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ABSTRACT

Climate change poses a collective action problem: countries bear the costs of carbon regulation, while benefits are shared globally. Carbon border adjustment mechanisms (CBAMs) aim to realign incentives by extending domestic carbon pricing to imports. Using plant-level data for aluminum and steel, which account for 11% of global CO2 emissions, we document that emissions intensity is income-neutral and uncorrelated with production costs. Carbon pricing introduces a new margin of green comparative advantage. With a quantitative trade model, we show that CBAMs can boost domestic competitiveness, reduce emissions leakage, and facilitate collective climate action, while largely avoiding disproportionate burdens on lower-income countries.

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1 Introduction

Climate change is a collective action problem. The principal challenge is free-riding: unregulated countries enjoy the global benefits of reduced emissions, while regulated countries must bear the costs of carbon regulation (Carraro and Siniscalco 1993, Barrett 1994). The consequence is policy inaction, with some countries regulating while most do not. This lack of global regulation further increases the burden on regulated countries, which suffer diminished competitiveness and carbon leakage as consumption and production shift toward unregulated countries (Hoel 1991).

Economists have argued that trade policy can address these difficulties (Nordhaus 2015). The European Union's carbon border adjustment mechanism (CBAM) is the most ambitious effort to date to implement green trade policy at scale. CBAMs apply domestic carbon taxes to imports at the border, while offering credits for carbon taxes paid abroad. This policy has three effects relative to carbon pricing without a CBAM. First, the border tax levels the competitive playing field and reduces carbon leakage. Second, the border credit encourages foreign governments to regulate. Third, the second effect amplifies the first because competitiveness and leakage concerns diminish as the regulating coalition grows. Carbon taxes become strategic complements. At the same time, the EU itself has raised concerns that the CBAM will disproportionately harm lower-income trading partners (European Commission 2021).

We study the potential for CBAM policies to advance collective climate action, and we show how their benefits and costs are distributed across countries. We focus on aluminum and steel, which are among the largest emissions-intensive and trade-exposed industries in the world. Together, they account for 11% of world emissions and more than \$1 trillion in international trade. We compile detailed, plant-level data that record production, costs, emissions, and regulation for the near-universe of aluminum and steel producers globally.

Our data deliver two stylized facts about emissions intensity that shape the effects of carbon policy. First, emissions intensity is income-neutral. The emissions-income gradient across countries is flat for both aluminum and steel: a 1% change in GDP per capita corresponds to a change in emissions intensity of only -0.04% for aluminum and 0.03% for steel. Production in lower-income countries is therefore no more emissions-intensive than production in higher-income countries, with direct implications for who bears the burden of border adjustment. This pattern extends beyond aluminum and steel to other industrial sectors. Direct emissions from industrial production are income-neutral because they depend primarily on chemistry, not income. Indirect emissions from electricity inputs are income-neutral because power grids in lower-income countries are also no more emissions-intensive than those in higher-income countries. Second, emissions intensity is uncorrelated with production costs. Green plants operate across the cost spectrum, and so carbon pricing introduces a new margin of comparative advantage that is distinct from cost competitiveness. Much of the variation in emissions intensity is within rather than across countries, making plant-level measurement essential for evaluating policies whose incidence runs through emissions.

To this end, we combine our plant-level data with a quantitative equilibrium model of global trade to evaluate the welfare and emissions effects of carbon border adjustment. We model consumption as a simple log-linear function of prices, and we estimate demand with global data over time. We address price endogeneity by instrumenting 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 estimate demand elasticities of -1.69 for aluminum and -1.34 for steel, which suggest that demand is elastic.

We model production as a function of competitive profit margins, which depend on prices and costs. Plants also choose where to export and how much to abate in response to carbon regulation. We leverage plant-level cost data for estimation as in Asker et al. (2019) and Domínguez-Iino et al. (2026). The typical approach specifies and estimates the cost structure of production, but we observe costs directly and need only to estimate the elasticity of production with respect to profit margins. Our cost data provide the variation that we need to identify this elasticity, while avoiding the bias that otherwise arises from unobserved costs. Like Domínguez-Iino et al. (2026), we depart from Asker et al. (2019) in allowing marginal costs to rise as plants approach capacity, rather than assuming that average and marginal costs coincide. We estimate supply elasticities of 0.91 for aluminum and 0.01 for steel, which suggest that supply is inelastic. Steel is especially inelastic because of its primary production technology: blast furnaces must run continuously, as they are costly to idle or restart.

We use the estimated model to quantify the global impacts of carbon taxation and border adjustment 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 reducing foreign prices. At the same time, Europe pays for its green preference with European prices that rise as European supply falls. 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 \$13.5 billion. 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 \$4.9 billion – an improvement of 64%.

Second, CBAMs reduce emissions leakage to unregulated markets. When Europe imposes a \$100 carbon tax without a CBAM, European consumers react by shifting toward imports from foreign producers, who remain beyond the reach of the \$100 tax. On net, European consumption falls by only 0.20%. When Europe taxes carbon with a CBAM, the CBAM extends the tax to foreign imports. European consumers can no longer avoid the tax by increasing imports, and so European consumption falls by a larger 8.0%. Moreover, the CBAM makes European consumption greener by targeting and reducing emissions-intensive imports. The emissions embodied in European consumption fall by 91.8 Mt with a CBAM, relative to a smaller 32.2 Mt without a CBAM – an improvement of 185%.

Third, CBAMs help to encourage carbon taxation in other countries, albeit to varying degrees. For China, it is domestically costly to join Europe in taxing carbon at \$100 per ton of CO_2. Without any border adjustment, Chinese carbon taxation leads to \$205 billion in losses to Chinese consumers and producers, even as it raises \$173 billion in government revenue. Domestic welfare losses total \$31.4 billion, while global emissions fall by 677 Mt. While China may already value these emissions reductions by enough to regulate, we show that a CBAM helps to narrow the gap. With full border adjustment, domestic welfare losses fall to $30.2 billion for China – a meaningful but modest improvement of 4%, which reflects that China exports little to Europe and imports little to tax at its own border. For Japan, South Korea, and Russia, which export more to Europe, border adjustment reduces the domestic welfare costs of regulation by 17%, 17%, and 32%. For the US, where imports to a large home market provide a broad revenue base, border adjustment reduces these costs by 80%. Moreover, as the CBAM coalition grows, the costs of regulation fall further. Carbon taxes are strategic complements when combined with border adjustment.

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 is income-neutral because producers in lower-income countries are not systematically more emissions-intensive than those in higher-income countries. The second is income-neutral because it affects all unregulated producers equally. Nonetheless, a CBAM may still be damaging for producers in particular lower-income countries. For example, when Europe imposes a $100 carbon tax, adding a CBAM reduces Indian producer surplus by $1.54 billion because Indian production is relatively emissions-intensive. At the same time, the CBAM also raises Indian consumer surplus by $1.56 billion, more than offsetting the producer losses.

Fifth, CBAMs encourage emissions abatement among foreign producers. In our model, we explicitly allow plants to invest in abatement technology to reduce their emissions intensity. Carbon taxation encourages this costly abatement. Without a CBAM, carbon taxation achieves emissions reductions with abatement only among European producers, who encounter increasing marginal costs that limit the extent of total abatement. For a $100 carbon tax, we find that emissions fall by 37.3 Mt. With a CBAM, carbon taxation extends to foreign producers who export to Europe, spreading abatement across a larger set of total producers with lower marginal costs. Emissions fall by a larger 48.4 Mt – an improvement of 30%.

Sixth, CBAMs also encourage costly trade reshuffling among foreign producers. While border adjustment induces abatement among foreign producers that continue to export to Europe, it incentivizes others to avoid the border tax by rerouting their exports elsewhere. This reshuffling incurs trade costs and deadweight loss without reducing emissions. We use our plant-level data to simulate border adjustment based on plant-specific emissions, but a practical alternative is coarse adjustment on country-level averages. Another alternative is partial adjustment that taxes 50%, rather than 100%, of the difference in carbon taxation between Europe and the origin country. For a given regulating coalition, we find that coarse adjustment is less effective because plants cannot reduce their individual border charges by abating. Coarse adjustment gives up abatement while retaining reshuffling. Partial adjustment is more effective because it retains abatement while reducing reshuffling.

We build on a body of work that studies international environmental policy coordination and global collective action (Nordhaus 2015, Böhringer et al. 2016, Bourany 2025, Farrokhi and Lashkaripour 2025, Hsiao 2026). Incomplete regulation is of central importance in this literature, particularly as it relates to unilateral climate policy, because incomplete regulation creates competitiveness and leakage concerns (Markusen 1975, Copeland and Taylor 1994, 1995, 2003, Hoel 1996, Rauscher 1997, Elliott et al. 2010, Kortum and Weisbach 2017, Clausing and Wolfram 2023, Harstad 2024, 2025, Brunel and Levinson 2025). We show that border adjustment lessens these concerns and lowers the cost of joining a climate coalition.

Methodologically, a growing number of papers use quantitative trade models or computable general equilibrium models to study the environmental effects of carbon border adjustment (Böhringer et al. 2012, Larch and Wanner 2017, Mörsdorf 2022, Bellora and Fontagné 2023, Casey et al. 2026, Kortum and Weisbach 2026) and of trade more broadly (Shapiro and Walker 2018, Abuin 2024, Caliendo et al. 2024, Farrokhi et al. 2025, Garcia-Lembergman et al. 2025). These papers feature rich global equilibrium effects, but often abstract from plant-level emissions and heterogeneity. Other papers capture this granularity, but with less emphasis on global equilibrium effects (Fowlie 2009, Fowlie et al. 2016, Fowlie and Reguant 2022, Chen et al. 2025, Coster et al. 2025). Our framework combines both elements.

CBAMs are a landmark development for green trade policy. Economists have long studied border adjustment, and policymakers are now putting these ideas into practice. We leverage economic modeling and plant-level measurement to inform the ongoing implementation of CBAM policies across Europe. We highlight their potential as a crucial new tool in our fight against climate change.

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 initially reported the emissions of imported goods, but without financial obligation, and the definitive regime began in January 2026. Free allowances, which are the existing trade competitiveness measure, will be phased out by 2034.[2] The CBAM 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.

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

[1] Draft regulations define qualifying foreign carbon prices as mandatory ETS or carbon taxes, measured net of rebates, refunds, free allocations, and export-linked compensation (European Commission 2026).

[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.

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 Canada's federal backstop for carbon pricing, and the governments of Australia, Brazil, Taiwan, and Turkey are also currently considering CBAMs. Clausing et al. (2024) document that EU CBAM discussions have coincided 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 explicit concerns that the broad adoption of CBAM policies will particularly disadvantage lower-income countries (European Commission 2021, UNCTAD 2021).

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 11% of total global CO_2 emissions, relative to only 4% of global GDP. Other target industries have more limited exposure to CBAM policies. Fertilizers are heavily traded but only a small share of global emissions. Electricity and cement are a large share of global emissions but not heavily traded. Hydrogen is neither heavily traded nor a large share of global emissions.

2.2 Aluminum and steel

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

Table 1: Trade and emissions for CBAM-targeted industries

	Trade intensity (%)	Global emissions (%)
Aluminum	20	3
Steel	18	8
Fertilizer	52	1
Cement	3	6
Electricity	2	33
Hydrogen	0.1	2

Trade intensity is the quantity share of production exported in 2023. Global emissions is the share of total global CO_2 emissions in 2023. Production data come from Climate TRACE for steel, WoodMac and the World Bureau of Metal Statistics for aluminum, the US Geological Survey for cement, the FAO for fertilizer, and the International Energy Agency (IEA) for electricity and hydrogen. Export data come from UN Comtrade. Emission shares for aluminum are from the International Aluminium Institute, and those for other sectors are from the IEA (IAI 2024, IEA 2024).

production extracts aluminum from alumina, which is a compound of aluminum and oxygen. During smelting, carbon combines with alumina to yield aluminum with CO_2 as a byproduct.[3] Moreover, the electricity used in smelting can itself generate substantial CO_2 emissions, particularly when power is drawn from 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.

Steel is a crucial component for global manufacturing, construction, infrastructure, transportation, and energy. It accounts for 8% 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 involves primary production that takes iron ore and metallurgical coal as raw materials. In the production process, pig iron is produced by reducing iron ore in a blast furnace fired by coke, which is a fuel made from coal. Molten pig iron is then transformed into steel by blowing

[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.

oxygen in a basic oxygen furnace to remove carbon, which is released as CO_2. EAF steel involves secondary production that recycles 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.

Both industries are competitive. Aluminum and steel are homogeneous commodities that trade in world markets, and the largest producers of each metal account for only a small share of global output. The top one, five, and ten plants account for 6%, 14%, and 21% of global aluminum production and 1%, 5%, and 8% of global steel production, respectively. Even plants that are large within their national markets face global competition from imports, which are highly substitutable with domestic production. Indeed, it is import substitutability that motivates European CBAM policy in the first place. These competitive downstream markets contrast sharply with upstream markets for ore, where a handful of firms control much of the global production of bauxite and iron ore.

3 Data

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

3.1 Production and consumption

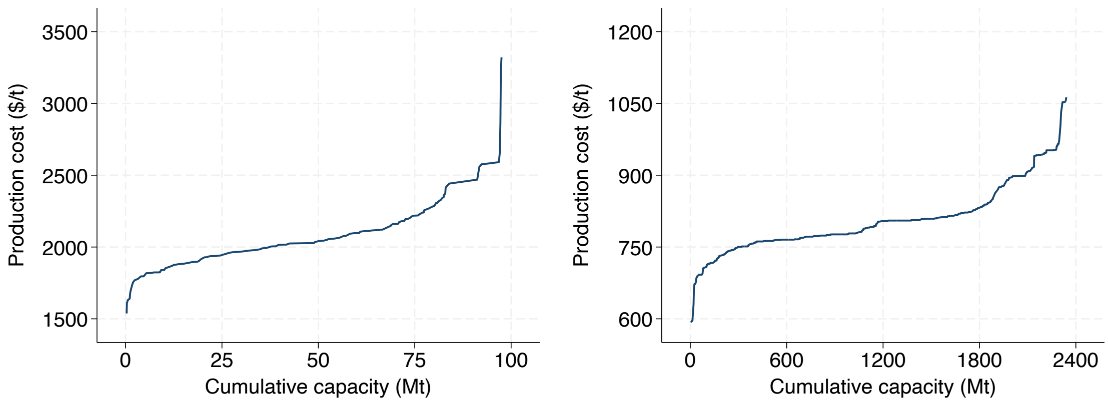
We measure primary aluminum production at the plant level with detailed data from Wood Mackenzie (WoodMac), a leading data provider focused on energy industries and related sectors. These data include 153 plants, covering the global universe of primary aluminum smelters in 2023. The data combine public information with periodic site visits to each plant.[5] We observe detailed information on plant capacity,

[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 average total costs in USD per ton of production. These costs include materials, energy, labor, maintenance, and capital costs. Cumulative capacity is in megatons of production per year, and it sums over plants in ascending order of production costs.

annual production, and average costs of production, along with estimates of both Scope 1 and Scope 2 carbon emissions. Production costs include those from alumina, other raw materials, consumables, energy, labor, maintenance, and depreciation. 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 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 58% of the market.

We obtain steel data at the plant level from Climate TRACE (Tracking Real-time Atmospheric Carbon Emissions), an independent coalition that monitors global greenhouse gas emissions. Climate TRACE publishes monthly estimates of steel capacity, production, and emissions for plants in the Global Steel Plant Tracker (GSPT)

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.

database. These data include 892 plants across 77 countries, covering the global universe of steel mills with a capacity of more than 500 thousand tons. Data on 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] Data on 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 obtain the average costs of production from the Global Steel Cost Tracker (GSCT), which records costs from raw materials, energy, labor, and overhead. 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.[7] China is again dominant at 50% of the market.

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

[7] Energy costs account for roughly half of the cross-plant variation in production costs for both metals, while wage differences play a smaller role.

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.

3.2 Prices and trade

We observe world prices for aluminum and steel. Aluminum prices come from World Bank commodity price data, which derive from the London Metal Exchange 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 measure bilateral trade flows from the UN Comtrade database for 2023, covering unwrought aluminum and non-alloy steel products that match the primary metals our plants produce. We summarize these trade flows in appendix table A3. Most metal is consumed where it is produced: 80% of aluminum and 82% of steel production is sold domestically. China drives this pattern by consuming nearly all of its own production. The European CBAM affects foreign suppliers to Europe, which we list in appendix table A3. CBAM exposure varies widely in proportional terms. Europe's largest aluminum and steel suppliers are the United Arab Emirates and South Korea. The United Arab Emirates exports 27% of its aluminum production to Europe, while South Korea exports a smaller 9% of its steel production to Europe. India is a major supplier of both aluminum and steel. Mozambique is a top aluminum supplier and exports 73% of its production to Europe. China is a top steel supplier but exports only 1% of its production to Europe.

3.3 Regulation and ownership

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 emissions 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 table A4 presents both sets of prices for aluminum and steel in jurisdictions with nonzero carbon prices.

We construct state and foreign ownership for each plant, with ownership defined by the majority-stakeholder parent company. Appendix table A5 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.

4 Stylized Facts

We describe emissions intensity in aluminum and steel production, and we discuss implications for the distributional and competitive effects of carbon policy.

4.1 Emissions intensity is income-neutral

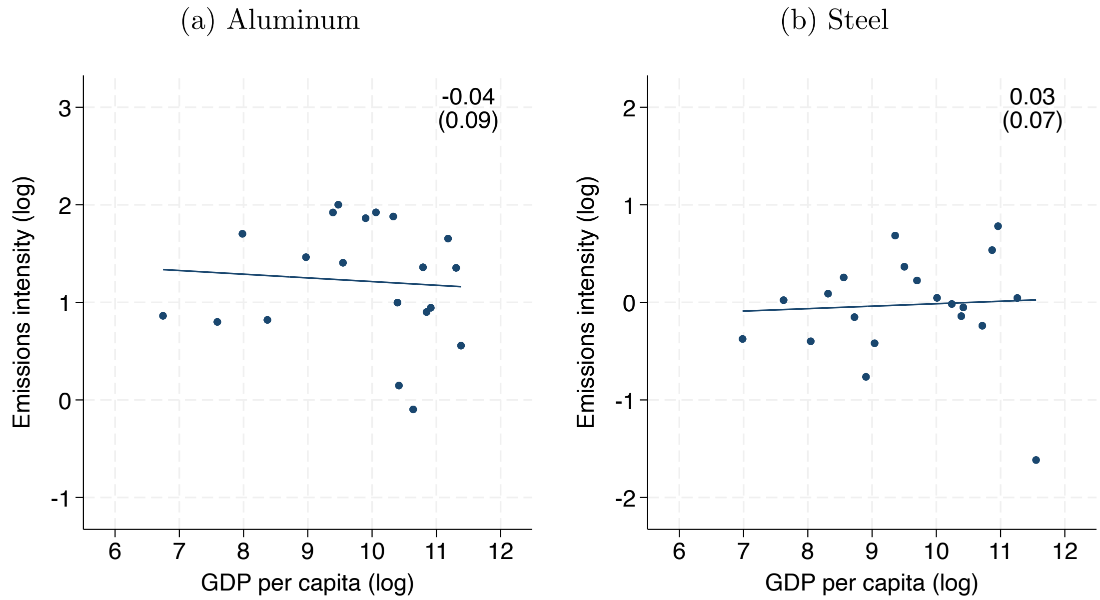
We begin with the distributional effects of carbon policy. If high-emission production is concentrated in lower-income countries, then it is lower-income countries that will bear the tax burden of global carbon pricing. Figure 2 plots emissions intensity against GDP per capita across countries. We plot each in logs so that the slope can be read as an elasticity. We find that the emissions-income gradient is flat for both aluminum and steel, with estimated slopes that are small in magnitude 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 this finding in appendix B. Appendix table B1 shows that the emissions-income gradient remains flat, even when we control for compositional differences in production. Appendix table B2 decomposes total emissions, highlighting electricity emissions (Scope 2) as the main component for aluminum and production emissions (Scope 1) as that for steel. Appendix table B1 then reestimates the gradient along each margin. For aluminum, electricity emissions are no higher in lower-income countries. A flat Scope 2 gradient then yields a flat total gradient. For steel, the flat gradient traces to production emissions, which are dictated by chemical processes. Iron oxide (from iron ore) and carbon monoxide (from coke) react to form CO_2 in fixed proportions, compressing the distribution of emissions intensity across countries. This compression yields a flat Scope 1 gradient and in turn a flat total gradient.[8]

We find that these patterns extend beyond aluminum and steel. Appendix figure B1 shows that the flat electricity gradient holds generally, using two global datasets on electricity emissions intensity across national power grids. Furthermore, the chemical process constraints on Scope 1 emissions may apply across other industrial sectors. We evaluate these other sectors with four global datasets that measure emissions at the country-sector level. Our main dataset comes from Climate TRACE, which covers a range of lower- and higher-income countries and measures emissions per unit of physical output. Appendix figure B2 replicates the flat gradient for aluminum and steel and shows that the same holds for chemicals, petrochemicals, and cement. Together, these five sectors account for 20% of global CO_2 emissions (IEA 2024). Across all datasets, we estimate an elasticity of less than 0.5 in magnitude for 24 of

[8] The chemical reaction between iron oxide and carbon monoxide describes primary BF-BOF steel production. Secondary EAF steel production is less emissions-intensive but has its own chemical-process emissions from direct reduction, electrode oxidation, and flux calcination, which again form CO_2 in fixed proportions. EAF steel accounts for 45% of production in higher-income countries, relative to 28% in lower-income countries. Appendix table B1 shows that the steel gradient is flat both unconditionally and when we control for the extent of EAF production.

Figure 2: 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. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

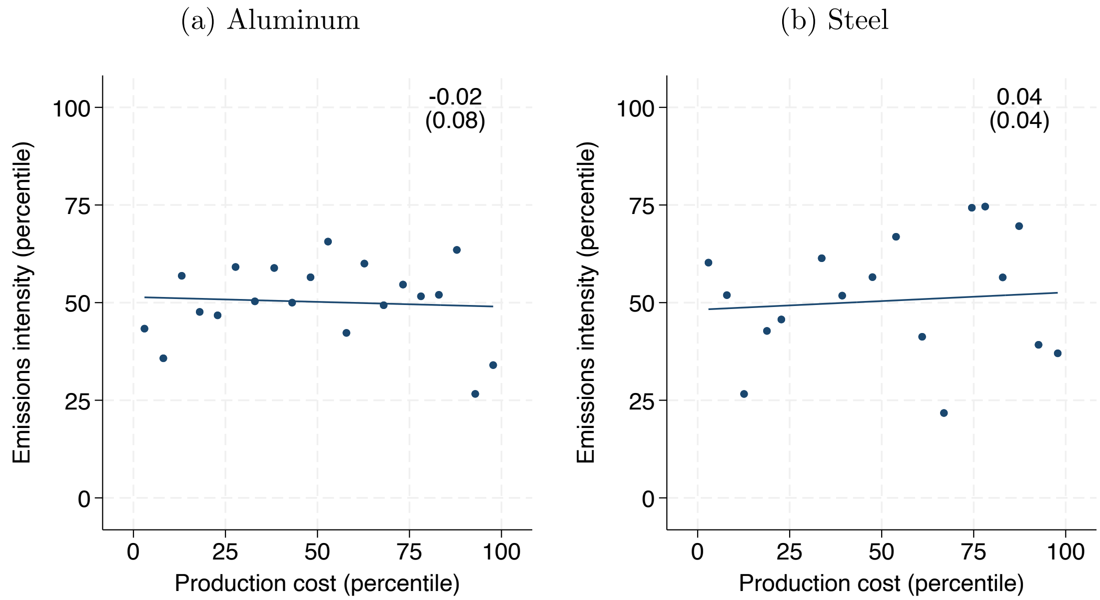
32 sectoral measures.[9] Emissions intensity seems to be broadly income-neutral.

4.2 Carbon pricing rewards green competitiveness

We turn to the competitive effects of carbon policy. When carbon is unpriced, the most competitive plants are those with low production costs. When carbon is priced, low emissions intensity becomes another source of competitiveness. Figure 3 plots plant-level emissions intensity against production costs, where percentiles highlight relative rankings. If emissions intensity and production costs were perfectly positively correlated, then carbon pricing would have no impact on relative competitiveness. We find instead that the emissions-cost gradient is flat for both aluminum and steel, with green plants across the cost spectrum. Carbon pricing therefore introduces a new margin of comparative advantage: the plants that are cost-competitive are not necessarily carbon-competitive.

[9] The more negative gradients are from datasets that record emissions per unit of output value, rather than output quantity. These datasets thus overstate emissions intensity per physical unit in lower-income countries with lower output prices, biasing us toward steeper negative gradients.

Figure 3: Emissions intensity by production costs



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. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

The green competitiveness landscape reflects substantial heterogeneity in emissions intensity across plants, particularly within countries. Appendix table B3 shows that country averages capture less than half of the variation in emissions intensity, but most of the variation in production costs. This contrast makes plant-level measurement especially important for carbon policy because its incidence runs through emissions rather than costs. The same logic constrains the regulator, as a border adjustment levied on country-average emissions would misprice most plants and blunt their incentive to abate. We measure emissions at the plant level and carry this detail into our modeling.

5 Model

We model carbon taxation and a carbon border adjustment mechanism (CBAM) in a world commodity market. We characterize demand, supply, and equilibrium prices under carbon regulation.

5.1 Demand

We specify demand d_{jk} for each product j and country k as a log-linear function of prices p_{jk}.

$$\log d_{jk} = a_{jk} + b_j \log p_{jk} \tag{1}$$

Intercept a_{jk} allows countries to vary in their baseline levels of demand for each product. We will estimate parameter b_j, which captures the sensitivity of consumption to changes in prices. The elasticity of demand is simply

$$\frac{\partial \log d_{jk}}{\partial \log p_{jk}} = b_j,$$

where $b_j < 0$ for downward-sloping demand. Consumer surplus follows from integrating equation 1.[10]

$$\log CS_{jk} = \log d_{jk} + \log p_{jk} - \log(-1 - b_j)$$

5.2 Supply

We specify supply s_{ijk} for competitive plants i, which produce products j in countries k, as a function of prices p_{ijk}.[11] Plants choose how much to produce, where to export, and how much to abate in response to carbon regulation.

Production

A plant i has a collection of production lines $l \in \mathcal{L}_i$, and we model the choice to operate each line. At price p_{ijk}, the utility of operating a line is

$$u^l_{ijk} = v_{ijk} + \epsilon^l_{ijk}, \quad v_{ijk} = \beta_j(p_{ijk} - c_{ijk}). \tag{2}$$

Within a plant, production lines have common costs c_{ijk}, which we do not directly observe, and idiosyncratic cost shocks ϵ^l_{ijk}, which we assume are logit-distributed. We will estimate parameter β_j, which captures the sensitivity of production to changes

[10] Integrating, we have $CS_{jk} = \int_{p_{jk}}^{\infty} \exp(a_{jk}) p^{b_j} dp = \exp(a_{jk}) p_{jk}^{1+b_j} (-1-b_j)^{-1} = d_{jk} p_{jk} (-1-b_j)^{-1}$. If $b_j < -1$, we have CS_{jk} in levels. If $b_j \geq -1$, integrating over $[p_{jk}, p'_{jk}]$ gives CS_{jk} in changes.

[11] We model plants as price-takers, consistent with the competitive market structure described in section 2. Allowing for markups would rescale producer surplus but not affect our main mechanism of interest, by which border adjustment diverts high-emission trade from regulated markets.

in prices and costs.[12]

Logit shocks give production in closed form. At the plant level, production reflects capacity $s_{ijk}^{\max}$ and the probability o_{ijk} of operating a production line.

$$s_{ijk} = s_{ijk}^{\max}\, o_{ijk}, \quad o_{ijk} = \frac{\exp(v_{ijk})}{1 + \exp(v_{ijk})} \tag{3}$$

We take capacity as given, noting that adjustment would require substantial capital investment. Probability o_{ijk} is equivalent to capacity utilization $\frac{s_{ijk}}{s_{ijk}^{\max}}$. The elasticity of supply is

$$\frac{\partial \log s_{ijk}}{\partial \log p_{ijk}} = \beta_j p_{ijk}(1 - o_{ijk}),$$

where $\beta_j > 0$ for upward-sloping supply. Aggregating by product and country, we have $s_{jk} = \sum_{i \in \mathcal{I}_{jk}} s_{ijk}$. Producer surplus follows from the logit log-sum formula, written in terms of utilization.[13]

$$PS_{jk} = -\frac{1}{\beta_j} \sum_{i \in \mathcal{I}_{jk}} s_{ijk}^{\max} \log(1 - o_{ijk})$$

Trade

Through trade, plants can sell to any country ℓ. Each plant chooses destination ℓ to maximize destination price p_{ijk}^{ℓ}, subject to logit shocks ε_{ijk}^{ℓ} with scale $\theta_j > 0$. Price p_{ijk} is the resulting expected price.

$$p_{ijk} = \mathbb{E}\big[\max_{\ell} \{p_{ijk}^{\ell} + \varepsilon_{ijk}^{\ell}\}\big]$$

Destination shares σ_{ijk}^{ℓ} and price p_{ijk} take typical logit form.

$$\sigma_{ijk}^{\ell} = \frac{\exp\big(p_{ijk}^{\ell}/\theta_j\big)}{\sum_{\ell'} \exp\big(p_{ijk}^{\ell'}/\theta_j\big)}, \quad p_{ijk} = \theta_j \log \sum_{\ell} \exp\left(\frac{p_{ijk}^{\ell}}{\theta_j}\right) \tag{4}$$

[12] As is typical, β_j is a profit coefficient that captures how plants value profits in utility terms. Equivalently, we can take profits $(p_{ijk} - c_{ijk})$ as the numeraire, setting $\beta_j = 1$, and instead estimate the scale of the logit shocks.

[13] For a given line, expected utility is $\frac{1}{\beta_j} \log(1 + \exp(v_{ijk})) = -\frac{1}{\beta_j} \log(1 - o_{ijk})$, where the equality holds by equation 3. Summing over lines and plants, we obtain $-\frac{1}{\beta_j} \sum_{i \in \mathcal{I}_{jk}} s_{ijk}^{\max} \log(1 - o_{ijk})$.

Destination shares σ^ℓ_{ijk} determine destination quantities s^ℓ_{ijk}. Destination prices p^ℓ_{ijk} are given by market prices $p_{j\ell}$, net of trade costs δ^ℓ_{jk} and regulatory costs r^ℓ_{ijk}.

$$s^\ell_{ijk} = \sigma^\ell_{ijk} s_{ijk}, \quad p^\ell_{ijk} = p_{j\ell} - \delta^\ell_{jk} - r^\ell_{ijk} \tag{5}$$

Trade costs capture home bias, freight, tariffs, and other frictions that determine the patterns of trade observed in the data. The trade elasticity captures how destination shares respond to market prices. Expressed in gravity form, we have

$$\frac{\partial \log\left(\sigma^\ell_{ijk}/\sigma^k_{ijk}\right)}{\partial \log p_{j\ell}} = \frac{p_{j\ell}}{\theta_j}. \tag{6}$$

Abatement

Regulatory costs r^ℓ_{ijk} capture the costs of carbon taxation. Production involves emissions intensity e, which is subject to carbon taxation τ^ℓ_{jk} that can depend on both origin k and destination ℓ. We allow plants to abate emissions at cost f_{ijk}. Plants choose their emissions intensity to minimize regulatory costs.[14]

$$r^\ell_{ijk} = \min_e \left\{\tau^\ell_{jk} e + f_{ijk}(e)\right\}$$

We specify abatement costs with scale $\gamma_j > 0$, where $(\bar{e}_{ijk}, \bar{\tau}_{jk})$ denote the emissions intensity and carbon taxation observed in the data.

$$f_{ijk}(e) = \gamma_j \left[e \log\left(\frac{e}{\bar{e}_{ijk}}\right) - (e - \bar{e}_{ijk})\right] - \bar{\tau}_{jk}(e - \bar{e}_{ijk})$$

This expression is anchored to match our observed $(\bar{e}_{ijk}, \bar{\tau}_{jk})$.

The minimization problem yields optimal emissions intensity e^ℓ_{ijk} and minimized regulatory costs r^ℓ_{ijk}.

$$e^\ell_{ijk} = \bar{e}_{ijk} \exp\left(\frac{\bar{\tau}_{jk} - \tau^\ell_{jk}}{\gamma_j}\right), \quad r^\ell_{ijk} = \bar{\tau}_{jk}\bar{e}_{ijk} - \gamma_j(e^\ell_{ijk} - \bar{e}_{ijk}) \tag{7}$$

[14] Emissions intensity e measures total emissions, which include direct (Scope 1) and indirect (Scope 2) components. Observed carbon prices apply only to direct emissions, and plants abate only the direct component. Appendix E specifies this distinction.

The elasticity of emissions intensity with respect to the carbon tax is

$$\frac{\partial \log e_{ijk}^{\ell}}{\partial \log \tau_{jk}^{\ell}} = -\frac{\tau_{jk}^{\ell}}{\gamma_j}. \tag{8}$$

Carbon taxation encourages abatement, which reduces emissions intensity. Substituting, we obtain destination prices net of regulatory responses.

$$p_{ijk}^{\ell} = p_{j\ell} - \delta_{jk}^{\ell} - \bar{\tau}_{jk}\bar{e}_{ijk} + \gamma_j(e_{ijk}^{\ell} - \bar{e}_{ijk}) \tag{9}$$

5.3 Regulation

Carbon taxation τ_{jk}^{ℓ} can depend on both origin k and destination ℓ. Consider domestic carbon taxes τ_{jk} and $\tau_{j\ell}$, which countries apply on production within their borders. Without border adjustment, plants are subject only to τ_{jk} at origin k.

$$\tau_{jk}^{\ell} = \tau_{jk} \quad \forall\, \ell$$

By equation 7, it follows that emissions intensity $e_{ijk}^{\ell} = e_{ijk}$ is also destination-invariant. Domestic carbon tax revenue and emissions are

$$G_{jk} = \tau_{jk}E_{jk}, \quad E_{jk} = \sum_{i \in \mathcal{I}_{jk}} e_{ijk}s_{ijk}.$$

With border adjustment, destination ℓ pairs its carbon tax $\tau_{j\ell}$ with a CBAM on imports from other countries k, which may have weaker taxes $\tau_{jk} < \tau_{j\ell}$. The CBAM addresses this discrepancy in carbon taxation.[15]

$$\alpha_{jk}^{\ell} = \tau_{j\ell} - \tau_{jk}$$

The result is that all consumption in ℓ is taxed at $\tau_{j\ell}$, regardless of origin.

$$\tau_{jk}^{\ell} = \tau_{jk} + \alpha_{jk}^{\ell} = \tau_{j\ell} \quad \forall\, k$$

[15] While we levy the CBAM on plants in k that export to ℓ, it is equivalent to levy the CBAM on consumers in ℓ that import from k. Appendix C presents this equivalence result.

The adjustment applies only on imports, as exports from ℓ do not receive a refund at the border. Furthermore, the CBAM generates border tax revenue for ℓ.

$$B_{j\ell} = \sum_{k \neq \ell} \alpha_{jk}^{\ell} \sum_{i \in \mathcal{I}_{jk}} e_{ijk}^{\ell} s_{ijk}^{\ell}$$

The CBAM induces trade diversion with selection on emissions. Consider the trade effects of carbon taxation $\tau_{j\ell}$. Without a CBAM, we have $\tau_{jk}^{\ell} = \tau_{jk}$. Plants are subject only to origin taxes τ_{jk}, and so destination taxes $\tau_{j\ell}$ have no impact on destination shares.[16] With a CBAM, we instead have $\tau_{jk}^{\ell} = \tau_{j\ell}$. It follows that

$$\frac{\partial \log \sigma_{ijk}^{\ell}}{\partial \tau_{j\ell}} = -\frac{(1 - \sigma_{ijk}^{\ell}) e_{ijk}^{\ell}}{\theta_j} < 0,$$

such that $\tau_{j\ell}$ induces plants to shift their exports away from ℓ. High-emission plants shift strongly, while low-emission plants shift weakly. The average emissions intensity of imports into ℓ falls, and that of imports elsewhere rises.

5.4 Equilibrium

Equilibrium prices $\boldsymbol{p}_j = \{p_{jk}\}$ clear markets for each product j and country k. These market prices satisfy equilibrium conditions

$$d_{jk}(p_{jk}) = \sum_{\ell} \sum_{i \in \mathcal{I}_{j\ell}} s_{ij\ell}^{k}(\boldsymbol{p}_j) \quad \forall j, k. \tag{10}$$

On the left-hand side, the quantity demanded d_{jk} depends on market price p_{jk} alone. On the right-hand side, the quantity supplied sums over the flows $s_{ij\ell}^{k}$ into destination k from all origins ℓ, and each flow depends on the full vector of market prices $\boldsymbol{p}_j$ through plants' production and destination choices. The CBAM enters through destination shares, pushing high-emission supply from non-CBAM origins toward non-CBAM destinations, which in turn reduces supply and raises market prices in CBAM destinations.

[16] If $\tau_{jk}^{\ell} = \tau_{jk}$ for all ℓ, then $\frac{\partial p_{ijk}^{\ell}}{\partial \tau_{j\ell}} = 0$ for $\ell \neq k$ by equation 9. Thus, $\frac{\partial \log \sigma_{ijk}^{\ell}}{\partial \tau_{j\ell}} = 0$ by equation 4.

6 Estimation

We construct empirical demand and supply curves for aluminum and steel. The estimated model captures market-level demand responses and plant-level supply responses, which we use to evaluate counterfactual policy.

6.1 Demand

We estimate demand with annual historical data on world consumption. We begin with equation 1, which specifies demand elasticities that are product-specific but common across countries.[17] Adding subscripts for years t,

$$\log d_{jkt} = a_{jkt} + b_j \log p_{jkt},$$

where elasticity b_j is stable over time. Summing across countries k,

$$\log D_{jt} = a_{jt} + b_j \log P_{jt}, \quad a_{jt} = \log \sum_k \exp(a_{jkt}) \left(\frac{p_{jkt}}{P_{jt}} \right)^{b_j}$$

for world demand D_{jt} and world price P_{jt}. Intercept a_{jt} absorbs any dispersion in market prices p_{jkt} relative to world price P_{jt}. Further decomposing $a_{jt} = a_j + a_t + \epsilon_{jt}$, we obtain a panel regression that we estimate with data on aluminum and steel consumption from 1976 to 2024.

$$\log D_{jt} = a_j + a_t + b_j \log P_{jt} + \epsilon_{jt} \tag{11}$$

The coefficient of interest is demand elasticity b_j for aluminum and steel. Although product and year fixed effects a_j and a_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

[17] Country-specific elasticities would require annual data on country-specific consumption, which is more challenging to measure historically.

instrument acts as a supply shifter to the extent that Australian market power raises prices.[18] 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 Australia's ore share is uncorrelated with shocks to world metal demand. We consider two threats to exclusion. The first is a direct effect of Australia's ore share on world metal demand. This threat is limited because, despite being a major ore producer, Australia is a small consumer of aluminum and steel (tables 2 and 3) and thus a small share of world metal demand. The second is a reverse effect of world metal demand on Australia's ore share. This threat is limited if increases in world metal demand lead to proportional increases in ore production across countries. In this case, Australia's ore share remains unaffected, even as the level of Australian ore production rises.[19]

Table 4 presents our estimated demand elasticities. Our baseline IV specification yields elasticities of -1.69 and -1.34, suggesting that demand is elastic. The OLS estimates of -0.40 and -0.61 are biased toward being more inelastic, although the product and year fixed effects help to minimize this bias. In addition to 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 range from -0.80 to -1.17 and are again more elastic than the OLS estimates.

Appendix table D1 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

[18] 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.

[19] The remaining threat is that high world metal demand implies high Australian metal demand, which disproportionately raises Australian ore production and thus increases Australia's ore share. However, each link is weak: Australian metal demand is a small share of world metal demand, Australian ore production is overwhelmingly for export and thus not driven by Australian metal demand, and Australia's ore share increases less than proportionately with Australian ore production because foreign ore production remains in the denominator.

Table 4: Demand elasticities

	Aluminum		Steel		
	Estimate	SE	Estimate	SE	Obs
1976 to 2024					
OLS	-0.40***	0.10	-0.61***	0.06	98
IV: Australian share of ore production	-1.69***	0.61	-1.34***	0.31	98
1998 to 2022					
OLS	-0.47***	0.12	-0.47***	0.08	50
IV: Australian share of ore production	-1.17***	0.41	-0.97***	0.27	50
IV: concentration of ore production	-0.86***	0.33	-0.81***	0.20	50
IV: both instruments	-0.97***	0.30	-0.80***	0.19	50

Each row is a regression of log world consumption on log world prices, controlling for product and year fixed effects. Each observation is a product-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. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

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.

6.2 Supply

We use plant-level production data to estimate supply. We derive an estimating equation in three steps. First, we characterize average costs. Rewriting equation 2,

$$u^l_{ijk} = \beta_j \left(p_{ijk} - c_{ijk} + \frac{\epsilon^l_{ijk}}{\beta_j} \right).$$

For a particular production line l, the marginal revenue from operating the line is given by price p_{ijk}. The marginal cost reflects both plant-specific cost c_{ijk} and line-specific cost shock ϵ^l_{ijk}.

$$MC^l_{ijk} = c_{ijk} - \frac{\epsilon^l_{ijk}}{\beta_j} = p_{ijk} - \frac{u^l_{ijk}}{\beta_j}$$

The first equality follows from the u^l_{ijk} expression above, and the second follows from substituting equation 2. The average cost reflects marginal costs among lines that operate, where a line operates if and only if $u^l_{ijk} > 0$. This conditional average is

$$AC_{ijk} = \mathbb{E}[MC^l_{ijk} \,|\, u^l_{ijk} > 0] = p_{ijk} + \frac{\log(1 - o_{ijk})}{\beta_j o_{ijk}}. \tag{12}$$

The first equality is definitional. The second substitutes the MC^l_{ijk} expression above and applies the properties of the logit distribution.[20]

Second, we characterize prices. In the sample data, carbon taxation is at observed levels $\bar{\tau}_{jk}$ without border adjustment, such that $\tau^\ell_{jk} = \bar{\tau}_{jk}$. Equation 9 simplifies to

$$p^\ell_{ijk} = p_{j\ell} - \delta^\ell_{jk} - \bar{\tau}_{jk}\bar{e}_{ijk},$$

and equation 4 becomes

$$p_{ijk} = P_j - \bar{\tau}_{jk}\bar{e}_{ijk} + \frac{1}{\beta_j}\eta_{jk}, \quad \eta_{jk} = \beta_j\theta_j \log \sum_\ell \exp\left(\frac{p_{j\ell} - \delta^\ell_{jk} - P_j}{\theta_j}\right). \tag{13}$$

This expression decomposes prices p_{ijk} into world price P_j, regulatory costs $\bar{\tau}_{jk}\bar{e}_{ijk}$, and a trade term η_{jk}. The trade term is common across plants, and it captures deviations between destination prices and the world price, inclusive of trade costs δ^ℓ_{jk}. It sums over destinations ℓ and thus depends only on product j and origin k.

Third, we combine equations 12 and 13 to obtain our estimating equation, which expresses parameter of interest β_j as a function of the data.

$$-\frac{\log(1 - o_{ijk})}{o_{ijk}} = \beta_j(P_j - \bar{\tau}_{jk}\bar{e}_{ijk} - AC_{ijk}) + \eta_{jk} + \xi_{ijk} \tag{14}$$

We compute capacity utilization $o_{ijk} = \frac{s_{ijk}}{s^{\max}_{ijk}}$ from observed production s_{ijk} and ca-

[20] We have $\mathbb{E}[MC \,|\, u > 0] = p - \frac{E}{\beta}$ for $E = \mathbb{E}[u \,|\, u > 0] = \frac{1}{\Pr(u>0)} \int_0^\infty ug(u)du = \frac{1}{o} \int_0^\infty ug(u)du$, where $o = \Pr(u > 0)$ by definition. We define $w = G(u)$, such that $dw = g(u)du$, $u = G^{-1}(w)$, $w = G(0) = 1 - o$ when $u = 0$, and $w = 1$ when $u = \infty$. By this change of variables, $U = \int_0^\infty ug(u)du = \int_{1-o}^1 G^{-1}(w)dw$. We note that u is logit-distributed with mean v, and so the CDF is $w = G(u) = 1/[1 + \exp(v - u)]$. Inverting, we have $u = G^{-1}(w) = v + \log w - \log(1 - w)$, which we apply to $U = \int_{1-o}^1 [v + \log w - \log(1 - w)]dw$. Combining, we have $E = \frac{U}{o} = \frac{1}{o}[vw + w\log w + (1-w)\log(1 - w)]^1_{1-o} = v - \log o - (\frac{1-o}{o})\log(1 - o)$. Finally, we apply the logit expression $\log o - \log(1 - o) = v$, and we simplify to obtain $E = -\frac{1}{o}\log(1 - o)$.

pacity $s_{ijk}^{\max}$. We directly observe world price P_j, regulatory costs $\bar{\tau}_{jk}\bar{e}_{ijk}$, and average costs AC_{ijk}. We do not observe trade term η_{jk} or optimization error ξ_{ijk}, which arises because, with finitely many lines, realized utilization may deviate idiosyncratically from model-implied operating probabilities. We estimate equation 14 separately by product, absorbing trade term η_{jk} and world price P_j with country fixed effects. We further include plant-level controls for primary production, foreign and state ownership, and plant age, which increase precision and control for systematic differences in optimization error.[21]

Without cost data, we would instead apply the typical logit inversion to equation 3. Combined with equation 13, which continues to hold, we obtain an estimating equation that does not rely on cost data. Unobserved costs c_{ijk} form the error term.

$$\log\left(\frac{o_{ijk}}{1-o_{ijk}}\right) = \beta_j(P_j - \bar{\tau}_{jk}\bar{e}_{ijk}) + \eta_{jk} - \beta_j c_{ijk} \tag{15}$$

We highlight two problems with this approach. First, trade term η_{jk} is correlated with carbon pricing $\bar{\tau}_{jk}$, which is concentrated among European economies whose trade costs are not representative of countries without carbon pricing. Country fixed effects absorb the trade term, as well as world price P_j and carbon pricing $\bar{\tau}_{jk}$ itself, but then identification of β_j rests entirely on within-country variation in emissions intensity $\bar{e}_{ijk}$. Second, this residual variation is limited because it exists only in the small subset of countries that price carbon. It also remains correlated with the error term if, within countries, emissions intensity $\bar{e}_{ijk}$ is predictive of unobserved costs c_{ijk}. We would be left with identifying variation that is thin and potentially contaminated. Our cost data resolve both problems.

Table 5 presents our estimates, reporting our computed supply elasticities and the underlying supply parameters. Our baseline specification uses our cost data and yields elasticities of 0.91 and 0.01, suggesting that supply is inelastic – especially for steel. Blast furnaces typically operate continuously, as they are costly to idle or restart, and so output responds weakly to changes in profit margins.[22] By contrast,

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[21] Because observed carbon pricing falls only on direct emissions, the baseline regulatory cost here is computed with direct intensity $\bar{e}_{ijk}^1$. Counterfactuals will instead price total intensity $\bar{e}_{ijk} = \bar{e}_{ijk}^1 + \bar{e}_{ijk}^2$. Appendix E specifies this distinction.

[22] Steel blast furnaces are used in primary production, while secondary production relies instead on electric arc furnaces that can operate more flexibly. However, secondary production is constrained

Table 5: Supply estimates

	Aluminum			Steel		
	Estimate	SE	Obs	Estimate	SE	Obs
Elasticities						
With cost data	0.91**	0.36	153	0.01	0.16	881
No cost data	7.59	8.02	153	-0.41	1.04	881
Parameters						
With cost data	2.51**	0.99	153	0.02	0.51	881
No cost data	21.0	22.3	153	-1.30	3.33	881

Each observation is a plant. We report supply elasticities computed from our estimated β_j parameters, evaluated at the sample means for prices p_{ijk} and capacity utilization o_{ijk}. We also report the estimated parameters themselves. Within each panel, we report estimates from equation 14, which is our baseline specification that uses cost data, as well as estimates from equation 15, which does not use cost data. All specifications include country fixed effects and plant-level controls for primary production, foreign and state ownership, and plant age. We cluster standard errors by country. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

without cost data, we obtain estimated elasticities that rely on thin variation and thus are particularly imprecise. The standard error for the aluminum supply elasticity is 8.02. That is, our cost data are valuable for identification. Observed average costs provide identifying variation, and they also proxy for the unobserved costs c_{ijk} that otherwise contaminate estimation.

We compare our approach to others that use cost data. In each case, the goal is to use average cost data to characterize marginal costs, which are needed to predict supply responses and run counterfactuals. Asker et al. (2019) assume constant marginal costs, such that average and marginal costs coincide. Marginal costs can thus be read directly from observed average costs. By contrast, marginal costs rise in our model as plants approach capacity: lines with better cost shocks operate first, while those with worse cost shocks operate last. The wedge between marginal and average costs is pinned down by the logit distribution of our line-level cost shocks.[23]

on the input side, relying on the stock of end-of-life steel that accumulates slowly and is largely independent of current steel prices.

[23] For the marginal line, which is indifferent between operating and not, marginal cost MC^*_{ijk} equals market price p_{ijk}. The wedge between this marginal cost and the plant's average cost is positive, and it increases as the plant approaches capacity ($o_{ijk} \to 1$).

$$MC^*_{ijk} - AC_{ijk} = -\frac{\log(1 - o_{ijk})}{\beta_j o_{ijk}}$$

Domínguez-Iino et al. (2026) take a related approach to estimate a dynamic supply model for critical minerals, where the wedge between marginal and average costs is given by convex extraction costs at the mine level. We similarly pair average cost data with model structure to characterize marginal costs, rather than assuming that average and marginal costs coincide.

Appendix table D2 shows that our estimates are stable across alternative specifications: dropping the plant-level controls, weighting plants by capacity, and excluding plants that operate near full capacity. They are also insensitive to setting observed carbon taxation to zero, confirming that our identifying variation comes from the cost data rather than from carbon pricing. Indeed, carbon pricing in our sample is especially limited once we adjust for allowances and credits.

Appendix table D3 assesses heterogeneity in our baseline estimates. For aluminum, we find that supply is less elastic for Chinese plants and for plants in net-importing countries. These results are linked, as China is a net importer of aluminum. Supply is also less elastic for low-capacity plants that operate at smaller scale and for low-emission plants, but the differences with high-capacity and high-emission plants are not statistically significant. For steel, supply remains inelastic across every cut. For both metals, the margin most relevant for carbon policy is emissions intensity, as the effect of carbon pricing is proportional to plant emissions. Because we detect no significant difference between high- and low-emission elasticities, our baseline analysis pools across plants within each product.

6.3 Calibration

We calibrate trade parameter θ_j and abatement parameter γ_j to match elasticities drawn from the literature.[24] For θ_j, we target a trade elasticity of 8 as in Caliendo and Parro (2015). We evaluate equation 6 at world price P_j, and we solve to obtain $\theta_j = 282$ for aluminum and 126 for steel. For γ_j, we target an abatement elasticity of -0.3 as in Sen and Vollebergh (2018). We evaluate equation 8 at a carbon tax of \$100 per ton of CO_2, which we simulate in our main counterfactual, and we solve to

[24] Caliendo and Parro (2015) estimate a trade elasticity of 7.99 for "basic metals," as defined by the International Standard Industrial Classification. Sen and Vollebergh (2018) estimate an abatement elasticity of 0.32 from variation in effective energy tax rates across OECD countries.

obtain $\gamma_j = 333$ for aluminum and steel.

We calibrate trade costs δ^ℓ_{jk} to match observed destination shares $\bar{\sigma}^\ell_{ijk}$. We do so in our sample data, which features observed carbon taxation $\tau_{jk} = \bar{\tau}_{jk}$ without border adjustment. Inverting equation 4, we have

$$\log\left(\frac{\bar{\sigma}^\ell_{ijk}}{\bar{\sigma}^k_{ijk}}\right) = \frac{1}{\theta_j}(\bar{p}^\ell_{ijk} - \bar{p}^k_{ijk}).$$

For $\tau_{jk} = \bar{\tau}_{jk}$, equation 9 simplifies to $\bar{p}^\ell_{ijk} = \bar{p}_{j\ell} - \delta^\ell_{jk} - \bar{\tau}_{jk}\bar{e}_{ijk}$. Without border adjustment, the plant-specific term $\bar{\tau}_{jk}\bar{e}_{ijk}$ cancels in the difference $\bar{p}^\ell_{ijk} - \bar{p}^k_{ijk}$, and so plants share common destination shares $\bar{\sigma}^\ell_{ijk} = \bar{\sigma}^\ell_{jk}$. Furthermore, $\delta^k_{jk} = 0$ because domestic sales face no trade costs. Applying these expressions, it follows that

$$\log\left(\frac{\bar{\sigma}^\ell_{jk}}{\bar{\sigma}^k_{jk}}\right) = \frac{1}{\theta_j}(\bar{p}_{j\ell} - \delta^\ell_{jk} - \bar{p}_{jk}).$$

To recover trade costs δ^ℓ_{jk}, we must take a stand on baseline market prices $\{\bar{p}_{j\ell}\}$.[25] We normalize baseline market prices to the observed world price, setting $\bar{p}_{j\ell} = P_j$ for all destinations ℓ. Solving for trade costs, we obtain

$$\delta^\ell_{jk} = -\theta_j \log\left(\frac{\bar{\sigma}^\ell_{jk}}{\bar{\sigma}^k_{jk}}\right). \tag{16}$$

These trade costs discipline the patterns of trade in our model.[26] In normalizing, we attribute all cross-market price dispersion to trade costs, which we hold fixed in counterfactuals.[27]

[25] The expression shows that differences in bilateral shares identify only $\bar{p}_{j\ell} - \delta^\ell_{jk} - \bar{p}_{jk}$. If we normalize origin price $\bar{p}_{jk}$, then we identify only $\bar{p}_{j\ell} - \delta^\ell_{jk}$. To isolate trade costs δ^ℓ_{jk}, we must also normalize destination price $\bar{p}_{j\ell}$.

[26] Trade costs need not be positive. Equation 16 returns $\delta^\ell_{jk} < 0$ when an origin k ships a larger share to a foreign destination ℓ than it retains at home, reflecting that sales from k are structurally oriented toward ℓ. Two boundary cases require care. First, re-export hubs and small producers whose recorded exports exceed output have a home share of zero, as described in appendix A. We floor the home share at 10^{-4} so that equation 16 remains finite. Second, origin-destination pairs with no observed trade are assigned an infinite trade cost, such that counterfactuals continue to permit no trade on these routes.

[27] Supply estimation is independent of the normalization. The normalization aims to separate market prices $\bar{p}_{j\ell}$ and trade costs δ^ℓ_{jk}, while estimation works only with the difference $\bar{p}_{j\ell} - \delta^\ell_{jk}$. This difference enters estimating equation 14 via trade term η_{jk}, which we fully absorb with country fixed effects.

7 Counterfactuals

We use the estimated model to evaluate counterfactual carbon policy. We quantify impacts of carbon border adjustment, incentives to regulate, and incidence across countries. We then turn to implementation, optimal policy, and robustness. Appendix E details how we solve the model for counterfactuals.

7.1 Impacts

We simulate European carbon taxation at \$100 per ton of CO_2, both with and without a CBAM. The difference isolates the marginal impact of border adjustment, which imposes European carbon pricing on European imports. We evaluate how welfare outcomes change relative to a baseline scenario in which carbon prices are as we observe in the data, accounting for free allowances and exemptions that reduce the effective prices paid by firms. Our \$100 target aligns with the prices that European firms will pay once these allowances are phased out.[28] We define two welfare measures:

$$W = CS + PS + G, \quad SW = W - \kappa E.$$

Welfare W sums over consumer surplus CS, producer surplus PS, and government revenue G. Social welfare SW further accounts for emissions E at social cost of carbon κ. Our main analysis adopts $\kappa = \$100$, as is consistent with our target tax rate of \$100 per ton of CO_2.

Table 6 reports the results. First, consider European carbon taxation without a CBAM. The carbon tax raises prices and reduces quantities. Prices rise modestly, increasing by only 0.12% in Europe and 0.01% in the rest of the world, because Europe is less than 10% of world production (tables 2 and 3). Prices rise everywhere because regulated European producers serve consumers worldwide, but European prices rise more steeply because trade costs imply that European producers disproportionately serve European consumers. In terms of quantities, European production falls by a modest 0.47% because supply is inelastic. European consumption falls by a smaller

[28] Appendix table A4 shows unadjusted carbon prices by country, relative to adjusted prices that account for allowances and exemptions. Weighting by production, the average unadjusted and adjusted prices in Europe are \$95.86 and \$23.60, respectively.

Table 6: Impacts of European carbon taxation

	Without CBAM			With CBAM		
	Europe	Rest of world	World	Europe	Rest of world	World
Price (%)	0.12	0.01	0.02	6.12	-0.50	0.08
Quantity consumed (%)	-0.20	-0.02	-0.04	-7.98	0.70	-0.05
Quantity produced (%)	-0.47	0.01	-0.04	-0.04	-0.05	-0.05
Consumer surplus ($1B)	-0.20	-0.20	-0.40	-9.51	8.59	-0.92
Producer surplus ($1B)	-13.5	0.29	-13.2	-4.90	-11.9	-16.8
Government revenue ($1B)	11.0	0.00	11.0	14.1	-0.01	14.1
Welfare ($1B)	-2.64	0.09	-2.55	-0.29	-3.32	-3.61
Emissions consumed (Mt)	-32.2	-5.09	-37.3	-91.8	43.4	-48.4
Emissions produced (Mt)	-37.7	0.40	-37.3	-37.0	-11.5	-48.4
Social welfare ($1B)			1.18			1.23

We simulate European carbon taxation at $100 per ton of CO_2, with and without a CBAM, leaving carbon taxes unchanged in the rest of the world. We compute effects relative to observed baseline carbon taxes $\bar{\tau}_{jk}$. Prices and quantities are in percentage changes relative to observed values; consumer surplus, producer surplus, and government revenue are in billions of USD; and emissions are in megatons of CO_2. Emissions produced attribute emissions to producers, while emissions consumed attribute embodied emissions to consumers. Welfare is the sum of consumer surplus, producer surplus, and government revenue, while social welfare is world welfare net of world emissions valued at a social cost of carbon of $100 per ton of CO_2. Price and quantity effects are revenue-weighted averages of aluminum and steel, and other effects are sums.

0.20% because of leakage. European consumers respond to scarcer domestic supply by increasing imports from the rest of the world, and foreign producers respond in turn by increasing production and emissions.[29]

Turning to welfare effects, consumers worldwide face higher prices, and consumer surplus falls. European producers benefit from higher prices, but they must also pay the carbon tax. European producer surplus falls by a meaningful $13.5B, offset in part by European carbon tax revenue of $11.0B. On net, the welfare cost of regulation is $2.64B for Europe. At the same time, the benefit of regulation is 37.3 Mt in global emissions reductions, yielding $1.18B in social welfare gains on net. With a social cost of carbon of $200, the social welfare gain would instead be $4.91B. By comparison,

[29] Coster et al. (2025) use firm-level data to document this channel in partial equilibrium, showing that the EU ETS led French manufacturers to shift input sourcing toward unregulated suppliers. We use our plant-level data to capture the complementary margins of production, export, and abatement in global equilibrium.

total baseline emissions covered by the European carbon tax are 240 Mt, and total baseline revenue for European producers is $166B.

Second, consider European carbon taxation with a CBAM. The CBAM extends carbon pricing to European imports, and foreign producers respond by shifting sales away from Europe. European prices rise by 6.12%, and European consumption falls by 7.98%. Consumption responds strongly to prices because demand is elastic. Conversely, prices fall and consumption rises in foreign markets, which receive the supply rerouted from Europe. It is specifically high-emission supply that is reshuffled away: the emissions embodied in European consumption fall by 91.8 Mt, while those embodied in foreign consumption rise by 43.4 Mt.[30] Production again responds modestly because supply is inelastic. The CBAM reallocates trade rather than relocating production.

Again turning to welfare effects, consumers lose as prices rise. The CBAM concentrates this burden on European consumers, who lose $9.51B in consumer surplus. But European producers benefit from higher prices, even as they bear the burden of the domestic tax. The CBAM enhances domestic competitiveness and reduces European producer losses by 64%, cutting losses from $13.5B to $4.90B. The CBAM also generates additional revenue, raising European government revenue by 28% from $11.0B to $14.1B. On net, the gains to producers and the government outweigh losses to consumers. The domestic welfare costs of regulation fall by 89%, from $2.64B without a CBAM to $0.29B with a CBAM. As Europe seeks to raise its carbon price, the CBAM makes it far less costly at home.[31]

Furthermore, the CBAM increases global emissions reductions by 30%, from 37.3 Mt to 48.4 Mt.[32] The CBAM curbs leakage by lowering prices in the rest of the world and discouraging foreign production.[33] Without the CBAM, these prices

[30] 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%.

[31] The CBAM may also reduce political costs. The incidence of regulation shapes its durability: concentrated producer losses invite political resistance, which can lead to repeal (Burgess et al. 2026). The CBAM helps by converting concentrated producer losses into diffuse consumer losses.

[32] The magnitude of this effect on global emissions is consistent with computable general equilibrium assessments in the literature, which find that border adjustment reduces emissions leakage by roughly one third (Böhringer et al. 2012, Mörsdorf 2022, Bellora and Fontagné 2023).

[33] The CBAM also slightly dampens emissions reductions among European producers, who expand production as European prices rise. But this response is without social loss because European emissions are carbon-priced.

would instead rise and encourage foreign producers to produce and emit more. The CBAM also induces foreign abatement, as high-emission exporters to Europe react to carbon pricing by investing in abatement technology and reducing their emissions intensity. In our setting, the abatement margin drives the reductions in emissions, which fall proportionally more than quantities. The CBAM achieves what carbon taxation alone cannot: emissions reductions beyond the borders of the regulating market. In doing so, it raises the social welfare gains of European regulation from \$1.18B to \$1.23B.[34] With a social cost of carbon of \$200, the gains rise from \$4.91B to \$6.07B. The CBAM improves on carbon taxation alone.

7.2 Incentives

We study the incentives of other governments to regulate. Carbon taxation generates social welfare gains by reducing carbon emissions, but it also has welfare costs for countries that regulate: consumers pay higher prices, and producers must bear the tax. We ask whether border adjustment lessens these costs. For each producing country, we calculate how its domestic welfare changes when it joins Europe in taxing carbon at \$100 per ton of CO_2. We do so without a CBAM, either by Europe or the partner country. We then repeat this calculation with a CBAM for Europe and a CBAM for the partner country. Finally, we repeat this calculation once more with China in the coalition, such that Europe, China, and the partner country each regulate with a CBAM. Table 7 lists the six producing countries for which regulation incurs over \$1B in domestic welfare costs.

Carbon regulation is domestically costly. In the baseline case with no border adjustment, China loses a substantial \$31.4B by taxing carbon at \$100. Appendix table E3 breaks out the welfare effects for this important partner country, which would expand coverage to the majority of world production and consumption. Although the Chinese carbon tax raises \$173B in government revenue, it also leads to \$15B and \$190B in losses to Chinese consumers and producers, respectively. At the same time, global emissions fall by 677 Mt. If China values the additional emissions reductions

[34] Appendix tables E1 and E2 separate aluminum and steel. Steel is the larger industry and drives our totals: social welfare gains are \$1.1B without a CBAM and \$1.5B with a CBAM. For aluminum, most embodied emissions come from electricity and lie beyond the plant's scope of abatement. Border adjustment reroutes trade more than it disciplines emissions, and so social welfare gains fall from \$0.1B without a CBAM to a loss of \$0.3B with a CBAM.

Table 7: Incentives for partner countries

	Welfare cost of regulation						
	Without CBAM ($1B)	EU CBAM ($1B)	EU CBAM (%Δ)	Partner CBAM ($1B)	Partner CBAM (%Δ)	With China ($1B)	With China (%Δ)
China	31.4	31.1	-1.12	30.2	-4.04		
India	3.20	3.14	-1.90	3.75	17.1	3.48	8.56
Japan	1.92	1.57	-18.0	1.60	-16.7	1.36	-28.9
Russia	1.42	0.95	-33.3	0.97	-31.7	0.55	-61.2
USA	1.25	1.23	-1.87	0.25	-80.3	0.27	-78.0
South Korea	1.21	0.76	-37.5	1.01	-16.8	0.90	-25.9

For each producing country outside Europe, we calculate the welfare cost of joining Europe in taxing carbon at $100 per ton of CO_2. Welfare is the sum of consumer surplus, producer surplus, and government revenue. It does not include the social welfare benefit of emissions reductions. The first column is the welfare cost to the partner country when neither Europe nor the partner country regulates with a CBAM. We show the six countries with welfare costs exceeding $1B. The second column is the welfare cost when Europe regulates with a CBAM but the partner country does not. The fourth column is the welfare cost when both Europe and the partner country regulate with a CBAM. The sixth column is the welfare cost when Europe, China, and the partner country regulate with a CBAM. The remaining columns show percentage changes, each relative to the first column. We compute effects relative to observed baseline carbon taxes $\bar{\tau}_{jk}$. We sum over aluminum and steel.

from its participation at more than $49.1 per ton, then the domestic welfare losses are more than justified.[35] If the world values these emissions reductions at $100, then global social welfare rises by $34.5B. With a social cost of carbon of $200, the gains are $102B.[36] A climate coalition between Europe and China has large global benefits.

To this end, we show that border adjustment helps to narrow the gap for Chinese participation. When Europe applies a CBAM, China's welfare costs of regulation fall by 1.12% from $31.4B to $31.1B. When Europe and China both apply a CBAM, China's welfare costs fall by 4.04% to $30.2B. The European CBAM acts along two margins: it erodes the value of Chinese non-regulation by penalizing high-emission exports to Europe, and it offers a fiscal incentive for regulation by allowing China to capture revenue that would otherwise flow to Europe.[37] Indeed, China has already

[35] Relative to European taxation alone, Chinese welfare losses rise from nearly zero to $31.4B, while global emissions reductions rise from 37.3 Mt to 677 Mt (appendix tables E1, E2, and E3).

[36] By comparison, total baseline emissions covered by the Chinese carbon tax are 2,378 Mt, and total baseline revenue for Chinese producers is $979B.

[37] The fiscal mechanism is revenue switching. The European border adjustment $\alpha^{\ell}_{jk} = \tau_{j\ell} - \tau_{jk}$ falls one-for-one with the foreign carbon tax τ_{jk}, and so foreign exporters to Europe pay the same total

begun to extend its carbon regulation to the sectors targeted by the European CBAM. The Chinese CBAM acts to further improve domestic competitiveness and minimize domestic costs, just as the European CBAM does for Europe. China should pair regulation with a CBAM.

The comparison with other trade partners reveals two sources of heterogeneity. The European CBAM matters most for countries oriented toward European markets: it cuts the cost of regulating by 37.5% for South Korea, 33.3% for Russia, and 18.0% for Japan, whose high-emission exports to Europe already pay the European border charge. It does less for India, the US, and China, which export little to Europe relative to their size. The partner CBAM operates instead through the home market: the partner's own border adjustment shields domestic producers from untaxed imports and collects border revenue, but at the expense of domestic consumers. The gains are largest where domestic producers serve a large home market and imports provide a broad revenue base – for the US, the cost of regulating falls by 80.3%. But the channel can flip where consumer losses dominate – for India, the cost rises by 17.1%. On balance, border adjustment tilts incentives toward participation, particularly for trade-exposed exporters and for large producers serving their own markets.

An expanded coalition lowers the cost of regulation even further. The last two columns add China to the coalition, such that Europe, China, and the partner country each regulate with a CBAM. Except for the US, each partner's welfare cost of regulation is lower with China than without. The US sees little change, from \$0.25B without China to \$0.27B with China, because its incentives are primarily shaped by its own home market. But for other partner countries, the competitiveness and leakage costs of regulation fall as the regulating coalition expands. Russia's costs fall most, from \$0.97B to \$0.55B, reflecting close competition with China in low-cost production. India's costs fall from \$3.75B to \$3.48B, with comparable effects for Japan and South Korea. Without a CBAM, carbon taxes are strategic substitutes: each country can free-ride when others regulate. With a CBAM, carbon taxes become strategic complements: each regulating country lowers costs for the rest.

tax $\tau_{j\ell}$ regardless of their own government's tax τ_{jk}. Raising τ_{jk} to $\tau_{j\ell}$ thus shifts CBAM revenue from Europe to the foreign government without changing the tax burden on its exporters, giving governments a fiscal incentive to align their carbon taxes with Europe's. Reshuffling undercuts this incentive as firms avoid the tax by shifting sales away from Europe.

7.3 Incidence

We assess the incidence of CBAM impacts across countries. For each country, we compute the difference in welfare outcomes under European carbon taxation with and without a CBAM. Figure 4 plots these country-level effects by income for countries outside of Europe. We control for baseline quantities to avoid confounding incidence with the tendency of higher-income countries to be larger consumers and producers. We find that the CBAM is not disproportionately burdensome for either consumers or producers in lower-income countries. For consumer surplus, patterns of consumption are similar across income levels, and so countries benefit evenly as the CBAM lowers prices outside of Europe. For producer surplus, emissions intensity is similar across income levels (as in section 4), and so CBAM exposure is similar as well.[38]

Appendix table E4 lists the largest gains and losses for individual countries.[39] We highlight opposite and offsetting effects for consumers and producers. Outside of Europe, Chinese consumers gain most with \$3.20B in additional consumer surplus, followed by Indian consumers at \$1.56B. These consumer gains are offset by producer losses. Chinese and Indian producers are relatively emissions-intensive and thus bear a double burden: the CBAM taxes their exports to Europe, and it also depresses prices elsewhere. Within Europe, the CBAM raises prices. German and Italian consumers lose \$1.97B and \$1.44B in consumer surplus, while German and Italian producers gain \$2.08B and \$1.45B in producer surplus. The burdens of the CBAM fall on high-emission producers, not on lower-income countries.

7.4 Implementation

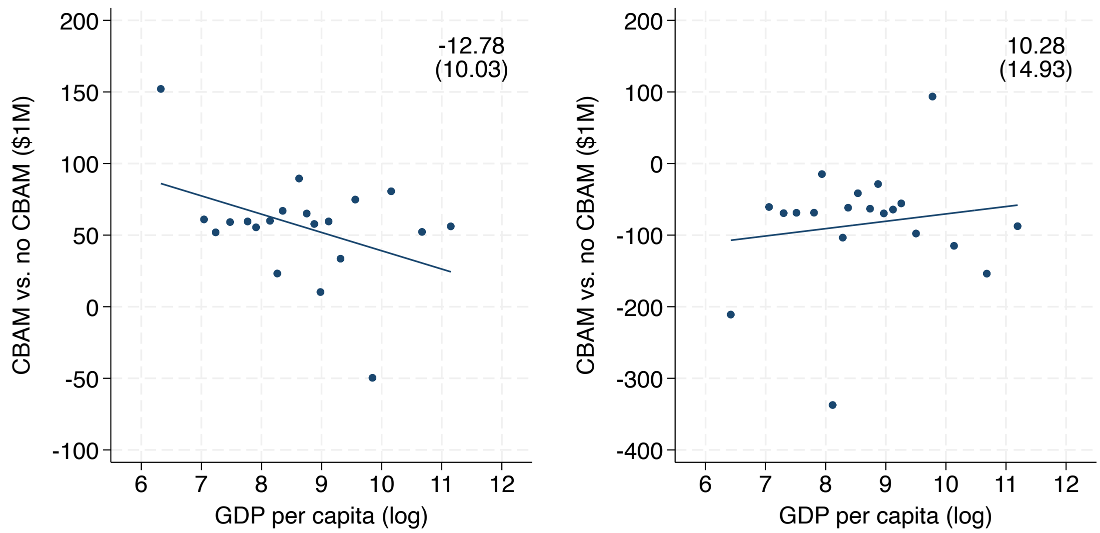
Border adjustment calls for measuring the emissions embodied in imports. The country of origin is straightforward to observe, but the plant of origin is not. We use our plant-level emissions data to assess the losses from border adjustment based on country-mode, country, and global average measures. Table 8a shows that this coarse adjustment weakens the CBAM. Social welfare falls from \$1.23B under plant-

38 This result is consistent with the World Bank's CBAM exposure indices, which show that "developing economies' economic exposure to [the EU] CBAM is expected to be small" (Maliszewska et al. 2025). The World Bank calculates exposure as a function of emissions intensity and trade dependence on EU markets, using country-sector average measures and abstracting from price, trade, and abatement responses.

39 Appendix tables E1 and E2 report the full set of effects for all individual countries.

Figure 4: Incidence by income

(a) Consumer surplus (b) Producer surplus



We simulate European carbon taxation at $100 per ton of CO_2, with and without a CBAM, leaving carbon taxes unchanged elsewhere, and we compute the difference between CBAM and no-CBAM effects for each country. 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 by residualizing both axes against these variables. We report the slope and standard error of the fitted line in the top-right corner of each panel. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

specific adjustment to as low as $0.73B under the coarse measures. Each coarse adjustment is dominated by the $1.18B achieved with no border adjustment at all. The reason is that coarse adjustment charges each plant based on its group average, and a plant can no longer lower its individual border bill by abating. Meanwhile, the border charge still reroutes trade away from Europe, incurring real trade costs and creating deadweight loss without reducing world emissions. Coarse adjustment keeps this costly reshuffling but forfeits the abatement incentive that justifies it.[40]

We also consider partial border adjustment, which levies only a fraction of the difference in carbon pricing. Table 8b shows that this partial adjustment strengthens the CBAM. The relationship is hump-shaped: social welfare rises from $1.18B with

[40] Existing quantitative analyses effectively restrict attention to this coarse regime, levying border charges on sectoral or regional measures of emissions intensity (Böhringer et al. 2012, Larch and Wanner 2017, Mörsdorf 2022, Bellora and Fontagné 2023, Casey et al. 2026). Even Coster et al. (2025), which is firm-level in sourcing, bases the border charge on sector-country averages.

Table 8: Implementation challenges

(a) Coarse adjustment

	Global emissions (Mt)	Global social welfare ($1B)
Plant-specific measures	-48.4	1.23
Country-mode averages by metal	-40.9	0.73
Country averages by metal	-41.0	1.12
Global averages by metal	-41.8	1.08
No border adjustment	-37.3	1.18

(b) Partial adjustment

	Global emissions (Mt)	Global social welfare ($1B)
Full	-48.4	1.23
75%	-47.7	1.68
50%	-46.1	1.99
25%	-43.0	1.96
None	-37.3	1.18

We simulate European carbon taxation at $100 per ton of CO_2, with and without a CBAM, leaving carbon taxes unchanged in the rest of the world. We compute effects relative to observed baseline carbon taxes $\bar{\tau}_{jk}$. In the coarse adjustment, the CBAM taxes imports on their plant-specific, country-mode average, country average, or global average emissions intensity, with averages distinguishing aluminum and steel and, for country-mode, primary and secondary production; the domestic carbon tax remains plant-specific. In the partial adjustment, the CBAM levies a fraction of the border adjustment $\alpha_{jk}^{\ell} = \tau_{j\ell} - \tau_{jk}$, from full adjustment to none. The final row of each panel imposes carbon taxation with no border adjustment. Welfare is the sum of consumer surplus, producer surplus, and government revenue, while social welfare is world welfare net of world emissions valued at a social cost of carbon of $100 per ton of CO_2. We sum over aluminum and steel.

no adjustment to $1.99B at half adjustment, and then falls back to $1.23B at full adjustment. We again emphasize two underlying mechanisms. First, the abatement incentive survives. Half adjustment is still plant-specific, and emissions reductions of 46.1 Mt come close to the 48.4 Mt of full adjustment. Second, the reshuffling incentive shrinks. Halving the border charge reduces the extent of reshuffling. Taken together, full adjustment buys little additional abatement relative to the reshuffling that it prompts. The contrast with coarse adjustment highlights the importance of plant-level incentives to abate. Partial adjustment preserves these incentives while reducing reshuffling; coarse adjustment keeps reshuffling while eliminating these incentives.[41]

[41] In practice, the EU CBAM features both dimensions of this analysis. On measurement, it treats verified, plant-level emissions as the preferred basis for border charges, but it falls back on default values when importers do not report. Default values are coarse and set based on average emissions intensities in exporting countries. The preferred basis preserves abatement incentives for plants that are cleaner than average, while the default values eliminate these incentives for plants that are not. On intensity, the CBAM phases in gradually: importers currently surrender certificates for only the share of embedded emissions left uncovered by free ETS allowances. This coverage is partial and rises from 2.5% in 2026 to 100% in 2034 as free allowances are phased out. This gradual implementation reduces reshuffling.

At the same time, coarse and partial adjustment both interact with policy incentives. Coarse adjustment reduces plant-level abatement, thereby increasing the taxes paid by plants that continue to export to Europe. These higher taxes increase the fiscal incentive for exporting countries to regulate. Furthermore, country-level adjustment shifts the incentives to abate from the plant level to the country level. Exporting countries may seek to implement policy that reduces their country-level emissions intensity, which in turn reduces border taxes for all exporting firms. By contrast, partial adjustment weakens policy incentives by reducing the magnitude of border adjustment.

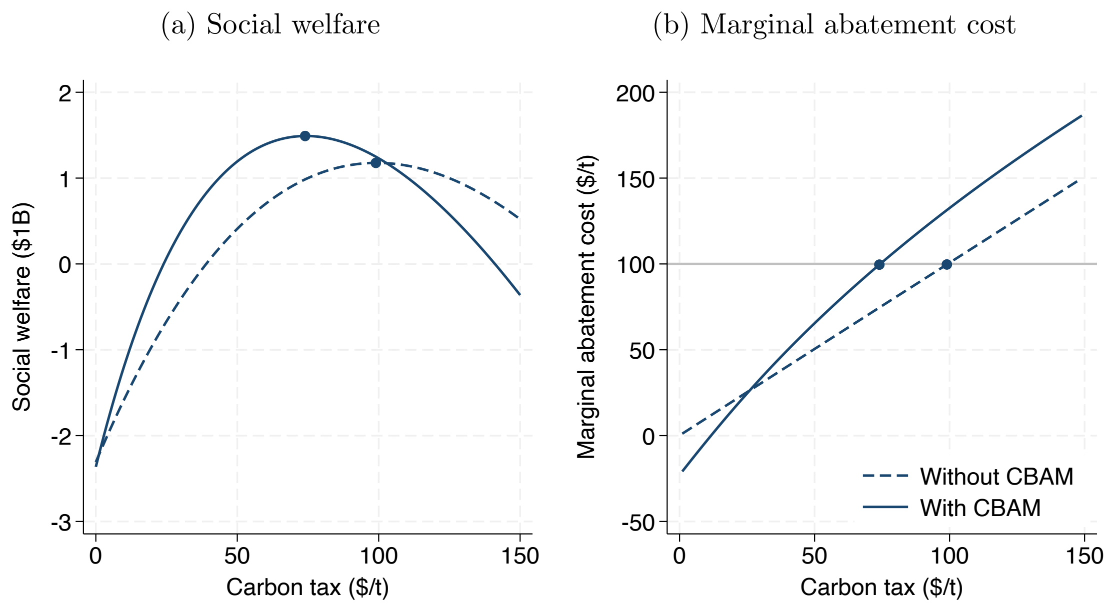
7.5 Optimal policy

We characterize optimal policy for Europe. Regulation raises social welfare when the gains from reducing global emissions, valued at the social cost of carbon, exceed the welfare costs of regulation. Figure 5a plots social welfare gains against the European carbon tax. Optimizing over the tax, we see that border adjustment raises the achievable social welfare gains, lifting the peak from \$1.2B to \$1.5B. It also lowers the optimal tax from roughly \$100 without a CBAM to \$75 with a CBAM. Without a CBAM, the carbon tax falls only on European producers, and a high tax is needed to draw out much abatement. Welfare gains are limited because abatement has increasing marginal costs, and so it is costly when concentrated among European producers. With a CBAM, the carbon tax extends to foreign exporters, who respond by abating to lower their border charge, even with a lower tax. Welfare gains rise as abatement is spread across European and foreign producers.[42]

The marginal abatement cost is the welfare cost of each additional ton reduced, and regulation maximizes social welfare where the marginal abatement cost equals the social cost of carbon. Figure 5b plots the marginal abatement cost against the European carbon tax. With a CBAM, the marginal abatement cost reaches the \$100 social cost of carbon at a lower tax. The marginal abatement cost is lower with a CBAM at low tax rates, but it is lower without a CBAM at high tax rates. As

[42] Border adjustment is part of the optimal unilateral carbon policy described by Kortum and Weisbach (2026), who combine an import tax on embodied carbon with a fossil fuel extraction tax and an export subsidy. Consistent with our result, they find that adding the border instrument raises welfare. Similarly, Casey et al. (2026) find that pairing a carbon tariff with a domestic carbon tax raises the regulating country's welfare through improved terms of trade.

Figure 5: Optimal policy for Europe



We simulate European carbon taxation of increasing severity, as plotted on the x-axis. The dashed lines show impacts without a CBAM, and the solid lines with a CBAM. We compute effects relative to observed baseline carbon taxes $\bar{\tau}_{jk}$. Social welfare is global welfare in billions of USD, net of global emissions valued at a social cost of carbon of $100 per ton of CO_2. The gray horizontal line marks this $100 social cost of carbon. Marginal abatement cost is the welfare loss per additional ton of emissions reduced, as measured in USD per ton of CO_2. We sum over aluminum and steel.

with partial and coarse adjustment, this result reflects abatement and reshuffling: the former dominates at low tax rates, and the latter at high tax rates.[43]

7.6 Robustness

Our baseline analysis pools primary and secondary metals, treating them as perfect substitutes in consumption, but industries like aerospace and automotive manufacturing rely more heavily on higher-grade primary metals. Appendix table E5 segments the markets for primary and secondary metals. Without a CBAM, the segmented markets behave like our pooled baseline. With a CBAM, social welfare gains are only $0.36B under segmentation, relative to $1.23B under pooling, as primary

[43] At the lowest tax rates, the marginal abatement cost is negative. That is, regulation with a CBAM is welfare-improving, even without accounting for the benefits of reduced emissions. The reason is the welfare costs of demand-side leakage. Without a CBAM, carbon taxation prompts European consumers to shift to foreign imports, incurring trade costs and creating deadweight loss without reducing emissions. The CBAM eliminates this shift by taxing foreign imports.

consumers can no longer substitute toward low-emission secondary supply.

We also assess our estimated and calibrated parameters. Appendix table E6 reports global social welfare gains under a European CBAM across demand and supply elasticities that span our estimates. Larger supply elasticities raise the gains, as supply responds strongly and abatement increases. Larger demand elasticities reduce the gains, as consumption reroutes strongly from Europe to the rest of the world – costly reshuffling. Appendix table E7 varies the trade elasticity, with higher θ_j implying less trade openness. Trade openness tilts toward reshuffling, as exporters dodge border charges by rerouting sales rather than abating. Appendix table E8 varies the abatement elasticity. The long run may bring new green technology and stronger abatement than our data capture. A strong response amplifies abatement and strengthens the CBAM, while a weak response allows reshuffling to dominate and weakens the CBAM. Across parameters, CBAM impacts turn on the balance between abatement and reshuffling.

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 emissions-intensive than it is in higher-income countries.

Our analysis rests on assumptions that bound its scope. We model the aluminum and steel markets in isolation, abstracting from economy-wide feedback and linkages with other sectors. We also treat producers as competitive, abstracting from market power and strategic interaction. These assumptions are most appropriate for homogeneous, globally traded commodities, which indeed encompass many sectors targeted by current or future CBAM policy. These assumptions are less appropriate for highly differentiated products, where market power within fragmented markets may play a larger role. We also abstract from strategic policy responses, such as retaliatory tariffs, although net foreign welfare effects are limited because producer losses are largely offset by consumer gains.

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 our global climate targets.

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Appendix

A Data

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, energy, labor, maintenance, and depreciation costs. For aluminum scrap, which is the most costly input, we estimate country-level domestic prices as the weighted average of the import and export prices reported under HS code 7602 (Aluminum; waste and scrap). For other 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. Following a life cycle assessment by the Aluminum Association (2022), which reports that "secondary ingot production requires only 8% of the energy used to produce primary ingot," we impute secondary energy costs as 8% of our observed primary energy costs.

Steel production

Our steel cost data are 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

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)	686	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, and we validate it against comparable data from Climate TRACE. Emissions are in megatons of CO_2.

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 accounts 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 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. 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 11% for steel. We adjust the consumption data by scal-

Table A2: World quantities

	Production (Mt)	Consumption (Mt)	Difference (%)
Aluminum	84	87	3
Steel	1,673	1,849	11

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 align them.

ing 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.

Trade flows

We measure bilateral trade from the UN Comtrade database for 2023. For aluminum, we focus on unwrought aluminum (HS 7601). For steel, we focus on semi-finished and finished non-alloy steel products (HS 7206–7217), excluding scrap and raw materials (HS 7201–7205) and alloy and stainless products (HS 7218–7229). For each directed country pair, we use importer-reported flows where available and exporter-reported flows where not, summing across product codes. We aggregate European producers into a single bloc, dropping intra-bloc and self-trade that reflects transshipment through ports and cross-border processing within the integrated market. We construct destination shares for each producer from these trade flows. We compute the home share as one minus the ratio of gross exports to production, converting export values into quantities by matching aggregate net exports to net production for each metal. We bound the home share to the unit interval, such that re-export hubs and small producers whose recorded exports exceed output have a home share of zero. Table A3 summarizes the resulting home and Europe shares, weighting by production, and lists the largest foreign suppliers to Europe.

Table A3: Trade flows

(a) Destination shares

	Home share (%)				Europe share (%)			
	Mean	SD	p5	p95	Mean	SD	p5	p95
Aluminum	80	31	13	100	10	23	0.0	94
Steel	82	16	48	91	10	25	0.1	88

(b) Aluminum exports to Europe

	Supply to Europe (Mt)	Share to Europe (%)
UAE	0.7	27
India	0.6	13
Russia	0.5	14
Mozambique	0.4	73
Bahrain	0.4	22
Rest of world	1.2	2

(c) Steel exports to Europe

	Supply to Europe (Mt)	Share to Europe (%)
South Korea	5	9
India	5	6
China	4	1
Turkey	4	10
Vietnam	3	23
Rest of world	19	4

Bilateral trade flows come from the UN Comtrade database for 2023, covering unwrought aluminum (HS 7601) and non-alloy steel products (HS 7206–7217) and aggregating Europe into a single bloc. Europe includes the EU, UK, and EFTA. Home share is the percentage of production sold domestically, and Europe share is the percentage sold to Europe. We calculate means, standard deviations, and 5th and 95th percentiles across countries, weighting by production. Supply to Europe is the quantity exported, and share to Europe is the percentage of total production exported.

Carbon pricing

Carbon is priced subnationally in China, Canada, Mexico, and Japan, and so we match plants in these countries to carbon schemes by province or state. European Economic Area members take the EU ETS price, while Switzerland and the United Kingdom keep their own schemes. We compute adjusted prices for each plant by netting out free allocations and assessing carbon pricing only on Scope 1 emissions that exceed free-allocation benchmarks. We use separate benchmarks for aluminum and steel, distinguishing between primary and secondary production and applying scheme-specific exemptions and reductions from official regulatory documents. Where regulators publish explicit adjusted rates, we use them directly. Secondary aluminum is benchmarked on energy use rather than output, and we treat its free allocation as covering its limited Scope 1 emissions in full. Table A4 reports our unadjusted and adjusted prices by country, weighting by plant-level production.

Table A4: Carbon pricing

Country	Aluminum Full ($/t)	Aluminum Adjusted ($/t)	Steel Full ($/t)	Steel Adjusted ($/t)
Argentina	3.27	3.27	3.27	3.27
Austria			96.29	42.88
Belgium			96.29	29.72
Bulgaria			96.29	0.00
Canada	31.93	8.93	44.35	18.74
Chile			5.00	5.00
China	0.25	0.01	1.16	0.16
Czechia			96.29	16.12
Finland			96.29	25.49
France	96.29	19.36	96.29	30.18
Germany	96.29	5.40	96.29	28.85
Greece	96.29	20.40	96.29	0.00
Hungary			96.29	35.49
Iceland	96.29	16.63		
Italy	96.29	0.00	96.29	10.57
Japan	2.17	2.17	2.17	2.17
Kazakhstan	1.12	0.19	1.12	0.12
Luxembourg			96.29	0.00
Mexico			1.20	1.20
Netherlands			96.29	42.88
New Zealand	34.20	7.59	34.20	0.00
Norway	96.29	13.24	96.29	0.00
Poland			96.29	21.62
Portugal			96.29	0.00
Romania	96.29	26.09	96.29	31.77
Singapore			3.77	3.77
Slovakia			96.29	42.88
Slovenia	96.29	18.26	96.29	0.00
South Africa	8.93	2.23	8.93	2.23
South Korea	11.24	0.00	11.24	4.41
Spain			96.29	3.49
Sweden	96.29	25.31	96.29	57.89
Switzerland			93.81	0.00
Ukraine			0.82	0.82
United Kingdom	88.13	35.59	88.13	32.48

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

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. Table A5 presents ownership by country, production-weighting across plants within each country.

Table A5: 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. For each plant, we record whether the majority-stakeholder parent company is a state-owned enterprise (state) or headquartered in a different country (foreign). We compute the production-weighted average across plants within each country.

B Stylized Facts

Emissions and income

Figure 2 indicates a flat relationship between emissions intensity and GDP per capita across countries. We probe these findings in table B1, which estimates the emissions-income gradient separately for total, direct (Scope 1), and indirect (Scope 2) emissions intensity. We use Poisson pseudo-maximum likelihood (PPML) estimation to retain countries with zero indirect emissions – specifically those with aluminum smelters that run on green energy with zero emissions. The coefficients read as elasticities. We additionally control for the share of primary production, average scale of production, shares of state and foreign ownership, and average plant age. The gradient for total emissions intensity is small and statistically insignificant for both metals, with and without controls.

The scope-level estimates rationalize the flat gradient. For aluminum, table B2 shows that emissions are dominated by indirect emissions from the electricity used in production (Scope 2). The Scope 2 gradient is itself flat, and so the flat gradient traces to electricity: energy systems are, on average, no more emissions-intensive in lower-income countries. The Scope 1 gradient is similarly flat, noting that the estimate without controls is statistically significant but with a small magnitude of -0.08. For steel, table B2 shows that emissions are dominated by direct emissions from the production process itself (Scope 1). Without controls, we obtain a small and marginally significant positive gradient that reflects a modestly larger share of primary production in higher-income countries.[44] With controls, we compare countries within a mode of production, and the Scope 1 gradient is entirely flat. Steel emissions are determined by chemical principles rather than economic forces, compressing the distribution of emissions intensity across countries.

For the same reasons, we hypothesize that these results generalize to other heavy industries. Scope 1 emissions are dictated by chemistry, while Scope 2 emissions are

[44] The same compositional difference pulls Scope 2 in the opposite direction, as primary (BF-BOF) production uses less purchased electricity than secondary (EAF) production. Steel's Scope 2 intensity thus declines somewhat in income without controls, offsetting the small rise in Scope 1 intensity; with controls, the gradient attenuates by more than half. In both cases, indirect emissions are less than 10% of steel emissions and thus too limited to affect our results.

Table B1: Emissions intensity by income

	Without controls			With controls		
	Estimate	SE	Obs	Estimate	SE	Obs
Aluminum						
Total emissions	−0.04	0.10	38	−0.07	0.11	34
Direct (Scope 1)	−0.08**	0.03	38	−0.02	0.01	34
Indirect (Scope 2)	−0.01	0.18	38	−0.09	0.17	34
Steel						
Total emissions	0.07	0.05	77	−0.04	0.04	77
Direct (Scope 1)	0.14*	0.07	77	0.00	0.06	77
Indirect (Scope 2)	−0.24***	0.05	77	−0.09*	0.05	77

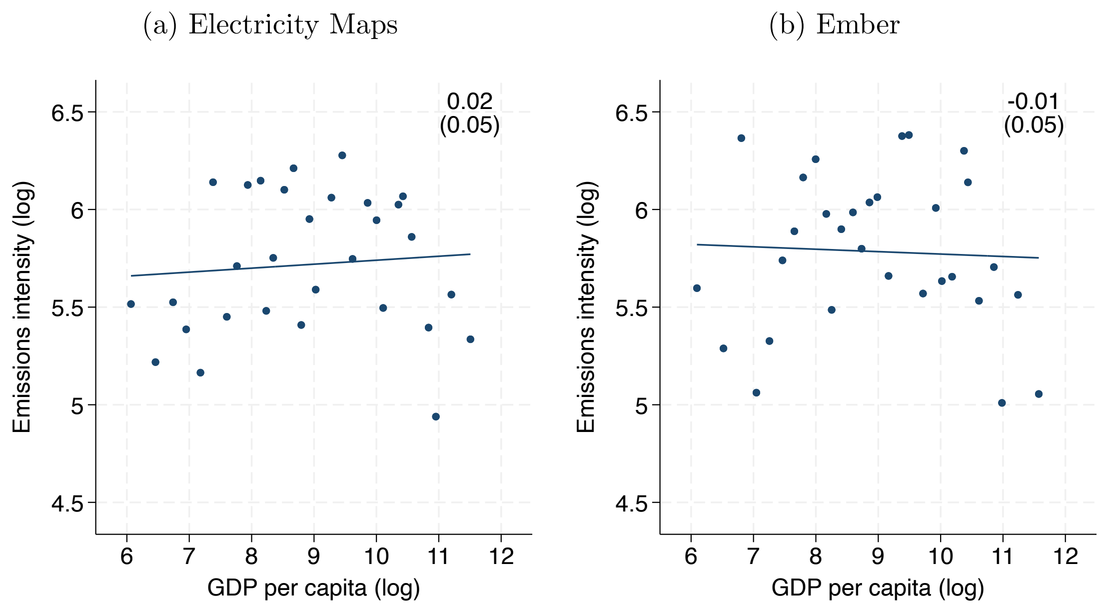
Each estimate is one PPML regression of emissions intensity on log GDP per capita, and each observation is a country. Emissions intensity is in tons of CO_2 emitted per ton of production, and coefficients read as elasticities with respect to GDP per capita. GDP data are from the World Bank. Controls 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. Standard errors are robust. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

Table B2: Direct and indirect emissions

	Aluminum (%)	Steel (%)
Direct (Scope 1)	23.2	90.9
Indirect (Scope 2)	76.8	9.1

Direct emissions are from production itself, while indirect emissions are from electricity used in production. We aggregate across plants in our sample.

Figure B1: Electricity emissions intensity by income



Each figure is a binned scatter plot, and each observation is a country. Electricity emissions intensity is in grams of CO_2 per kilowatt-hour, as measured at the country level in two datasets with a total of 391 observations (Electricity Maps 2026, Ember 2026). 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. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

dictated by national grids. We compile data for 2023 on national grids from two independent global datasets, which measure the emissions intensity of electricity generation across countries. These datasets use different inputs and emission factors. Electricity Maps (2026) builds its measure from generation data published by grid operators, applying technology-specific lifecycle emission factors. It traces electricity flows across interconnected grids and accounts for emissions over the full fuel and power-plant lifecycle. Ember (2026) instead builds its measure from generation data on fuel type, applying fuel-specific emission factors. Figure B1 shows the result: in both datasets, we document an emissions-income gradient that is small in magnitude and not statistically significant. Lower-income countries do not draw on systematically dirtier grids.

Emissions and income across sectors

We broaden our scope to other heavy industries beyond aluminum and steel, using data from four independent global datasets that measure emissions intensity by sector. Our key criteria are (1) production measured in physical units, which allow us to calculate emissions intensity in tons per unit of output, and (2) direct measures for lower-income countries, rather than imputation based on data from higher-income countries. We describe each dataset before turning to our estimates.

Our primary data source is Climate TRACE, which reports facility-level emissions for 13 manufacturing sectors in 2023. It measures production in physical units for some sectors, and it includes broad coverage of lower-income countries. It also measures all greenhouse gas emissions, which can be summed into CO_2 equivalents. We keep only the sectors measured in physical units, dropping those reported in dollars or factory counts. We also drop pulp and paper, to which Climate TRACE assigns a single global emissions factor, and glass and lime, which are imputed from EDGAR-style inventories that lack lower-income coverage.

Our second data source is the IEA's Energy and Emissions per Value Added (EVA) database, which reports carbon intensity for 10 manufacturing sectors in 2019. It features a consistent methodology that supports cross-sector comparison. It measures intensity per dollar of value added, rather than per physical unit, and it covers CO_2 alone, rather than all greenhouse gases. Its main limitation is coverage: the database contains no low- or lower-middle-income country in any manufacturing sector. This restriction follows from reliance on national-accounts value-added data, which are available at the sectoral level primarily for high-income economies. Furthermore, the value-added denominator folds price levels and product mix into the intensity measure, such that cross-country differences reflect economic structure as much as physical efficiency.

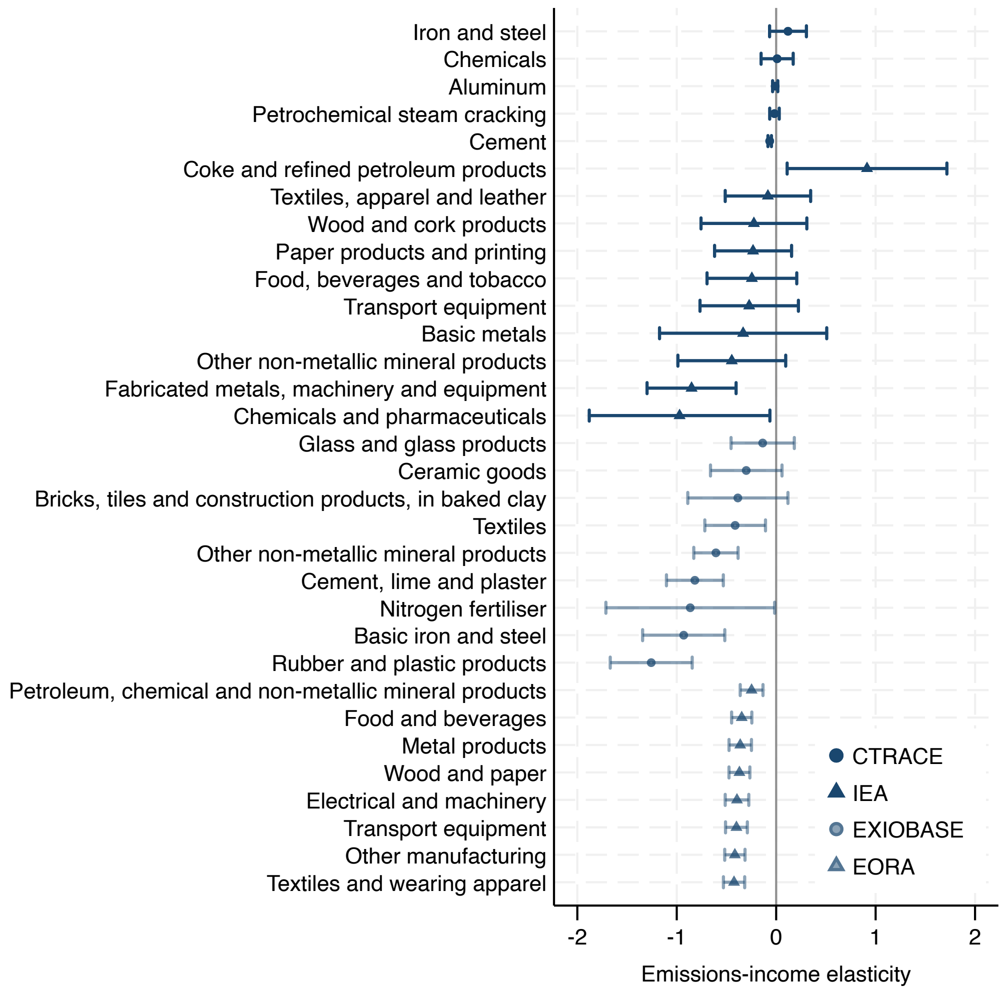
Our third data source is EXIOBASE. This global input-output dataset has broad sectoral coverage with 83 manufacturing products for 2019. We use the product-by-product tables, which isolate products more cleanly than the industry-by-industry tables. The main disadvantage is that underlying emissions are largely imputed rather than measured. Furthermore, it includes only 44 individual countries and pools the rest of the world – including most lower-income countries – into five regional aggregates that cannot be separated. Like the IEA data, it measures emissions intensity per unit of gross output value, which is a monetary unit rather than a physical unit.

Our fourth data source is EORA, which is also a global input-output dataset. We use its 26-sector tables for 2017. Its strength is country coverage: unlike EXIOBASE, it tracks a broad set of individual economies, including many lower-income countries, within a consistent global framework. However, its weaknesses otherwise mirror those of EXIOBASE. It measures emissions intensity per unit of gross output value, and the tables include substantial imputation to fill gaps in the underlying accounts. Furthermore, its 26 sectors are relatively coarse and do not align directly with the finer classifications of Climate TRACE or the IEA data.

We considered and set aside four additional datasets. CEDS and EDGAR are widely used emissions inventories, but neither reports output. We require output measures to compute emissions intensity. GTAP pairs emissions with output and trade for roughly 160 economies and 65 sectors, but it again reports only output values rather than quantities. Furthermore, its emissions are imputed from energy-balance data and carbon coefficients, rather than independently measured. The OECD's input-output emissions data report many countries, but only by imputing lower-income economies from a single global average emissions factor. Only higher-income economies are measured directly.

Figure B2 presents our results. For each sector, we regress log emissions intensity on log GDP per capita across countries, and we plot the slopes and standard errors. These slopes are elasticities in this log-log specification. In the Climate TRACE data, we replicate our flat gradient for aluminum and steel. We find that the same holds for chemicals and petrochemical steam cracking. Cement is negative and statistically significant but with a very small magnitude of -0.06. The value-based datasets behave differently. Estimates from the IEA data are mostly flat, while those from EXIOBASE and EORA suggest more negative slopes. However, output prices are lower in poorer countries, and so identical emissions per ton translate into higher emissions per dollar. The value-based datasets are biased toward negative slopes because they capture prices and not only production.

Figure B2: Emissions and income by sector



Each point is the OLS slope of log emissions intensity on log GDP per capita across countries within a manufacturing sector. We focus on sectors with at least 10 reported countries. Climate TRACE data are for sectors with physical output units. We show 95% confidence intervals.

Table B3: Plant heterogeneity within and across countries

	Aluminum		Steel	
	Emissions intensity	Production costs	Emissions intensity	Production costs
Across countries	48%	55%	31%	75%
Within countries	52%	45%	69%	25%

Across countries, we show R^2 when regressing plant-level emissions intensity and production costs on country fixed effects. Within countries, we show $1 - R^2$.

C Model

Equivalence

We note the equivalence between imposing a CBAM on exporters in k, as written in our baseline model, and imposing a CBAM on importers in ℓ, as implemented in practice. Consider regulated country ℓ with carbon tax $\tau_{j\ell}$ and unregulated country k with carbon tax $\tau_{jk} < \tau_{j\ell}$. The CBAM is $\alpha^{\ell}_{jk} = \tau_{j\ell} - \tau_{jk}$. We suppress product subscript j and specialize to these two countries to lighten notation. In general form, our baseline equilibrium conditions are

$$d_\ell(p_\ell) = \sum_{i \in \mathcal{I}_\ell} s^{\ell}_{i\ell}(p_\ell, p_k) + \sum_{i \in \mathcal{I}_k} s^{\ell}_{ik}(g_i(p_\ell, \alpha), p_k),$$
$$d_k(p_k) = \sum_{i \in \mathcal{I}_\ell} s^{k}_{i\ell}(p_\ell, p_k) + \sum_{i \in \mathcal{I}_k} s^{k}_{ik}(g_i(p_\ell, \alpha), p_k).$$

We impose CBAM α on the supply side, summing over plants i. Demand $d_\ell(p_\ell)$ in each market ℓ is met by domestic flow $s^{\ell}_{i\ell}$ and imports s^{ℓ}_{ik} from k. The same holds for $d_k(p_k)$ in k. Producers in ℓ face only their domestic tax τ_ℓ, regardless of destination. Producers in k face origin tax τ_k on domestic sales, as well as CBAM α on exports to ℓ, which enters through $g_i(p_\ell, \alpha)$. Function g_i captures that the impact of the CBAM depends on the emissions intensity $\bar{e}_{ik}$ of each plant $i \in \mathcal{I}_k$.

We show that the same equilibrium obtains when the CBAM is levied on imports rather than exports. For each exporter $i \in \mathcal{I}_k$, define $\hat{p}_{i\ell} = g_i(p_\ell, \alpha)$ as the price net of the CBAM that the plant receives on sales to ℓ. We thus have $p_\ell = h_i(\hat{p}_{i\ell}, \alpha)$, where h_i inverts g_i. Written in terms of $\hat{p}_{i\ell}$, exporters in k respond to the net price $\hat{p}_{i\ell}$ they receive, while consumers in ℓ pay p_ℓ. The CBAM is the wedge $p_\ell - \hat{p}_{i\ell}$ between the two, equivalently collected from importers in ℓ rather than remitted by exporters in k. We thus establish equivalence.

D Estimation

Table D1: Demand estimation first stage

	1976-2024	1998-2022	1998-2022	1998-2022
Australian share of ore production	1.19***	0.89***		1.38***
	(0.14)	(0.15)		(0.51)
Concentration of ore production			3.03***	-2.01
			(0.51)	(1.94)
Observations	98	50	50	50
F-statistic	76.4	34.7	34.8	18.7

Each column is a regression of log world prices on the instrumental variables, controlling for product and year fixed effects. Each observation is a product-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 D2: Supply estimation with alternative specifications

	Aluminum			Steel		
	Estimate	SE	Obs	Estimate	SE	Obs
Baseline	0.91**	0.36	153	0.01	0.16	881
Regressors						
No plant controls	0.90**	0.42	153	-0.23	0.15	881
No carbon pricing	0.90**	0.36	153	0.04	0.12	881
Capacity						
Capacity weighting	0.88***	0.29	153	-0.13	0.09	881
Dropping near capacity	0.89***	0.34	130	-0.05	0.11	792

Each estimate is one regression, and each observation is a plant. We report supply elasticities as in table 5. Baseline reproduces our cost-data specification. The regressors panel drops the plant-level controls and, separately, sets observed carbon taxation $\bar{\tau}_{jk}$ to zero. The capacity panel weights plants by capacity and excludes plants operating near full capacity. We cluster standard errors by country. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

Table D3: Supply estimation with heterogeneity

	Aluminum			Steel		
	Estimate	SE	Obs	Estimate	SE	Obs
Baseline	0.91**	0.36	153	0.01	0.16	881
Region						
China	0.21	0.45	71	0.12	0.13	355
Not China	1.52***	0.48	82	-0.14	0.28	526
Difference	-1.31***	0.42	153	0.26	0.27	881
Trade						
Net exporter	1.37***	0.16	63	0.03	0.18	614
Net importer	0.26***	0.05	90	-0.08	0.32	267
Difference	1.11***	0.16	153	0.11	0.35	881
Capacity						
High capacity	1.10***	0.36	76	0.13*	0.07	439
Low capacity	0.69	1.08	77	-0.07	0.28	442
Difference	0.41	0.88	153	0.20	0.25	881
Emissions						
High emissions	1.49**	0.70	76	0.09*	0.05	436
Low emissions	0.22	1.43	77	0.19*	0.10	445
Difference	1.28	1.99	153	-0.10	0.11	881

Each estimate is one regression, and each observation is a plant. We report supply elasticities as in table 5. Baseline reproduces our cost-data specification for the full sample. The region panel splits plants into China and the rest of the world. The trade panel splits plants by whether their country is a net exporter or net importer. The capacity panel splits plants by whether their capacity is above or below median. The emissions panel splits plants by whether their emissions intensity is above or below median. Difference rows report the gap in elasticities between the two subgroups. We cluster standard errors by country when the sample spans multiple countries. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

E Counterfactuals

Solving the model

For counterfactual policy $\boldsymbol{\tau}_j = \{\tau^\ell_{jk}\}$, which may include border adjustment $\boldsymbol{\alpha}_j = \{\alpha^\ell_{jk}\}$, we solve for prices $\boldsymbol{p}_j = \{p_{jk}\}$ that satisfy equilibrium conditions 10 for each product j and country k. For each candidate price vector $\boldsymbol{p}_j$, we compute demand and supply in changes relative to baseline values $(\bar{d}_{jk}, \bar{s}^\ell_{ijk})$,[45] which we denote with

$$\Delta x = x - \bar{x}.$$

We normalize $\bar{p}_{jk} = P_j$ for baseline market prices $\bar{p}_{jk}$ and observed world prices P_j, as we do in calibrating trade costs δ^ℓ_{jk}.

For demand, we want to compute $\log d_{jk} = a_{jk} + b_j \log p_{jk}$ as in equation 1. Rewriting in differences, we have

$$\Delta \log d_{jk} = b_j \Delta \log p_{jk}$$

for estimated demand parameter b_j. For any candidate $\boldsymbol{p}_j$, market price changes $\Delta \log p_{jk}$ yield demand responses $\Delta \log d_{jk}$.

For supply, we want to compute $s^\ell_{ijk} = \sigma^\ell_{ijk}\, s^{\max}_{ijk}\, o_{ijk}$ as in equations 3 and 5. We observe capacity $s^{\max}_{ijk}$. By equations 3 and 4, we can rewrite destination shares σ^ℓ_{ijk} and utilization o_{ijk} in differences as

$$\Delta \log \sigma^\ell_{ijk} = \frac{1}{\theta_j}\big(\Delta p^\ell_{ijk} - \Delta p_{ijk}\big), \quad \Delta \log \left(\frac{o_{ijk}}{1 - o_{ijk}}\right) = \beta_j \Delta p_{ijk}$$

for calibrated trade parameter θ_j and estimated supply parameter β_j. Unobserved costs c_{ijk} are held fixed and differenced out. To evaluate these quantities, we require

[45] We compute outcomes in differences because our consumer and producer surplus measures are not identified in levels, as is typical. Producer surplus inherits the logit's location normalization, and consumer surplus levels depend on extrapolating demand to the choke price. Differences avoid both problems.

price changes Δp_{ijk} and destination price changes Δp^{ℓ}_{ijk}. For prices, equation 4 yields

$$\Delta p_{ijk} = \theta_j \log \sum_{\ell} \bar{\sigma}^{\ell}_{ijk} \exp\left(\frac{\Delta p^{\ell}_{ijk}}{\theta_j}\right).$$

We observe baseline destination shares $\bar{\sigma}^{\ell}_{ijk}$. For destination prices, equation 9 yields

$$\Delta p^{\ell}_{ijk} = \Delta p_{j\ell} + \gamma_j \bar{e}_{ijk} \left[\exp\left(-\frac{\Delta \tau^{\ell}_{jk}}{\gamma_j}\right) - 1\right]$$

for counterfactual policy $\boldsymbol{\tau}_j$ and calibrated abatement parameter γ_j. We observe baseline emissions $\bar{e}_{ijk}$. Trade costs δ^{ℓ}_{jk} are held fixed and differenced out.

Direct and indirect emissions

Our data distinguish direct emissions from the production process (Scope 1) and indirect emissions from the electricity used in production (Scope 2). We write plant intensity as the sum of a direct and an indirect component, $\bar{e}_{ijk} = \bar{e}^{1}_{ijk} + \bar{e}^{2}_{ijk}$. The two components meet carbon policy differently. Observed carbon pricing applies only to direct emissions, as is the case in practice. Thus, for estimation, baseline regulatory costs $\bar{\tau}_{jk}\bar{e}_{ijk}$ in equation 14 are computed with direct intensity $\bar{e}^{1}_{ijk}$. Counterfactual carbon pricing applies instead to total intensity $\bar{e}_{ijk}$. Plants react by abating direct intensity $\bar{e}^{1}_{ijk}$ but not indirect intensity $\bar{e}^{2}_{ijk}$, which depends on national grids that plants take as given. Making the components explicit, the destination price differences above become

$$\Delta p^{\ell}_{ijk} = \Delta p_{j\ell} + \gamma_j \bar{e}^{1}_{ijk} \left[\exp\left(-\frac{\Delta \tau^{\ell}_{jk}}{\gamma_j}\right) - 1\right] - \Delta \tau^{\ell}_{jk} \bar{e}^{2}_{ijk}.$$

At $\Delta \boldsymbol{\tau}_j = \mathbf{0}$, the model reproduces the data. Total intensity is $\bar{e}^{1}_{ijk} \exp\big(-\Delta \tau^{\ell}_{jk}/\gamma_j\big) + \bar{e}^{2}_{ijk}$. The CBAM taxes total emissions at the border, and it is total emissions that we report for our counterfactual emissions outcomes.

Table E1: European carbon taxation, aluminum

	Without CBAM					With CBAM				
	CS	PS	G	W	E	CS	PS	G	W	E
Australia	0.0	0.0	0.0	0.0	0.0	0.0	−0.1	0.0	−0.1	−0.2
Bahrain	0.0	0.0	0.0	0.0	0.0	0.0	−0.2	0.0	−0.1	−0.1
China	0.0	0.0	0.0	0.0	0.1	0.2	−0.2	0.0	0.0	−0.6
France	0.0	−0.1	0.0	0.0	−0.2	−0.2	0.0	0.1	0.0	−0.2
Germany	0.0	−0.1	0.0	−0.1	−1.1	−0.5	0.0	0.2	−0.2	−0.8
Greece	0.0	−0.1	0.1	0.0	−0.1	−0.1	−0.1	0.1	0.0	−0.1
Iceland	0.0	−0.1	0.1	0.0	−0.4	0.0	0.1	0.1	0.2	−0.4
India	0.0	0.0	0.0	0.0	0.1	0.2	−0.4	0.0	−0.2	−1.9
Italy	0.0	0.0	0.0	0.0	0.0	−0.3	0.1	0.1	−0.1	0.0
Japan	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.1	0.0
Malaysia	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	−0.1
Mozambique	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	−0.2
Norway	0.0	−0.2	0.2	0.0	−0.7	−0.1	0.1	0.2	0.3	−0.6
Romania	0.0	0.0	0.0	0.0	−0.3	0.0	0.0	0.0	0.0	−0.2
Russia	0.0	0.0	0.0	0.0	0.0	0.0	−0.1	0.0	−0.1	−0.7
South Africa	0.0	0.0	0.0	0.0	0.0	0.0	−0.1	0.0	−0.1	−0.1
Spain	0.0	0.0	0.0	0.0	0.0	−0.1	0.0	0.1	−0.1	0.0
United Arab Emirates	0.0	0.0	0.0	0.0	0.0	0.1	−0.3	0.0	−0.2	−0.3
United States	0.0	0.0	0.0	0.0	0.0	0.3	−0.1	0.0	0.1	−0.2
World	−0.3	−0.3	0.5	−0.2	−2.7	−0.6	−1.6	1.2	−1.0	−7.3
Social welfare			0.1					−0.3		

We raise European carbon taxes to $100 per ton of Scope 1 and 2 carbon emissions, with and without a CBAM. We compute effects relative to observed baseline carbon taxes $\bar{\tau}_{jk}$. We report changes in domestic consumer surplus, producer surplus, and government revenue in billions of USD, and changes in domestic emissions in megatons of CO_2. Welfare is the sum of consumer surplus, producer surplus, and government revenue, while social welfare is world welfare net of world emissions valued at a social cost of carbon of $100 per ton of CO_2. We omit country rows below 0.1 in magnitude in every column, retaining them in the world totals.

Table E2: European carbon taxation, steel

	Without CBAM					With CBAM				
	CS	PS	G	W	E	CS	PS	G	W	E
Austria	0.0	−0.8	0.6	−0.2	−2.5	−0.2	−0.5	0.6	0.0	−2.5
Belgium	0.0	−0.6	0.5	−0.1	−1.7	−0.2	−0.3	0.5	0.0	−1.7
China	0.0	0.0	0.0	0.0	0.0	2.9	−3.5	0.0	−0.6	−0.8
Czechia	0.0	−0.3	0.3	−0.1	−0.9	−0.3	−0.1	0.4	0.0	−0.9
Finland	0.0	−0.3	0.3	−0.1	−0.9	−0.2	−0.1	0.3	0.0	−0.9
France	0.0	−1.3	1.0	−0.3	−3.8	−0.6	−0.6	1.0	−0.2	−3.8
Germany	0.0	−3.8	3.1	−0.7	−10	−1.5	−1.8	3.1	−0.3	−10
Hungary	0.0	−0.2	0.1	0.0	−0.5	−0.1	−0.1	0.2	0.0	−0.5
India	0.0	0.0	0.0	0.0	0.0	1.3	−1.1	0.0	0.3	−0.7
Italy	0.0	−1.5	1.3	−0.2	−3.3	−1.2	−0.2	1.3	−0.1	−3.3
Japan	0.0	0.0	0.0	0.0	0.0	0.4	−0.8	0.0	−0.4	−0.4
Netherlands	0.0	−0.7	0.6	−0.1	−2.1	−0.2	−0.4	0.6	−0.1	−2.1
Poland	0.0	−0.8	0.7	−0.1	−1.7	−0.7	−0.4	1.4	0.3	−1.7
Romania	0.0	−0.4	0.3	−0.1	−1.1	−0.2	−0.2	0.3	−0.1	−1.1
Russia	0.0	0.0	0.0	0.0	0.0	0.5	−0.7	0.0	−0.2	−0.6
Slovakia	0.0	−0.4	0.3	−0.1	−1.2	−0.1	−0.2	0.3	0.0	−1.1
South Korea	0.0	0.0	0.0	0.0	0.0	0.4	−0.7	0.0	−0.3	−0.8
Spain	0.0	−0.4	0.3	−0.1	−0.9	−0.7	0.2	0.4	0.0	−0.9
Sweden	0.0	−0.2	0.2	−0.1	−0.7	−0.2	0.0	0.2	0.0	−0.7
Ukraine	0.0	0.0	0.0	0.0	0.0	0.2	−1.4	0.0	−1.2	−0.8
United Kingdom	0.0	−0.9	0.8	−0.2	−2.7	−0.4	−0.5	0.8	−0.2	−2.7
Vietnam	0.0	0.0	0.0	0.0	0.0	0.2	−0.3	0.0	−0.2	−0.6
World	−0.1	−13	11	−2.4	−35	−0.3	−15	13	−2.6	−41
Social welfare			1.1					1.5		

We raise European carbon taxes to $100 per ton of Scope 1 and 2 carbon emissions, with and without a CBAM. We compute effects relative to observed baseline carbon taxes $\overline{\tau}_{jk}$. We report changes in domestic consumer surplus, producer surplus, and government revenue in billions of USD, and changes in domestic emissions in megatons of CO_2. Welfare is the sum of consumer surplus, producer surplus, and government revenue, while social welfare is world welfare net of world emissions valued at a social cost of carbon of $100 per ton of CO_2. We omit country rows below 0.5 in magnitude in every column, retaining them in the world totals.

Table E3: European and Chinese carbon taxation

	Without CBAM				With CBAM			
	Europe	China	Rest of world	World	Europe	China	Rest of world	World
Price (%)	0.38	1.75	0.19	1.00	5.07	2.00	-0.96	1.06
Quantity consumed (%)	-0.61	-2.47	-0.30	-1.43	-6.73	-2.78	1.35	-1.45
Quantity produced (%)	-0.38	-2.80	0.16	-1.43	-0.02	-2.72	-0.08	-1.45
Consumer surplus ($1B)	-0.60	-15.0	-1.43	-17.0	-7.90	-17.1	7.43	-17.6
Producer surplus ($1B)	-13.2	-190	2.46	-201	-6.70	-188	-10.9	-206
Government revenue ($1B)	11.0	173	0.00	184	13.7	174	-0.01	188
Welfare ($1B)	-2.81	-31.4	1.03	-33.2	-0.85	-30.8	-3.51	-35.1
Emissions consumed (Mt)	-36.2	-592	-48.1	-677	-86.4	-604	3.54	-687
Emissions produced (Mt)	-37.5	-642	3.26	-677	-36.9	-638	-11.9	-687
Social welfare ($1B)				34.5				33.5

We simulate European and Chinese carbon taxation at $100 per ton of CO_2, with and without a CBAM, leaving carbon taxes unchanged in the rest of the world. We compute effects relative to observed baseline carbon taxes $\bar{\tau}_{jk}$. Prices and quantities are in percentage changes relative to observed values; consumer surplus, producer surplus, and government revenue are in billions of USD; and emissions are in megatons of CO_2. Emissions produced attribute emissions to producers, while emissions consumed attribute embodied emissions to consumers. Welfare is the sum of consumer surplus, producer surplus, and government revenue, while social welfare is world welfare net of world emissions valued at a social cost of carbon of $100 per ton of CO_2. Price and quantity effects are revenue-weighted averages of aluminum and steel, and other effects are sums.

Table E4: European CBAM impacts by country

(a) Consumer surplus

Largest gains ($1B)		Largest losses ($1B)	
China	3.20	Germany	-1.97
India	1.56	Italy	-1.44
Japan	0.57	Spain	-0.80
Russia	0.54	Poland	-0.75
South Korea	0.48	France	-0.73

(b) Producer surplus

Largest gains ($1B)		Largest losses ($1B)	
Germany	2.08	China	-3.80
Italy	1.45	India	-1.54
France	0.74	Ukraine	-1.39
Spain	0.61	Japan	-0.83
UK	0.40	Russia	-0.82

We simulate European carbon taxation at $100 per ton of CO_2, with and without a CBAM, leaving carbon taxes unchanged elsewhere, and we compute the difference between CBAM and no-CBAM effects for each country. We sum over aluminum and steel. We report the countries with the largest gains and losses in consumer surplus and producer surplus in billions of USD.

Table E5: Primary and secondary metals

	Without CBAM		With CBAM	
	Global emissions (Mt)	Global social welfare ($1B)	Global emissions (Mt)	Global social welfare ($1B)
Primary	-34.3	1.02	-45.3	-0.42
Secondary	-2.89	0.15	-4.18	0.79
Total	-37.2	1.17	-49.5	0.36

We simulate European carbon taxation at $100 per ton of CO_2, with and without a CBAM, leaving carbon taxes unchanged in the rest of the world. We compute effects relative to observed baseline carbon taxes $\bar{\tau}_{jk}$. We split the market into primary and secondary metals, with the total being their sum. We report global emissions and global social welfare for each. Welfare is the sum of consumer surplus, producer surplus, and government revenue, while social welfare is world welfare net of world emissions valued at a social cost of carbon of $100 per ton of CO_2. We sum over aluminum and steel.

Table E6: Demand and supply elasticities

	Supply parameter β				
Demand $\|b\|$	0.01	0.25	0.50	0.75	1.00
1.01	1.22	1.50	1.76	2.00	2.21
1.25	0.91	1.18	1.45	1.69	1.91
1.50	0.64	0.92	1.18	1.42	1.65
1.75	0.42	0.69	0.95	1.20	1.43
2.00	0.24	0.51	0.77	1.01	1.24

We report global social welfare in billions of USD. We simulate a European CBAM at $100 per ton of CO_2, leaving carbon taxes unchanged in the rest of the world. We compute effects relative to observed baseline carbon taxes $\bar{\tau}_{jk}$. We show robustness as we vary the parameters of the estimated model, holding the remaining parameters at their estimated and calibrated values. Here we vary demand elasticity $|b_j|$ and supply parameter β_j, imposed common across aluminum and steel. Welfare is the sum of consumer surplus, producer surplus, and government revenue, while social welfare is world welfare net of world emissions valued at a social cost of carbon of $100 per ton of CO_2. We sum over aluminum and steel.

Table E7: Trade openness

	Trade parameter θ				
	100	150	200	250	300
Without CBAM					
Global emissions (Mt)	-37.2	-37.2	-37.2	-37.3	-37.3
Global social welfare ($1B)	1.17	1.18	1.18	1.18	1.18
With CBAM					
Global emissions (Mt)	-46.3	-48.8	-50.4	-51.7	-52.6
Global social welfare ($1B)	1.23	1.29	1.31	1.31	1.30

We simulate European carbon taxation at $100 per ton of CO_2, with and without a CBAM, leaving carbon taxes unchanged in the rest of the world. We compute effects relative to observed baseline carbon taxes $\bar{\tau}_{jk}$. We show robustness as we vary the parameters of the estimated model, holding the remaining parameters at their estimated and calibrated values. Here we vary trade parameter θ_j, imposed common across aluminum and steel, without and with a CBAM. We report global emissions and global social welfare. Welfare is the sum of consumer surplus, producer surplus, and government revenue, while social welfare is world welfare net of world emissions valued at a social cost of carbon of $100 per ton of CO_2. We sum over aluminum and steel.

Table E8: Abatement elasticity

	Abatement parameter γ				
	100	200	300	400	500
Without CBAM					
Global emissions (Mt)	-99.3	-57.8	-40.9	-31.7	-26.0
Global social welfare ($1B)	3.36	1.87	1.30	1.00	0.81
With CBAM					
Global emissions (Mt)	-126	-73.8	-52.8	-41.6	-34.7
Global social welfare ($1B)	4.77	2.34	1.42	0.94	0.65

We simulate European carbon taxation at $100 per ton of CO_2, with and without a CBAM, leaving carbon taxes unchanged in the rest of the world. We compute effects relative to observed baseline carbon taxes $\bar{\tau}_{jk}$. We show robustness as we vary the parameters of the estimated model, holding the remaining parameters at their estimated and calibrated values. Here we vary abatement parameter γ_j, imposed common across aluminum and steel, without and with a CBAM. We report global emissions and global social welfare. Welfare is the sum of consumer surplus, producer surplus, and government revenue, while social welfare is world welfare net of world emissions valued at a social cost of carbon of $100 per ton of CO_2. We sum over aluminum and steel.