The Global Effects of Carbon Border Adjustment Mechanisms

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

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1 Introduction

As the European Union and United Kingdom implement the first carbon border adjustment mechanisms (CBAM), the world is experiencing a new climate policy tool. Domestic carbon taxes are important steps toward a global carbon tax, but they are subject to leakage and free-riding concerns. Leakage arises because domestic consumers can shift toward importing from unregulated foreign producers. Free-riding arises because foreign markets benefit from emission reductions, which are a global problem. CBAMs aim to address both concerns by imposing domestic carbon taxes at the border, combined with credits for foreign carbon taxes paid. The border tax reduces leakage toward importers, and the border credit encourages foreign markets to regulate. At the same time, the EU's own analysis cites concerns that the CBAM may disadvantage its lower-income trading partners (European Commission 2021).

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

The data do not support the presumption that production in lower-income countries is more emission-intensive than production in higher-income countries. For both aluminum and steel, lower- and higher-income countries emit similar levels of CO_2 per unit of production. The reason is that emissions intensity is increasing in the scale of production, and producers in lower-income countries generally operate at smaller scale. Moreover, clean producers in lower-income countries stand to benefit from a CBAM, under which low emissions intensity becomes a source of comparative advantage. For example, Mozambique's aluminum production is largely hydropowered, and this green energy translates into cost-competitiveness under an EU CBAM.

We build a quantitative equilibrium model of global trade to evaluate how CBAM policies affect CBAM-adopting and non-adopting markets. We simulate domestic carbon taxation both with and without border adjustment, and we evaluate impacts on consumers, producers, government revenue, and emissions relative to zero taxation under business as usual. We show how these impacts vary across two coalitions: the existing EU-UK coalition and one in which China joins, noting that China is a dominant player in aluminum and steel. We then turn to evaluating the extent to which CBAMs reduce leakage and encourage regulation, including for lower-income countries relative to higher-income countries.

We have four key findings. First, we quantify the impacts of domestic regulation alone. Domestic carbon pricing reduces domestic private welfare in most instances, as consumer and producer losses outweigh government revenue gains. Even so, we find meaningful emissions reductions that generate social welfare gains at reasonable valuations of the social cost of carbon. Moreover, foreign markets experience private welfare gains on net. Domestic regulation raises world price, hurting foreign consumers but greatly benefiting foreign producers. At the same time, higher world prices raise foreign production and thus foreign emissions.

Second, we quantify the impacts of domestic regulation when paired with a CBAM. Imposing a CBAM generates price divergence, as producers react by reallocating sales toward foreign markets. This reallocation leads to lower domestic supply and higher foreign supply, such that domestic prices rise and foreign prices fall. These price effects turn out to have positive welfare implications for domestic markets, relative to domestic regulation without a CBAM. The reason is that CBAM policies are import tariffs that allow domestic markets to exercise market power and manipulate their terms of trade. Even setting carbon considerations aside, domestic markets experience net welfare gains when imposing a CBAM alongside carbon taxation at modest levels. More generally, a CBAM limits welfare losses for domestic markets and limits welfare gains for foreign markets.

Third, CBAMs reduce emissions leakage. Without a CBAM, domestic regulation leads to large increases in foreign emissions. Pairing domestic regulation with a CBAM reduces these increases in emissions by roughly one third. We do not find that CBAMs place disproportionate pressure on lower-income countries. Under the existing EU-UK coalition, a CBAM induces less abatement among lower-income countries

than among higher-income countries. When the coalition expands to include China, abatement pressures are similar across lower- and higher-income countries.

Fourth, CBAMs encourage carbon regulation. CBAMs reduce the extent to which domestic regulation raises foreign welfare, thereby reducing the incentives to free-ride. That is, in relative terms, CBAMs increase the welfare incentives for foreign markets to regulate. CBAMs also create revenue incentives. Foreign markets can collect carbon tax revenue without distorting exports to CBAM markets, precisely because CBAMs credit these exports for carbon taxes paid. That is, exporters face the same total taxes, but the tax revenue flows instead to foreign governments.

We build on a growing body of work that studies international environmental policy coordination (Barrett 2001, 2006, Nordhaus 2015, Böhringer et al. 2016, Kortum and Weisbach 2022, Bourany 2024, Farrokhi and Lashkaripour 2024, Hsiao 2024) and the environmental effects of trade policy (Copeland and Taylor 2003, Kortum and Weisbach 2017, Shapiro 2021, Abuin 2024, Harstad 2024). Issues of leakage and free-riding are of central concern in this literature, particularly as they relate to unilateral climate policies. CBAMs have emerged as a leading proposal for minimizing leakage (Markusen 1975, Copeland and Taylor 1994, 1995, Hoel 1996, Rauscher 1997, Fowlie 2009, Elliott et al. 2010, Fowlie et al. 2016, Kortum and Weisbach 2017, 2022) and for encouraging broader climate cooperation (Clausing and Wolfram 2023). This proposal has now reached policymakers.

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

2 Background

We describe recent CBAM policies in the EU and UK, as well as two key industries targeted in the initial phases of implementation.

2.1 Existing CBAM policies

The European Union was the first jurisdiction to enact a CBAM, triggering a significant shift in global climate and trade policy. The idea of a carbon border adjustment mechanism gained momentum in 2019, when European Commission President Ursula von der Leyen announced the European Green Deal, a comprehensive plan to make the EU climate neutral by 2050. One of the major challenges of the Green Deal was ensuring that stringent EU climate policies did not drive production to countries with weaker carbon regulations.

Policymakers debated several alternatives before formally proposing the CBAM in July 2021. Under the CBAM, importers must purchase certificates equivalent to the EU carbon price under the Emissions Trading System (ETS) to cover the emissions used to produce imported goods, ensuring parity between domestic and foreign producers. Crucially, imported goods are credited for any domestic carbon price that has already been paid.

The CBAM started with a phase-in period on October 1, 2023. Importers are required to report the emissions used to produce traded goods, but without financial obligation until January 1, 2026. The policy initially covers six carbon-intensive industries – iron and steel, aluminum, cement, electricity, fertilizer, and hydrogen – with the potential to expand to others over time.[1] After January 1, 2026, the EU CBAM will phase in slowly as the allocation of free allowances – the existing trade protection measure – is phased out.[2]

In December 2023, the UK government announced its intention to implement a

[1] Early European Commission analysis of the proposed CBAM indicated that four industries – iron and steel, aluminum, cement, and fertilizer – accounted for more than half of EU industrial emissions and 13 percent of total EU emissions (European Commission 2021).

[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 emission levels. Free allocations will be phased out gradually between 2026 and 2035, and the share of emissions covered by the CBAM increases to backfill for emissions no longer eligible for free allowances.

CBAM by 2027. While the UK CBAM is not yet law, the government has issued position papers outlining its plans (HMRC 2024). The UK CBAM would cover the same sectors as the EU with the exception of electricity imports.[3]

Other countries are also discussing CBAMs. Canadian Prime Minister Mark Carney has proposed a CBAM, arguing that it will level the playing field for industrial producers subject to the federal carbon price backstop in Canada. The governments of both Australia and Taiwan are currently considering CBAMs. Clausing et al. (2024) document the correlation between EU CBAM discussion and the expansion of carbon pricing around the world. China has expanded its emissions trading system to cover CBAM-targeted industries, and other countries have cited the EU CBAM as motivation for considering and enacting carbon pricing.

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

We analyze EU and UK CBAM policy, focusing on the aluminum and steel industries. These industries are both heavily traded and emission-intensive. Aluminum and steel represent a larger share of global trade than other CBAM-targeted industries, and a much of aluminum and steel production is traded. Furthermore, aluminum and steel are emission-intensive and account for almost 15% of total global CO_2 emissions (Table 1). Electricity and cement account for a large share of global emissions, but only a small share of production is traded. Exposure to CBAM policies is therefore limited. Fertilizers are heavily traded but only a small share of global emissions. Hydrogen is neither heavily traded nor a large share of global emissions. We simulate a CBAM with full implementation, incorporating both Scope 1 and Scope 2 emissions

[3] In both the EU and the UK, several issues remain. EU regulations suggest that exporters will be credited for paying an "explicit" carbon price, but what qualifies as an explicit price, including whether the carbon price must apply to all production or only production for export, will be determined by implementing regulations. Similarly, details on reporting requirements for importers and what default values apply when importers do not meet reporting requirements are not yet finalized. EU regulations require CBAM payments for the carbon emissions associated with the electricity used in the production of cement, steel and fertilizers, but not aluminum.

Table 1: Trade and emissions for CBAM-targeted industries

	Global Trade Share (%)	Trade Value (1B USD)	Trade Intensity (%)	Global Emissions Share (%)
Iron & Steel	3.5	839	23	11
Aluminum	1.0	253	41	3
Electricity	0.6	136	2	33
Fertilizers	0.5	131	60	1
Cement	0.1	17	2	6
Hydrogen	0.001	0.3	0.1	2

Trade intensity is defined as the share of production that is exported. We construct this measure from production and trade data. Production data come from Climate TRACE for iron and steel, WoodMac for primary aluminum, the World Bureau of Metal Statistics for secondary aluminum, the US Energy Information Administration for electricity, the US Geological Survey for cement, the FAO for fertilizer, and the International Energy Association for hydrogen. Trade data come from UN Comtrade. Emissions data are from Bataille (2020) and the IEA.

and abstracting from the gradual phase-out of free allowances. Scope 1 emissions are direct production emissions, while Scope 2 emissions are those from the electricity used in production.

2.2 Aluminum

Aluminum is a globally traded commodity used in the transportation, construction, packaging, and energy sectors. Its price is determined by international markets like the London Metal Exchange (LME), and it accounts for 3% percent of global carbon emissions (Table 1).

There are two production technologies: primary and secondary. Primary production involves extracting aluminum from alumina, a compound of aluminum and oxygen. During the smelting process, carbon molecules combine with the oxygen of alumina to yield pure aluminum. CO_2 is released as a byproduct of this chemical reaction.[4] Moreover, the electricity used in the smelting process can itself generate substantial CO_2 emissions, particularly when power is drawn from coal or other fossil fuels. Smelters that rely on low- or zero-emissions electricity sources, such as hydro-

[4] The reaction has a theoretical lower limit on the amount of CO_2 it can release: the production of 1 metric ton of aluminum emits at least 1.22 ton of CO_2, meaning that emissions are inevitable even with the most efficient processes. Carbon-free aluminum production, using inert-anode technologies, is not yet commercially viable.

electric power, can produce aluminum with lower emissions. Secondary production involves recycling aluminum scrap. This process requires only 5-10% of the energy required for primary production, and it involves no direct CO_2 emissions.

2.3 Iron and steel

Steel is a crucial component of the global manufacturing, construction, infrastructure, transportation, and energy sectors. Steelmaking is also one of the most energy and emission-intensive industries in the world and is largely dependent on coal. It accounts for 11% of global carbon emissions (Table 1).

As with aluminum, there are two production technologies: blast furnace/basic oxygen furnace (BF-BOF) and electric arc furnace (EAF). BF-BOF steel is also known as primary steel. The raw materials are iron ore and metallurgical coal, and the process involves two energy-intensive steps. First, pig iron is produced by reducing iron ore in a blast furnace fired by coke, which is a fuel made from coal. Second, molten pig iron is decarbonized and transformed into steel by blowing oxygen in a basic oxygen furnace. BF-BOF steel accounts for 67% of production but 84% of emissions globally (including emissions from electricity). The IEA forecasts continued construction of blast furnaces, which have a useful life of 20-40 years.

EAF steel is also known as secondary steel. Recycled steel scrap is melted in an electric arc furnace to produce new steel. Electricity is the main input, and so emissions intensity is determined by the energy mix used in electricity generation. A smaller portion of EAF steel 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 can then be transformed into steel in an electric arc furnace. This process is more carbon-intensive than EAF steel made from scrap, but less so than BF-BOF steel. Green steel efforts aim to produce direct reduced iron through electrolysis using green hydrogen and zero-emission electricity, but these methods are not yet economically feasible at commercial scale. In our data, BF-BOF and EAF steel average 2.4 and 0.9 tons of CO_2 per ton of steel produced, respectively.

3 Data

We compile data on global aluminum and steel markets, covering production, consumption, prices, and regulation.

3.1 Production

Aluminum

We measure primary aluminum production at the firm level with detailed data from Wood Mackenzie (WoodMac), a leading data and analytics provider focused on energy industries and related sectors.[5] These data cover the near-universe of primary aluminum smelters globally: we observe 153 smelters that represent 100% percent of the world's active smelters in 2023. WoodMac specialists compile these data by combining public information with periodic site visits to each smelter.[6] We observe detailed information on plant capacity, annual production from 2000 to 2023, and operating and capital costs, along with estimates of both Scope 1 and Scope 2 carbon emissions.[7] Costs include those from electricity, alumina, other raw materials, consumables, labor, maintenance, and freight, which we supplement with our own estimates of transport costs. We measure secondary aluminum production at the country level with data from the World Bureau of Metal Statistics (WBMS), which we describe in Appendix C.1. We observe production for the top 10 secondary producers, which account for 90% of global secondary production in 2023.

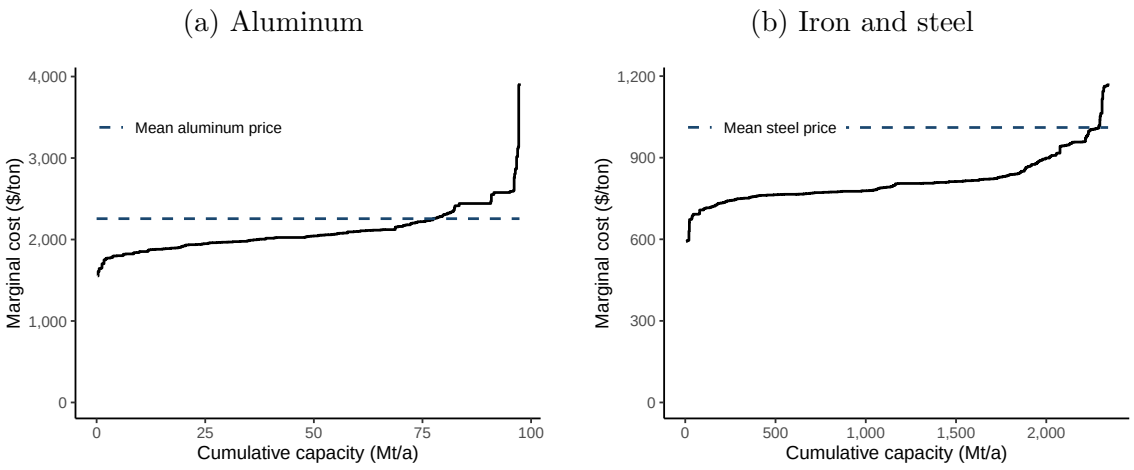
In total, we observe 84.4 Mt of global aluminum production in 2023, accounting for 691 Mt of CO_2 emissions. Primary aluminum is 69.4 Mt (82%) of global production and 676 Mt (98%) of global emissions, while secondary aluminum is 15.0 Mt of production and 14.7 Mt of emissions. Figure 1 plots the production costs of primary and secondary aluminum against cumulative capacity. Table 2 lists the top ten producing countries, which together account for 77.4 Mt. China is a dominant producer

[5] The WoodMac data are similar to the data used in Corts (1999), a business case taught in many microeconomics classes.

[6] Some Chinese smelters, for which data availability is limited, have been grouped and their values approximated to provide a comprehensive picture.

[7] Scope 1 emissions refer to the direct emissions from the smelting process itself, while Scope 2 emissions come from the electricity used in the production process.

Figure 1: Production costs and capacity



Marginal costs are in nominal 2023 USD. Cumulative capacity is in metric megatonnes per annum. Marginal costs are operating costs, defined as cash costs plus depreciation. Aluminum includes both primary and secondary aluminum. Costs and capacities are estimated at the asset level except secondary aluminum, which is at the country level.

and consumer of aluminum, accounting for about 60 percent of the market. These measures are consistent with country-level estimates from the US Geological Survey. Lower-income countries account for 5.7 Mt of global production. In our production data, these countries include Cameroon, Egypt, Ghana, India, Mozambique, Tajikistan, and Venezuela. We define lower-income countries as those classified as low and lower-middle income by the World Bank.[8]

Iron and steel

We obtain iron and steel data at the plant level from Climate TRACE (Tracking Real-time Atmospheric Carbon Emissions), an independent non-profit that monitors and reports global greenhouse gas emissions.[9] Climate TRACE publishes monthly estimates of steel production, capacity, and emissions for the plants included in the Global Steel Plant Tracker (GSPT) database from Global Energy Monitor (GEM).

[8] Because of a lack of GNI data, Venezuela remained unclassified in the 2023 World Bank income group classification. But GDP data for 2023 put Venezuela within range of the lower-middle income group, and so we treat it as such in our analysis.

[9] Climate TRACE also monitors the primary aluminum market. A comparison with our WoodMac data shows consistency between the two sources. See Appendix Table B6 for an overview of production, capacity, and emissions from each source.

Table 2: Aluminum by country

(a) Top ten producers

Country	Mt
China	48.9
India	4.7
EU + UK	4.6
USA	4.1
Russia	4.0
Canada	3.3
UAE	2.7
Brazil	1.9
Bahrain	1.6
Australia	1.6
Rest of world	7.0

(b) Top ten consumers

Country	Mt
China	50.8
EU + UK	9.1
USA	8.6
India	3.0
Japan	2.9
Brazil	1.8
Turkey	1.7
Russia	0.9
Saudi Arabia	0.9
Mexico	0.7
Rest of world	4.0

The EU + UK include 27 EU member countries plus Norway, Iceland, Switzerland, Liechtenstein, and the United Kingdom. We measure production and consumption in 2023 in units of one million metric tons.

These data cover every iron and steel plant with a capacity of more than 500 thousand tons. Emissions data include both Scope 1 and Scope 2 emissions. The data derive from more than 300 satellites and 11,000 sensors that capture facility-level activity, covering more than 660 million individual sources of emissions in 2024.[10] We describe data construction in Appendix C.2.

In total, we observe 1,673 Mt of global steel production in 2023, covering 892 plants across 77 countries and accounting for 3,163 Mt of CO_2 emissions. Primary steel is 1,114 Mt (67%) of global production and 2,657 Mt (84%) of global emissions, while secondary steel is 559 Mt of production and 506 Mt of emissions. Figure 1 plots production costs against cumulative capacity. Table 3 lists the top ten producing countries, which together account for 1,482 Mt. As with aluminum, China is a dominant producer and consumer of steel, accounting for about 50% of the market. In our production data, lower-income countries include Bangladesh, Egypt, Ghana, India, Kenya, Morocco, Nigeria, North Korea, Pakistan, the Philippines, Syria, Uganda, Uzbekistan, Venezuela, and Vietnam, which together account for 113 Mt (7%) of

[10] Climate TRACE uses multispectral satellite imagery from the European Space Agency Copernicus Sentinel missions and the NASA/USGS Landsat missions.

Table 3: Iron and steel by country

(a) Top ten producers

Country	Mt
China	860
EU + UK	153
Japan	88
USA	86
India	76
Russia	60
South Korea	59
Turkey	35
Brazil	33
Iran	31
Rest of world	191

(b) Top ten consumers

Country	Mt
China	827
EU + UK	169
USA	101
India	77
Japan	68
South Korea	49
Turkey	43
Russia	39
Mexico	33
Iran	31
Rest of world	236

The EU + UK include 27 EU member countries plus Norway, Iceland, Switzerland, Liechtenstein, and the United Kingdom. We measure production and consumption in 2023 in units of one million metric tons.

global production and 202 Mt (6%) of global emissions.

3.2 Consumption

Aluminum

We construct aluminum consumption by combining the production data with country-level trade data for 2023 from UN Comtrade.[11] We focus on "Aluminium; unwrought, (not alloyed)" with HS code 760110 for primary aluminum and "Aluminium; unwrought alloy" with HS code 760120 for secondary aluminum.[12] Trade values are reported more consistently than trade quantities, and so we focus on the trade value data. We compute quantities by dividing these values by the average aluminum price in 2023. Consumption follows as the sum of production and net imports. For example, consider the EU and UK. In 2023, the EU and UK produced 4.7 Mt, imported 12.1 Mt, and exported 7.7 Mt. The sum of production and net imports yields 9.1 Mt in EU and UK consumption. We repeat this calculation for

[11] We use 2021 trade data for Russia because data are not reported for 2022 or 2023.
[12] Together, they comprise "Aluminum; unwrought" with HS code 7601.

other countries to identify the top ten consumers globally, as listed in table 2. These top consumers consume a total of 80.4 Mt. Assuming balanced trade, such that total production and consumption are equal at 84.4 Mt, we attribute the remaining 4.0 Mt of consumption to the rest of the world. We measure both primary and secondary aluminum, which we treat as perfectly substitutable in consumption.

Iron and steel

We construct iron and steel consumption similarly. We compile trade data on iron and steel products that are targeted by the EU CBAM: HS codes 7201, 720211, 720219, 720241, 720249, 720260, 7303, and 7205 through 7229. We exclude products classified as articles of iron and steel. As above, we compute trade quantities and calculate country-level consumption as the sum of production and net imports. In 2023, the EU and UK produced 153 Mt of iron and steel, imported 150 Mt, and exported 135 Mt. The sum of production and net imports yields 169 Mt in EU and UK consumption. Table 3 lists the top ten global consumers, which together consume 1,437 Mt. We attribute the remaining 236 Mt of consumption to the rest of the world. We measure both primary and secondary steel, which we again treat as perfect substitutes.

3.3 Prices and regulation

World price data for aluminum comes from the World Bank's Commodities Price Data, "The Pink Sheet" which uses the London Metal Exchange (LME) aluminum cash benchmark price for unalloyed primary ingots. The average aluminum price was 2,256 USD per ton in 2023. This price does not include any regional premia. Crude steel is not widely traded on exchanges, and so we calculate a global price as the weighted average of export prices for CBAM-targeted iron and steel products. The average steel price was 1,011 USD per ton in 2023.

We construct global data on carbon pricing. We collect carbon prices as of April 1, 2023 from the World Bank's Carbon Pricing Dashboard, which cover 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 country-level, and one – the EU

ETS – is supranational. Nine are carbon taxes, and 18 are emission trading systems. Tax exemptions and free allowances are common, resulting in lower average prices paid per ton of CO_2 than the reported tax rates or allowance trading price. We account for exemptions and allowances to construct the adjusted carbon prices that apply to each plant. Plants pay these lower, adjusted prices. Appendix tables B1, B2, and B3 present both sets of prices for primary aluminum, secondary aluminum, and steel, respectively, in jurisdictions with nonzero carbon prices.

4 Stylized Facts

We describe the distributional patterns of emissions intensity and CBAM exposure for aluminum and steel producers globally.

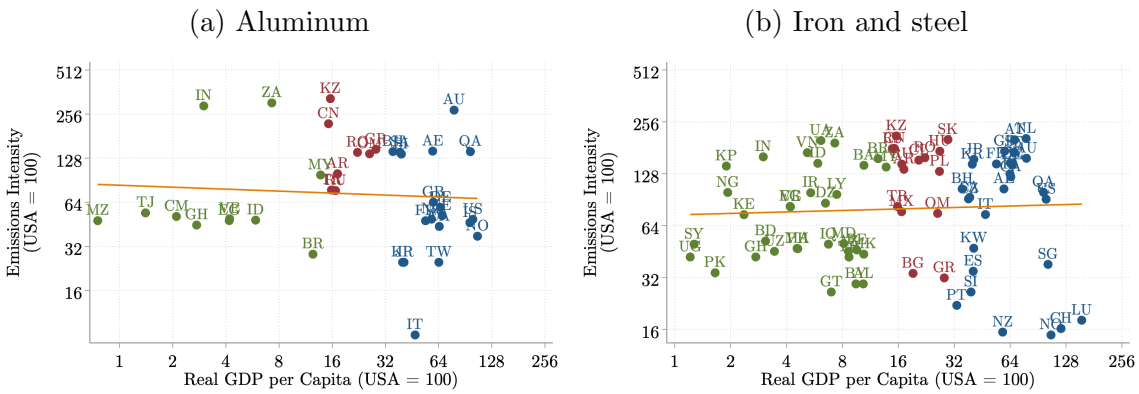
4.1 Lower-income countries have similar emissions intensity

Figure 2 plots the relationship between the emissions intensity of production and real GDP per capita across countries. We normalize both measures to 100 for the US. Emissions intensity refers to the emissions generated per unit of production. We do not find support for the common presumption that production in lower-income countries is more carbon-intensive. Instead, we observe a flat relationship between emissions intensity and GDP that holds for both aluminum and steel. The slightly negative correlation for aluminum and the slightly positive correlation for steel are weak and not statistically significant. Production in lower-income countries is not systematically more emission-intensive than production in higher-income countries.

4.2 Lower-income countries have smaller-scale production

Production in lower-income countries is of smaller scale. Appendix figure A1 shows a positive relationship between emissions intensity and the scale of production, as well as a negative relationship between emissions intensity and plant age. There is a negative relationship between production scale and plant age. That is, plants in lower-income countries produce at smaller scale, which tends to reduce emissions intensity (scale effects). At the same time, plants in lower-income countries are older and lack the latest, cleanest technology, which tends to raise emissions intensity (technology

Figure 2: Emissions intensity and GDP per capita



Each point is a country. The y-axis is the average level of emissions intensity of production within a country, and the x-axis is real GDP per capita. Both axes are in log scale.

effects). On net, scale effects seem to dominate.

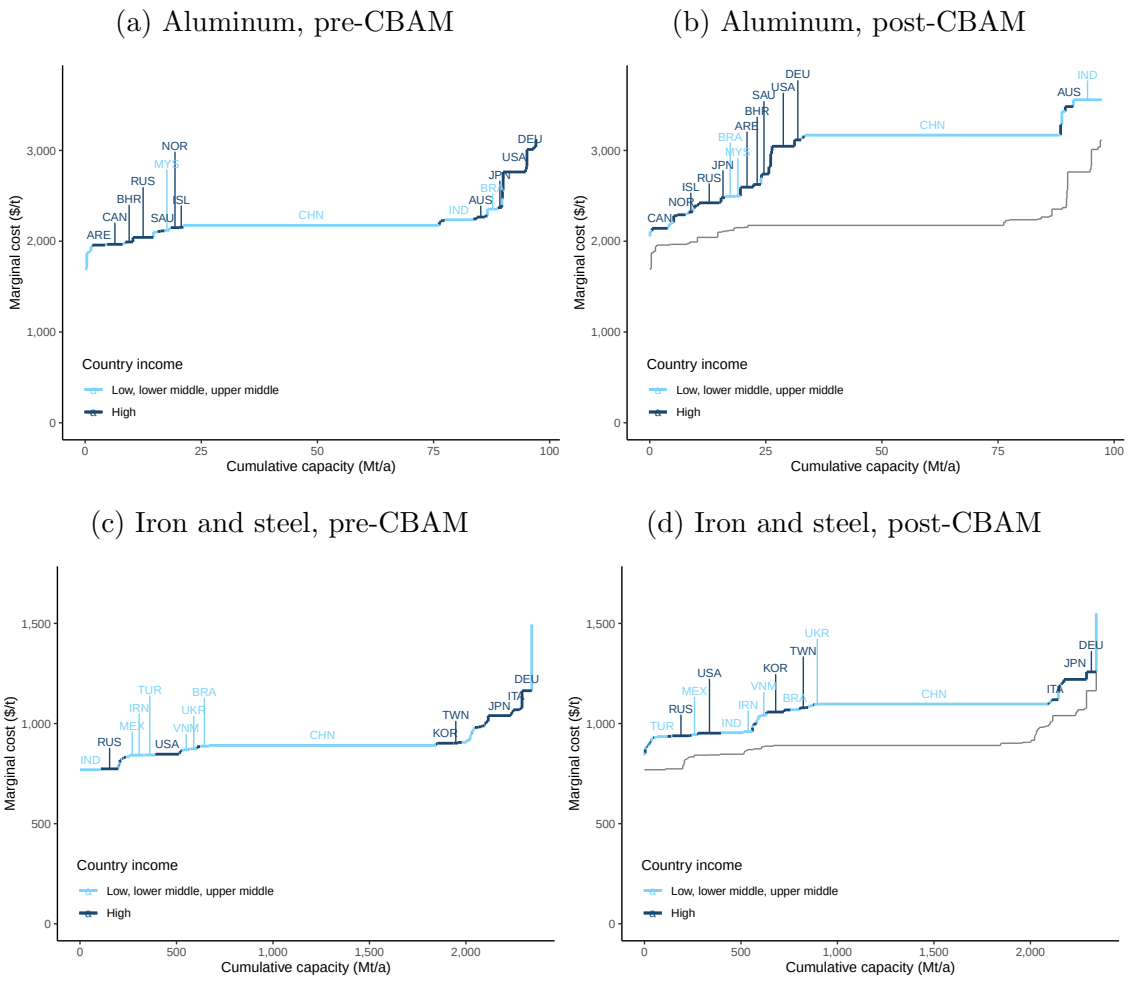
4.3 Some lower-income countries benefit from a CBAM

In Figure 3 we consider how the introduction of a CBAM may affect the cost of production for facilities in our data. We do this for aluminum plants (panels a and b) and steel plants (panels c and d).

In panel a) and c) we plot cumulative capacity in order of marginal cost for each facility in our data. This captures the distribution of facilities prior to the introduction of CBAM. Panels b) and d) simulate the introduction of a CBAM, reflecting a flat \$96 fee per ton of CO_2. This fee is equivalent to the average ETS price in the EU and UK in 2023. Including this carbon price shifts up marginal costs for all producers. However, differences in the emissions intensity of production across producers result in changes in position. This change captures a new margin of comparative advantage that emerges once carbon is priced.

Appendix figure A2 reports some of the determinants associated with the changes in marginal cost rank under this CBAM simulation. We observe that there is little association between the change in marginal cost rank and real GDP per capita. We estimate a much stronger relationship between the change in rank and the emissions intensity of production. Smelters with lower emissions intensities result in much larger reductions in marginal cost rank compared to smelters with higher emissions

Figure 3: Production costs under a CBAM



Marginal costs in 2023 USD. Cumulative capacity is in megatons per annum. Aluminum includes both primary and secondary aluminum. Marginal costs are operating costs, defined as cash costs plus depreciation. Costs include shipping costs. Pre-CBAM costs include pre-existing carbon pricing. Post-CBAM costs include carbon taxation of $96 USD per ton of Scope 1 or 2 CO_2 emissions with no free allowances. The 15 highest capacity producers are labeled in each plot.

intensities. An important predictor of emissions intensity in this context is the carbon intensity of power emissions. Facilities that use less carbon intensive power have much lower emissions intensities and experience greater reductions in marginal cost rank.

5 Model

We model carbon taxation and a carbon border adjustment mechanism (CBAM) in a world commodity market. We distinguish between two markets $m \in \mathcal{M}$, where the set of markets $\mathcal{M} = \{H, L\}$ includes those with high (H) and low (L) levels of carbon regulation. Regulators in H consider a CBAM on imports from L.

5.1 Demand

We specify simple, log-linear demand in each market. For intercepts δ^m, elasticities ε^m, and prices P^m, demand is

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

World demand aggregates across markets.

$$D = \sum_m D^m \tag{2}$$

5.2 Supply

Producers $i \in \mathcal{I}$ operate under carbon regulation. We study domestic carbon taxation and a carbon border adjustment mechanism.

Production

A producer i in market m chooses production s_i as a function of production capacity $\bar{s}_i$, constant marginal cost c_i, and price p_i^m for its product. We observe production, capacity, and costs. We take capacity and costs as given, noting that adjustment requires substantial investment that is difficult in the short run. Prices will depend on regulation. Each producer has a collection of production lines l, and we model choices at the level of the production line. The utility from operating a production line is

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

For a given producer, production lines have common observed costs c_i, common unobserved costs ϵ_i, and idiosyncratic unobserved costs ϵ_{il}, which we assume are logit-distributed. The β parameter captures the utility of profits, which we will estimate.[13] Unobserved costs rationalize production in spite of high observed costs.

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

$$o_i^m = \frac{\exp(v_i^m)}{1 + \exp(v_i^m)}. \tag{3}$$

For a given producer, this probability corresponds to capacity utilization. We aggregate across production lines, as given by capacity, to obtain production at the producer level.

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

World supply then aggregates across producers.

$$S = \sum_m \sum_{i \in \mathcal{I}^m} \bar{s}_i o_i^m \tag{4}$$

High prices p_i^m encourage greater production s_i^m by raising the proportion o_i^m of production lines in operation. Production is given by capacity and capacity utilization.

Carbon taxation

Prices p_i^m are net of regulation. Production involves emissions e_i, which are subject to domestic carbon taxes τ^m. We observe emissions across producers and carbon taxes across markets. Producers receive net prices

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

which depend on producer-specific emissions. In the absence of a CBAM, producers face a single world price P, which we also observe.

We incorporate abatement technology in simple form. We allow for emissions e_i

[13] As is typical, we can equivalently take per-unit profits $(p_i^m - c_i)$ as the numeraire, setting $\beta = 1$, then estimate the variance of the logit shocks.

to respond to carbon taxation τ^m with elasticity γ, such that

$$\log e_i = \log \bar{e}_i - \gamma(\tau^m - \bar{\tau}^m),$$

where $\gamma = -\frac{\partial \log e_i}{\partial \tau^m} = -\frac{\partial e_i}{\partial \tau^m}\frac{1}{e_i}$ captures the percentage decrease in emission intensity per dollar of carbon regulation. We observe $\bar{e}_i$ and $\bar{\tau}^m$ as data. If $\gamma = 0$, then emissions are fixed, and so $e_i = \bar{e}_i$ as observed. If $\gamma > 0$, then higher taxes $\tau^m > \bar{\tau}^m$ induce lower emissions $e_i < \bar{e}_i$, each relative to those observed. We treat abatement technology as costless for producers.[14] Substituting, net prices become

$$p_i^m = P^m - \frac{\tau^m \bar{e}_i}{\exp[\gamma(\tau^m - \bar{\tau}^m)]}.$$

The first-order effect of taxation τ^m is to lower net prices by taxing each ton of emissions. But the second-order effect is to raise net prices by reducing emissions. The second-order effect blunts the impact of carbon taxation on production.

Carbon border adjustment mechanism

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

$$\alpha^H = \tau^H - \tau^L > 0$$

The adjustment is such that all aluminum consumed in H is subject to total tax τ^H. Goods produced in H face carbon tax τ^H during production, while goods imported from L face τ^L during production and $\tau^H - \tau^L$ at the border. Prices no longer equalize across markets, and so we distinguish between prices (P^H, P^L). Producers decide which market to serve, and so regulation affects trade.

Producers in H can choose among the two prices, but they are always subject to domestic carbon tax τ^H. The reason is that they do not receive a tax refund when

[14] The $\gamma = 0$ case precludes abatement, and so it implicitly imposes infinite abatement costs. The $\gamma > 0$ case imposes zero abatement costs. Our simulations will present estimates for both cases, which we can interpret as bounds. Infinite abatement costs will understate the benefits for producers, while zero abatement costs will overstate the benefits.

exporting to the unregulated market. Net prices are

$$p_i^{HH} = P^H - \tau^H e_i, \quad p_i^{HL} = P^L - \tau^H e_i$$

for sales from H to H (HH) and for sales from H to L (HL). Producers in L can choose among the two prices, but they only pay the higher tax when exporting to H. Net prices are

$$p_i^{LH} = P^H - \tau^H e_i, \quad p_i^{LL} = P^L - \tau^L e_i.$$

Producers choose their highest net price.

$$p_i^m = \max\{p_i^{mH}, p_i^{mL}\}$$

Producers serve H when prices in H dominate, otherwise they serve L.

$$h_i^m = \mathbb{1}(p_i^{mH} > p_i^{mL}), \quad \ell_i^m = \mathbb{1}(p_i^{mL} > p_i^{mH})$$

As before, production is given by capacity and the choice to operate. Total supply to H aggregates across producers in both markets, as does total supply to L.

$$S^H = \sum_m \sum_{i \in \mathcal{I}^m} \bar{s}_i o_i^m h_i^m, \quad S^L = \sum_m \sum_{i \in \mathcal{I}^m} \bar{s}_i o_i^m \ell_i^m \tag{5}$$

5.3 Equilibrium

Without a CBAM, equilibrium prices P^* clear global markets. For world demand and supply as defined by equations 2 and 4,

$$D(P^*) = S(P^*).$$

Under a CBAM, adjustment α^H imposes a price wedge. In equilibrium, prices (P^{H*}, P^{L*}) must clear each market separately. The marginal producer will be indifferent between selling to H or L.

$$D^H(P^{H*}) = S^H(P^{H*}, P^{L*}; \alpha^H), \quad D^L(P^{L*}) = S^L(P^{H*}, P^{L*}; \alpha^H)$$

There are two cases. In the first case, the marginal producer is a producer in market H. Indifference implies $p_i^{HH} = p_i^{HL}$ and thus

$$P^H = P^L.$$

The law of one price holds. In this case, the CBAM is not binding and has no impact on world prices. However, this case only obtains when market H does not import from L. The CBAM targets imports, and so without imports it is trivally moot.

In the second case, the marginal producer is a producer in market L. It is this case that is empirically relevant, as it captures that H imports from L. Indifference implies $p_i^{LH} = p_i^{LL}$ and thus

$$P^H - P^L = \tau^H e_i(\tau^H) - \tau^L e_i(\tau^L).$$

We make explicit the dependence of emissions on carbon taxation, reflecting producers' abatement responses. The first-order impact of higher taxation $\tau^H > \tau^L$ dominates the second-order impact of higher abatement $e_i(\tau^H) < e_i(\tau^L)$, and so the right-hand side is positive. It follows that the left-hand side is positive, implying higher prices $P^H > P^L$. But in equilibrium, the benefit of higher prices in H is offset by the cost of higher taxation.

Intuitively, when H imposes border adjustment α^H, it restricts supply and raises prices in H. Clean exporters enjoy access to these higher prices and thus increase production destined for H, raising supply and dampening the initial rise in prices in H. Dirty exporters cannot access the higher prices in H because of the CBAM, and so they instead direct sales toward L. Higher supply depresses prices in L.

5.4 Welfare

We evaluate welfare by considering consumer surplus, producer surplus, and government revenue. For the given demand function, consumer surplus for market m is

$$\log \mathrm{CS}^m = \log \delta^m + (1 + \varepsilon^m) \log P^m - \log(-1 - \varepsilon^m).$$

Producer surplus stems from profits, which are revenues less costs. Producer surplus for market m aggregates across smelters in m.

$$\mathrm{PS}^m = \sum_{i \in \mathcal{I}^m} (p_i^m - c_i) \bar{s}_i o_i^m$$

Government revenue for H comes from domestic carbon taxes τ^H on production in H, as well as border adjustments α^H on imports from L.

$$\mathrm{G}^H = \sum_{i \in \mathcal{I}^H} \tau^H e_i \bar{s}_i o_i^H + \sum_{i \in \mathcal{I}^L} \alpha^H e_i \bar{s}_i o_i^L h_i^L$$

Government revenue for L comes only from domestic carbon taxes τ^L on production in L.

$$\mathrm{G}^L = \sum_{i \in \mathcal{I}^L} \tau^L e_i \bar{s}_i o_i^L$$

We define domestic welfare as the sum of consumer surplus, producer surplus, and government revenue.[15]

$$\mathrm{W}^m = \mathrm{CS}^m + \mathrm{PS}^m + \mathrm{G}^m$$

We treat emissions separately, where emissions are given by per-ton emissions and production.

$$\mathrm{E}^m = \sum_{i \in \mathcal{I}^m} e_i \bar{s}_i o_i^m$$

Carbon regulation has the benefit of reducing emissions at the cost of reducing welfare. The social planner considers both effects. If the social cost of carbon is high, then the social planner is willing to sustain large welfare losses in order to reduce emissions.

We also evaluate the potential for policy spillovers. In particular, a CBAM in H can encourage carbon taxation in L. The reason is that producers in L pay total tax τ^H on all exports to H, given adjustment $\alpha^H = \tau^H - \tau^L$, regardless of the size

[15] We weight surplus and revenue equally, but an alternative approach is to treat government revenue differently. On one hand, fiscal interactions imply that government revenue should receive more weight. Carbon tariffs correct an externality and thus raise revenue without distortions to social welfare, thereby lessening the need for revenue from other, more distortionary taxes. On one hand, "leaky bucket" concerns imply that government revenue should receive less weight. Direct surplus gains dominate when transfers from the government are inefficient.

of domestic tax τ^L (as long as $\tau^L < \tau^H$). Producers in L are thus indifferent to τ^L. It follows that regulators in L can collect revenue without distorting outcomes. Consider the extremes. When $\tau^L = 0$, exporters pay $\alpha^H = \tau^H$ and the revenue goes entirely to H. When $\tau^L = \tau^H$, exporters pay $\alpha^H = 0$ and the revenue goes entirely to L. Exporters pay the same total tax because $\tau^L + \alpha^H = \tau^H$ in both cases.

6 Estimation

We construct empirical demand and supply curves for aluminum and steel. We do so by market, noting that counterfactuals will vary the set of countries in markets H and L.

6.1 Demand

We use country-level consumption data to construct demand. We set the demand elasticities of both aluminum and steel to -0.25, which is consistent with low empirical estimates of -0.2 to -0.4 for aluminum and steel respectively (Söderholm and Ekvall 2020).[16]

$$\varepsilon^m = -0.25 \quad \forall\, m$$

In the absence of an existing CBAM, prices equalize across markets at a single world price P that we observe.

$$P^m = P \quad \forall\, m$$

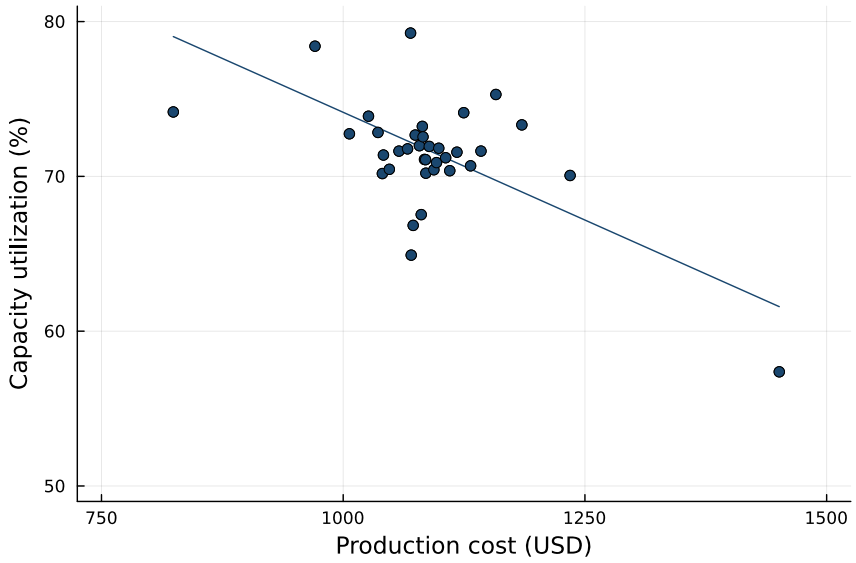
We observe consumption by country, and we aggregate across countries to measure consumption D^m by market. We then recover the intercepts by inverting equation 1.

$$\delta^m = \log D^m - \varepsilon^m \log P.$$

We thus obtain empirical demand curves $D^m(P^m)$ that specify how demand in each market responds to prices.

[16] Estimated elasticities are also low for recycled metals: -0.2 to -0.3 for secondary aluminum, -0.39 for steel scrap, -0.25 to -0.29 for recycled copper, and -0.25 for recycled lead.

Figure 4: Capacity utilization



We plot observed capacity utilization against production costs as a binned scatter plot. The unit of observation is an aluminum or steel producer in our sample. Capacity utilization is the percentage of capacity used for production. Production cost is the cost of producing one additional ton of aluminum. We control for product and country fixed effects.

6.2 Supply

We use plant-level production data to construct supply. We observe production s_i^m and production capacity $\bar{s}_i$, which we use to compute capacity utilization $o_i^m = s_i^m/\bar{s}_i$. Under the assumption of constant marginal costs, the average costs that we observe coincide with the costs c_i that we model. Figure 4 shows that our observed costs are meaningful: capacity utilization is highest for low-cost producers and lowest for high-cost producers. Given constant marginal costs, this downward-sloping relationship captures that higher profits encourage higher production. Conversely, greater regulation reduces profits and thus reduces production.

Our cost data simplify estimation. We need only to estimate parameter β, which captures the slope of the plotted relationship between production and costs. Applying the typical logit inversion, choice probability equation 3 gives a regression equation for estimation.

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

We can construct the left-hand side from data, having computed capacity utilization. We similarly construct the main regressor from data. We observe prices p_i^m and costs c_i, where prices in the data are given by $p_i^m = P - \bar{\tau}^m \bar{e}_i$ for common world price P, observed carbon taxation $\bar{\tau}^m$, and observed emissions $\bar{e}_i$. Error term ϵ_i represents unobserved costs.

In practice, we pool data across producers i of products j, and we measure carbon taxation at the level of countries k. Our products include aluminum and steel. Allowing for product and country fixed effects, the regression equation becomes

$$\log\left(\frac{o_{ijk}}{1-o_{ijk}}\right) = \beta(P_j - \bar{\tau}_k \bar{e}_{ijk} - c_{ijk}) + \mu_j + \mu_k + \epsilon_{ijk}. \tag{6}$$

Our cost data provide identifying variation. World prices P_j, which vary by product, are absorbed by product fixed effects μ_j. Carbon taxation $\bar{\tau}_k$, which varies by country, remains modest: 92% of production is subject to zero taxation, which limits variation in the $\bar{\tau}_k \bar{e}_{ijk}$ term. We take costs as given, subject to product and country fixed effects.

Lastly, we set parameter $\gamma = 0.3$. We therefore allow emissions e_i to respond modestly to carbon taxation τ^m, consistent with empirical studies of the abatement response to carbon pricing. Sen and Vollebergh (2018) use data on energy tax rates of 20 OECD countries to study the responsiveness of fossil fuel emissions to changes in a carbon tax, estimating an elasticity of -0.32. Choi et al. (2010) set a fixed elasticity of -0.3 across 30 sectors to capture the emissions effects of a US carbon price in an input-output model.

7 Counterfactuals

We illustrate the impacts of a CBAM by simulating carbon taxation with and without border adjustment, and we discuss the resulting regulation and reallocation effects. We show that a CBAM reduces carbon leakage and encourages stronger carbon policy in low-regulation markets.

7.1 Policy simulations

We simulate unilateral carbon taxation τ^H by a high-regulation market H. We vary the intensity of carbon taxation, the coverage of market H, and whether carbon taxation is paired with border adjustment. We solve for equilibrium prices, and we compute consumer surplus, producer surplus, government revenue, domestic welfare, and emissions. Domestic welfare excludes emissions, and so we can compare the costs of welfare losses to the benefits of emission reductions for any given value of the social (or local) cost of carbon. We compute each of these quantities relative to a benchmark scenario of business as usual, which we define as zero carbon taxation $\tau^H = \tau^L = 0$ across high- and low-regulation markets H and L. We evaluate impacts for markets $\mathcal{M} \in \{H, L, LL, LH\}$, where markets LL and LH divide market L into lower- and higher-income countries. Lower-income countries are those that the World Bank classifies as low and lower-middle income. We present pooled results that aggregate over aluminum and steel.

We study the role of regulatory intensity by increasing the magnitude of carbon taxation τ^H in market H from zero to \$100 per ton CO_2, while maintaining $\tau^L = 0$ in market L. We study the role of scope by considering two regulatory coalitions. When market H includes the EU and UK, where CBAMs are slated for full implementation in 2026 and 2027, it covers 9% of global aluminum consumption and 10% of global steel consumption; expanding the coalition to include China increases coverage to 70% and 60%, respectively.

These policy simulations allow us to quantify the global effects of carbon taxation, relative to business as usual. We then move to quantifying the marginal impact of border adjustment. We compare outcomes under carbon taxation with a CBAM to those under carbon taxation without a CBAM. The differences speak to the impact of CBAM policies being discussed and implemented by the EU and UK today, relative to a world in which these countries continue to tax carbon without border adjustment.

7.2 Regulation and reallocation

We document two forces: regulation and reallocation. Without a CBAM, we isolate the regulation force. Regulation in market H adds to production costs and shifts the global supply curve inward. The impact of regulation is to reduce world

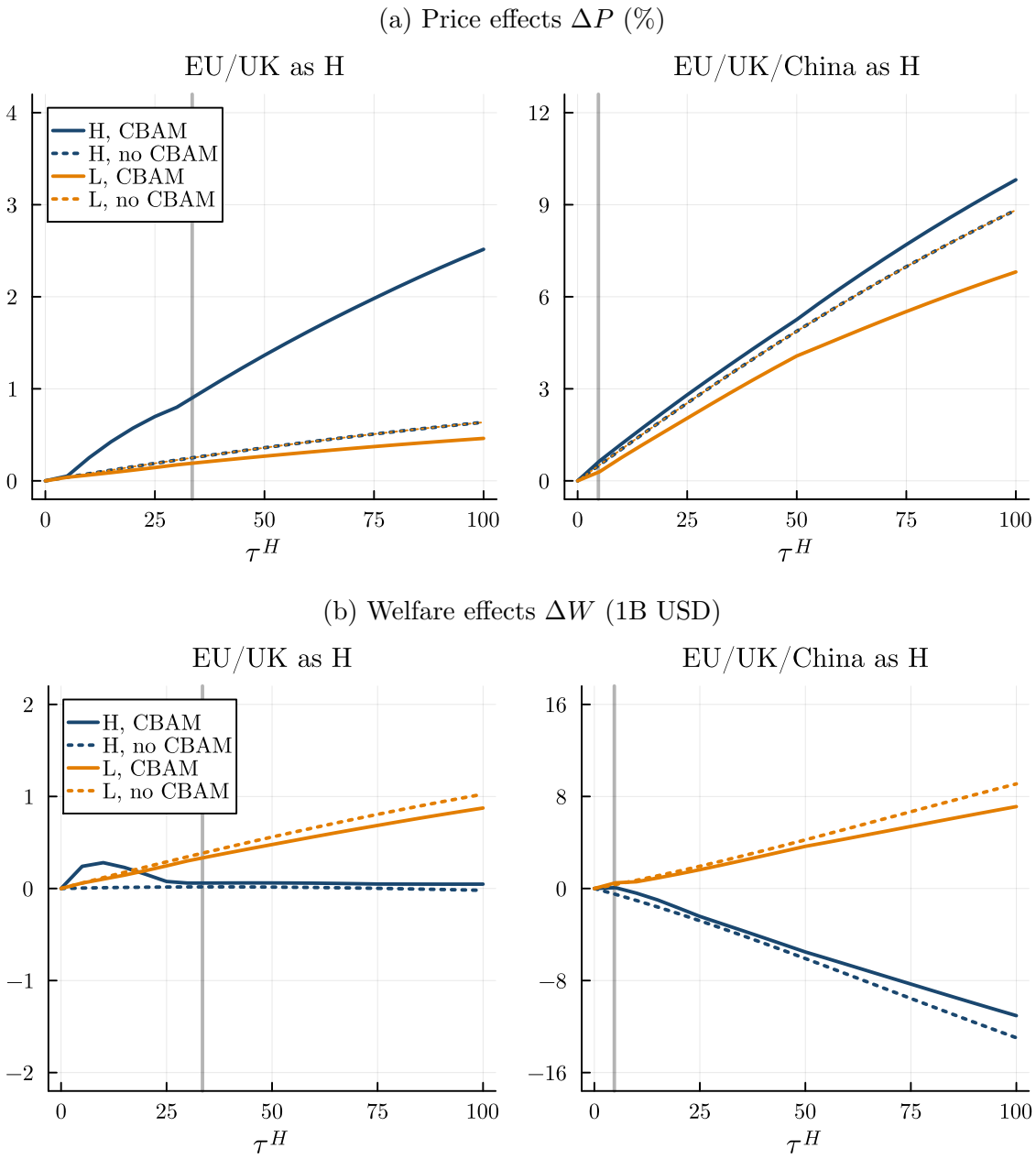
supply and raise world prices. With a CBAM, the reallocation force emerges. Dirty producers in L seek to avoid the CBAM by reallocating sales away from H. The impact of reallocation is to reduce supply in H and raise supply in L, thereby raising prices in H and reducing prices in L.

Figure 5a illustrates these price effects. Gray vertical lines mark carbon taxation τ^H at current, observed levels, which we compute as production-weighted averages of carbon taxes for countries in H. Dashed lines show price effects without a CBAM, and solid lines show price effects with a CBAM. Blue lines correspond to H, and orange lines to L. Without a CBAM, the blue and orange dashed lines coincide because prices equalize globally. The regulation force leads to higher world prices. With a CBAM, the blue and orange solid lines diverge. The reallocation force leads to higher prices in H and lower prices in L. We find price increases to be relatively modest. Even with carbon taxation in H at \$100 per ton of CO_2, prices rise by no more than 2.5% when H includes the EU and UK and 10% when H expands to include China.

We highlight the outsized role of China in both production and consumption. On the left, when H does not include China, the reallocation force dominates. A CBAM induces substantial reallocation of sales toward L as regulation τ^H becomes more stringent, placing strong upward pressure on prices in H relative to prices in L. The solid blue line lies far above the solid orange line. Without a CBAM, impacts are limited because regulation τ^H is restricted to a small proportion of global production. The dashed lines show price effects of less than 1%. On the right, when H does include China, the regulation force dominates. Even without a CBAM, impacts are large because regulation τ^H covers most of global production. The dashed lines show price effects of up to 9%. A CBAM induces reallocation toward L, but the scope for reallocation is limited by the small size of L. The solid blue line lies only somewhat above the solid orange line.

Figure 5b shows the resulting welfare effects. For H, carbon regulation is typically welfare-reducing relative to business as usual. When H includes China, losses to domestic welfare – excluding the benefits of emission reductions – can exceed \$10B in magnitude. But when H includes the EU and UK alone, welfare losses are minimal. Moreover, border adjustment reduces these losses. The solid blue lines lie above the dashed blue lines. When H includes China, carbon taxation with a CBAM improves welfare by up to \$2B relative to carbon taxation without a CBAM. When H includes

Figure 5: Carbon taxation with border adjustment



We simulate carbon regulation $\tau^H > 0$ in high-regulation market H, imposing $\tau^L = 0$ in low-regulation market L. We compute effects relative to business as usual, which we define as $\tau^H = \tau^L = 0$. We simulate regulation with and without a CBAM, and we compute effects separately for markets H and L. In the top panel, price effects average over aluminum and steel, weighting by observed revenues. In the bottom panel, welfare effects sum over aluminum and steel. Gray vertical lines mark observed, production-weighted average carbon taxation $\bar{\tau}^H$ among countries in markets H.

the EU and UK alone, carbon taxation with a CBAM can even generate welfare gains. On the left, the solid blue line lies above zero for taxation below $25 per ton of CO_2. While consumers suffer as the CBAM raises prices in H, producers benefit from these higher prices. And the CBAM itself generates significant government revenue. The CBAM amounts to trade policy that – independent of emission concerns – allows H to exercise its market power and manipulate its terms of trade. In doing so, H realizes welfare gains by extracting government revenue from foreign producers.

For L, carbon taxation in H is welfare-enhancing. Whether H pairs taxation with a CBAM or not, producers in L gain from the higher prices induced by regulation, even as consumers in L lose. Producer gains outweigh consumer losses, and so welfare in L rises overall. The solid and dashed orange lines both lie above zero. At the same time, a CBAM in H serves to reduce these welfare gains. The solid orange lines lie below the dashed orange lines. When H includes China, the welfare gains for L are up to $2B less under carbon taxation with a CBAM, relative to carbon taxation without a CBAM. The reason is that the CBAM imposes a double burden on producers in L: lower prices in L and taxes on exports to H. Smaller benefits for producers in L lead to smaller welfare gains for L.

Appendix figure A3 shows component effects on consumer surplus, producer surplus, and government revenue. Relative to business as usual, carbon taxation raises prices and hurts consumers globally. A CBAM then worsens consumer losses in H by worsening price increases in H, while lessening consumer losses in L by lessening price increases in L. Carbon taxation hurts producers in H by imposing regulation, but it helps producers in L by reducing foreign competition. A CBAM then lessens producer losses in H and lessens producer gains in L, again through its impact on prices. Carbon taxation generates significant revenues for H: up to $20B for the EU and UK and $180B when China joins. The CBAM adds to these revenues, although only marginally so because it pushes producers in L to reallocate sales away from H. Appendix figures A4 and A5 show similar price and welfare effects when we treat aluminum and steel separately.

7.3 CBAMs reduce leakage

A major goal of EU CBAM policy is to address leakage concerns, which apply to both demand and supply. On the demand side, carbon taxation without a CBAM

in H encourages imports from L, where carbon is untaxed. These additional imports bypass carbon taxes in H. Carbon taxation with a CBAM addresses this concern by directly taxing imports from L. On the supply side, carbon taxation without a CBAM in H raise prices in L, encouraging increased production in L. This additional production undercuts emission reductions in H. Carbon taxation with a CBAM addresses this concern through the reallocation effect, which limits the extent to which prices rise in L.[17] In both cases, the CBAM reduces leakage to L.

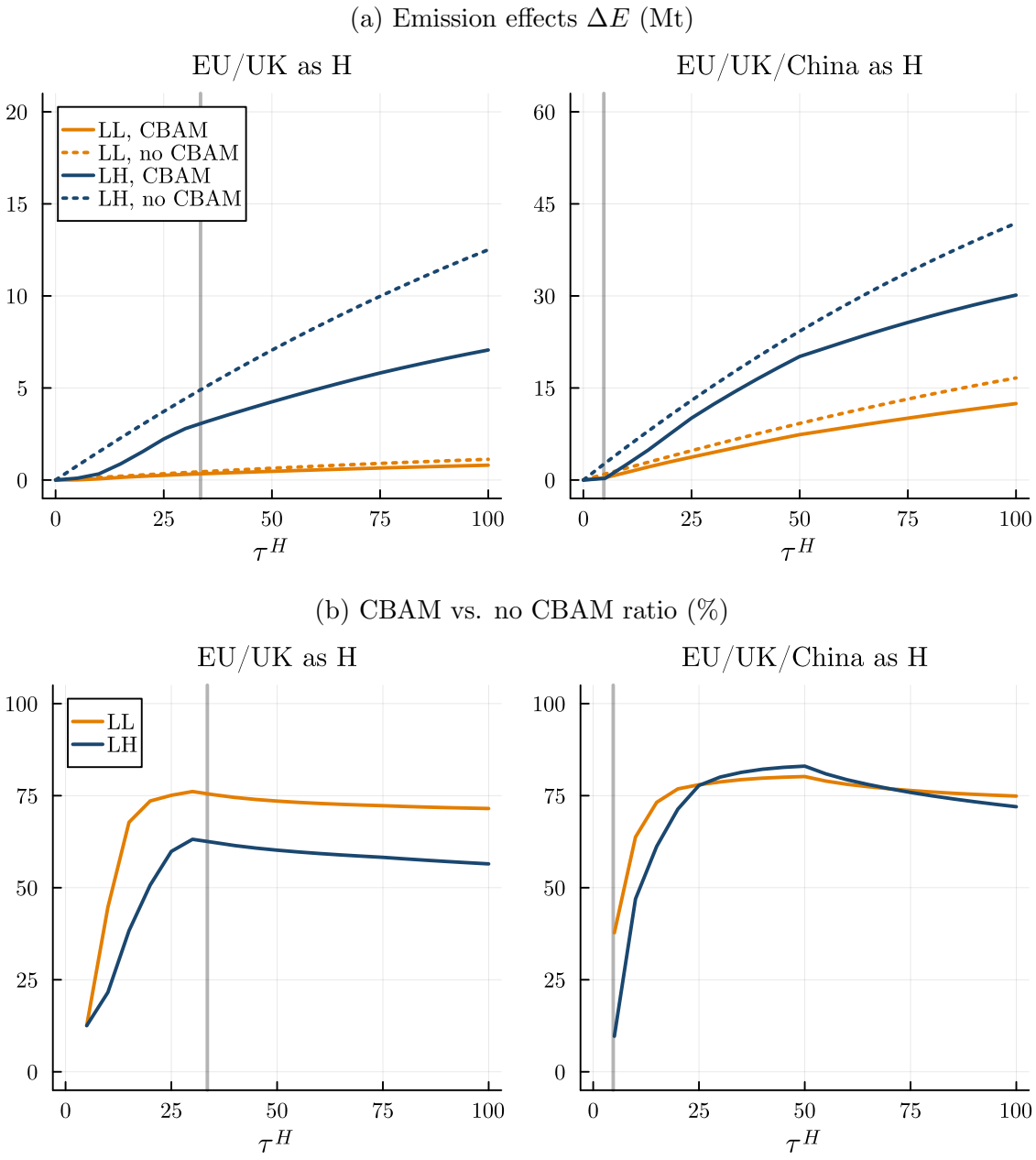
We study the incidence of these leakage reductions across lower- and higher-income countries. Figure 6 presents our findings. The top panel shows the emission effects of carbon policy in H. This carbon policy leads to increased emissions in L, reflecting leakage. All lines lie above zero. There is more leakage for higher-income countries, where production is of larger scale, and when the EU and UK act in partnership with China, noting the larger scale of the y-axis on the right. Leakage is consistently lower under the CBAM than it is without the CBAM: the solid lines each lie below the corresponding dashed lines. The bottom panel shows the extent to which carbon taxation with a CBAM reduces leakage emissions in percentage terms, relative to carbon taxation without a CBAM. When H includes the EU and UK, the CBAM places greater pressure on higher-income countries than it does on lower-income countries. When H expands to include China, the incidence on lower- and higher-income countries is more balanced, particularly for carbon taxation at levels beyond \$25 per ton CO_2. Appendix figures A6 and A7 show broadly similar results for aluminum and steel separately.

We quantify the impact of abatement technology by setting $\gamma = 0$, such that emission intensity remains fixed under carbon taxation. In this world, producers can only reduce emissions by reducing production, rather than by reducing their emission intensity. Appendix figure A8 shows that abatement responses drive the difference in incidence between lower- and higher-income countries. When we shut down abatement responses, the CBAM places similar pressure on both groups of countries. But leakage levels rise, as these responses also help in reducing emissions.

Despite leakage to L, regulation in H nonetheless leads to large emission reduc-

[17] Relative to carbon taxation without a CBAM, carbon taxation with a CBAM also raises prices in H. These higher prices encourage production in L for export to H. But the resulting emissions are taxed by the CBAM, and so this increased production is non-distortionary.

Figure 6: Carbon leakage



We simulate carbon regulation $\tau^H > 0$ in high-regulation market H, imposing $\tau^L = 0$ in low-regulation market L. We compute effects relative to business as usual, which we define as $\tau^H = \tau^L = 0$. We simulate regulation with and without a CBAM, and we compute effects separately for markets LL and LH, which divide L into lower- and higher-income countries based on World Bank income groups. In the top panel, emission effects sum over aluminum and steel. In the bottom panel, we divide emission effects under a CBAM by emission effects without a CBAM. Gray vertical lines mark observed, production-weighted average carbon taxation $\bar{\tau}^H$ among countries in markets H.

tions in H. Appendix figure A9 plots these reductions. Across aluminum and steel, total emissions fall by nearly one gigaton when H includes China and when it imposes carbon taxation at \$100 per ton of CO_2. We note that although the CBAM reduces carbon leakage to L, relative to carbon taxation without a CBAM, it also raises emissions in H. The reason is that the CBAM raises prices and production in H. However, this additional production is subject to carbon taxation in H, and so the emissions are priced.[18]

7.4 CBAMs encourage regulation

Another major goal of the EU CBAM is to encourage carbon regulation abroad. We study these policy incentives. We simulate carbon taxation in H, both with and without border adjustment, and we evaluate the welfare implications for L, which we separate into lower-income countries (LL) and higher-income countries (LH). We then simulate global regulation, in which L joins H in taxing carbon, such that $\tau^L = \tau^H$.[19] We again evaluate welfare outcomes for LL and LH. Figure 7 presents our results. We show that joining H in taxing carbon can be welfare-enhancing for countries in L, particularly when H implements a CBAM.

Global regulation can itself be welfare-enhancing for countries in L, relative to a business-as-usual world with $\tau^H = \tau^L = 0$. When H includes the EU, UK, and China, we find that global regulation increases welfare in LH at all levels of carbon taxation. The orange line in the lower-right subfigure lies above zero. Under a global carbon tax of \$100 per ton of CO_2, welfare in LH increases by more than \$3B.[20] Appendix figures A10, A11, A12 show the component effects on consumer surplus, producer surplus, and government revenue for LL and LH.[21] We again focus on the orange lines in

[18] Another margin of emission responses is those from trade diversion. We consider shipping emissions in Appendix C.3. We do not model country-specific destination choices, and so we cannot explicitly accommodate changes in shipping emissions. It is therefore reassuring that shipping emissions are limited in our setting, accounting for less than one percent of production emissions.

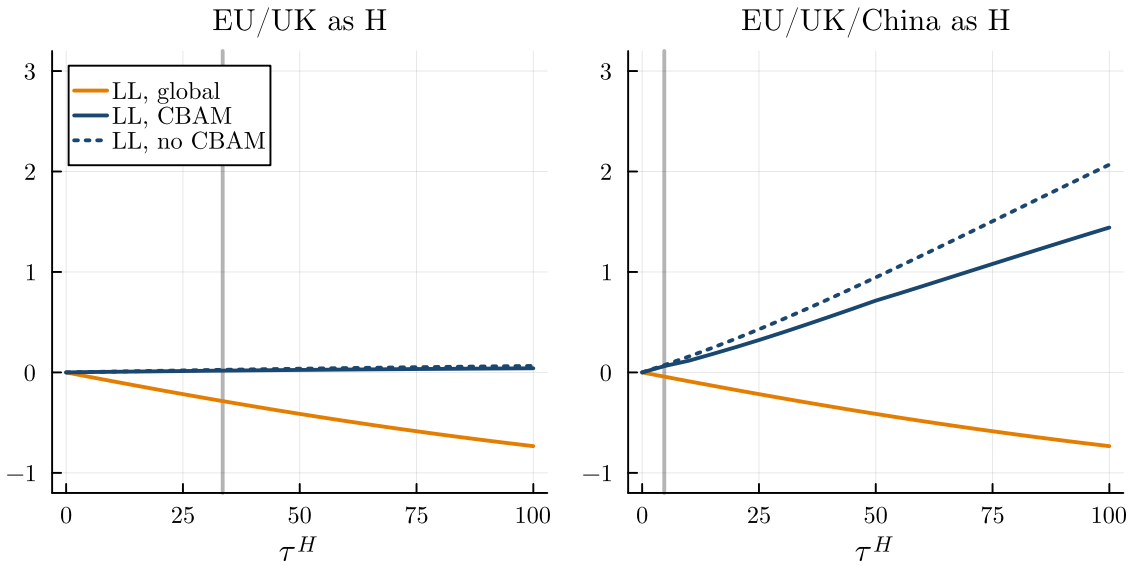
[19] Under global regulation, note that adjustment $\alpha^H = 0$. Border adjustment does not bind.

[20] In figure 7a, the orange lines coincide because the left and right subfigures differ only in whether market H includes China. LL includes the same set of countries in both cases. And under global regulation, the definition of H does not affect regulation because global regulation is uniform across countries. In figure 7b, the orange lines do not coincide even though global regulation applies equally to the left and right subfigures. The reason is that LH includes China on the left but not on the right.

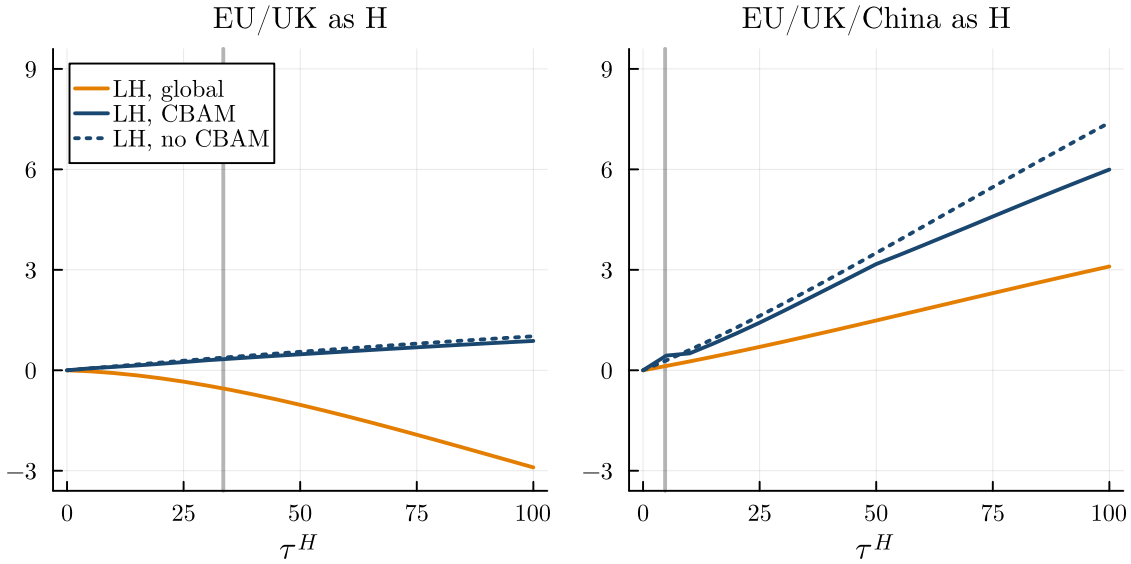
[21] Appendix tables B8, B9, B10 present similar information for all markets in tabular form.

Figure 7: Policy spillovers

(a) Welfare effects ΔW for market LL (1B USD)



(b) Welfare effects ΔW for market LH (1B USD)



We simulate carbon regulation in three forms. Global regulation $\tau = \tau^H = \tau^L$ is uniform across high- and low-regulation markets H and L. CBAM regulation involves carbon regulation $\tau^H > 0$ and border adjustment in H, imposing $\tau^L = 0$ in L. No-CBAM regulation involves carbon regulation $\tau^H > 0$ in H, imposing $\tau^L = 0$ in L. We compute effects relative to business as usual, which we define as $\tau^H = \tau^L = 0$. We compute effects separately for markets LL and LH, which divide L into lower- and higher-income countries based on World Bank income groups. Welfare effects sum over aluminum and steel. Gray vertical lines mark observed, production-weighted average carbon taxation $\bar{\tau}^H$ among countries in markets H.

the lower-right subfigures. Global regulation leads to large consumer surplus losses for LH as world prices rise. But producer surplus losses are limited because higher world prices, which reflect reduced foreign competition, offset the direct burden of regulation. Moreover, government revenues are substantial at \$40B and \$70B under carbon taxes of \$50 and \$100 per ton of CO_2.

We next compare global regulation to the more policy-relevant benchmark of carbon regulation in H. That is, in a world with an EU and UK CBAM and carbon taxation in place, can countries in L gain from taxing carbon? We find on net that the answer is no. In each subfigure of figure 7, the orange lines lie below the solid blue lines. The reason is that carbon regulation in H leads to the welfare gains for both LL and LH, while global regulation largely leads to welfare losses.

At the same time, we note four important findings. First, a CBAM in H closes the gap for global regulation. Free-riding disincentivizes regulation in LL and LH because each enjoys welfare gains following carbon regulation in H. In figure 7, the blue lines lie above zero and grow with τ^H, widening their distance to the orange lines. However, the CBAM reduces these welfare gains and thus reduces free-riding incentives. Without a CBAM, the orange lines lie far below the dashed blue lines. With a CBAM, the distance narrows – especially when H includes China. The orange lines lie closer to the solid blue lines. A CBAM encourages regulation in L in relative terms.

Second, a CBAM in H creates revenue incentives for global regulation. Appendix figure A12 shows that global regulation generates large government revenue in LL and LH. These revenues do not depend on whether H imposes a CBAM because, absent global regulation, LL and LH do not regulate and so regulatory revenues are zero regardless. But appendix figure A11 shows that a CBAM reduces the relative costs of global regulation for producers. The reason is that the CBAM adjustment falls as LL and LH regulate, such that producers that export to H face no change in regulatory pressure. That is, under a CBAM in H, governments in LL and LH can collect revenue without distorting productive outcomes. While the production channel dominates, appendix figure A10 shows a countervailing effect through consumption. A CBAM helps consumers in LL and LH by inducing reallocation that drives down prices. In regulating, LL and LH must sacrifice these consumer surplus gains.

Third, countries in L also benefit from reduced emissions. We compute welfare losses focusing exclusively on consumer surplus, producer surplus, and government revenue. But appendix figure A13 shows that emission reductions are also meaningful. We again highlight the lower-right subfigures. LH loses roughly \$3B under global regulation at \$100 per ton of CO_2, relative to a CBAM in H with no regulation in L. But emissions in LH also fall by more than 300 Mt.[22] For governments in LH, a local cost of carbon of \$10 per ton would imply that emission reductions more than compensate for welfare losses. Regulation can lead to net gains.

Fourth, global regulation is directly appealing for aluminum, as we show in appendix figure A14.[23] The top panel describes lower-income countries in LL. When H includes the EU and UK alone, global regulation strongly dominates non-regulation in LL. The orange line lies far above the blue lines, and LL gains up to \$1B in welfare by joining H in taxing carbon. When H expands to include China, global regulation continues to dominate up to \$25 per ton of carbon taxation. At higher levels, regulatory incentives for LL hinge on the CBAM in H. The orange line lies above the solid blue line, but below the dashed blue line. That is, without a CBAM in place, LL gains more by not regulating. The bottom panel describes higher-income countries in LH. Regulatory incentives for LL hinge on the coalition in H. The orange line lies below the blue lines on the left, but above the blue lines on the right. That is, global regulation is appealing for LH when H includes China, but not otherwise.

8 Conclusion

CBAMs are the only major existing climate policy that takes on the global free-rider problems inherent in addressing climate change. Yet, they are not without controversy. Some policymakers have accused the EU and UK of practicing "regulatory colonialism" by imposing CBAMs on other countries and appear ready to dismiss them out of hand. In this context, it is especially important to have careful models that capture the nuances of this important new policy tool. We combine a quantitative equilibrium model with detailed plant-level data to evaluate the global impacts

[22] In each case, we calculate these changes by computing the distance between the orange and solid blue lines at $\tau^H = 100$.

[23] Appendix figure A15 shows welfare impacts for steel.

of CBAM policies. We show that CBAMs reduce emissions leakage and encourage carbon regulation, each without placing disproportionate pressure on lower-income countries. The reason is that production in lower-income countries not systematically more carbon-intensive than it is in higher-income countries.

Future work could extend our analysis in several directions. First, while we have examined the two most emission-intensive and highly traded industries, the EU and UK CBAM will eventually be extended to other key sectors. Second, country-specific analyses could help inform policy, particularly to the extent that they can capture granular heterogeneity across a broader range of sectors and geographies. Third, as real-world experience with CBAMs evolves, researchers will learn more about how this policy tool operates in practice.

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C.2 Iron and steel . . . . . .

C.3 Shipping emissions . . . . . .

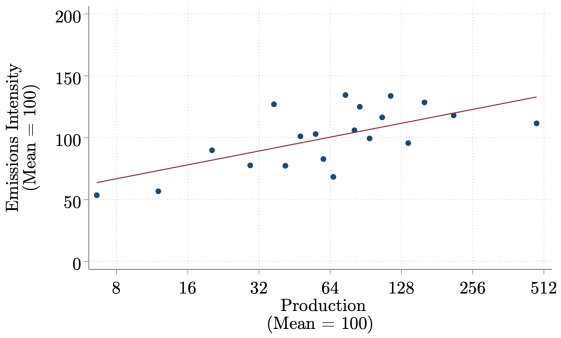
D Mozambique

A Figures

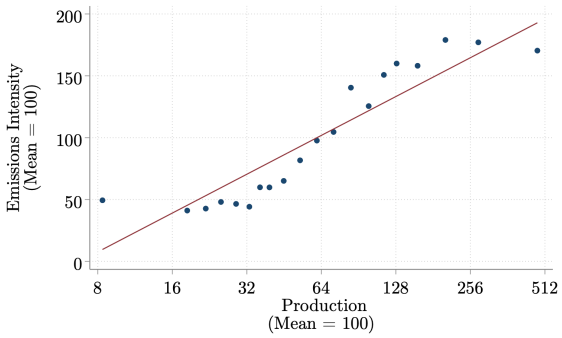
Figure A1: Emissions intensity, production, and plant age

Emissions intensity vs. production

(a) Aluminum

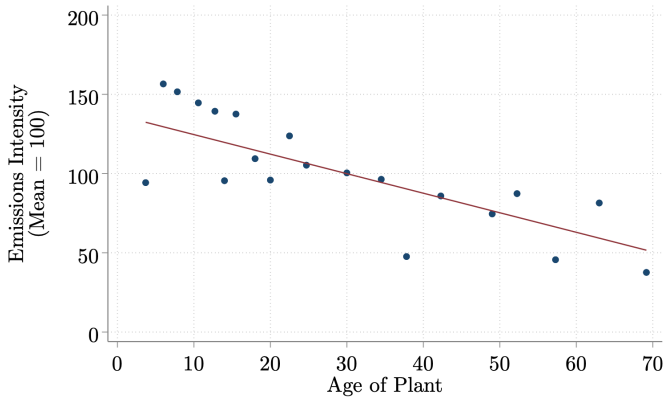


(b) Iron and steel



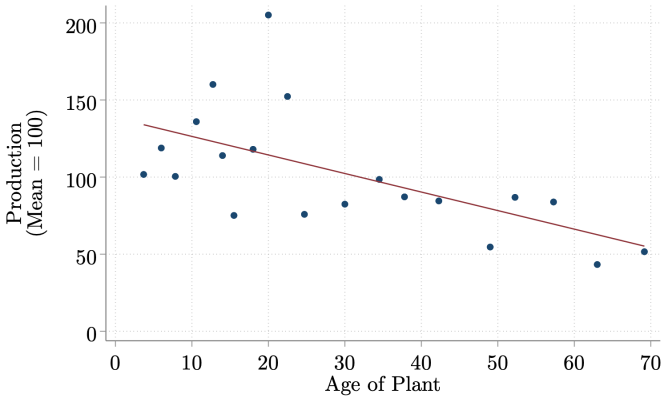
Each point is an equal-size bin of plants based on production in 2023. The y-axis represents bin-level average emissions intensity of production, normalized such that the mean emission intensity = 100. The x-axis is the bin-level average production volume in thousand metric tons per annum, normalized so that that the mean production level = 100. Aluminum data includes primary and secondary aluminum.

(c) Primary aluminum emissions intensity vs. plant age



Each point is an equal-size bin of primary aluminum smelters based on smelter age. The y-axis represents bin-level average emissions intensity of production, normalized such that the mean emission intensity = 100. The x-axis is the bin-level average plant age. We do not observe plant age in our secondary aluminum nor iron and steel data.

(d) Primary aluminum production vs. plant age

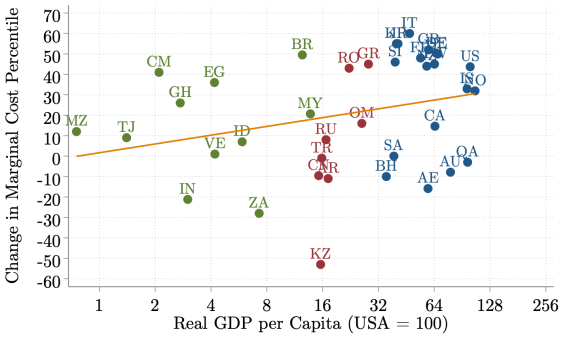


Each point is an equal-size bin of primary aluminum smelters based on smelter age. The y-axis represents bin-level average production volume in thousand metric tons per annum, normalized so that that the mean production level = 100. The x-axis is the bin-level average plant age. We do not observe plant age in our secondary aluminum nor iron and steel data.

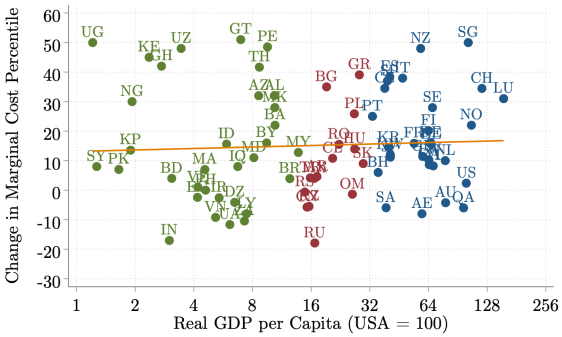
Figure A2: Heterogeneity in changes in marginal costs under a CBAM

Percentile changes vs. real GDP per capita

(a) Aluminum



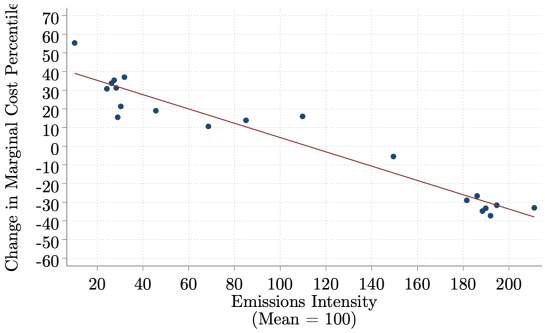
(b) Iron and steel



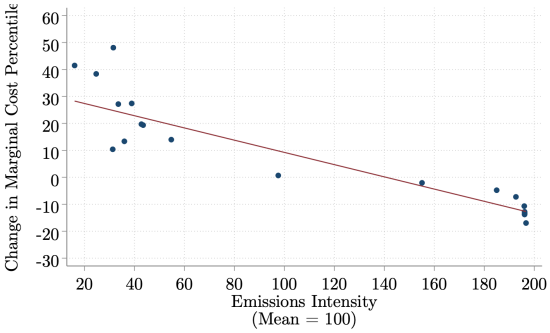
Each point represents a country. The y-axis represents the country-level average change in the marginal cost percentile, determined from the cumulative capacity ranking of plant marginal costs before and after the introduction of a CBAM, simulated with a flat fee of \$96 per metric ton CO_2. The x-axis represents 2023 GDP per capita, normalized such that the US is 100 and is shown in log scale. Countries are grouped into three income categories. Aluminum data include primary and secondary aluminum.

Percentile changes vs. emissions intensity

(c) Aluminum

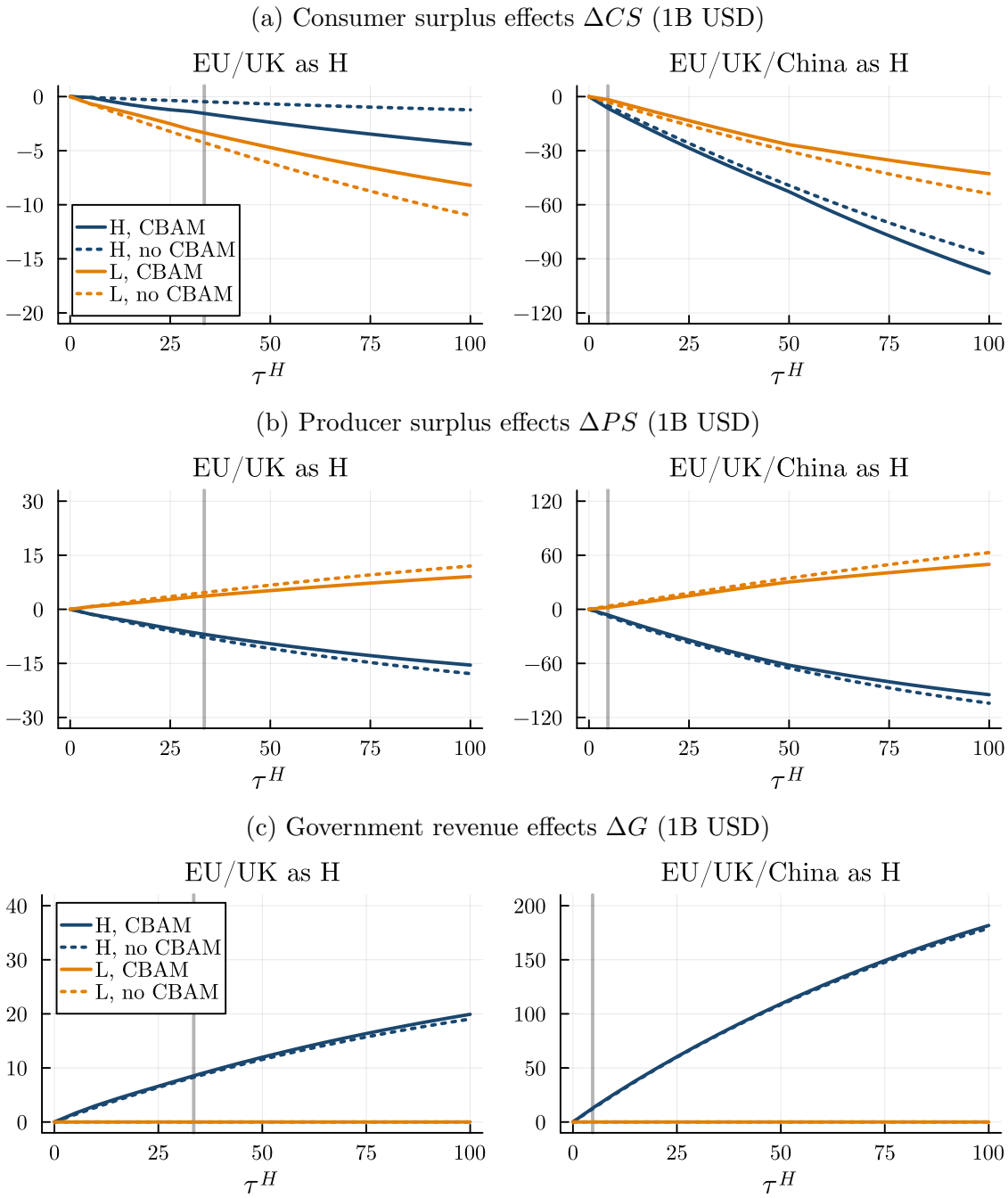


(d) Iron and steel



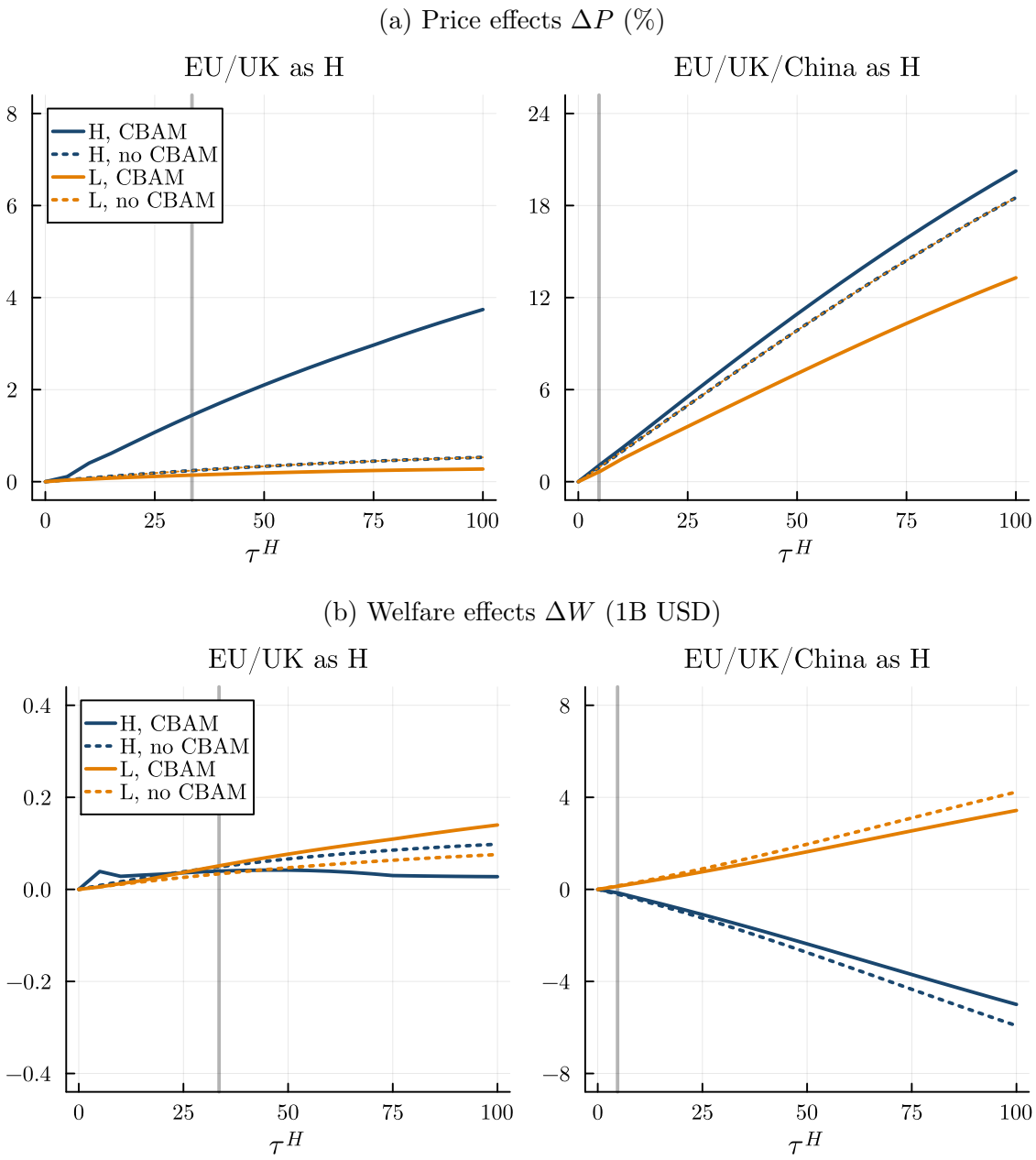
Each point is an equal-size bin of plants based on emissions intensity. The y-axis represents the bin-level average change in the marginal cost percentile, determined from the cumulative capacity ranking of plant marginal costs before and after the introduction of a CBAM, simulated with a flat fee of \$96 per metric ton CO_2. The x-axis is the bin-level average emissions intensity of production, normalized such that the mean emission intensity is 100. Aluminum data include primary and secondary aluminum.

Figure A3: Carbon taxation with border adjustment, surplus and revenue



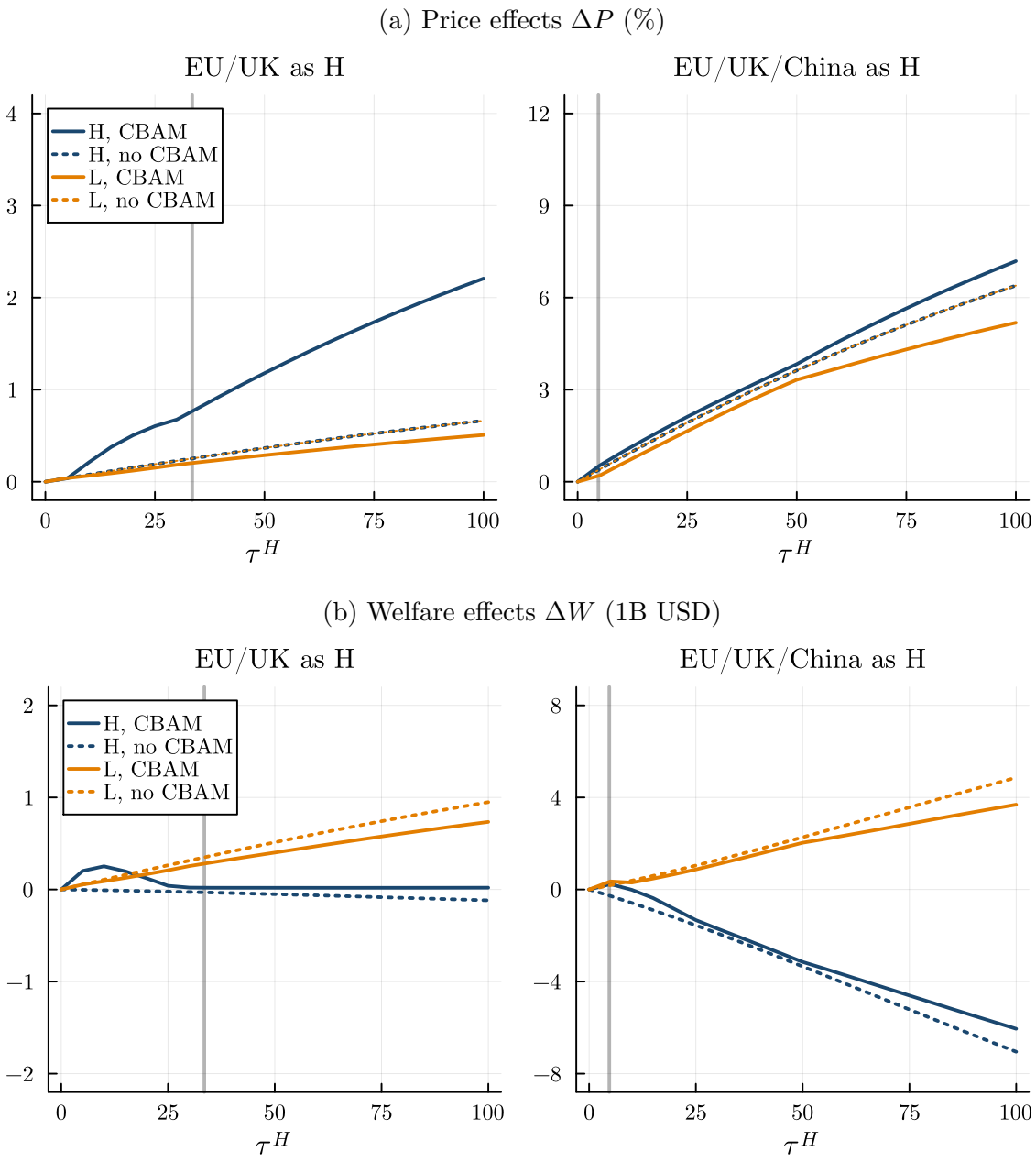
We simulate carbon regulation $\tau^H > 0$ in high-regulation market H, imposing $\tau^L = 0$ in low-regulation market L. We compute effects relative to business as usual, which we define as $\tau^H = \tau^L = 0$. We simulate regulation with and without a CBAM, and we compute effects separately for markets H and L. Surplus and revenue effects sum over aluminum and steel. Gray vertical lines mark observed, production-weighted average carbon taxation $\bar{\tau}^H$ among countries in markets H.

Figure A4: Carbon taxation with border adjustment, aluminum only



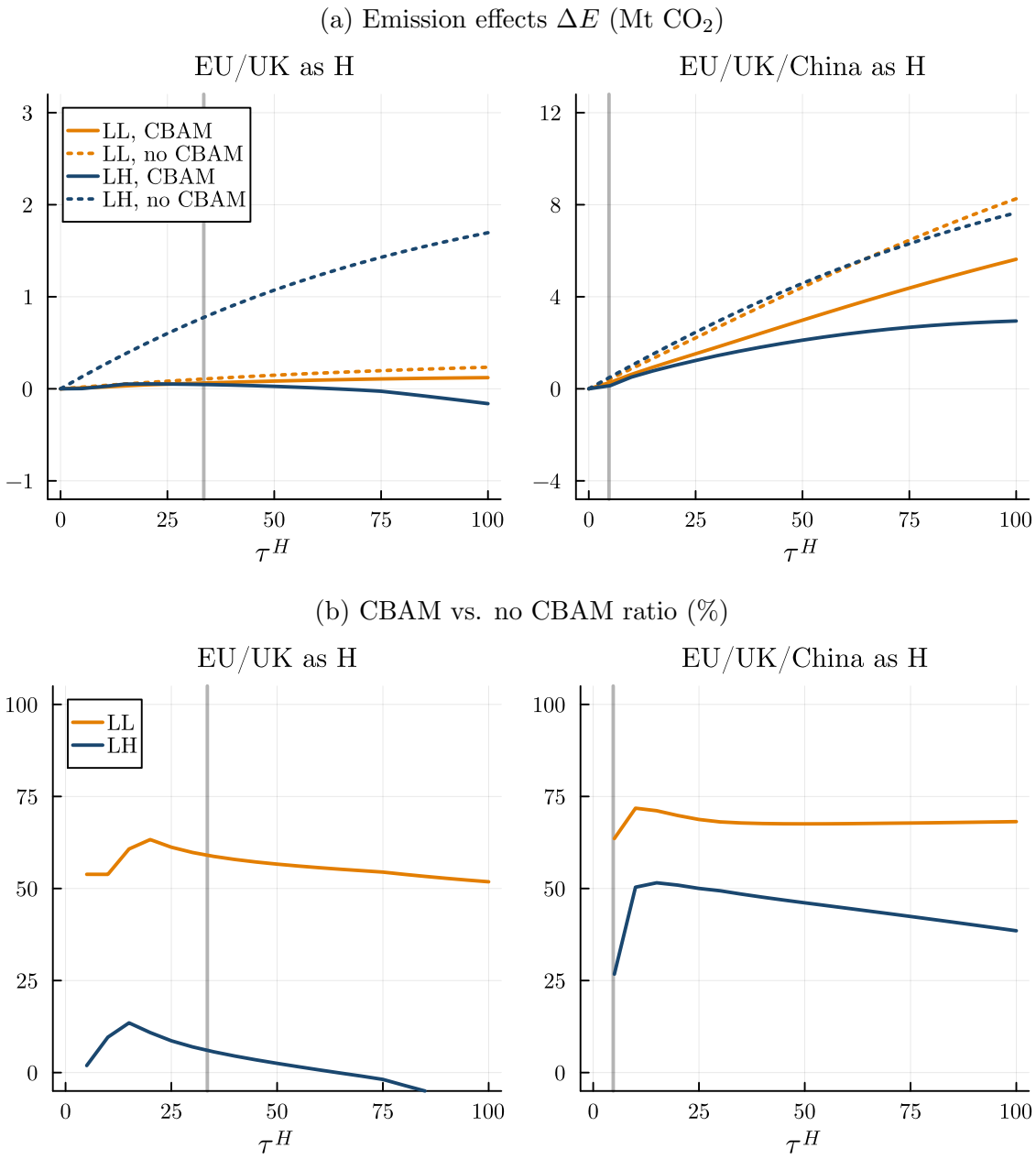
For aluminum, we simulate carbon regulation $\tau^H > 0$ in high-regulation market H, imposing $\tau^L = 0$ in low-regulation market L. We compute effects relative to business as usual, which we define as $\tau^H = \tau^L = 0$. We simulate regulation with and without a CBAM, and we compute effects separately for markets H and L. Gray vertical lines mark observed, production-weighted average carbon taxation $\bar{\tau}^H$ among countries in markets H.

Figure A5: Carbon taxation with border adjustment, iron and steel only



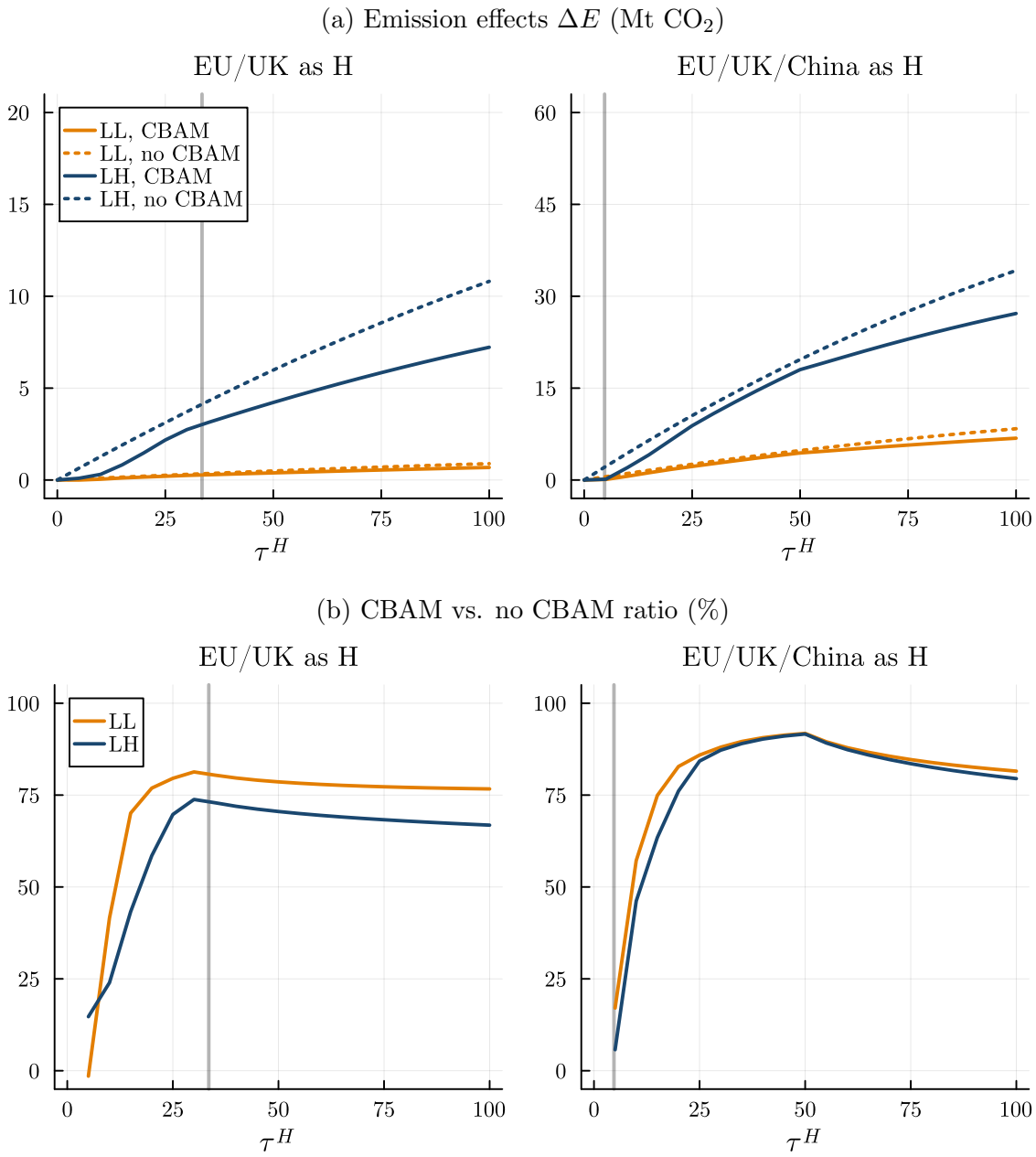
For iron and steel, we simulate carbon regulation $\tau^H > 0$ in high-regulation market H, imposing $\tau^L = 0$ in low-regulation market L. We compute effects relative to business as usual, which we define as $\tau^H = \tau^L = 0$. We simulate regulation with and without a CBAM, and we compute effects separately for markets H and L. Gray vertical lines mark observed, production-weighted average carbon taxation $\bar{\tau}^H$ among countries in markets H.

Figure A6: Carbon leakage, aluminum only



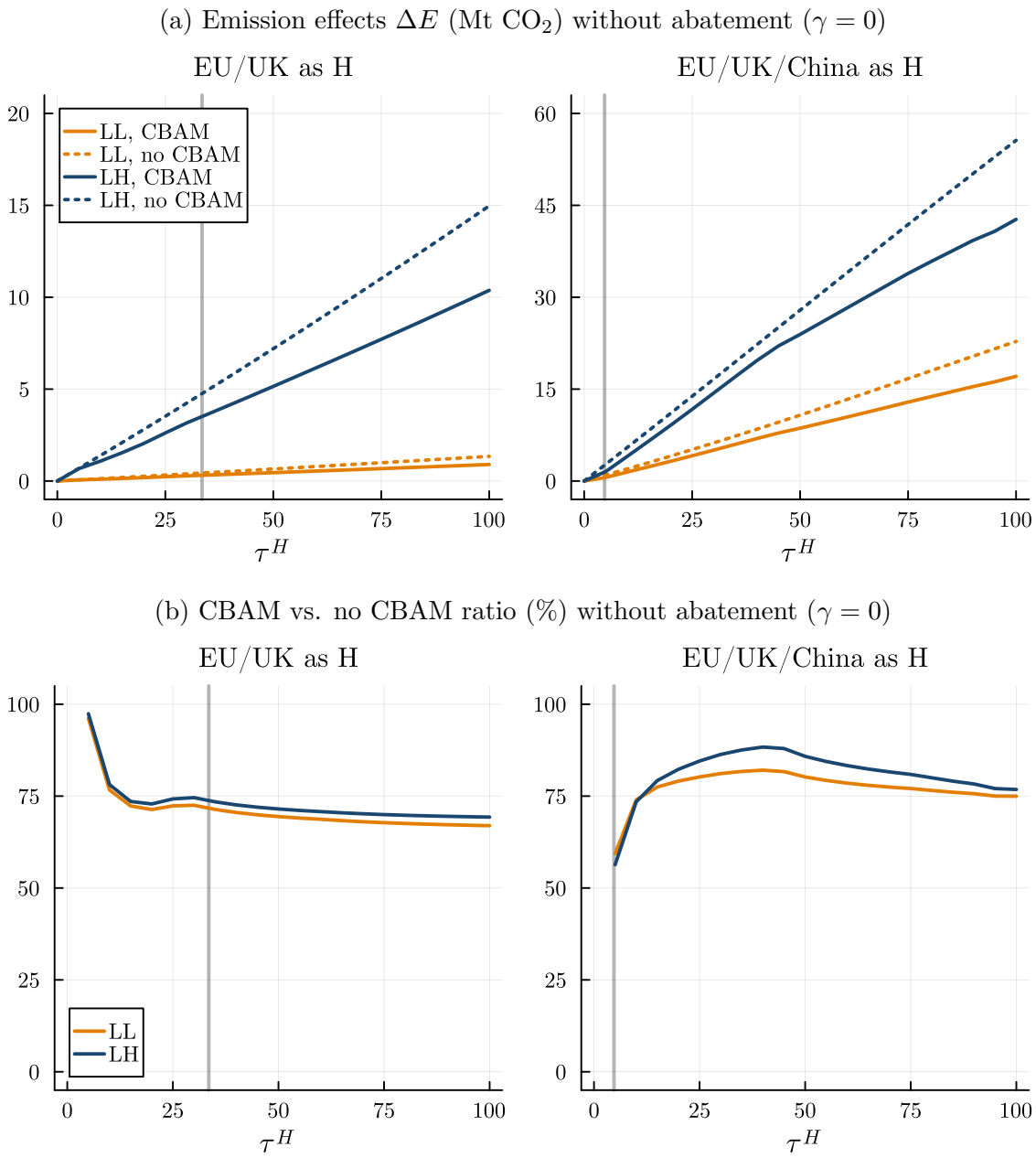
For aluminum, we simulate carbon regulation $\tau^H > 0$ in high-regulation market H, imposing $\tau^L = 0$ in low-regulation market L. We compute effects relative to business as usual, which we define as $\tau^H = \tau^L = 0$. We simulate regulation with and without a CBAM, and we compute effects separately for markets LL and LH, which divide L into lower- and higher-income countries based on World Bank income groups. In the bottom panel, we divide emission effects under a CBAM by emission effects without a CBAM. Gray vertical lines mark observed, production-weighted average carbon taxation $\bar{\tau}^H$ among countries in markets H.

Figure A7: Carbon leakage, iron and steel only



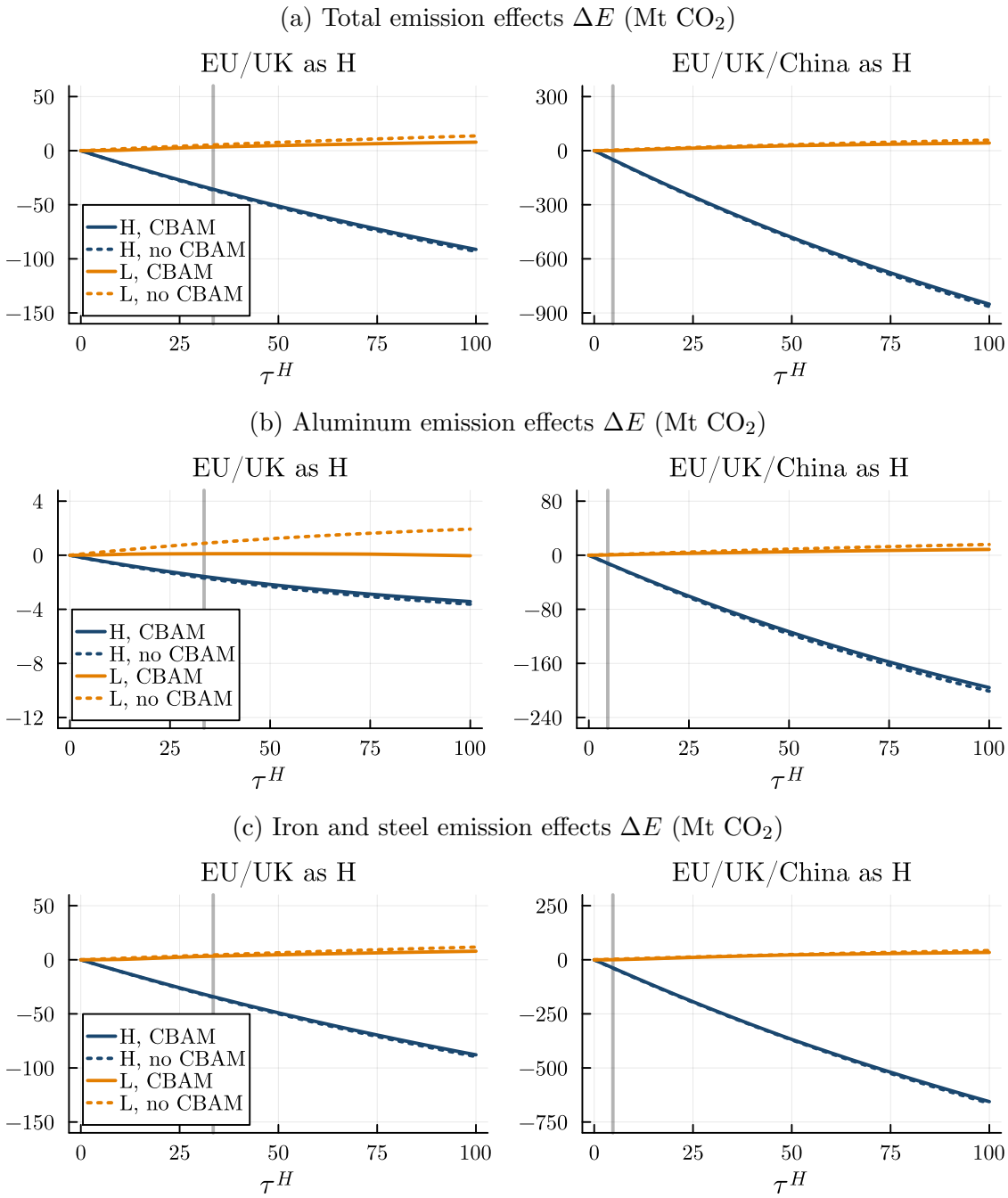
For iron and steel, we simulate carbon regulation $\tau^H > 0$ in high-regulation market H, imposing $\tau^L = 0$ in low-regulation market L. We compute effects relative to business as usual, which we define as $\tau^H = \tau^L = 0$. We simulate regulation with and without a CBAM, and we compute effects separately for markets LL and LH, which divide L into lower- and higher-income countries based on World Bank income groups. In the bottom panel, we divide emission effects under a CBAM by emission effects without a CBAM. Gray vertical lines mark observed, production-weighted average carbon taxation $\bar{\tau}^H$ among countries in markets H.

Figure A8: Abatement technology



We eliminate the ability of firms to curb emissions in response to carbon taxation, imposing $\gamma = 0$ in place of baseline $\gamma = 0.3$. We simulate carbon regulation $\tau^H > 0$ in high-regulation market H, imposing $\tau^L = 0$ in low-regulation market L. We compute effects relative to business as usual, which we define as $\tau^H = \tau^L = 0$. We simulate regulation with and without a CBAM, and we compute effects separately for markets LL and LH, which divide L into lower- and higher-income countries based on World Bank income groups. In the top panel, emission effects sum over aluminum and steel. In the bottom panel, we divide emission effects under a CBAM by emission effects without a CBAM. Gray vertical lines mark observed, production-weighted average carbon taxation $\bar{\tau}^H$ among countries in markets H.

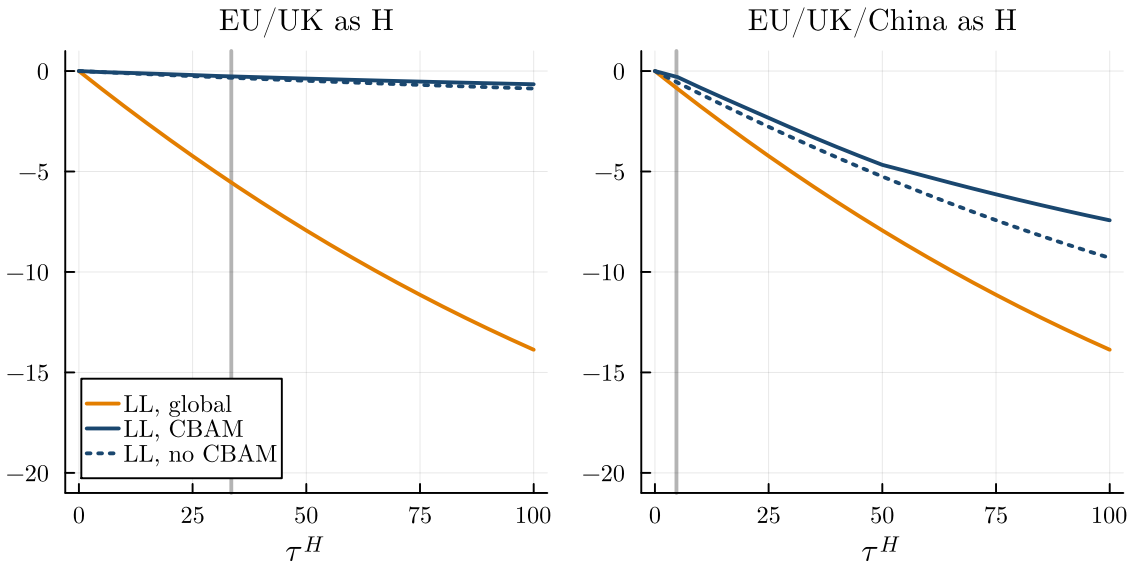
Figure A9: Carbon taxation with border adjustment, emissions



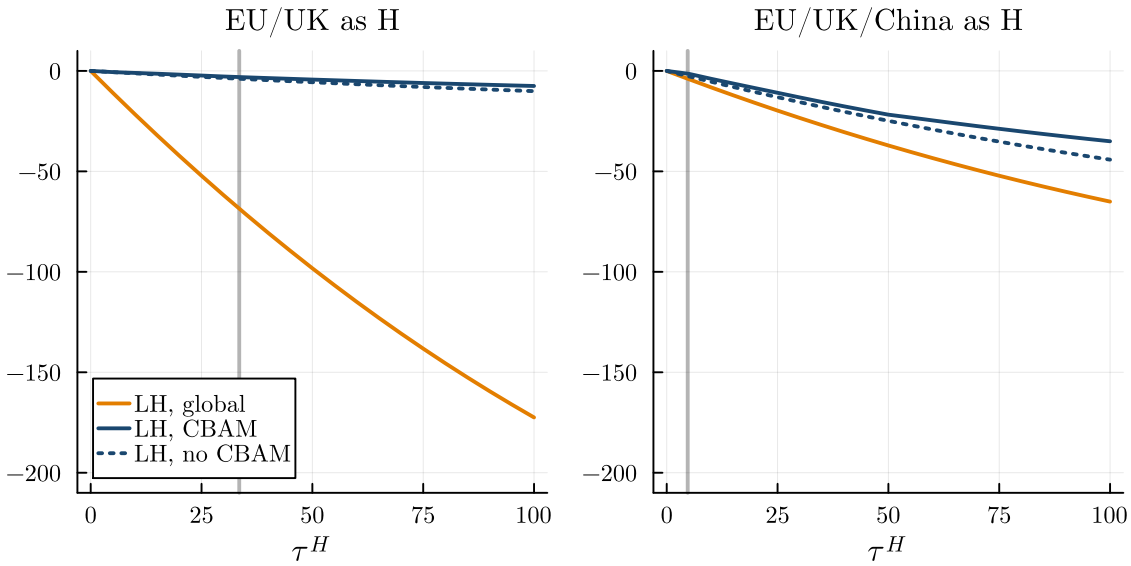
We simulate carbon regulation $\tau^H > 0$ in high-regulation market H, imposing $\tau^L = 0$ in low-regulation market L. We compute effects relative to business as usual, which we define as $\tau^H = \tau^L = 0$. We simulate regulation with and without a CBAM, and we compute effects separately for markets H and L. Total emission effects sum over aluminum and steel. Gray vertical lines mark observed, production-weighted average carbon taxation $\bar{\tau}^H$ among countries in markets H.

Figure A10: Policy spillovers, consumer surplus

(a) Consumer surplus effects ΔCS for market LL (1B USD)



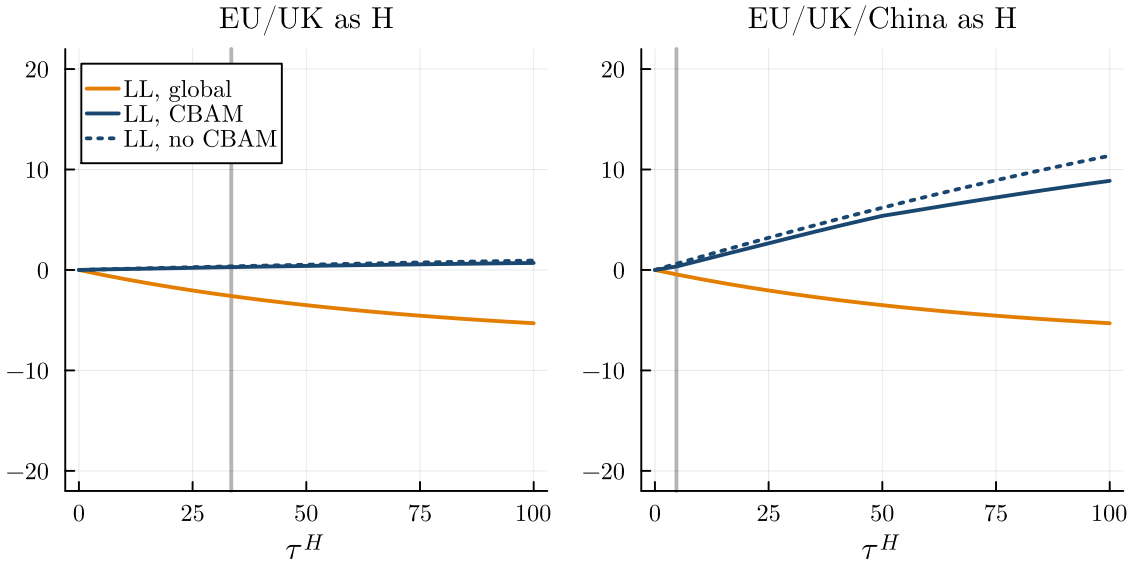
(b) Consumer surplus effects ΔCS for market LH (1B USD)



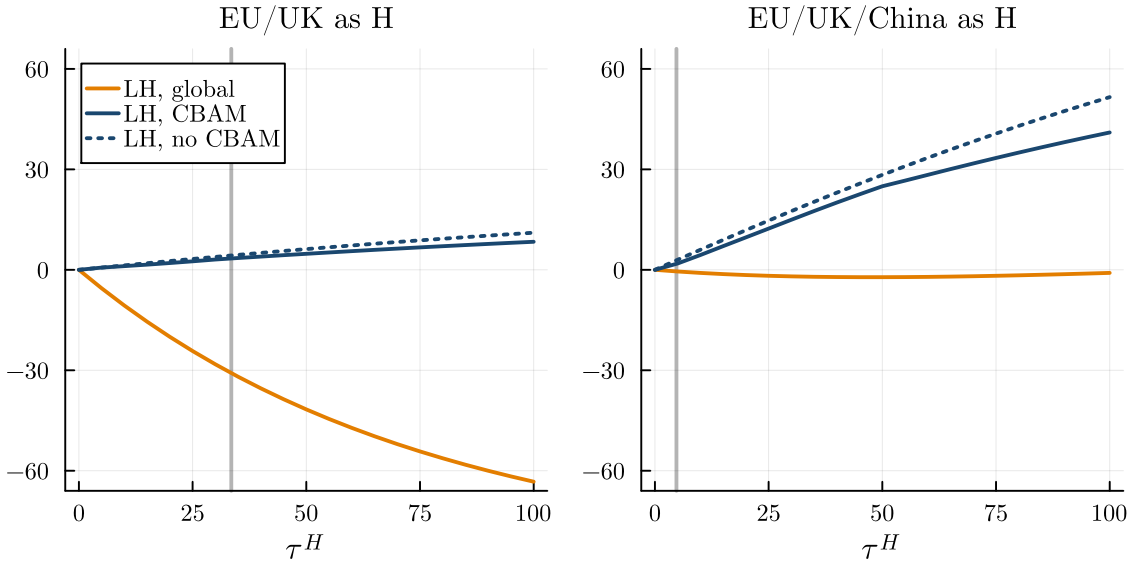
We simulate carbon regulation in three forms. Global regulation $\tau = \tau^H = \tau^L$ is uniform across high- and low-regulation markets H and L. CBAM regulation involves carbon regulation $\tau^H > 0$ and border adjustment in H, imposing $\tau^L = 0$ in L. No-CBAM regulation involves carbon regulation $\tau^H > 0$ in H, imposing $\tau^L = 0$ in L. We compute effects relative to business as usual, which we define as $\tau^H = \tau^L = 0$. We compute effects separately for markets LL and LH, which divide L into lower- and higher-income countries based on World Bank income groups. Consumer surplus effects sum over aluminum and steel. Gray vertical lines mark observed, production-weighted average carbon taxation $\bar{\tau}^H$ among countries in markets H.

Figure A11: Policy spillovers, producer surplus

(a) Producer surplus effects ΔPS for market LL (1B USD)



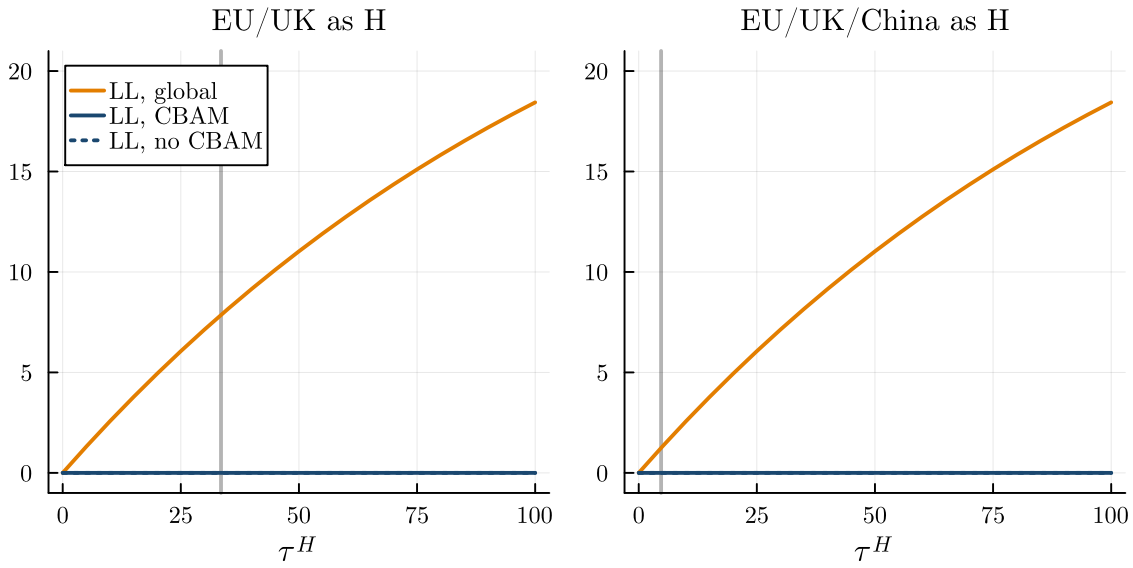
(b) Producer surplus effects ΔPS for market LH (1B USD)



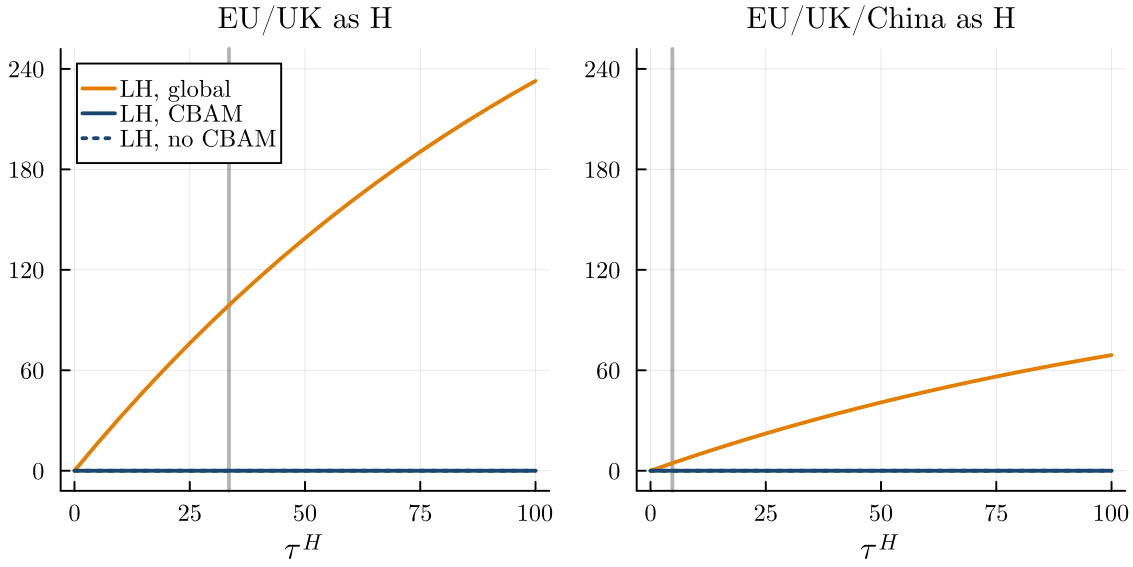
We simulate carbon regulation in three forms. Global regulation $\tau = \tau^H = \tau^L$ is uniform across high- and low-regulation markets H and L. CBAM regulation involves carbon regulation $\tau^H > 0$ and border adjustment in H, imposing $\tau^L = 0$ in L. No-CBAM regulation involves carbon regulation $\tau^H > 0$ in H, imposing $\tau^L = 0$ in L. We compute effects relative to business as usual, which we define as $\tau^H = \tau^L = 0$. We compute effects separately for markets LL and LH, which divide L into lower- and higher-income countries based on World Bank income groups. Producer surplus effects sum over aluminum and steel. Gray vertical lines mark observed, production-weighted average carbon taxation $\bar{\tau}^H$ among countries in markets H.

Figure A12: Policy spillovers, government revenue

(a) Government revenue effects ΔG for market LL (1B USD)



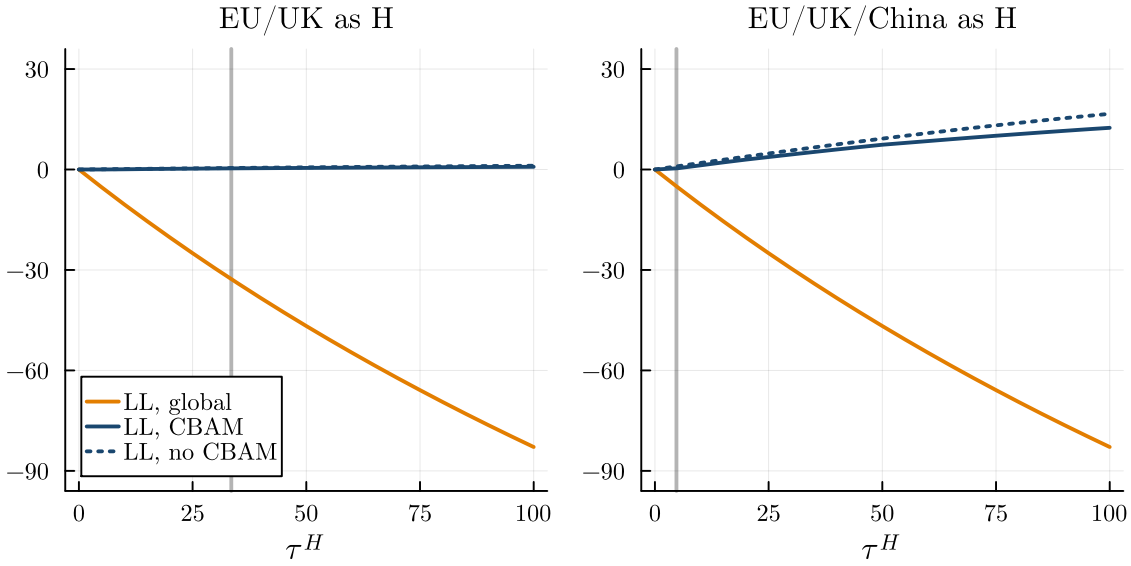
(b) Government revenue effects ΔG for market LH (1B USD)



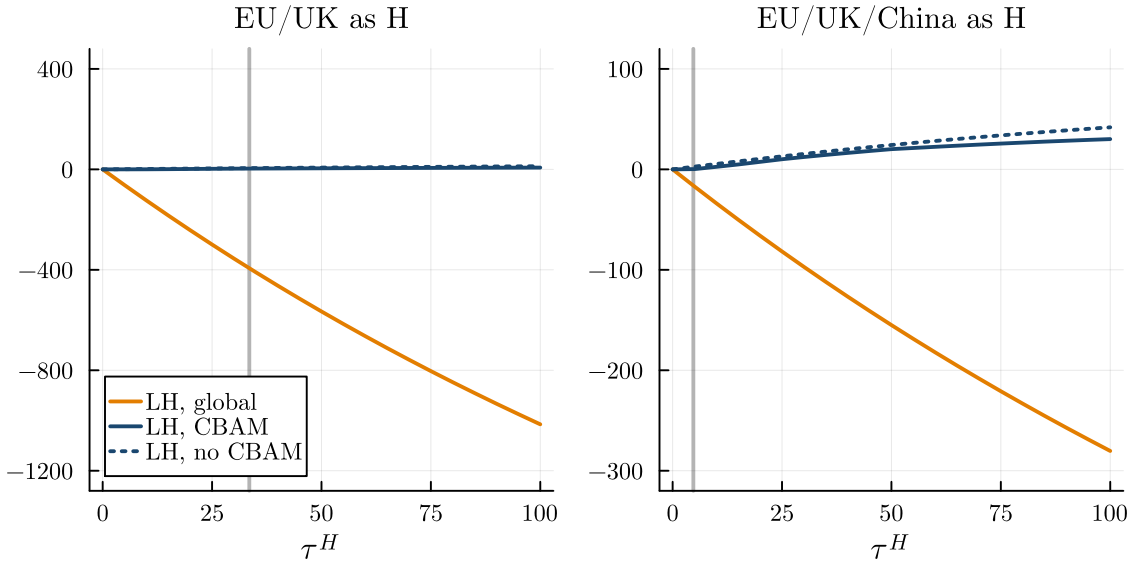
We simulate carbon regulation in three forms. Global regulation $\tau = \tau^H = \tau^L$ is uniform across high- and low-regulation markets H and L. CBAM regulation involves carbon regulation $\tau^H > 0$ and border adjustment in H, imposing $\tau^L = 0$ in L. No-CBAM regulation involves carbon regulation $\tau^H > 0$ in H, imposing $\tau^L = 0$ in L. We compute effects relative to business as usual, which we define as $\tau^H = \tau^L = 0$. We compute effects separately for markets LL and LH, which divide L into lower- and higher-income countries based on World Bank income groups. Government revenue effects sum over aluminum and steel. Gray vertical lines mark observed, production-weighted average carbon taxation $\bar{\tau}^H$ among countries in markets H.

Figure A13: Policy spillovers, emissions

(a) Emission effects ΔE for market LL (Mt CO_2)



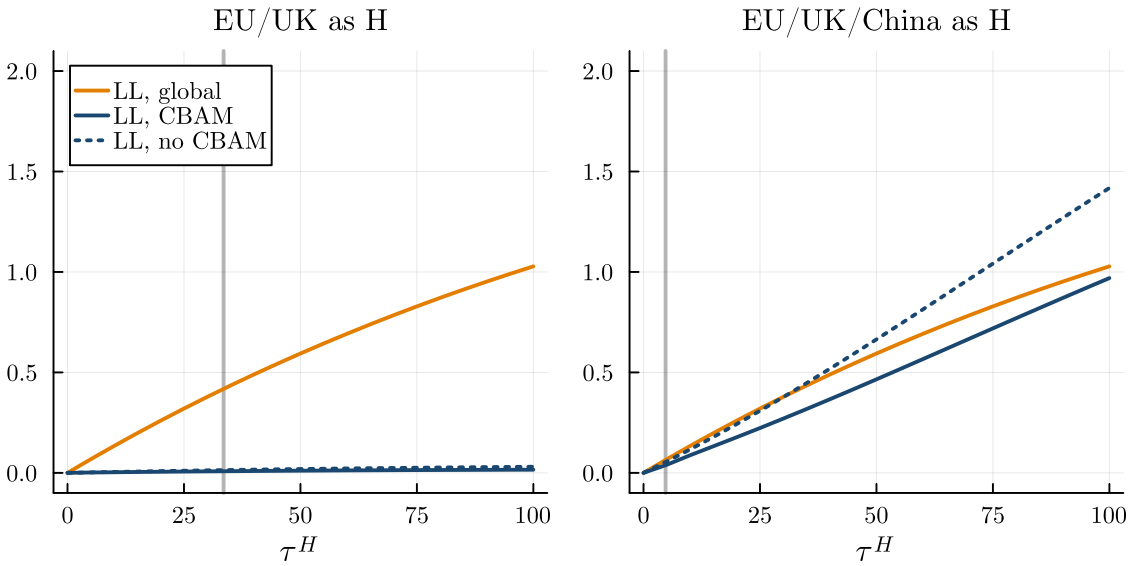
(b) Emission effects ΔE for market LH (Mt CO_2)



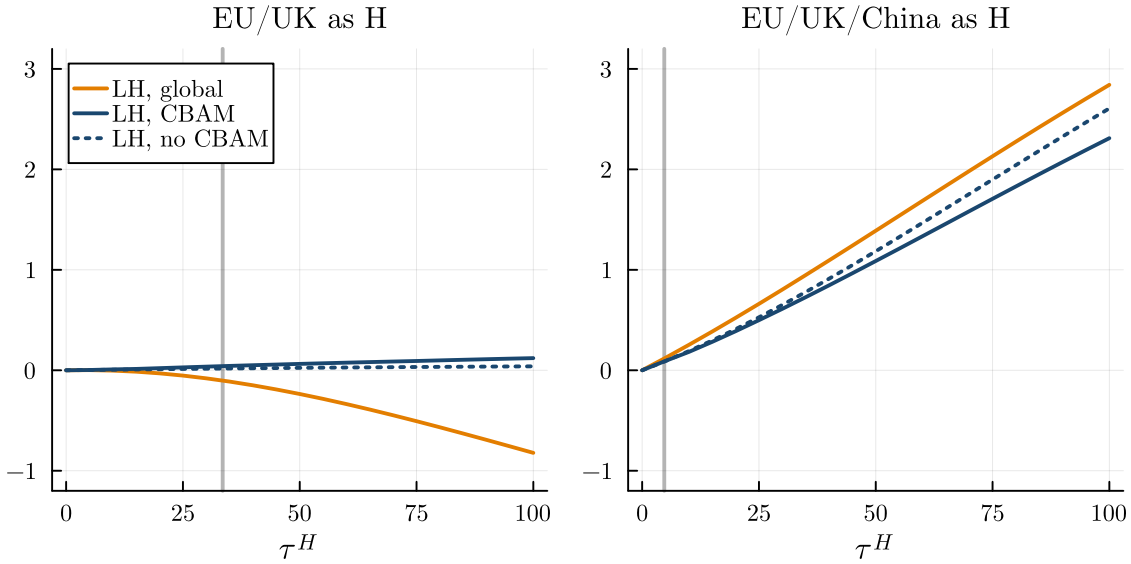
We simulate carbon regulation in three forms. Global regulation $\tau = \tau^H = \tau^L$ is uniform across high- and low-regulation markets H and L. CBAM regulation involves carbon regulation $\tau^H > 0$ and border adjustment in H, imposing $\tau^L = 0$ in L. No-CBAM regulation involves carbon regulation $\tau^H > 0$ in H, imposing $\tau^L = 0$ in L. We compute effects relative to business as usual, which we define as $\tau^H = \tau^L = 0$. We compute effects separately for markets LL and LH, which divide L into lower- and higher-income countries based on World Bank income groups. Emission effects sum over aluminum and steel. Gray vertical lines mark observed, production-weighted average carbon taxation $\bar{\tau}^H$ among countries in markets H.

Figure A14: Policy spillovers, aluminum only

(a) Welfare effects ΔW for market LL (1B USD)



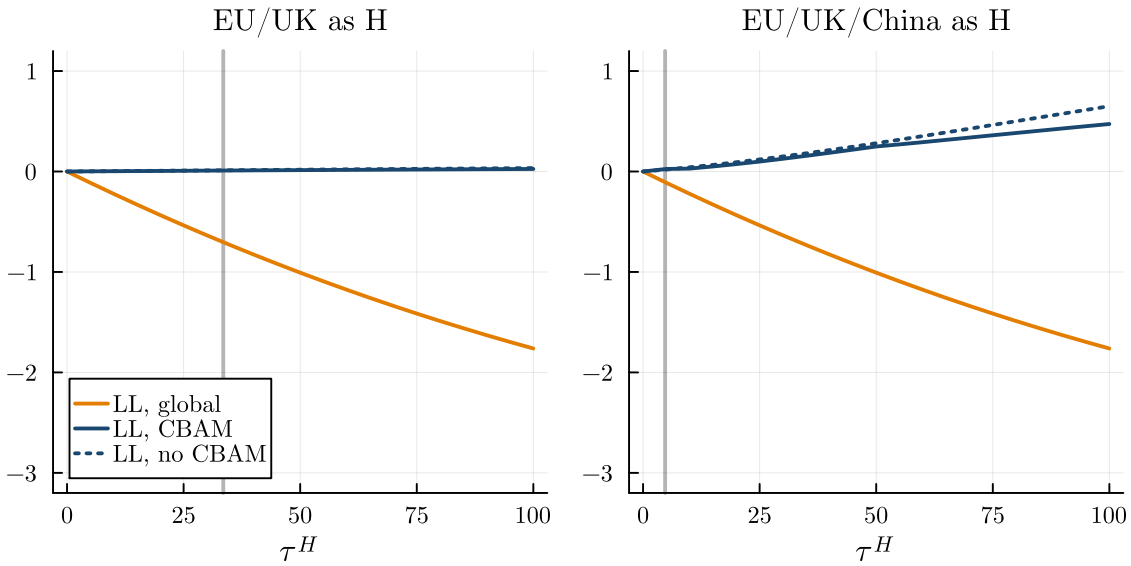
(b) Welfare effects ΔW for market LH (1B USD)



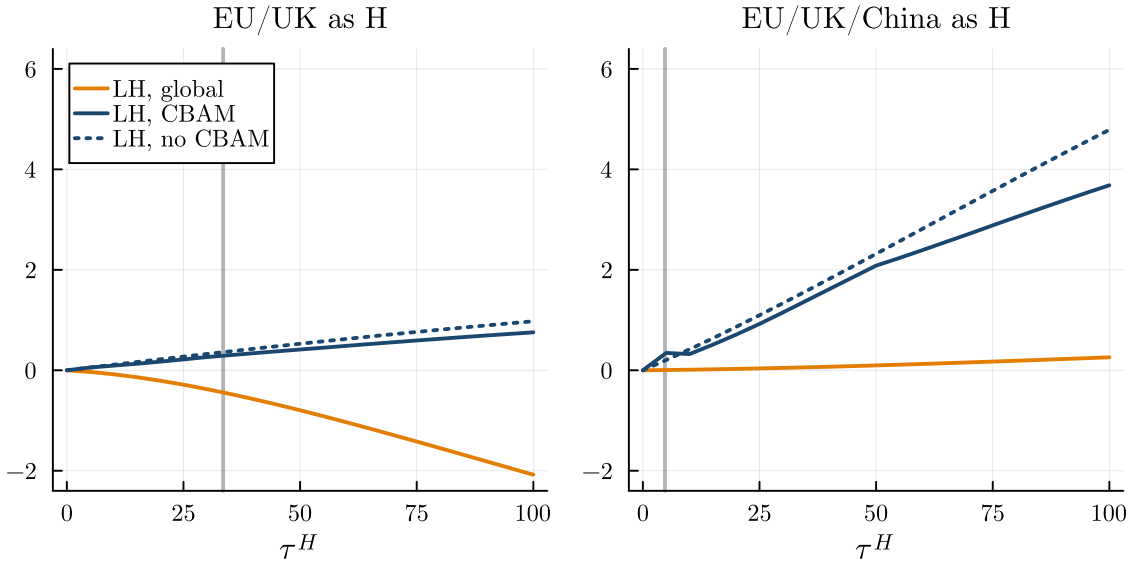
For aluminum, we simulate carbon regulation in three forms. Global regulation $\tau = \tau^H = \tau^L$ is uniform across high- and low-regulation markets H and L. CBAM regulation involves carbon regulation $\tau^H > 0$ and border adjustment in H, imposing $\tau^L = 0$ in L. No-CBAM regulation involves carbon regulation $\tau^H > 0$ in H, imposing $\tau^L = 0$ in L. We compute effects relative to business as usual, which we define as $\tau^H = \tau^L = 0$. We compute effects separately for markets LL and LH, which divide L into lower- and higher-income countries based on World Bank income groups. Gray vertical lines mark observed, production-weighted average carbon taxation $\bar{\tau}^H$ among countries in markets H.

Figure A15: Policy spillovers, iron and steel only

(a) Welfare effects ΔW for market LL (1B USD)



(b) Welfare effects ΔW for market LH (1B USD)



For iron and steel, we simulate carbon regulation in three forms. Global regulation $\tau = \tau^H = \tau^L$ is uniform across high- and low-regulation markets H and L. CBAM regulation involves carbon regulation $\tau^H > 0$ and border adjustment in H, imposing $\tau^L = 0$ in L. No-CBAM regulation involves carbon regulation $\tau^H > 0$ in H, imposing $\tau^L = 0$ in L. We compute effects relative to business as usual, which we define as $\tau^H = \tau^L = 0$. We compute effects separately for markets LL and LH, which divide L into lower- and higher-income countries based on World Bank income groups. Gray vertical lines mark observed, production-weighted average carbon taxation $\bar{\tau}^H$ among countries in markets H.

B Tables

Table B1: Carbon pricing for primary aluminum

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

Prices in 2023 USD per ton CO_2 equivalents. Adjusted prices are average prices paid. They deduct regional emission allowances based on 2023 emission estimates and production volumes.

Table B2: Carbon pricing for secondary aluminum

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

Prices in 2023 USD per ton CO_2 equivalents. Adjusted prices are average prices paid. They deduct regional emission allowances based on 2023 emission estimates and production volumes.

Table B3: Carbon pricing for iron and steel

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

Prices in 2023 USD per ton CO_2 equivalents. Adjusted prices are average prices paid. They deduct regional emission allowances based on 2023 emission estimates and production volumes.

Table B4: Changes in aluminum production cost efficiency percentiles

Country	Capacity (kta)	Cost Percentile (Pre)	Cost Percentile (Post)	Difference
Low income				
Mozambique	575	82	94	12
Subtotal	575	82	94	12
Lower middle income				
Cameroon	100	17	58	41
Egypt	300	46	82	36
Ghana	200	61	87	26
India	6,114	38	16	-22
Tajikistan	425	85	94	9
Venezuela	440	97	98	1
Subtotal	7,579	45	30	-15
Upper middle income				
Argentina	460	97	86	-11
Brazil	2,260	27	76	49
China	55,100	50	40	-10
Indonesia	300	88	95	7
Kazakhstan	265	100	47	-53
Malaysia	1,080	51	75	24
South Africa	728	61	33	-28
Turkey	82	100	99	-1
Subtotal	60,275	50	42	-8
High income				
Australia	1,728	30	22	-8
Bahrain	1,631	78	68	-10
Canada	3,357	79	94	15
France	437	32	80	48
Germany	1,426	3	47	44
Greece	187	6	51	45
Iceland	900	54	86	32
Italy	770	29	89	60
Japan	827	20	75	55
South Korea	574	26	81	55
New Zealand	357	33	77	44
Norway	1,802	54	87	33
Oman	395	39	55	16
Qatar	647	60	57	-3
Romania	290	1	44	43
Russian Federation	4,393	74	82	8
Saudi Arabia	805	57	57	0
Slovenia	108	5	51	46
Sweden	144	8	58	50
Taiwan	493	1	46	45
United Arab Emirates	2,742	85	69	-16
United Kingdom	50	19	71	52
United States	4,835	5	46	41
Subtotal	28,896	47	67	20

Table B5: Changes in steel production cost efficiency percentiles

Country	Capacity (Mt/a)	Cost Percentile (Pre)	Cost Percentile (Post)	Difference
Low income				
Uganda	0.4	20	70	50
Subtotal	0.4	20	70	50
Lower middle income				
Bangladesh	3.0	93	97	4
Egypt	14.5	83	80	-3
Ghana	0.8	30	72	42
India	108.8	94	77	-17
Kenya	1.0	20	65	45
Morocco	3.5	85	92	7
Nigeria	1.0	37	67	30
North Korea	8.0	16	41	25
Pakistan	0.9	91	98	7
Philippines	1.3	0	0	0
Syria	2.2	82	90	8
Uzbekistan	1.0	14	62	48
Venezuela	5.1	77	78	1
Vietnam	25.3	62	57	-5
Subtotal	176.3	82	73	-9
Upper middle income				
Albania	0.7	56	88	32
Algeria	8.1	86	81	-5
Argentina	7.5	58	63	5
Azerbaijan	1.0	46	78	32
Belarus	3.0	75	91	16
Bosnia & Herzegovina	1.9	19	41	22
Brazil	44.1	48	52	4
China	1,177.2	48	43	-5
Guatemala	0.5	19	70	51
Indonesia	18.2	27	43	16
Iran	44.7	76	74	-2
Iraq	2.6	82	90	8
Kazakhstan	6.8	19	17	-2
Libya	1.6	91	83	-8
Malaysia	15.5	33	55	22
Mexico	27.3	77	79	2
Moldova	1.0	76	87	11
North Macedonia	0.6	53	81	28
Peru	2.9	21	70	49
Serbia	2.7	25	24	-1
South Africa	7.8	55	45	-10
Thailand	8.2	32	74	42
Turkey	56.1	75	80	5

Table B5: Changes in steel production cost efficiency percentiles *(continued)*

Country	Capacity (Mt/a)	Cost Percentile (Pre)	Cost Percentile (Post)	Difference
Ukraine	33.2	54	43	-11
Subtotal	1,473.2	50	47	-3
High income				
Australia	5.9	62	56	-6
Austria	7.6	3	11	8
Bahrain	1.1	64	70	6
Belgium	8.0	25	42	17
Bulgaria	1.4	54	89	35
Canada	15.7	52	61	9
Chile	2.0	38	47	9
Czechia	6.4	12	46	34
Finland	4.4	19	40	21
France	19.1	27	44	17
Germany	50.5	2	17	15
Greece	4.1	42	82	40
Hungary	2.2	17	33	16
Italy	32.9	8	46	38
Japan	117.0	8	18	10
Kuwait	1.2	76	88	12
Luxembourg	3.0	60	91	31
Netherlands	7.5	4	14	10
New Zealand	0.7	2	50	48
Norway	0.8	72	94	22
Oman	4.3	87	86	-1
Poland	9.7	20	45	25
Portugal	1.7	66	91	25
Qatar	3.5	93	87	-6
Romania	5.3	19	39	20
Russia	89.4	95	78	-17
Saudi Arabia	10.8	84	78	-6
Singapore	0.8	19	69	50
Slovakia	4.5	2	11	9
Slovenia	0.7	50	87	37
South Korea	83.7	36	51	15
Spain	19.4	41	79	38
Sweden	4.8	11	40	29
Switzerland	1.4	56	90	34
Taiwan	23.6	35	45	10
United Arab Emirates	3.6	85	77	-8
United Kingdom	13.1	24	41	17
United States	120.7	71	73	2
Subtotal	692.5	41	51	10

Table B6: Climate TRACE and WoodMac primary aluminum data

	Climate TRACE	WoodMac
Production (Mt)	67	69
Capacity (Mt)	76	81
Scope 1 Emissions (Mt CO_2e)	169	156
Scope 1 and 2 Emissions (Mt CO_2e)	687	676
Number of Countries	36	34
Number of Smelters	148	153

Data for both sources is for 2023.

Table B7: Shipping emissions for aluminum

Year	Trade Volume (Mt)	Shipping Emissions (Mt CO_2)	Total Emissions (Mt CO_2)	Proportion (%)
2018	45.15	3.26	1,130	0.29
2019	47.79	3.74	1,133	0.33
2020	48.76	3.96	1,128	0.35
2021	54.96	4.27	1,112	0.38
2022	50.33	3.96	1,116	0.35

Column 4 data come from the International Aluminum Institute.

Table B8: Global carbon taxation

(H)	EU/UK			EU/UK/China		
(τ)	25	50	100	25	50	100
Market H						
Welfare (1B USD)	-0.94	-1.77	-3.11	-1.98	-4.29	-9.11
Consumer surplus (1B USD)	-6.22	-11.7	-20.5	-38.7	-72.8	-128
Producer surplus (1B USD)	-1.22	-2.00	-2.76	-23.7	-41.5	-65.1
Government revenue (1B USD)	6.50	11.9	20.2	60.4	110	184
Emissions (Mt CO_2)	-23.8	-45.2	-82.0	-241	-456	-817
Market L						
Welfare (1B USD)	-0.75	-1.81	-4.26	0.28	0.71	1.74
Consumer surplus (1B USD)	-56.6	-107	-187	-24.2	-45.4	-79.6
Producer surplus (1B USD)	-26.3	-45.2	-68.6	-3.83	-5.70	-6.22
Government revenue (1B USD)	82.2	150	251	28.3	51.8	87.5
Emissions (Mt CO_2)	-324	-613	-1098	-107	-202	-363
Market LL						
Welfare (1B USD)	-0.22	-0.41	-0.73	-0.22	-0.41	-0.73
Consumer surplus (1B USD)	-4.23	-7.93	-13.9	-4.23	-7.93	-13.9
Producer surplus (1B USD)	-2.04	-3.51	-5.30	-2.04	-3.51	-5.30
Government revenue (1B USD)	6.06	11.0	18.4	6.06	11.0	18.4
Emissions (Mt CO_2)	-25.0	-46.7	-82.9	-25.0	-46.7	-82.9
Market LH						
Welfare (1B USD)	-0.34	-1.03	-2.90	0.70	1.49	3.10
Consumer surplus (1B USD)	-52.2	-98.2	-172	-19.7	-37.1	-65.1
Producer surplus (1B USD)	-24.2	-41.7	-63.3	-1.79	-2.20	-0.92
Government revenue (1B USD)	76.1	139	233	22.2	40.8	69.1
Emissions (Mt CO_2)	-299	-566	-1015	-81.7	-155	-280

We simulate global carbon taxation $\tau = \tau^H = \tau^L$ across high- and low-regulation markets H and L. We compute effects relative to business as usual, which we define as $\tau^H = \tau^L = 0$. We report effects separately by market, where markets LL and LH divide L into lower- and higher-income countries based on World Bank income groups. Welfare, surplus, revenue, and emission effects sum over aluminum and steel. We consider carbon taxation τ of \$25, \$50, and \$100 per ton CO_2.

Table B9: Unilateral carbon taxation with border adjustment (CBAM)

(H)	EU/UK			EU/UK/China		
(τ^H)	25	50	100	25	50	100
Market H						
Welfare (1B USD)	0.08	0.06	0.05	-2.42	-5.52	-11.1
Consumer surplus (1B USD)	-1.22	-2.37	-4.40	-28.6	-52.7	-98.0
Producer surplus (1B USD)	-5.33	-9.55	-15.5	-34.2	-62.0	-94.7
Government revenue (1B USD)	6.62	12.0	19.9	60.3	109	182
Emissions (Mt CO_2)	-27.1	-51.2	-91.3	-255	-481	-852
Market L						
Welfare (1B USD)	0.25	0.48	0.87	1.63	3.66	7.12
Consumer surplus (1B USD)	-2.51	-4.70	-8.20	-13.3	-26.7	-42.8
Producer surplus (1B USD)	2.75	5.18	9.07	15.0	30.3	49.9
Government revenue (1B USD)	0.00	0.00	0.00	0.00	0.00	0.00
Emissions (Mt CO_2)	2.48	4.72	7.87	13.8	27.5	42.6
Market LL						
Welfare (1B USD)	0.01	0.02	0.04	0.32	0.71	1.44
Consumer surplus (1B USD)	-0.20	-0.37	-0.66	-2.33	-4.67	-7.43
Producer surplus (1B USD)	0.21	0.40	0.70	2.65	5.38	8.87
Government revenue (1B USD)	0.00	0.00	0.00	0.00	0.00	0.00
Emissions (Mt CO_2)	0.26	0.47	0.80	3.73	7.40	12.5
Market LH						
Welfare (1B USD)	0.24	0.48	0.88	1.42	3.17	5.99
Consumer surplus (1B USD)	-2.30	-4.31	-7.50	-10.9	-21.8	-35.0
Producer surplus (1B USD)	2.54	4.78	8.38	12.3	25.0	41.0
Government revenue (1B USD)	0.00	0.00	0.00	0.00	0.00	0.00
Emissions (Mt CO_2)	2.23	4.25	7.06	10.1	20.1	30.1

We simulate unilateral domestic carbon regulation $\tau^H > 0$ in high-regulation market H, paired with border adjustment $\alpha^H = \tau^H - \tau^L$, holding fixed $\tau^L = 0$ in low-regulation market L. We compute effects relative to business as usual, which we define as $\tau^H = \tau^L = 0$. We report effects separately by market, where markets LL and LH divide L into lower- and higher-income countries based on World Bank income groups. Welfare, surplus, revenue, and emission effects sum over aluminum and steel. We consider carbon taxation τ^H of \$25, \$50, and \$100 per ton CO_2.

Table B10: Unilateral carbon taxation (no CBAM)

(H)	EU/UK			EU/UK/China		
(τ^H)	25	50	100	25	50	100
Market H						
Welfare (1B USD)	0.02	0.02	-0.02	-2.80	-6.09	-13.0
Consumer surplus (1B USD)	-0.36	-0.68	-1.22	-25.9	-49.3	-87.9
Producer surplus (1B USD)	-6.02	-10.9	-17.8	-36.9	-65.3	-104
Government revenue (1B USD)	6.40	11.6	19.0	59.9	108	179
Emissions (Mt CO_2)	-27.7	-52.3	-93.2	-259	-487	-865
Market L						
Welfare (1B USD)	0.29	0.56	1.02	1.94	4.23	9.09
Consumer surplus (1B USD)	-3.23	-6.15	-11.0	-16.0	-30.3	-53.8
Producer surplus (1B USD)	3.52	6.71	12.0	17.9	34.5	62.9
Government revenue (1B USD)	0.00	0.00	0.00	0.00	0.00	0.00
Emissions (Mt CO_2)	4.06	7.70	13.6	17.8	33.5	58.5
Market LL						
Welfare (1B USD)	0.02	0.04	0.06	0.43	0.95	2.07
Consumer surplus (1B USD)	-0.25	-0.48	-0.87	-2.77	-5.25	-9.30
Producer surplus (1B USD)	0.27	0.52	0.93	3.20	6.20	11.4
Government revenue (1B USD)	0.00	0.00	0.00	0.00	0.00	0.00
Emissions (Mt CO_2)	0.34	0.64	1.12	4.78	9.22	16.6
Market LH						
Welfare (1B USD)	0.29	0.55	1.01	1.62	3.50	7.40
Consumer surplus (1B USD)	-2.96	-5.64	-10.1	-13.1	-24.8	-44.2
Producer surplus (1B USD)	3.24	6.19	11.1	14.7	28.4	51.6
Government revenue (1B USD)	0.00	0.00	0.00	0.00	0.00	0.00
Emissions (Mt CO_2)	3.72	7.06	12.5	13.0	24.2	41.9

We simulate unilateral domestic carbon regulation $\tau^H > 0$ in high-regulation market H, holding fixed $\tau^L = 0$ in low-regulation market L. We compute effects relative to business as usual, which we define as $\tau^H = \tau^L = 0$. We report effects separately by market, where markets LL and LH divide L into lower- and higher-income countries based on World Bank income groups. Welfare, surplus, revenue, and emission effects sum over aluminum and steel. We consider carbon taxation τ^H of \$25, \$50, and \$100 per ton CO_2.

C Data Construction

C.1 Secondary aluminum

We gather country-level data on secondary aluminum production from the World Bureau of Metal Statistics (WBMS) from the London Stock Exchange Group (LSEG). 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.

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

We estimate emissions per metric ton of secondary aluminum as 10% of the average emissions per metric ton of 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. We estimate average carbon prices paid for emissions from secondary aluminum as described in Section 3.3 and shown

in appendix table B2.

C.2 Iron and steel

Our steel cost data is based on the Global Steel Cost Tracker (GSCT), a dataset that estimates plant-level raw materials, energy, labor, and overhead costs for 433 plants in 13 of the major steel producing countries (Brazil, China, Germany, India, Italy, Japan, South Korea, Mexico, Russia, Turkey, Ukraine, the United States, and Vietnam). The dataset is produced in collaboration between TransitionZero, a climate data and analytics startup, and Global Efficiency Intelligence, a research and consulting firm focused on industrial decarbonization. We merge plant-level data from Climate TRACE with the plant-level data from GSCT using longitude and latitude. The set of plants that are in both datasets account for 71% of global production. For plants that are not included in the GSCT but are in one of the 13 countries, we estimate costs using separate country-level averages for BF-BOF and EAF plants. When countries do not overlap, we extrapolate costs using separate regional averages for BF-BOF and EAF steelmaking. We observe 357 BF-BOF plants and 535 EAF plants.

C.3 Shipping emissions

We compare shipping emissions to total production emissions for aluminum. We use bilateral trade data from 2017-2021 from the UN Comtrade Database[24] and bilateral distances for each trade flow from the CEPII GeoDist dataset.[25] We calculate shipping emissions as

$$\text{CO}_2 \text{ emissions (kg)} = \text{Trade Volume (mt)} \times \text{Bilateral Distacnce} \times \text{Emissions Factor}.$$

We use an emissions factor for maritime shipping of $0.01923\,\text{kg}\,\text{CO}_2$ per ton-kilometer, as in Mundaca et al. (2021). Appendix table B7 shows that shipping emissions account for a very small proportion of total production emissions. This proportion increased slightly over the sample period, reflecting a decrease in the carbon intensity of over this period. Shipping emissions remain constant over time in our calculations.

[24] UN Comtrade Database (2024). UN Comtrade Database.

[25] Mayer, T., & Zignago, S. (2011). Notes on CEPII distances measures: The GeoDist database. CEPII Working Paper 2011-25.

D Mozambique

Mozambique is a key player in the global aluminum industry due to the presence of Mozal, the second-largest aluminum smelter in Africa. The project began in 1998 as part of a recovery program driven by the Mozambican government's active desire for foreign investment to help rebuild the nation after the country's civil war in the early 1990s. The Mozal smelter was officially opened in September 2000. Mozal is primarily owned by South32, an Australian mining and metals company, which holds a 64% stake in the smelter. Mozal accounts for 10% of South32's annual revenues. The remaining ownership of Mozal is divided between the Industrial Development Corporation of South Africa (32%), and the Government of Mozambique (4%).

The Mozal smelter uses approximately half of Mozambique's total electricity production, highlighting both the energy-intensive nature of aluminum production and the country's relatively lower extent of economic development.[26] However, Mozambique's electric grid is not yet interconnected between the north and south of the country. This creates a unique dynamic: while the northern region produces clean hydroelectric power, much of it is exported to South Africa. Meanwhile, Mozal imports electricity from South Africa, where a significant portion of power generation relies on greenhouse gas-intensive coal production.

Mozal is a major employer in Mozambique, providing highly paid jobs relative to the national average. It is also a significant contributor to the country's export economy, with aluminum representing one of Mozambique's most important export products. In recent years, a large share of these exports has been directed to the EU. With UN Comtrade data, we calculate that aluminum was over 50% of Mozambique's total exports in 2011, then fell to about 17% by 2022. Exports to the EU and UK were more than 95% of Mozambique's total aluminum exports, then fell to about 75% in 2022. Even with these recent changes, aluminum exports to CBAM countries remain an important part of Mozambique's economy.

[26] By comparison, Canada (the world's fourth largest aluminum producer, after China, India, and Russia) has a population of 38 million – relative to 34 million for Mozambique – and uses only 7% of its total electricity to produce primary aluminum.