	44.17
New Zealand	34.20	34.20
Norway	96.29	0.00
Poland	96.29	53.00
Portugal	96.29	0.18
Romania	96.29	23.36
Singapore	3.77	3.77
Slovakia	96.29	43.43
Slovenia	96.29	15.91
South Africa	8.93	2.23
South Korea	11.24	3.49
Spain	96.29	3.11
Sweden	96.29	32.17
Switzerland	93.81	0.00
Ukraine	0.82	0.82
United Kingdom	88.13	20.78

Prices in USD per ton of CO_2. Adjusted prices deduct regional emissions allowances based on 2023 emissions estimates and production volumes.

B Stylized Facts

Table B1: Emissions intensity by GDP per capita

	Aluminum		Steel	
	GDP	Controls	GDP	Controls
GDP per capita (log)	-0.0378	0.0148	0.0252	-0.0921
	(0.0896)	(0.111)	(0.0728)	(0.0597)
Primary production (%)		0.990**		1.461***
		(0.440)		(0.279)
Average production (Mt)		0.585*		0.202*
		(0.309)		(0.111)
State ownership (%)		-0.271		0.474**
		(0.291)		(0.201)
Foreign ownership (%)		-0.105		-0.541*
		(0.367)		(0.297)
Average plant age (years)		-0.00933		-0.00259
		(0.00662)		(0.00249)
Observations	38	34	77	77

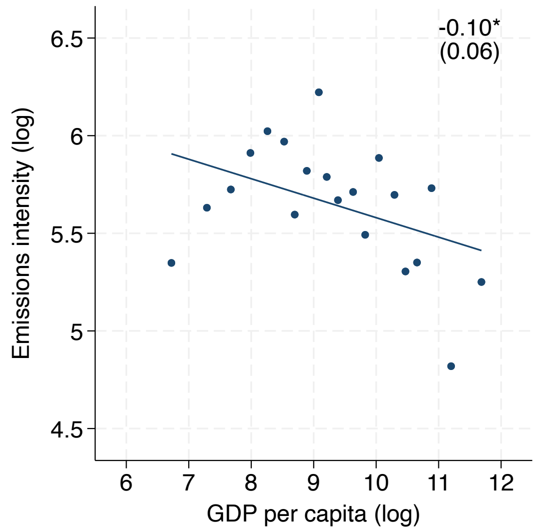
Each column is one regression, and each observation is a country. The outcome variable is the log of emissions intensity, which we measure in tons of CO_2 emitted per ton of production. GDP data are from the World Bank. Controls include the proportion of primary production, average quantity of production, proportion of state ownership, proportion of foreign ownership, and average plant age across plants within each country. Primary production refers to primary aluminum and BF-BOF steel. State ownership is whether the majority-stakeholder parent company is a state-owned enterprise. Foreign is whether the majority-stakeholder parent company is headquartered in a different country from a given plant. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

Table B2: Electricity emissions intensity by metal

	Aluminum (%)	Steel (%)
Direct (production)	23	91
Indirect (electricity)	77	9

Direct emissions are from production itself (Scope 1), while indirect emissions are from electricity use (Scope 2). We aggregate across plants in our sample.

Figure B1: Electricity emissions intensity by income



The figure is a binned scatter plot, and each observation is a dataset-country. Electricity emissions intensity is in grams of CO_2 per kilowatt-hour, as measured at the country level in four datasets with a total of 370 observations (Ang and Su 2016, EEA 2025, Electricity Maps 2025, Ember 2025). GDP data are from the World Bank. We plot each in log terms. We report the slope and standard error of the fitted line in the top-right corner of each figure. We control for dataset fixed effects, and we cluster standard errors by country. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

Table B3: Emissions intensity by country

(a) Aluminum

	t
Kazakhstan	15.2
South Africa	14.2
India	13.5
Australia	12.7
China	10.2
UAE	6.6
Bahrain	6.6
Qatar	6.6
Saudi Arabia	6.5
Oman	6.4
World average	8.2

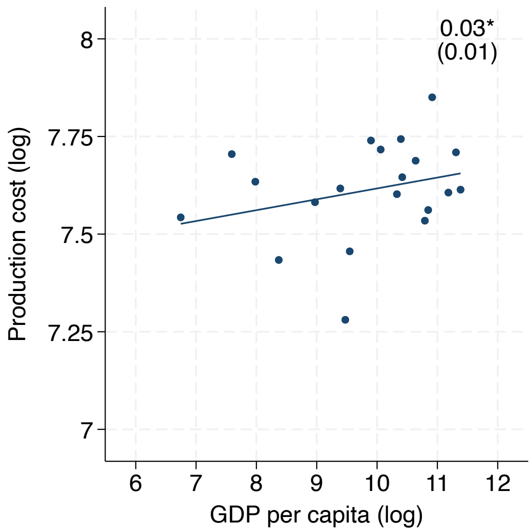
(b) Steel

	t
Kazakhstan	2.6
Ukraine	2.4
South Africa	2.3
China	2.2
Serbia	2.2
Vietnam	2.1
India	2.0
Australia	1.9
Brazil	1.9
Japan	1.9
World average	1.9

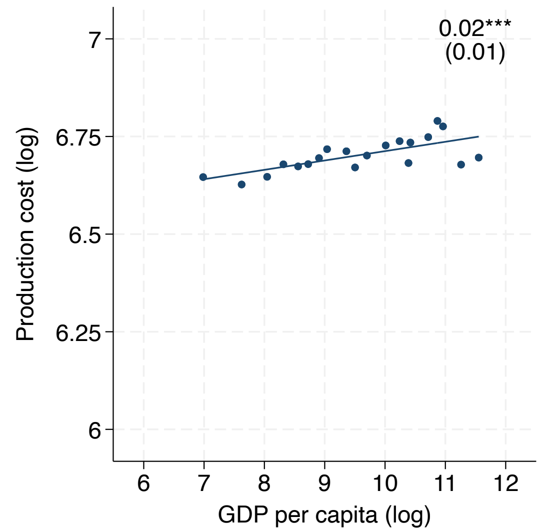
Emissions intensity is in tons of CO_2 per ton of production. We compute production-weighted averages across plants.

Figure B2: Production costs

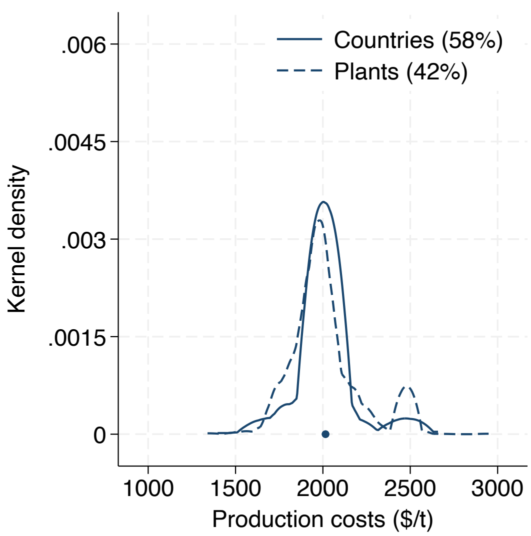
(a) Aluminum



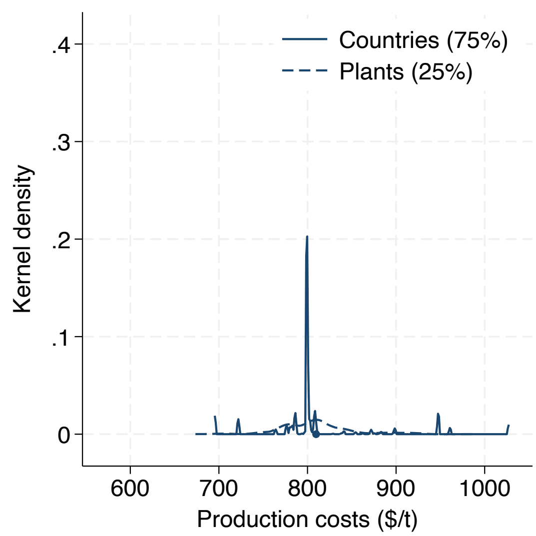
(b) Steel



(c) Aluminum



(d) Steel



On the top, each figure is a binned scatter plot, and each observation is a country. GDP data are from the World Bank. We plot each in log terms. We report the slope and standard error of the fitted line in the top-right corner of each figure. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$. On the bottom, each figure is a kernel density plot. Production costs are in USD per ton of production. The dot marks the world average. The solid line plots country averages, and the legend shows R^2 when regressing plant-level production costs on country fixed effects. The dashed line plots plant-level production costs, demeaned by the country averages and centered at the world average. The legend shows $1 - R^2$.

C Model and Estimation

Model equivalence

We note the equivalence between imposing a CBAM on importers in market R, as implemented in practice, and imposing a CBAM on exporters in market U, as written in our baseline model. We demonstrate this equivalence as follows.

Consider regulated market R and unregulated market U. For clarity, market R imposes carbon tax τ on domestic emissions and CBAM tax μ on imported emissions. We lighten notation by assuming that market U imposes zero regulation. We can express our baseline equilibrium conditions in the following general form.

$$
\begin{aligned}
D^R(P^R) &= S^{RR}(P^R,\tau)\cdot\pi^{RR}(P^R,P^U) + S^{UR}(f(P^R,\mu))\cdot\pi^{UR}(f(P^R,\mu),P^U),\\
D^U(P^U) &= S^{RU}(P^U,\tau)\cdot[1-\pi^{RR}(P^R,P^U)] + S^{UU}(P^U)\cdot[1-\pi^{UR}(f(P^R,\mu),P^U)]
\end{aligned}
$$

We impose CBAM μ on the supply side, with μ entering supply S^{UR} that originates in market U but is consumed in R. Consumption $D^R(P^R)$ in R then depends only on market price P^R, and the same holds for consumption $D^U(P^U)$ in U. Demand in each market can be filled by supply from both markets, with plants i selling to R if price P^R dominates price P^U net of taxes (τ,μ). For producers in R, the supply $S^{RR}(P^R,\tau)$ sold to R depends on price P^R, and the same holds for the supply $S^{RU}(P^U,\tau)$ sold to U. Each is subject to domestic tax τ, regardless of destination market, and so the proportion $\pi^{RR}(P^R,P^U)$ sold to R reflects only these prices. For producers in U, the supply $S^{UR}(f(P^R,\mu))$ sold to R depends on price P^R, subject to CBAM tax μ. Function f captures that the impact of μ on net prices in U will depend on the emissions intensity e_i of plants $i\in U$ that export to R. The supply $S^{UU}(P^U)$ sold to U depends on price P^U. The proportion $\pi^{UR}(f(P^R,\mu),P^U)$ sold to R reflects these prices.

We demonstrate equivalence with a change of variables. In particular, we define $\hat{P}^R = f(P^R,\mu)$, such that $P^R = g(\hat{P}^R,\mu)$. Function g captures that the impact of μ on net prices in R will depend on the emissions intensity e_i of plants $i\in U$ that export to R. We then rewrite our baseline equilibrium conditions as follows.

$$
\begin{aligned}
D^R(g(\hat{P}^R,\mu)) &= S^{RR}(g(\hat{P}^R,\mu),\tau)\cdot\pi^{RR}(g(\hat{P}^R,\mu),P^U) + S^{UR}(\hat{P}^R)\cdot\pi^{UR}(\hat{P}^R,P^U)\\
D^U(P^U) &= S^{RU}(P^U,\tau)\cdot[1-\pi^{RR}(g(\hat{P}^R,\mu),P^U)] + S^{UU}(P^U)\cdot[1-\pi^{UR}(\hat{P}^R,P^U)]
\end{aligned}
$$

These rewritten equilibrium conditions impose CBAM μ on the demand side, with μ entering consumption D^R in R. We thus establish equivalence.

CBAM price premium

Under a CBAM, the regulated market pays a price premium in equilibrium ($P^R > P^U$). Market clearing implies that the marginal plant is indifferent between selling to R or U. There are two cases. In the first case, the marginal plant is a plant in market U. It is this case that is empirically relevant, as it captures that R imports from U. Indifference implies $p_i^{UR} = p_i^{UU}$ and thus $P^R - P^U = (\tau^R - \tau^U)e_i$. Thus, $P^R > P^U$ follows immediately from $\tau^R > \tau^U$. In the second case, the marginal plant is a plant in market R. Indifference implies $p_i^{RR} = p_i^{RU}$ and thus $P^R = P^U$, such that the law of one price holds. In this case, the CBAM is not binding and has no impact on world prices. However, this case only obtains when market R does not import from U. The CBAM targets imports, and so without imports it is trivally moot.

Table C1: Demand estimation first stage

	1976-2024	1998-2022	1998-2022	1998-2022
Australian share of ore production	1.185***	0.889***		1.378**
	(0.136)	(0.151)		(0.513)
Concentration of ore production			3.028***	-2.013
			(0.513)	(1.936)
Observations	98	50	50	50
F-statistic	76.36	34.71	34.83	18.70

Each column is a regression of log world prices on the instrumental variables, controlling for metal and year fixed effects. Each observation is a metal-year. Column headers list the years included in each regression sample. The Australian share measures Australia's share of global ore production, where ore refers to bauxite for aluminum and iron ore for steel. The concentration measures the country-level market concentration of ore production, which we compute as a Herfindahl-Hirschman index. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

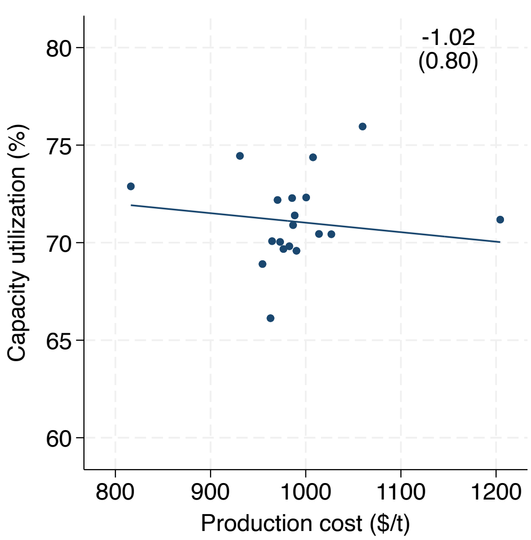
Table C2: Supply estimation

	All costs			Production costs		
	Estimate	SE	Obs	Estimate	SE	Obs
OLS	-1.245***	(0.264)	1,055	-1.244***	(0.265)	1,055
FE: country-metal	0.840	(0.782)	1,005	1.018	(0.804)	1,005
FE: country-metal + controls	2.032**	(0.804)	987	2.201**	(0.840)	987
FE: country-metal-group	2.095**	(0.830)	833	2.057**	(0.826)	833

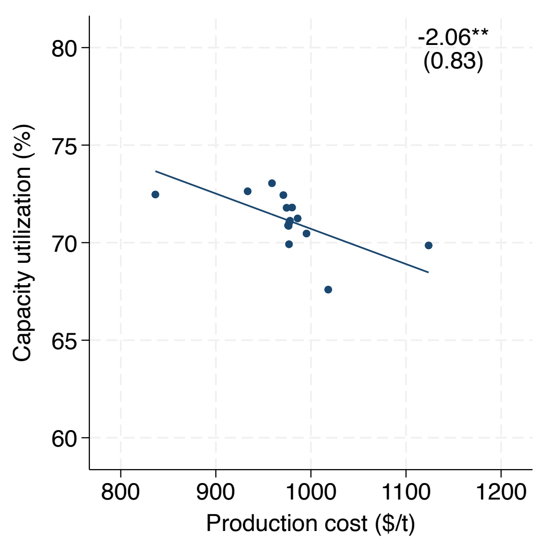
Each row corresponds to two regressions. The regressor sums production and regulatory costs in the first three columns, and it is production costs alone in the last three columns. We measure each in thousands of USD per ton of production. Metals include aluminum and steel. Controls include primary production, state ownership, foreign ownership, and plant age. Groups are the interaction the first three controls, which are binary variables, and quartiles of plant age. Primary production refers to primary aluminum and BF-BOF steel. State ownership is whether the majority-stakeholder parent company is a state-owned enterprise. Foreign is whether the majority-stakeholder parent company is headquartered in a different country from a given plant. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

Figure C1: Capacity utilization

(a) Country-metal FEs



(b) Country-metal-group FEs



Each figure is a binned scatter plot, and each observation is a plant. Capacity utilization is the percentage of capacity used for production. Production costs are in USD per ton of production. We control for country-metal and country-metal-group fixed effects. Groups combine plants by primary production, state ownership, foreign ownership, and plant age quartile. We report the slope and standard error of the corresponding supply regression in the top-right corner of each figure. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

D Counterfactuals

Table D1: CBAM regulation by metal

(a) Aluminum

	With CBAM			No CBAM		
	Europe	China	Rest of world	Europe	China	Rest of world
Price (%)	4.58	-0.15	-0.15	0.32	0.32	0.32
Consumer surplus ($1B)	-0.93	0.17	0.09	-0.07	-0.35	-0.18
Producer surplus ($1B)	-0.43	-0.17	0.05	-0.85	0.35	0.22
Government revenue ($1B)	1.14	0.00	0.00	0.80	0.00	0.00
Welfare ($1B)	-0.21	0.00	0.13	-0.11	-0.00	0.04
Global welfare ($1B)		-0.07			-0.08	
Emissions (Mt)	-1.49	-0.37	-0.11	-1.78	0.77	0.27
Global emissions (Mt)		-1.97			-0.74	

(b) Steel

	With CBAM			No CBAM		
	Europe	China	Rest of world	Europe	China	Rest of world
Price (%)	0.84	0.38	0.38	0.42	0.42	0.42
Consumer surplus ($1B)	-1.19	-3.24	-2.71	-0.60	-3.57	-2.98
Producer surplus ($1B)	-21.64	3.34	2.57	-22.23	3.67	2.82
Government revenue ($1B)	21.73	0.00	0.00	21.68	0.00	0.00
Welfare ($1B)	-1.11	0.10	-0.14	-1.15	0.11	-0.16
Global welfare ($1B)		-1.15			-1.20	
Emissions (Mt)	-22.54	3.71	2.34	-23.03	4.08	2.58
Global emissions (Mt)		-16.48			-16.37	

For each metal, we simulate European carbon taxation at $\tau^R = 100$ USD per ton of CO_2 with and without a CBAM, imposing $\tau^U = 0$ elsewhere. We compute effects relative to zero regulation ($\tau^R = \tau^U = 0$). Prices are in percentage changes relative to observed prices. Global welfare sums over domestic welfare, which in turn sums over domestic consumer surplus, producer surplus, and government revenue, as measured in billions of USD. Global emissions sum over domestic emissions, as measured in megatons of CO_2.

Table D2: CBAM regulation, primary metals

(a) Europe as R

	With CBAM			No CBAM		
	Europe	China	Rest of world	Europe	China	Rest of world
Price (%)	3.15	0.31	0.31	0.54	0.54	0.54
Consumer surplus ($1B)	-3.80	-1.82	-1.65	-0.59	-3.50	-2.83
Producer surplus ($1B)	-18.28	2.37	1.09	-20.52	4.34	2.04
Government revenue ($1B)	21.00	0.00	0.00	19.83	0.00	0.00
Welfare ($1B)	-1.07	0.55	-0.56	-1.29	0.84	-0.78
Global welfare ($1B)		-1.08			-1.23	
Emissions (Mt)	-21.37	2.29	1.40	-23.91	5.68	2.79
Global emissions (Mt)		-17.67			-15.43	

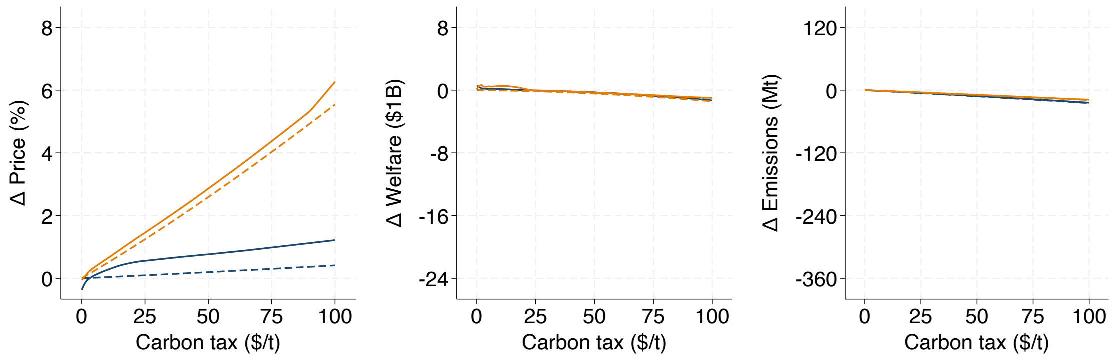
(b) Europe and China as R

	With CBAM			No CBAM		
	Europe	China	Rest of world	Europe	China	Rest of world
Price (%)	7.65	7.65	6.41	7.28	7.28	7.28
Consumer surplus ($1B)	-8.83	-50.88	-32.19	-8.34	-48.16	-36.03
Producer surplus ($1B)	-14.18	-141.8	25.42	-14.43	-144.1	30.09
Government revenue ($1B)	21.36	184.7	0.00	20.51	183.2	0.00
Welfare ($1B)	-1.65	-7.95	-6.76	-2.25	-9.08	-5.94
Global welfare ($1B)		-16.36			-17.27	
Emissions (Mt)	-16.81	-308.6	33.41	-17.06	-319.4	39.28
Global emissions (Mt)		-292.0			-297.2	

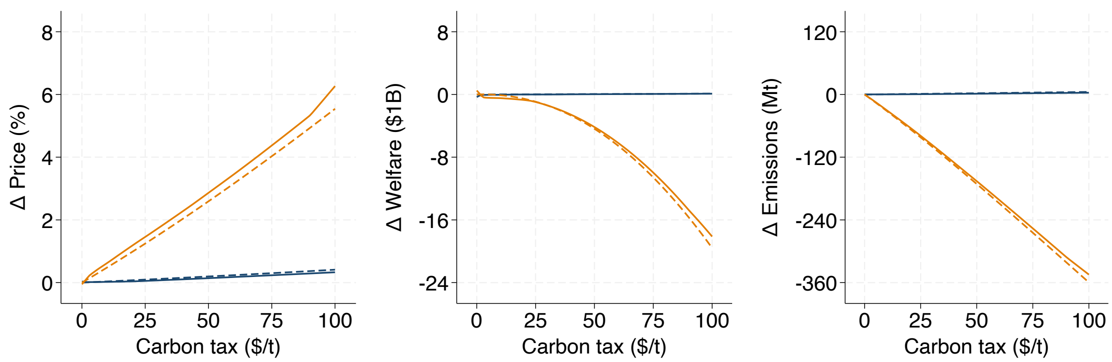
For primary aluminum and steel, we simulate carbon taxation at $\tau^R = 100$ USD per ton of CO_2 with and without a CBAM, imposing $\tau^U = 0$ elsewhere. Market R is Europe in the top table, and Europe and China in the bottom table. We compute effects relative to zero regulation ($\tau^R = \tau^U = 0$). Prices are in percentage changes relative to observed prices. Global welfare sums over domestic welfare, which in turn sums over domestic consumer surplus, producer surplus, and government revenue, as measured in billions of USD. Global emissions sum over domestic emissions, as measured in megatons of CO_2. Price effects are revenue-weighted averages of aluminum and steel, while other effects sum over aluminum and steel.

Figure D1: Prices, welfare, and emissions by market

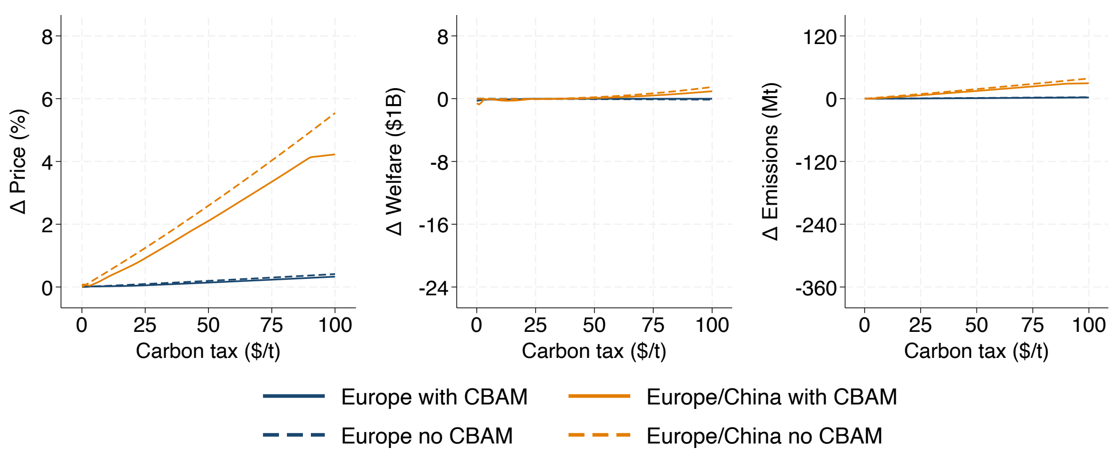
(a) Europe



(b) China



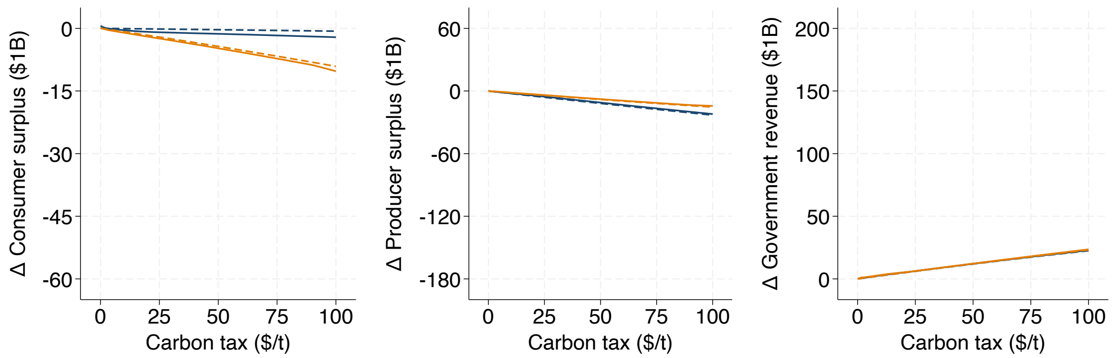
(c) Rest of world



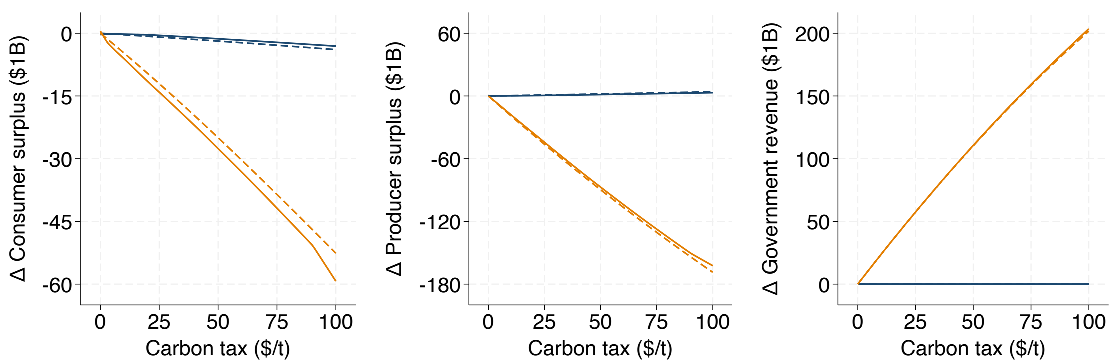
We simulate European carbon taxation τ^R of increasing severity, as plotted on the x-axis, imposing $\tau^U = 0$ in non-coalition markets. We compute effects relative to zero regulation ($\tau^R = \tau^U = 0$). The solid lines show impacts with a CBAM, and the dashed lines without a CBAM. The orange lines are in coalition with China. Prices are in percentage changes relative to observed prices. Welfare sums over consumer surplus, producer surplus, and government revenue. Price effects are revenue-weighted averages of aluminum and steel, while other effects sum over aluminum and steel.

Figure D2: Consumer surplus, producer surplus, and government revenue by market

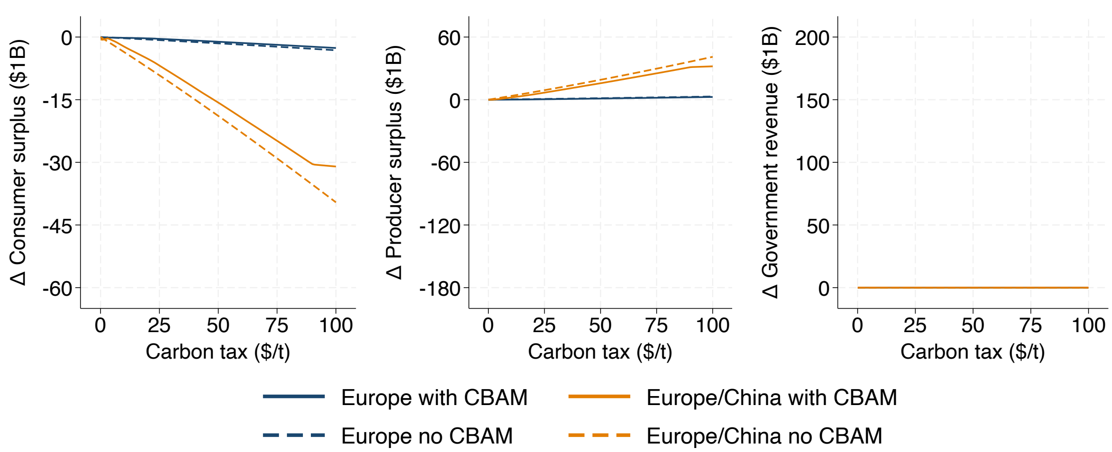
(a) Europe



(b) China



(c) Rest of world



We simulate European carbon taxation τ^R of increasing severity, as plotted on the x-axis, imposing $\tau^U = 0$ in non-coalition markets. We compute effects relative to zero regulation ($\tau^R = \tau^U = 0$). The solid lines show impacts with a CBAM, and the dashed lines without a CBAM. The orange lines are in coalition with China. We sum over aluminum and steel.

Table D3: European allowance phase-out

Europe	Removing allowances	Adding CBAM	Total effect
Price (%)	0.32	0.81	1.12
Consumer surplus ($1B)	-0.51	-1.45	-1.96
Producer surplus ($1B)	-17.07	1.01	-16.06
Government revenue ($1B)	16.38	0.39	16.77
Welfare ($1B)	-1.19	-0.06	-1.25
Global welfare ($1B)	-1.21	0.05	-1.16
Emissions (Mt)	-19.04	0.78	-18.26
Global emissions (Mt)	-13.16	-1.34	-14.50

We simulate European carbon taxation at $\tau^R = 100$ USD per ton of CO_2 with a CBAM (scenario a) and without a CBAM (scenario b), imposing $\tau^U = 0$ elsewhere. We compute effects for Europe relative to a pre-CBAM allowance benchmark with $\tau^R = 25$ and $\tau^U = 0$ (scenario c). The first column moves from $\tau^R = 25$ to 100 ($b - c$), and the second column then adds a CBAM ($a - b$). The third column combines the two ($a - c$). Prices are in percentage changes relative to observed prices. Global welfare sums over domestic welfare, which in turn sums over domestic consumer surplus, producer surplus, and government revenue, as measured in billions of USD. Global emissions sum over domestic emissions, as measured in megatons of CO_2. Price effects are revenue-weighted averages of aluminum and steel, while other effects sum over aluminum and steel.

Table D4: European and Chinese CBAM impacts by country

(a) Consumer surplus

Largest gains ($1M)		Largest losses ($1M)	
USA	1,617	China	-6,684
India	1,322	Germany	-258
Japan	781	Italy	-179
South Korea	575	Spain	-95
Russia	506	France	-92

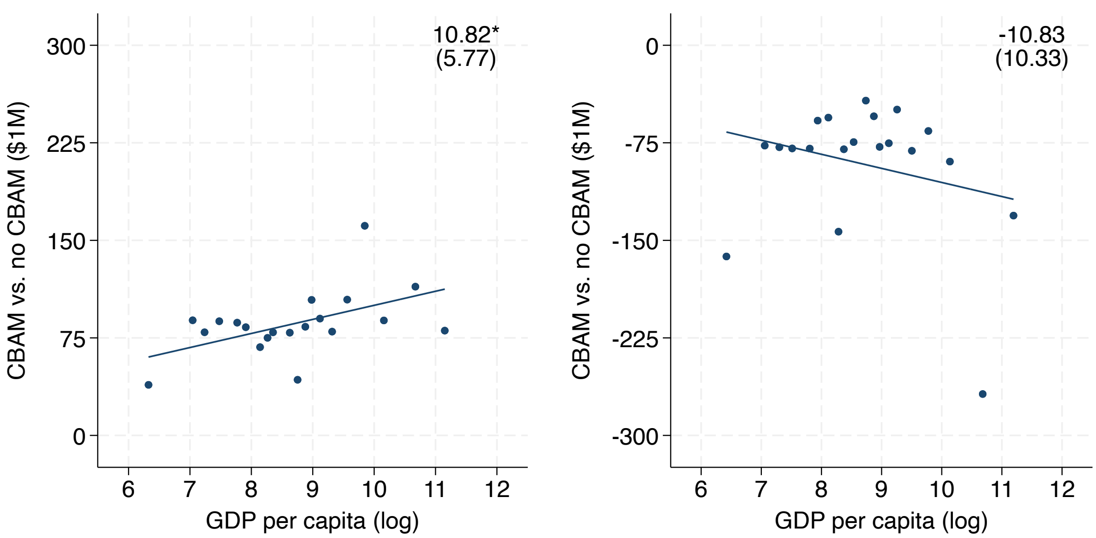
(b) Producer surplus

Largest gains ($1M)		Largest losses ($1M)	
China	6,300	India	-1,276
Germany	245	Russia	-1,055
Italy	182	USA	-927
France	93	Japan	-767
Norway	92	Canada	-551

We simulate European and Chinese carbon taxation at $\tau^R = 100$ USD per ton of CO_2 with and without a CBAM, imposing $\tau^U = 0$ elsewhere. For each country, we compute the difference between CBAM and no-CBAM effects. We sum over aluminum and steel. We show those with the largest gains and losses from the CBAM, as measured in millions of USD.

Figure D3: European and Chinese CBAM impacts by income

(a) Consumer surplus (b) Producer surplus



We simulate European and Chinese carbon taxation at $\tau^R = 100$ USD per ton of CO_2 with and without a CBAM, imposing $\tau^U = 0$ elsewhere. For each country, we compute the difference between CBAM and no-CBAM effects. We sum over aluminum and steel. For countries in the rest of the world, we plot these differences in millions of USD against log GDP per capita. GDP data are from the World Bank. We control for observed consumption on the left and for observed production on the right. We report the slope and standard error of the fitted line in the top-right corner of each figure. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

Table D5: Policy spillovers for rest of world

Rest of world	Europe/China With CBAM	Europe/China No CBAM
Price (%)	4.03	2.72
Consumer surplus ($1B)	-27.93	-19.35
Producer surplus ($1B)	-90.77	-99.88
Government revenue ($1B)	111.3	111.3
Welfare ($1B)	-7.35	-7.89
Global welfare ($1B)	-5.02	-3.67
Emissions (Mt)	-152.0	-161.1
Global emissions (Mt)	-121.7	-115.1

We simulate European and Chinese carbon taxation $\tau^R = 100$ USD per ton of CO_2 with a CBAM (scenario a) and without a CBAM (scenario b), imposing $\tau^U = 0$ elsewhere. We then simulate the rest of the world joining in regulation at τ^R (scenario c). We compute effects for the rest of the world in differences, resulting in two columns. The two columns isolate the impact of regulation in the rest of the world, relative to not regulating, when Europe and China regulate with a CBAM ($c-a$) and without a CBAM ($c-b$). Prices are in percentage changes relative to observed prices. Global welfare sums over domestic welfare, which in turn sums over domestic consumer surplus, producer surplus, and government revenue, as measured in billions of USD. Global emissions sum over domestic emissions, as measured in megatons of CO_2. Price effects are revenue-weighted averages of aluminum and steel, while other effects sum over aluminum and steel.

Table D6: Partial border adjustment

	Europe CBAM			Europe/China CBAM		
	Global welfare ($1B)	Global emissions (Mt)	MAC ($/t)	Global welfare ($1B)	Global emissions (Mt)	MAC ($/t)
Full adjustment	-1.23	-18.45	131.3	-18.16	-333.4	100.5
Partial adjustment (75%)	-1.22	-18.13	133.0	-18.42	-334.9	105.5
Partial adjustment (50%)	-1.22	-17.82	135.8	-18.77	-336.7	106.2
Partial adjustment (25%)	-1.23	-17.51	137.5	-19.09	-338.2	109.7

We simulate European carbon taxation at $\tau^R = 100$ USD per ton of CO_2 with a CBAM, alone and with China, imposing $\tau^U = 0$ in non-coalition markets. We compute effects relative to zero regulation ($\tau^R = \tau^U = 0$). Full adjustment levies 100% of $\alpha^R = \tau^R - \tau^U = 100$ at the border. Partial adjustment levies 25%, 50%, and 75% of α^R. Global welfare sums over domestic welfare, which in turn sums over domestic consumer surplus, producer surplus, and government revenue, as measured in billions of USD. Global emissions sum over domestic emissions, as measured in megatons of CO_2. Marginal abatement costs are the marginal losses to global welfare from further reductions in global emissions, as measured in USD per ton of CO_2. We sum over aluminum and steel.

Table D7: Green technology

	Europe CBAM			Europe/China CBAM		
	Global welfare ($1B)	Global emissions (Mt)	MAC ($/t)	Global welfare ($1B)	Global emissions (Mt)	MAC ($/t)
Fixed technology ($\gamma = 0$)	-1.23	-18.45	131.3	-18.16	-333.4	100.5
Green technology ($\gamma = 0.1$)	-1.08	-41.08	56.32	-15.11	-522.6	54.89
Green technology ($\gamma = 0.2$)	-0.95	-63.64	31.02	-12.36	-700.6	35.75
Green technology ($\gamma = 0.3$)	-0.84	-86.18	18.79	-10.10	-868.4	22.03

We simulate European carbon taxation at $\tau^R = 100$ USD per ton of CO_2 with a CBAM, alone and with China, imposing $\tau^U = 0$ in non-coalition markets. We compute effects relative to zero regulation ($\tau^R = \tau^U = 0$). Fixed technology takes emissions intensity levels as given in the data. Green technology allows emissions intensities to fall – with elasticities of 0.1, 0.2, and 0.3 – in response to carbon regulation, which may induce plants to invest in green technology. Global welfare sums over domestic welfare, which in turn sums over domestic consumer surplus, producer surplus, and government revenue, as measured in billions of USD. Global emissions sum over domestic emissions, as measured in megatons of CO_2. Marginal abatement costs are the marginal losses to global welfare from further reductions in global emissions, as measured in USD per ton of CO_2. We sum over aluminum and steel.