The Global Effects of Carbon Border Adjustment Mechanisms

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

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1 Introduction

As the European Union and United Kingdom implement the first carbon border adjustment mechanisms (CBAMs), the world is experiencing a new climate policy tool. Domestic carbon taxes are important steps toward a global carbon tax, but they are subject to competitiveness, leakage, and free-riding concerns. Competitiveness is an issue because regulation can hinder domestic producers who must compete in global markets. Leakage arises because domestic consumers can shift toward importing from unregulated foreign producers. Free-riding occurs because foreign markets benefit from emissions reductions, which are a global problem. CBAMs aim to address these concerns by imposing domestic carbon taxes at the border, combined with credits for foreign carbon taxes paid. The border tax levels the playing field and reduces leakage toward imports, while the border credit encourages foreign markets to regulate. At the same time, the EU's own analysis cites concerns that the CBAM may disproportionately harm 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 emissions-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 emissions-intensive than production in higher-income countries. For both aluminum and steel, lower- and higher-income countries emit similar levels of CO_2 per unit of production. 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 markets worldwide. We simulate regulated markets that implement carbon taxation, both with and without border adjustment, and we compute impacts across markets on consumers, producers, government revenue, and emissions relative to a benchmark of zero taxation. Given the dominance of China in aluminum and steel, we consider two coalitions of regulated markets: the existing coalition with the EU and UK alone and a hypothetical coalition with the EU, UK, and China. We then evaluate the extent to which CBAMs boost competitiveness, reduce leakage, and encourage regulation, including for lower-income countries relative to higher-income countries.

We have five main findings. First, we quantify the impacts of carbon taxation in regulated markets. This policy action reduces world supply and raises world prices. Regulated markets suffer private welfare losses 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, unregulated markets experience private welfare gains on net, as higher world prices hurt unregulated consumers but greatly benefit unregulated producers. At the same time, higher world prices raise unregulated production and thus unregulated emissions.

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

Third, CBAMs increase the global competitiveness of producers in regulated markets. Carbon regulation raises production costs for regulated producers, lowering their cost competitiveness and reducing their profits. A CBAM levels the playing field by imposing the same carbon regulation on goods imported from unregulated producers. We find that a CBAM reduces the profit losses from carbon regulation by as much as 15%. At the same time, a CBAM also reduces the profit gains for unregulated producers, who otherwise benefit from carbon regulation that targets their competition. We find that these negative impacts have equal incidence among lower- and higher-income countries.

Fourth, CBAMs reduce emissions leakage in unregulated markets. Without a CBAM, carbon taxation in regulated markets substantially increases emissions in unregulated markets. Imposing a CBAM reduces these increases in emissions by roughly one third. We do not find that CBAMs place greater 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.

Fifth, CBAMs encourage carbon regulation in unregulated markets. CBAMs reduce the extent to which carbon taxation in regulated markets raises welfare in unregulated markets, thereby reducing the incentives to free-ride. In relative terms, CBAMs increase the welfare incentives for unregulated markets to regulate. CBAMs also create revenue incentives. Unregulated markets can collect carbon tax revenue without distorting exports to regulated markets, precisely because CBAMs credit these exports for carbon taxes already paid. Exporters face the same total taxes, but the tax revenue flows instead to governments in unregulated markets.

We build on a growing body of work that studies international environmental policy coordination (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, Casey et al. 2025). 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, Coster et al. 2024) and for encouraging broader climate cooperation (Clausing and Wolfram 2023). This proposal has now been adopted by policymakers.

Our main contribution is to provide a quantitative global analysis of CBAM policies, as currently being implemented 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.

European policymakers debated several alternatives before formally proposing the CBAM in July 2021. Under the EU 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 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 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 argued that a CBAM will level the playing field for industrial producers, which are subject to Canada's federal backstop for carbon pricing, and the governments of Australia and Taiwan are also currently considering CBAMs. Clausing et al. (2024) document the correlation between discussion of the EU CBAM 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 particularly 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

[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 emissions 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.

[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 subject to the details of implementation. 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 will require CBAM payments for the carbon emissions associated with the electricity used in the production of cement and fertilizers, but not aluminum or steel.

Table 1: Trade and emissions for CBAM-targeted industries

	Global Trade Share (%)	Trade Value (1B USD)	Trade Intensity (%)	Global Emissions Share (%)
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 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. Steel refers to iron and steel.

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. We use "steel" in reference to "iron and steel." These industries are both heavily traded and emissions-intensive. Aluminum and steel represent a larger share of global trade than other CBAM-targeted industries, and much of aluminum and steel production is traded. Furthermore, aluminum and steel are emissions-intensive and account for 14% of total global CO_2 emissions (Table 1). Other target industries have more limited exposure to CBAM policies. Electricity and cement are a large share of global emissions but not heavily traded. Fertilizers are heavily traded but only a small share of global emissions. Hydrogen is neither heavily traded nor a large share of global emissions. We simulate a CBAM with full implementation, incorporating both Scope 1 and Scope 2 emissions 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 hydroelectric power, can produce aluminum with lower emissions. Secondary production involves recycling aluminum scrap. This process requires only 5 to 10% of the energy required for primary production, and it involves no direct CO_2 emissions. In our data, primary and secondary aluminum emissions average 9.7 and 1.0 tons of CO_2, respectively, per ton of production.

2.3 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 emissions-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 transformed into steel by blowing oxygen in a basic oxygen furnace to remove carbon, which is released as CO_2. 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

[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.

to 40 years (IEA 2023).

EAF steel is also known as secondary steel. Typically, 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 emissions average 2.4 and 0.9 tons of CO_2, respectively, per ton of production.

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 plant level with detailed data from Wood Mackenzie (WoodMac), a leading data and analytics provider focused on energy industries and related sectors.[5] These data include 153 plants, covering the global universe of primary aluminum smelters in 2023. WoodMac specialists compile these data by combining public information with periodic site visits to each plant.[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. Costs include those from electricity, alumina, other raw materials, consumables, labor, maintenance, and freight, which we supplement with our own

[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, are grouped together.

estimates of transport costs based on the UN Trade and Development (UNCTAD) trade and transport dataset. 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. This production accounts for 691 Mt of CO_2 emissions, including 160 Mt of Scope 1 emissions and 531 Mt of Scope 2. Primary aluminum is 70 Mt (82%) of global production and 676 Mt (98%) of global emissions, while secondary aluminum is 15 Mt of production and 15 Mt of emissions. Figure 1 plots the production costs of primary and secondary aluminum against cumulative capacity. Table 2 lists the top ten producing countries, which together account for 77 Mt. China is a dominant producer and consumer of aluminum, accounting for about 60% of the market. These measures are consistent with country-level estimates from the US Geological Survey. Lower-income countries account for 6 Mt (7%) of global production and 66 Mt (9%) of global emissions. 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.[7]

Steel

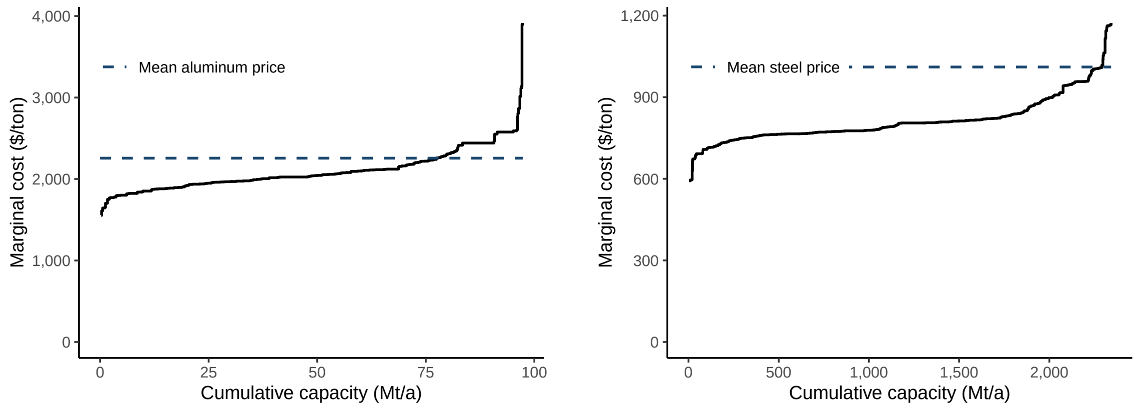
We obtain steel data at the plant level from Climate TRACE (Tracking Real-time Atmospheric Carbon Emissions), an independent non-profit that monitors and reports global greenhouse gas emissions.[8] Climate TRACE publishes monthly estimates of steel production, capacity, and emissions for plants in the Global Steel Plant Tracker (GSPT) database from Global Energy Monitor (GEM). These data include 892 plants across 77 countries, covering the global universe of steel mills with a capacity of more than 500 thousand tons. Emissions data include both Scope 1 and Scope 2 emissions. Scope 1 emissions derive from more than 300 satellites and 11,000 sensors that capture plant-level activity, covering more than 660 million individual sources

[7] 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.

[8] Climate TRACE also monitors the primary aluminum market. Appendix table B6 shows consistency with the WoodMac data.

Figure 1: Production costs and capacity

(a) Aluminum (b) Steel



Marginal costs are in nominal 2023 USD. Cumulative capacity is in metric megatons 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 for secondary aluminum, which is at the country level.

of emissions.[9] Scope 2 emissions are based on regional estimates of the emissions intensity of electricity production from Ember, a global energy think tank, as well as plant-level estimates of electricity use from the Mission Possible Partnership's 2024 Steel Transition Strategy. We describe data construction in Appendix C.2.

In total, we observe 1,673 Mt of global steel production in 2023. This production accounts for 3,163 Mt of CO_2 emissions, including 2,876 Mt of Scope 1 emissions and 287 Mt of Scope 2. Primary steel is 1,114 Mt (67%) of global production and 2,657 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 global production and 202 Mt (6%) of global emissions.

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

Table 2: Aluminum

(a) Top ten producers

Country	Mt	%
China	48.9	57.9
India	4.7	5.6
EU + UK	4.6	5.5
USA	4.1	4.9
Russia	4.0	4.7
Canada	3.3	3.9
UAE	2.7	3.2
Brazil	1.9	2.3
Bahrain	1.6	1.9
Australia	1.6	1.9
Rest of world	7.0	8.3

(b) Top ten consumers

Country	Mt	%
China	50.8	60.2
EU + UK	9.1	10.8
USA	8.6	10.2
India	3.0	3.6
Japan	2.9	3.4
Brazil	1.8	2.1
Turkey	1.7	2.0
Russia	0.9	1.1
Saudi Arabia	0.9	1.1
Mexico	0.7	0.8
Rest of world	4.0	4.7

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

3.2 Consumption

Aluminum

We construct aluminum consumption by combining the production data with country-level trade data for 2023 from UN Comtrade.[10] 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.[11] 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 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 worldwide consumption and production are equal at 84.4 Mt, we attribute the remaining 4.0 Mt of consumption

[10] We use 2021 trade data for Russia because data are not reported for 2022 or 2023.

[11] Together, they comprise "Aluminum; unwrought" with HS code 7601.

Table 3: Steel

(a) Top ten producers

Country	Mt	%
China	860	51
EU + UK	153	9
Japan	88	5
USA	86	5
India	76	5
Russia	60	4
South Korea	59	4
Turkey	35	2
Brazil	33	2
Iran	31	2
Rest of world	191	11

(b) Top ten consumers

Country	Mt	%
China	827	49
EU + UK	169	10
USA	101	6
India	77	5
Japan	68	4
South Korea	49	3
Turkey	43	3
Russia	39	2
Mexico	33	2
Iran	31	2
Rest of world	236	14

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

to the rest of the world. We measure both primary and secondary aluminum, which we treat as perfectly substitutable in consumption.

Steel

We construct steel consumption similarly. We compile trade data on 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 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 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, regulation, and ownership

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 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 prices. We account for exemptions and allowances to construct the adjusted carbon prices that apply to each plant. Plants pay these lower, adjusted prices on average, although unadjusted prices remain relevant on the margin once plants exhaust their exemptions or allowances. 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.

We construct state and foreign ownership for each plant, as detailed in appendix C.3. We define ownership based on majority-stakeholder parent companies. Appendix tables B7 and B8 present country-level statistics for the top aluminum and steel producers globally. State and foreign ownership are relatively common for aluminum, although not differentially so across lower- and higher-income countries. Much of Indian production is by foreign-owned firms, but the same holds for Canada and Australia. Chinese production is 39% state-owned and 0% foreign-owned. Both state and foreign ownership are less common for steel. Chinese production is 10% state-owned and 0% foreign-owned.

4 Stylized Facts

We describe emissions intensity and CBAM exposure for aluminum and steel producers globally.

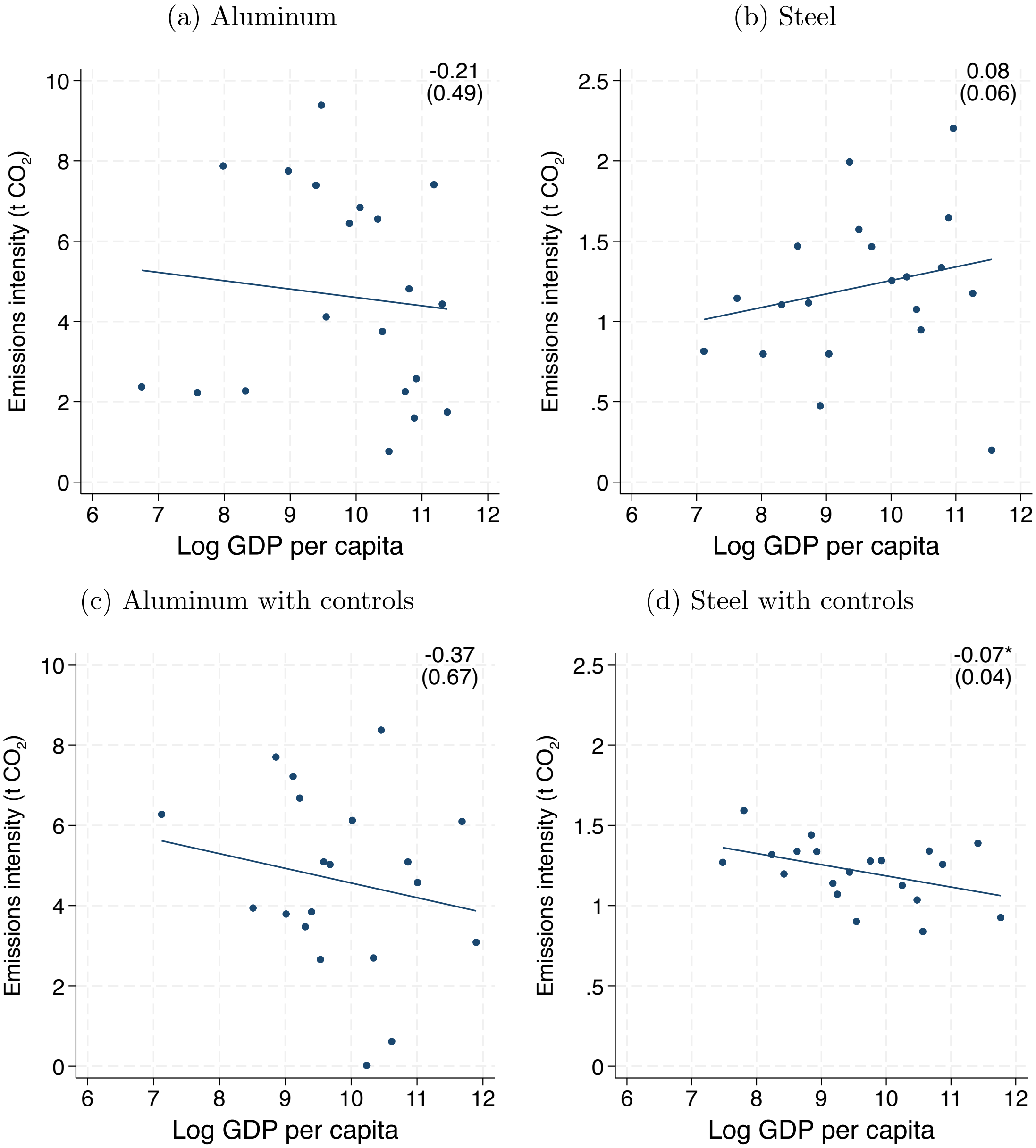
4.1 Emissions intensity by income

Figure 2 plots the emissions intensity of production against log GDP per capita across countries. 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. The top two figures show a flat relationship between emissions intensity and GDP that holds for both aluminum and steel. It is this key relationship that determines the exposure of lower-income trading partners to CBAM policy. 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 emissions-intensive than production in higher-income countries.

We find that the flat relationship between emissions intensity and GDP is partially explained by compositional differences in production across countries. The bottom two figures control for the proportion of primary production, which is more emissions-intensive than secondary production, as well as the scale of production, the proportion of state ownership, and the proportion of foreign ownership. When we control for differences along these dimensions, the negative relationship for aluminum is accentuated, and the positive relationship for steel becomes negative. But neither relationship is statistically significant at conventional confidence levels, and differences in emissions intensity remain modest in magnitude.[12] For aluminum, a one-percent increase in GDP per capita is associated with a decrease of 0.0037 tons of CO_2 per ton of production, relative to a mean value of 4.65 tons of CO_2. For steel, the effect is 0.0007 tons relative to a mean of 1.22 tons. Appendix figures A2 and A3 show broadly similar results for Scope 1 and Scope 2 emissions.

[12] Appendix table B10 presents the same results as regression tables. The regressions with controls show that emissions intensity is higher for primary production and large-scale production. Steel emissions intensity is higher for state-owned producers. Emissions intensity does not differ for foreign-owned producers.

Figure 2: Emissions intensity by GDP per capita



Each figure is a binned scatter plot. Each observation is a country. Emissions intensity is tons of CO_2 emitted per ton of production. Controls include primary production (%), average production (Mt), state ownership (%), and foreign ownership (%). Primary production refers to primary aluminum and BOF steel. State ownership is whether the majority-stakeholder parent company is a state-owned enterprise. Foreign is whether the majority-stakeholder parent company is headquartered in a different country from a given plant. We compute the production-weighted average across plants within each country. Average production is the average across plants within a country. We report the slope and standard error of the fitted line in the top-right corner of each figure. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

4.2 Cost competitiveness under a CBAM

Figure 3 considers how a CBAM affects cost competitiveness for facilities in our data. We begin with our observed production costs. Figures 3a and 3b plot these pre-CBAM cost curves in gray. We then consider a CBAM with a carbon tax of $96 per ton of CO_2, corresponding to the average ETS price in the EU and UK in 2023. We add this carbon tax to our cost curves, applying credits for pre-existing carbon pricing, and we plot these post-CBAM cost curves in black. Costs shift up for all producers, but their positions change. Appendix figures A1a and A1b show that emissions-intensive producers move up the cost curve. That is, producers with low emissions intensity become more cost-competitive, while those with high emissions intensity become less cost-competitive. These changes capture a new margin of comparative advantage that emerges when carbon is more globally priced.

The CBAM does not strongly advantage higher-income countries. For aluminum, figure 3c shows a small negative relationship between CBAM-induced changes in cost competitiveness and GDP per capita. Higher-income countries become more cost-competitive, but not statistically significantly so. For steel, figure 3d shows a flat relationship. In the remainder of the paper, we turn to more formal analysis of the CBAM and its welfare implications.

5 Model

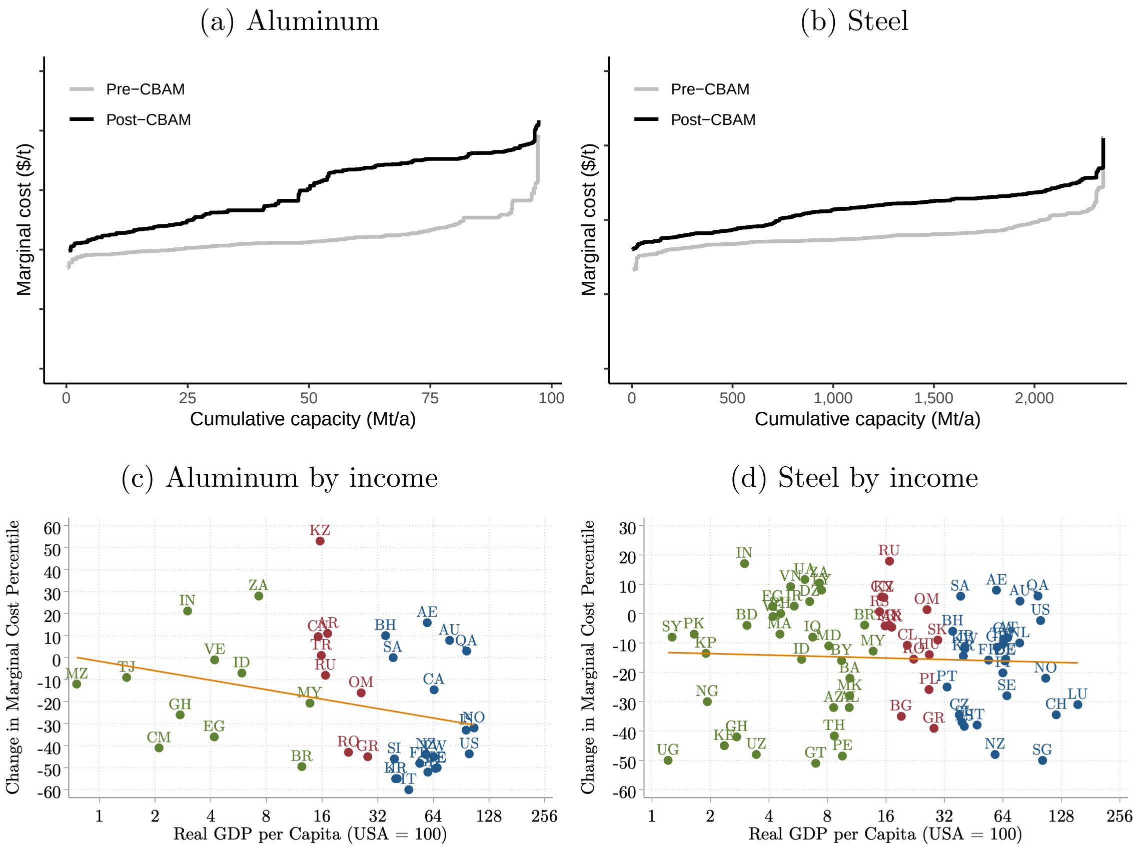
We model carbon taxation and a carbon border adjustment mechanism (CBAM) in a world commodity market. We distinguish between two markets $m \in \mathcal{M}$, where the set of markets $\mathcal{M} = \{R, U\}$ includes those that are regulated (R) and unregulated (U). Regulators in R consider a CBAM on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

5.1 Demand

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

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

Figure 3: Production costs under a CBAM



In the top figures, marginal costs are in 2023 USD. Cumulative capacity is in million metric tons per annum. 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. In the bottom figures, each point is a country. The y-axis is 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. We simulate a CBAM with a carbon tax of $96 per ton of CO_2. Countries with lower marginal costs are in lower cost percentiles. The x-axis is 2023 GDP per capita in log scale, normalized such that the US is 100. Countries are grouped into three income categories by GDP per capita: green is below $12,000, red is between $12,000 and $25,000, and blue is above $25,000.

Goods are homogeneous commodities, and 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 capacity $\bar{s}_i$, cost c_i, and price p_i^m. We observe capacity and costs, and we assume constant marginal costs. We take capacity and costs as given, noting that adjustment requires substantial investment that is difficult in the short run. We also observe production and prices, which we allow to respond endogenously to regulation. Each producer has a collection of production lines $\mathcal{L}$, 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. We will estimate the β parameter, which governs how changes in prices or costs translate into changes in production.[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 ag-

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

gregate 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 assume constant marginal emissions. We observe emissions across producers, and we observe 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. Producers take price P^m and regulation τ^m as given.

We incorporate abatement technology in simple form. In particular, we allow for emissions e_i to respond counterfactually 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 emissions intensity per dollar of carbon regulation. We observe actual emissions $\bar{e}_i$ and carbon taxes $\bar{\tau}^m$ 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

[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.

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

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

The adjustment is such that all consumption in R is subject to total tax τ^R. If U is entirely unregulated, then $\tau^U = 0$ and $\alpha^R = \tau^R$. Goods produced in R face carbon tax τ^R during production, while goods imported from U face τ^U during production and $\tau^R - \tau^U$ at the border. Prices no longer equalize across markets, and so we distinguish between prices (P^R, P^U). Producers decide which market to serve, and so regulation affects trade.

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

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

for sales from R to R (RR) and for sales from R to U (RU). Producers in U can choose among the two prices, but they only pay the higher tax when exporting to R. Net prices are

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

Producers choose their highest net price.

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

Producers serve R when prices in R dominate, otherwise they serve U.

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

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

$$S^R = \sum_m \sum_{i \in \mathcal{I}^m} \bar{s}_i o_i^m r_i^m, \quad S^U = \sum_m \sum_{i \in \mathcal{I}^m} \bar{s}_i o_i^m u_i^m \tag{5}$$

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^R imposes a price wedge. In equilibrium, prices (P^{R*}, P^{U*}) must clear each market separately. The marginal producer will be indifferent between selling to R or U.

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

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

$$P^R = P^U.$$

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

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

$$P^R - P^U = \tau^R e_i(\tau^R) - \tau^U e_i(\tau^U).$$

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

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

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 producers 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 R comes from domestic carbon taxes τ^R on production in R, as well as border adjustments α^R on imports from U.

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

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

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

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 R can encourage carbon taxation in U. The reason is that producers in U pay total tax τ^R on all exports to R, given adjustment $\alpha^R = \tau^R - \tau^U$, regardless of the size of domestic tax τ^U (as long as $\tau^U < \tau^R$). Producers in U are thus indifferent to τ^U. It follows that regulators in U can collect revenue without distorting outcomes. Consider the extremes. When $\tau^U = 0$, exporters pay $\alpha^R = \tau^R$ and the revenue goes entirely to R. When $\tau^U = \tau^R$, exporters pay $\alpha^R = 0$ and the revenue goes entirely to U. Exporters pay the same total tax because $\tau^U + \alpha^R = \tau^R$ 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 R and U.

[15] We weight surplus and revenue equally. While taxes are generally distortionary, carbon taxes correct an externality and thus raise revenue without distortions to social welfare. This revenue may lessen the need for other, more distortionary taxes.

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.

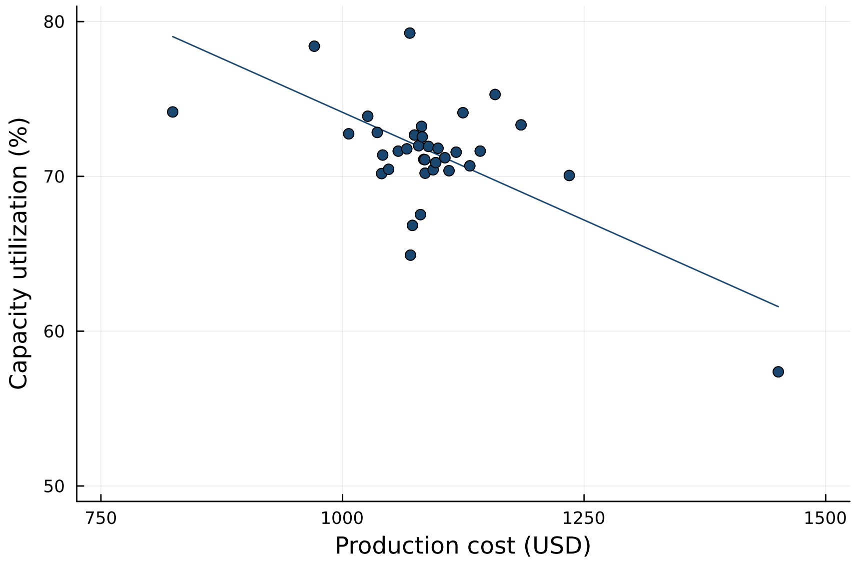
6.2 Supply

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

[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.

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

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

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. Thus, it is our cost data that provide identifying variation. We take these costs as given, subject to product and country fixed effects.

Equation 6 also clarifies the sources of heterogeneity in supply responses. Within a given producer, we have limited heterogeneity across different levels of production. The reason is that we model constant marginal costs, constant marginal emissions, and market prices that are taken as given. Thus, as prices fluctuate and regulation is imposed, production responses vary only to the extent allowed by the logit link function. This function captures diminishing marginal impacts at the extremes, such that regulation has smaller impacts on the highest- and lowest-cost producers. But across producers, differences in costs and emissions, which we observe, and in unobserved costs ϵ_{ijk}, which we recover, each generate rich variation in supply responses. An advantage of our plant-level data is that we observe many plants – 153 aluminum smelters and 892 steel mills – and so we capture substantial heterogeneity in practice.

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 increases domestic competitiveness, reduces carbon leakage, and encourages stronger carbon policy in unregulated markets. We discuss distributional implications for lower-income countries.

7.1 Policy simulations

We simulate unilateral carbon taxation τ^R by a regulated market R. We vary the intensity of carbon taxation, the coverage of market R, 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 emissions reductions for any given value of the social (or local) cost of carbon. We compute each of these quantities relative to a zero-regulation benchmark in which $\tau^R = \tau^U = 0$. We evaluate impacts for markets $\mathcal{M} \in \{R, U, UL, UH\}$, where markets UL and UH divide market U into lower- and higher-income countries, respectively. 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^R in market R from zero to \$100 per ton CO_2, while maintaining $\tau^U = 0$ in market U.[17] We study the role of scope by considering two regulatory coalitions. When market R 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 our benchmark scenario with zero carbon taxation. We also study 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. We do so by comparing outcomes under carbon taxation with a CBAM to those under carbon taxation without a CBAM. The differences isolate the marginal impact of border adjustment.

Table 4: EU and UK carbon taxation

$\tau^R = 100$ for EU/UK as R	No CBAM		With CBAM	
	R	U	R	U
Price (%)	0.64	0.64	2.52	0.46
Emissions (Mt CO_2)	-93.2	13.6	-91.3	7.87
Welfare (1B USD)	-0.02	1.02	0.05	0.87
Consumer surplus (1B USD)	-1.22	-11.0	-4.40	-8.20
Producer surplus (1B USD)	-17.8	12.0	-15.5	9.07
Government revenue (1B USD)	19.0	0.00	19.9	0.00

We simulate carbon regulation $\tau^R > 0$ in regulated market R, imposing $\tau^U = 0$ in unregulated market U. Market R is the EU and UK, and market U is all other countries. We compute effects relative to a zero-regulation benchmark with $\tau^R = \tau^U = 0$. We simulate regulation with and without a CBAM, and we compute effects separately for markets R and U. Price effects average over aluminum and steel, weighting by observed revenues. Emissions, welfare, surplus, and revenue effects sum over aluminum and steel.

7.2 EU and UK policy evaluation

We begin by evaluating EU and UK policy. Table 4 shows the impacts of carbon taxation at \$100 per ton of CO_2, which is roughly in line with the carbon prices we observe in our data.[18] Total effects are modest because the EU and UK account for only 10% of global aluminum and steel consumption (tables 2 and 3). Even so, regulation achieves meaningful emissions reductions of more than 90 Mt of CO_2 in the EU and UK. At the same time, higher world prices lead to carbon leakage. Without a CBAM, emissions abroad rise by 13.6 Mt. A CBAM reduces this carbon leakage by 5.7 Mt. Overall welfare effects are also modest. With a CBAM, welfare falls by \$0.02B for the EU and UK and rises by \$1.02B abroad. A CBAM shifts welfare gains toward the EU and UK.

The component effects of welfare are larger in magnitude. Without a CBAM, the EU and UK lose \$1.22B and \$17.8B in consumer and producer surplus, while

[17] We ignore current carbon pricing in U in order to focus attention on the impacts of carbon pricing in R. Appendix tables B1, B2, and B3 list this current carbon pricing by country. We note that $\tau^U = 0$ is correct to first order, particularly when weighted by production.

[18] Appendix tables B1, B2, and B3 show unadjusted carbon prices of \$96.29 for the EU and \$88.13 for the UK. These unadjusted prices do not account for allowances and exemptions, which are to be phased out over time.

gaining \$19.0B in government revenue. A CBAM worsens consumer losses by \$3.2B, while reducing producer losses \$2.3B and increasing revenue gains by \$0.9B. In what follows, we dissect the economic forces that drive these results.

7.3 Regulation and reallocation effects

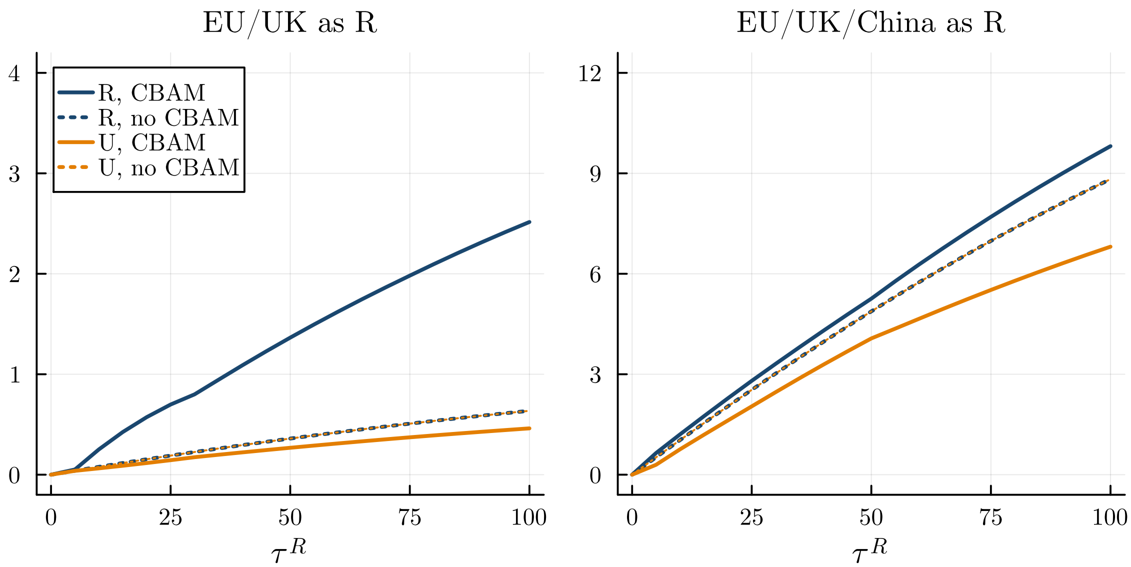
We document two forces: regulation and reallocation. Without a CBAM, we isolate the regulation force. Regulation in market R adds to production costs and shifts the global supply curve inward. The impact of regulation is to reduce world supply and raise world prices. With a CBAM, the reallocation force emerges. Dirty producers in U seek to avoid the CBAM by reallocating sales away from R. The impact of reallocation is to reduce supply in R and raise supply in U, thereby raising prices in R and reducing prices in U.

Figure 5a illustrates these price effects. Dashed lines show price effects without a CBAM, and solid lines show price effects with a CBAM. Blue lines correspond to R, and orange lines to U. 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 R and lower prices in U. We find price increases to be relatively modest. Even with carbon taxation in R at \$100 per ton of CO_2, prices rise by no more than 2.5% when R includes the EU and UK and 10% when R expands to include China.

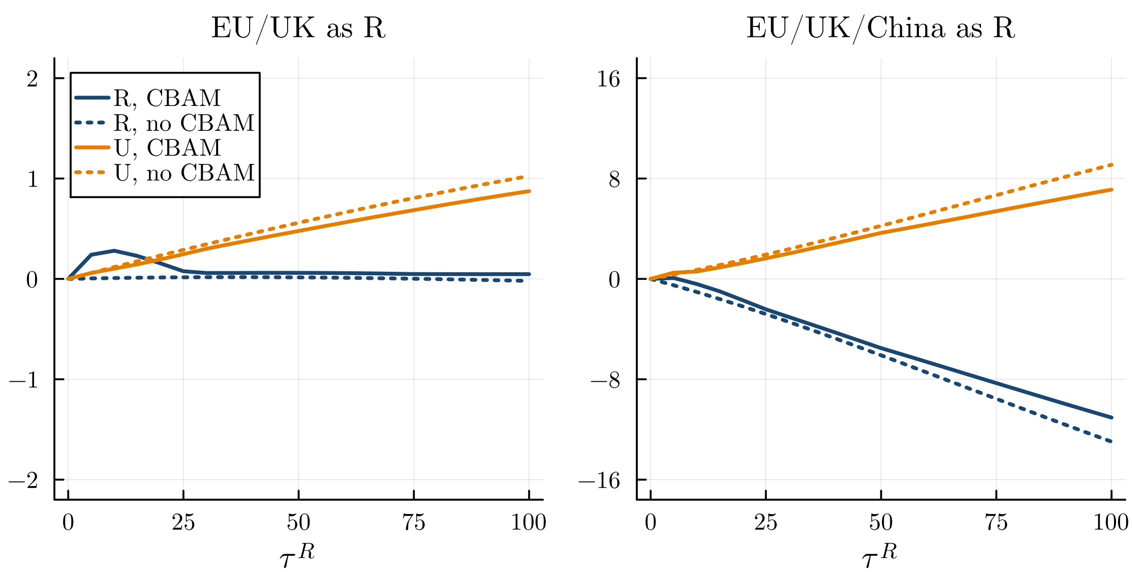
We highlight the outsized role of China in both production and consumption. On the left, when R does not include China, the reallocation force dominates. A CBAM induces substantial reallocation of sales toward U as regulation τ^R becomes more stringent, placing strong upward pressure on prices in R relative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

Figure 5: Carbon taxation with border adjustment

(a) Price effects ΔP (%)



(b) Welfare effects ΔW (1B USD)



We simulate carbon regulation $\tau^R > 0$ in regulated market R, imposing $\tau^U = 0$ in unregulated market U. We compute effects relative to a zero-regulation benchmark with $\tau^R = \tau^U = 0$. We simulate regulation with and without a CBAM, and we compute effects separately for markets R and U. 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.

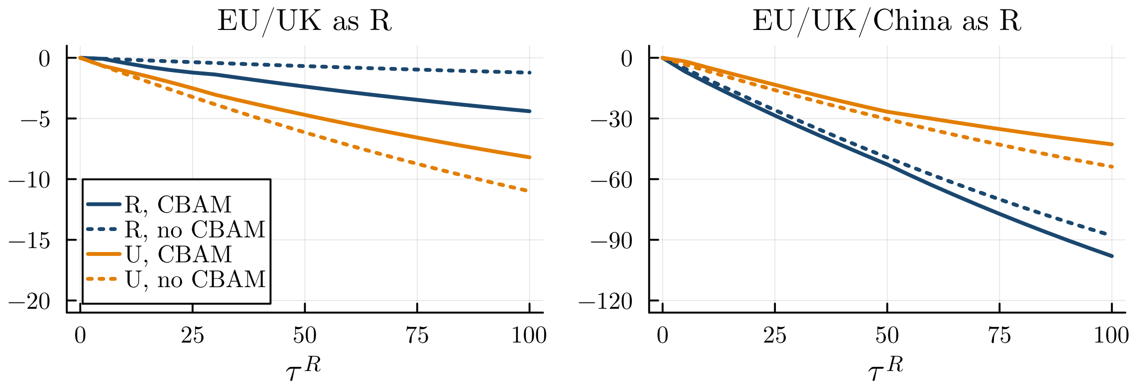
Figure 5b shows the resulting welfare effects. For R, carbon regulation is typically welfare-reducing. When R includes China, losses to domestic welfare – excluding the benefits of emissions reductions – can exceed \$10B in magnitude. But when R includes the EU and UK alone, welfare losses are minimal. Moreover, border adjustment reduces these losses. The solid blue lines lie above the dashed blue lines. When R includes China, carbon taxation with a CBAM improves welfare by up to \$2B relative to carbon taxation without a CBAM. When R includes 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 R, producers benefit from these higher prices. And the CBAM itself generates significant government revenue. The CBAM amounts to trade policy that – independent of emissions concerns – allows R to exercise its market power and manipulate its terms of trade. In doing so, R realizes welfare gains by extracting government revenue from foreign producers.

For U, carbon taxation in R is welfare-enhancing. Whether R pairs taxation with a CBAM or not, producers in U gain from the higher prices induced by regulation, even as consumers in U lose. Producer gains outweigh consumer losses, and so welfare in U rises overall. The solid and dashed orange lines both lie above zero. At the same time, a CBAM in R serves to reduce these welfare gains. The solid orange lines lie below the dashed orange lines. When R includes China, the welfare gains for U 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 U: lower prices in U and taxes on exports to R. Smaller benefits for producers in U lead to smaller welfare gains for U. Appendix figures A4 and A5 show similar price and welfare effects when we treat aluminum and steel separately.

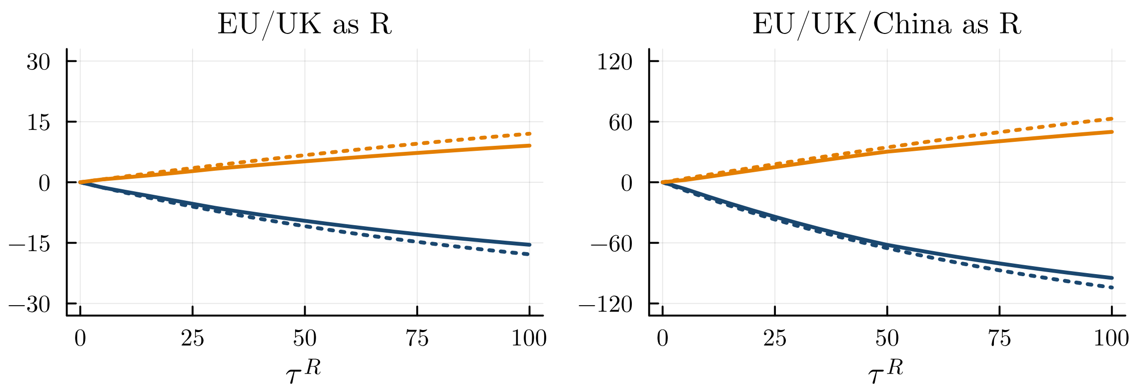
Figure 6 shows the component effects on consumer surplus, producer surplus, and government revenue. Relative to the zero-regulation benchmark, carbon taxation raises prices and hurts consumers globally. The CBAM then worsens consumer losses in R by worsening price increases in R, while lessening consumer losses in U by lessening price increases in U. The solid blue lines lie below the dashed blue lines, while the solid orange lines lie above the dashed orange lines. The opposite holds for producer surplus because producers benefit, rather than suffer, from high prices. For the government, carbon taxation generates significant revenues for R: up to \$20B for

Figure 6: Carbon taxation with border adjustment, surplus and revenue

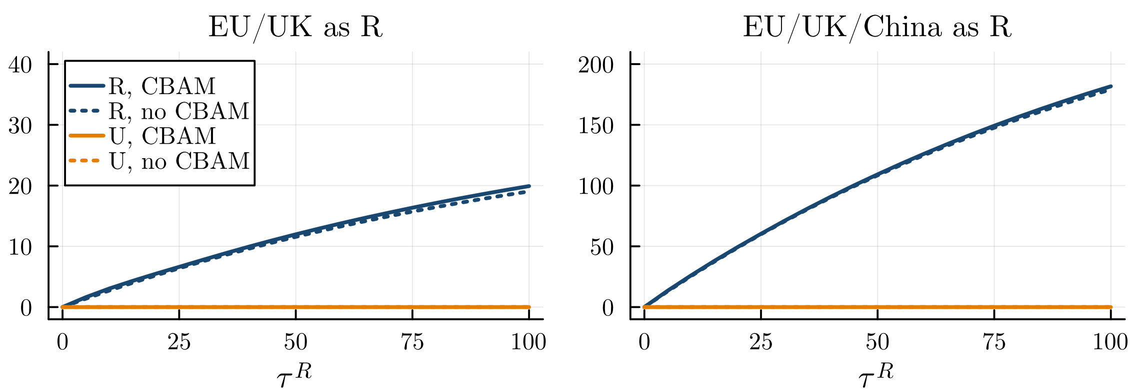
(a) Consumer surplus effects ΔCS (1B USD)



(b) Producer surplus effects ΔPS (1B USD)



(c) Government revenue effects ΔG (1B USD)



We simulate carbon regulation $\tau^R > 0$ in regulated market R, imposing $\tau^U = 0$ in unregulated market U. We compute effects relative to a zero-regulation benchmark with $\tau^R = \tau^U = 0$. We simulate regulation with and without a CBAM, and we compute effects separately for markets R and U. Surplus and revenue effects sum over aluminum and steel.

the EU and UK and \$180B when China joins. The CBAM adds to these revenues, although only marginally so because it pushes producers in U to reallocate sales away from R.

In terms of magnitudes, we highlight that the modest effects on total welfare mask substantial redistributive effects. While we compute total welfare effects of no more than \$10B in figure 5b, we compute effects that reach and exceed \$100B for both consumer surplus and producer surplus in figure 6. Government revenue reaches even larger magnitudes. Our baseline welfare calculations aggregate consumer surplus, producer surplus, and government revenue with equal weights, but policymakers can aggregate these component effects with different weights that reflect their particular circumstances.

7.4 CBAMs boost competitiveness

A major goal of EU CBAM policy is to increase domestic competitiveness. We evaluate the competitiveness concern by computing the domestic producer surplus losses from carbon regulation, and we quantify the extent to which a CBAM reduces these losses. Figure 6b presents both calculations. First, carbon taxation hurts producers in R and helps producers in U. The blue lines lie below zero, and the orange lines lie above zero. The reason is that regulation raises production costs in R, making producers in R less competitive and those in U more competitive. For R, these profit losses are as high as \$15B when R includes the EU and UK and \$100B when R expands to include China. The CBAM attenuates the loss of domestic competitiveness, reducing both producer losses in R and producer gains in U. The solid lines lie between the dashed lines. For R, the CBAM reduces domestic producer surplus losses by as much as 15% when R includes the EU and UK and 10% when R expands to include China.[19] The domestic competitiveness effect is proportionally larger in the first case because R is small relative to U, and so regulated producers face particularly stiff competition abroad.

Appendix figure A6 shows how the CBAM affects foreign competitiveness in lower- and higher-income countries. As in figure 6b, foreign producers gain from regulation in R, and the CBAM tempers these gains. The solid lines lie below the

[19] For $\tau^R = 100$, producer surplus losses fall from \$17.8B to \$15.5B in the first case and from \$104B to \$94.7B in the second case.

dashed lines. These losses are larger in magnitude for foreign producers in higher-income countries because the volume of production is higher in these countries. But in proportional terms, the CBAM has nearly identical impacts on foreign producers in lower- and higher-income countries. Appendix figures A7 and A8 show broadly similar results for aluminum and steel separately.

7.5 CBAMs curb leakage

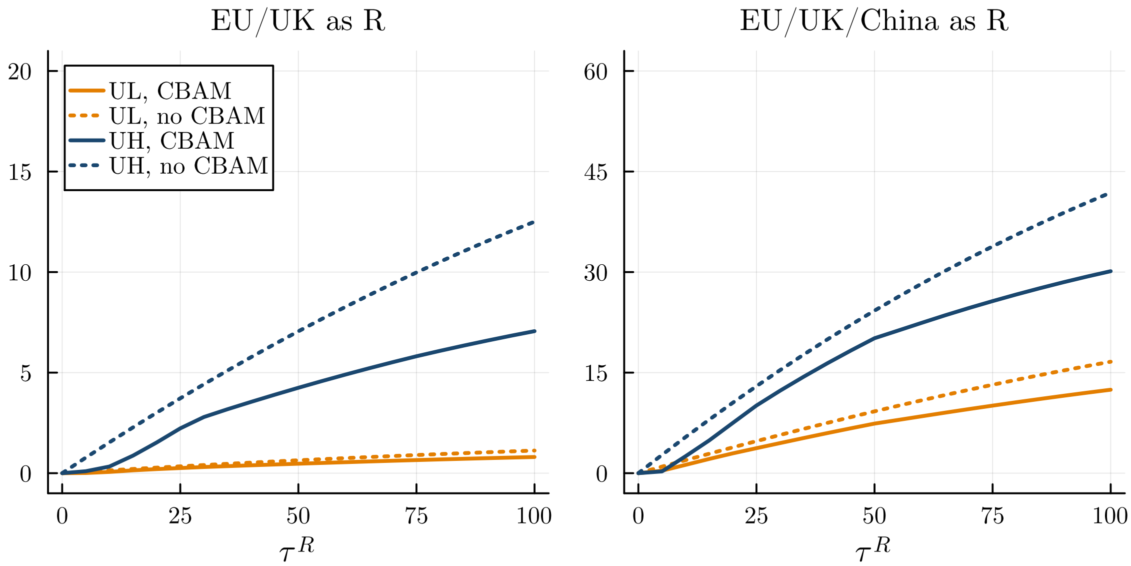
A second major goal of EU CBAM policy is to address leakage concerns, which apply to both demand and supply. On the demand side, carbon taxation without a CBAM in R encourages imports from U, where carbon is untaxed. These additional imports bypass carbon taxes in R. Indeed, Coster et al. (2024) document this import response empirically with data on firm imports in France at the product level. Carbon taxation with a CBAM addresses this concern by directly taxing imports from U. On the supply side, carbon taxation without a CBAM in R raise prices in U, encouraging increased production in U. This additional production undercuts emissions reductions in R. Carbon taxation with a CBAM addresses this concern through the reallocation effect, which limits the extent to which prices rise in U.[20] In both cases, the CBAM reduces leakage to U.

We study the incidence of these leakage reductions across lower- and higher-income countries. Figure 7 presents our findings. The top panel shows the emissions effects of carbon policy in R. This carbon policy leads to increased emissions in U, 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 R includes the EU and UK, the CBAM places greater pressure on higher-income countries than it does on lower-income countries. When R expands to include China, the incidence on lower- and

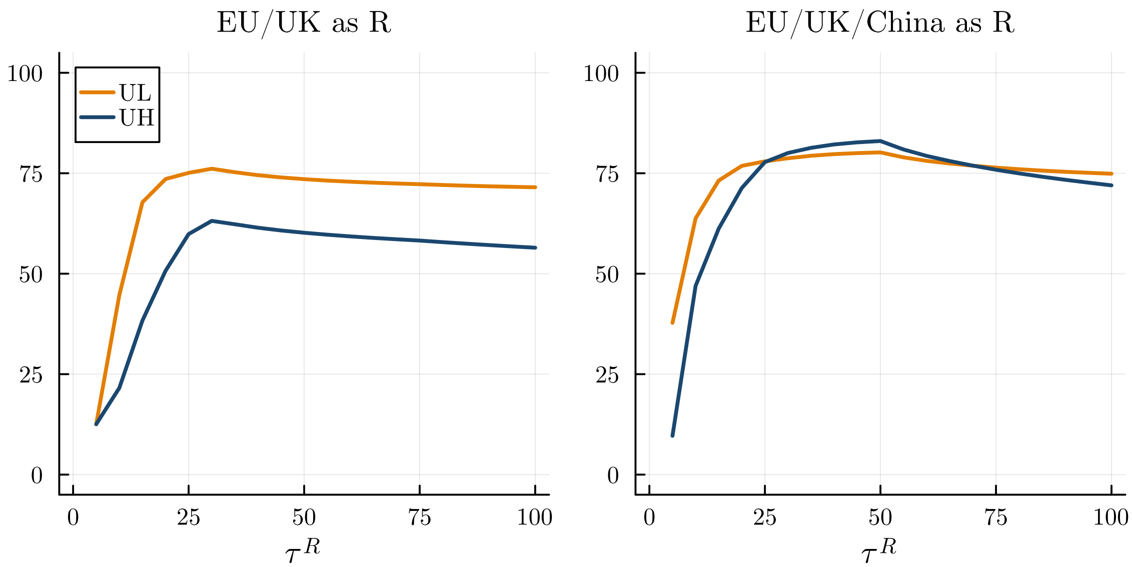
[20] Relative to carbon taxation without a CBAM, carbon taxation with a CBAM also raises prices in R. These higher prices encourage production in U for export to R. But the resulting emissions are taxed by the CBAM, and so this increased production is non-distortionary.

Figure 7: Carbon leakage

(a) Emissions effects ΔE (Mt CO_2)



(b) CBAM vs. no CBAM ratio (%)



We simulate carbon regulation $\tau^R > 0$ in regulated market R, imposing $\tau^U = 0$ in unregulated market U. We compute effects relative to a zero-regulation benchmark with $\tau^R = \tau^U = 0$. We simulate regulation with and without a CBAM, and we compute effects separately for markets UL and UH, which divide U into lower- and higher-income countries based on World Bank income groups. In the top panel, emissions effects sum over aluminum and steel. In the bottom panel, we divide emissions effects under a CBAM by emissions effects without a CBAM.

higher-income countries is more balanced, particularly for carbon taxation at levels beyond \$25 per ton CO_2. Appendix figures A9 and A10 show broadly similar results for aluminum and steel separately.

We quantify the impact of abatement technology by setting $\gamma = 0$, such that emissions intensity remains fixed under carbon taxation. In this world, producers can only reduce emissions by reducing production, rather than by reducing their emissions intensity. Appendix figure A11 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 U, regulation in R nonetheless leads to large emissions reductions in R. Appendix figure A12 plots these reductions. Across aluminum and steel, total emissions fall by nearly 1 Gt when R includes China and when it imposes carbon taxation at \$100 per ton of CO_2. By comparison, total industry emissions are 3.9 Gt in our baseline data. We note that although the CBAM reduces carbon leakage to U, relative to carbon taxation without a CBAM, it also raises emissions in R. The reason is that the CBAM raises prices and production in R. However, this additional production is subject to carbon taxation in R, and so the emissions are priced.[21]

7.6 CBAMs encourage regulation

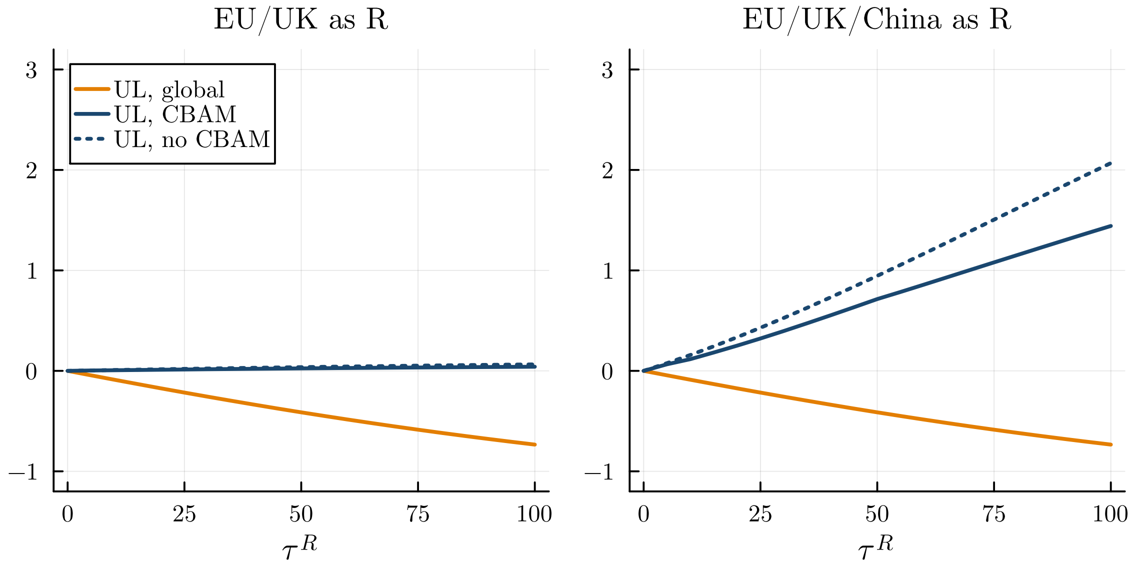
A third major goal of EU CBAM policy is to encourage carbon regulation abroad. We study these policy incentives. We simulate carbon taxation in R, both with and without border adjustment, and we evaluate the welfare implications for U, which we separate into lower-income countries (UL) and higher-income countries (UH). We then simulate global regulation, in which U joins R in taxing carbon, such that $\tau^U = \tau^R$.[22] We again evaluate welfare outcomes for UL and UH. Figure 8 presents our results. We show that joining R in taxing carbon can in some cases be welfare-enhancing for countries in U, particularly when R implements a CBAM.

[21] Another margin of emissions responses is that from trade diversion. We consider shipping emissions in Appendix C.4. 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.

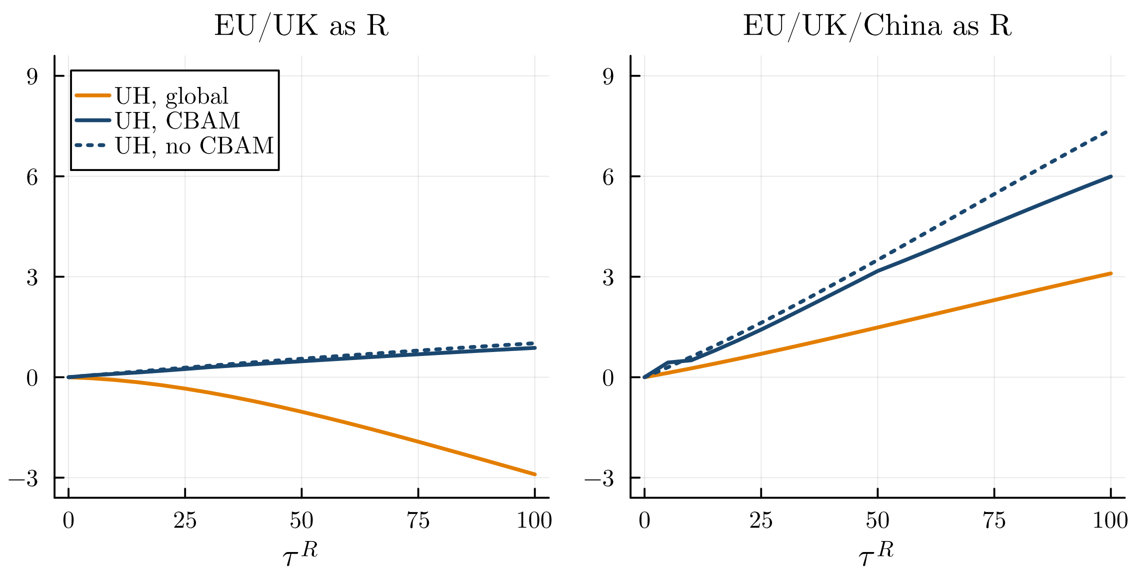
[22] Under global regulation, note that adjustment $\alpha^R = 0$. Border adjustment does not bind.

Figure 8: Policy spillovers

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



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



We simulate carbon regulation in three forms. Global regulation $\tau = \tau^R = \tau^U$ is uniform across regulated and unregulated markets R and U. CBAM regulation involves carbon regulation $\tau^R > 0$ and border adjustment in R, imposing $\tau^U = 0$ in U. No-CBAM regulation involves carbon regulation $\tau^R > 0$ in R, imposing $\tau^U = 0$ in U. We compute effects relative to a zero-regulation benchmark with $\tau^R = \tau^U = 0$. We compute effects separately for markets UL and UH, which divide U into lower- and higher-income countries based on World Bank income groups. Welfare effects sum over aluminum and steel.

Global regulation can itself be welfare-enhancing for countries in U, relative to a zero-regulation world with $\tau^R = \tau^U = 0$. When R includes the EU, UK, and China, we find that global regulation increases welfare in UH 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 UH increases by more than \$3B.[23] Appendix figures A13, A14, A15 show the component effects on consumer surplus, producer surplus, and government revenue for UL and UH.[24] We again focus on the orange lines in the lower-right subfigures. Global regulation leads to large consumer surplus losses for UH 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 R. That is, in a world with an EU and UK CBAM and carbon taxation in place, can countries in U gain from taxing carbon? We find on net that the answer is no. In each subfigure of figure 8, the orange lines lie below the solid blue lines. The reason is that carbon regulation in R leads to the welfare gains for UL and UH, where producers benefit from less foreign competition. By contrast, global regulation largely leads to welfare losses for UL and UH, where the surplus losses from domestic taxation do not outweigh the revenue gains.

At the same time, we note four important findings. First, a CBAM in R closes the gap for global regulation. Free-riding disincentivizes regulation in UL and UH because each enjoys private welfare gains following carbon regulation in R. In figure 8, the blue lines lie above zero and grow with τ^R, widening their distance to the orange lines. However, the CBAM reduces these welfare gains and thus reduces free-riding incentives.[25] Without a CBAM, the orange lines lie far below the dashed blue lines. With a CBAM, the distance narrows – especially when R includes China. The orange

[23] In figure 8a, the orange lines coincide because the left and right subfigures differ only in whether market R includes China. UL includes the same set of countries in both cases. And under global regulation, the definition of R does not affect regulation because global regulation is uniform across countries. In figure 8b, the orange lines do not coincide even though global regulation applies equally to the left and right subfigures. The reason is that UH includes China on the left but not on the right.

[24] Appendix tables B11, B12, B13 present similar information for all markets in tabular form.

[25] Separately, if unregulated markets also value emissions reductions, then U can also free-ride on those achieved by regulation in R.

lines lie closer to the solid blue lines. A CBAM encourages regulation in U in relative terms.

Second, a CBAM in R creates revenue incentives for global regulation. Appendix figure A15 shows that global regulation generates large government revenue in UL and UH. These revenues do not depend on whether R imposes a CBAM because, absent global regulation, UL and UH do not regulate and so regulatory revenues are zero regardless. But appendix figure A14 shows that a CBAM reduces the relative costs of global regulation for producers. The reason is that the CBAM adjustment falls as UL and UH regulate, such that producers that export to R face no change in regulatory pressure. That is, under a CBAM in R, governments in UL and UH can collect revenue without distorting productive outcomes. While the production channel dominates, appendix figure A13 shows a countervailing effect through consumption. A CBAM helps consumers in UL and UH by inducing reallocation that drives down prices. In regulating, UL and UH must sacrifice these consumer surplus gains.

Third, countries in U also benefit from reduced emissions. We compute welfare losses focusing exclusively on consumer surplus, producer surplus, and government revenue. But appendix figure A16 shows that emissions reductions are also meaningful. We again highlight the lower-right subfigures. UH loses roughly \$3B under global regulation at \$100 per ton of CO_2, relative to a CBAM in R with no regulation in U. But emissions in UH also fall by more than 300 Mt.[26] For governments in UH, a local cost of carbon of \$10 per ton would imply that emissions 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 A17.[27] The top panel describes lower-income countries in UL. When R includes the EU and UK alone, global regulation strongly dominates non-regulation in UL. The orange line lies far above the blue lines, and UL gains up to \$1B in welfare by joining R in taxing carbon. When R expands to include China, global regulation continues to dominate up to \$25 per ton of carbon taxation. At higher levels, regulatory incentives for UL hinge on the CBAM in R. The orange line lies above the solid

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

[27] Appendix figure A18 shows welfare impacts for steel. Results differ for aluminum and steel because aluminum producers in lower-income countries differ from their steel counterparts in where they lie within the global distributions of production costs and emissions intensities.

blue line, but below the dashed blue line. That is, without a CBAM in place, UL gains more by not regulating. The bottom panel describes higher-income countries in UH. Regulatory incentives for UL hinge on the coalition in R. 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 UH when R 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 of CBAM policies. We show that CBAMs increase domestic competitiveness, which may facilitate establishing carbon regulation in the first place. We also show that CBAMs reduce emissions leakage and encourage carbon regulation, each without placing disproportionate pressure on lower-income countries. The reason is that production in lower-income countries is not systematically more carbon-intensive than it is in higher-income countries.

Future work could extend our analysis in several directions. First, while we have examined the two most emissions-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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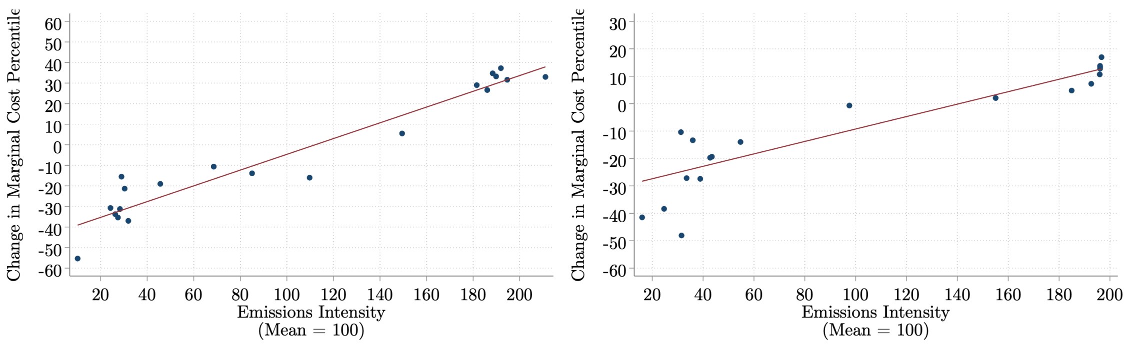
Online Appendices

Contents

A Figures

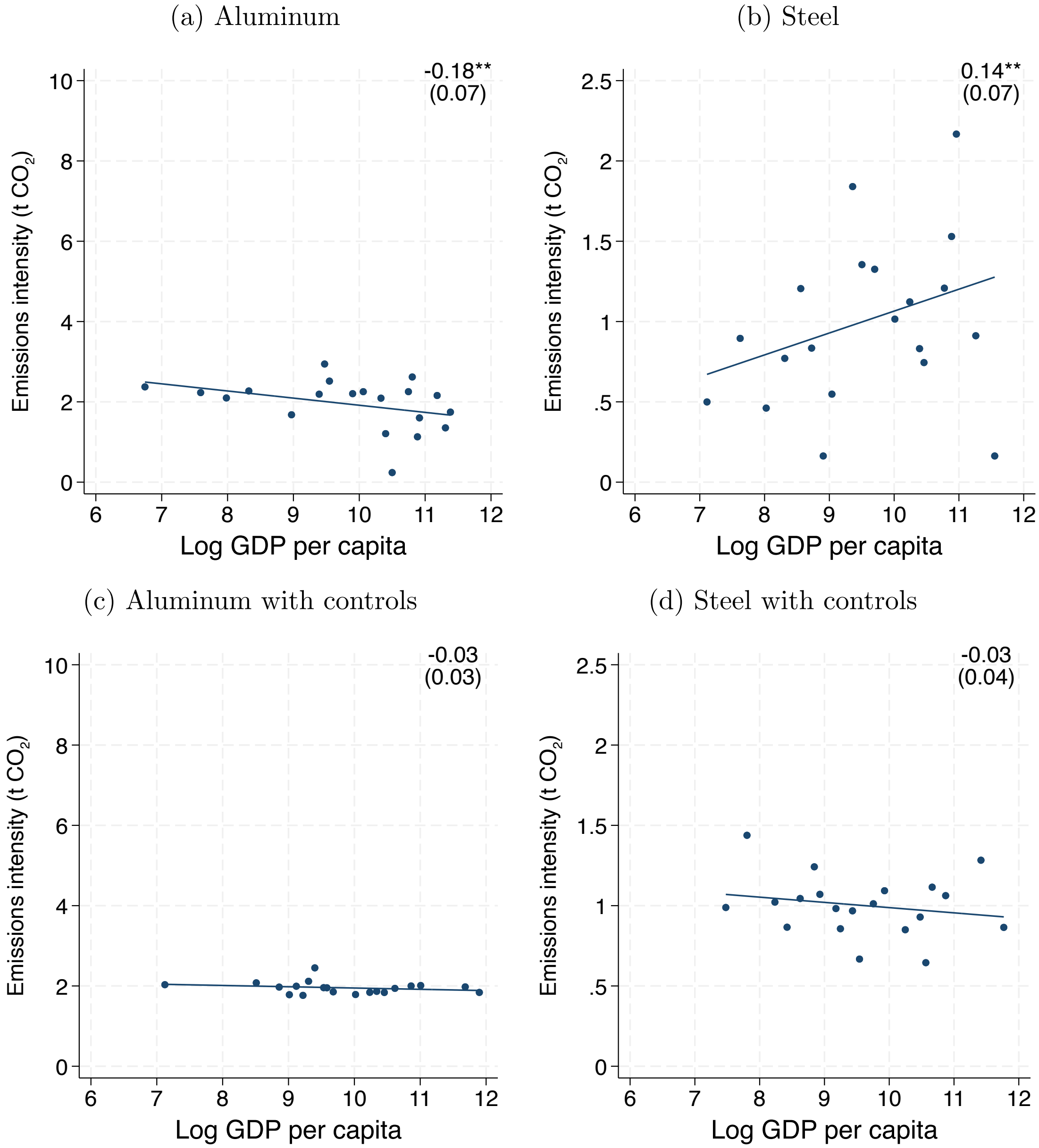
Figure A1: Changes in marginal cost percentiles under a CBAM

(a) Aluminum (b) Steel



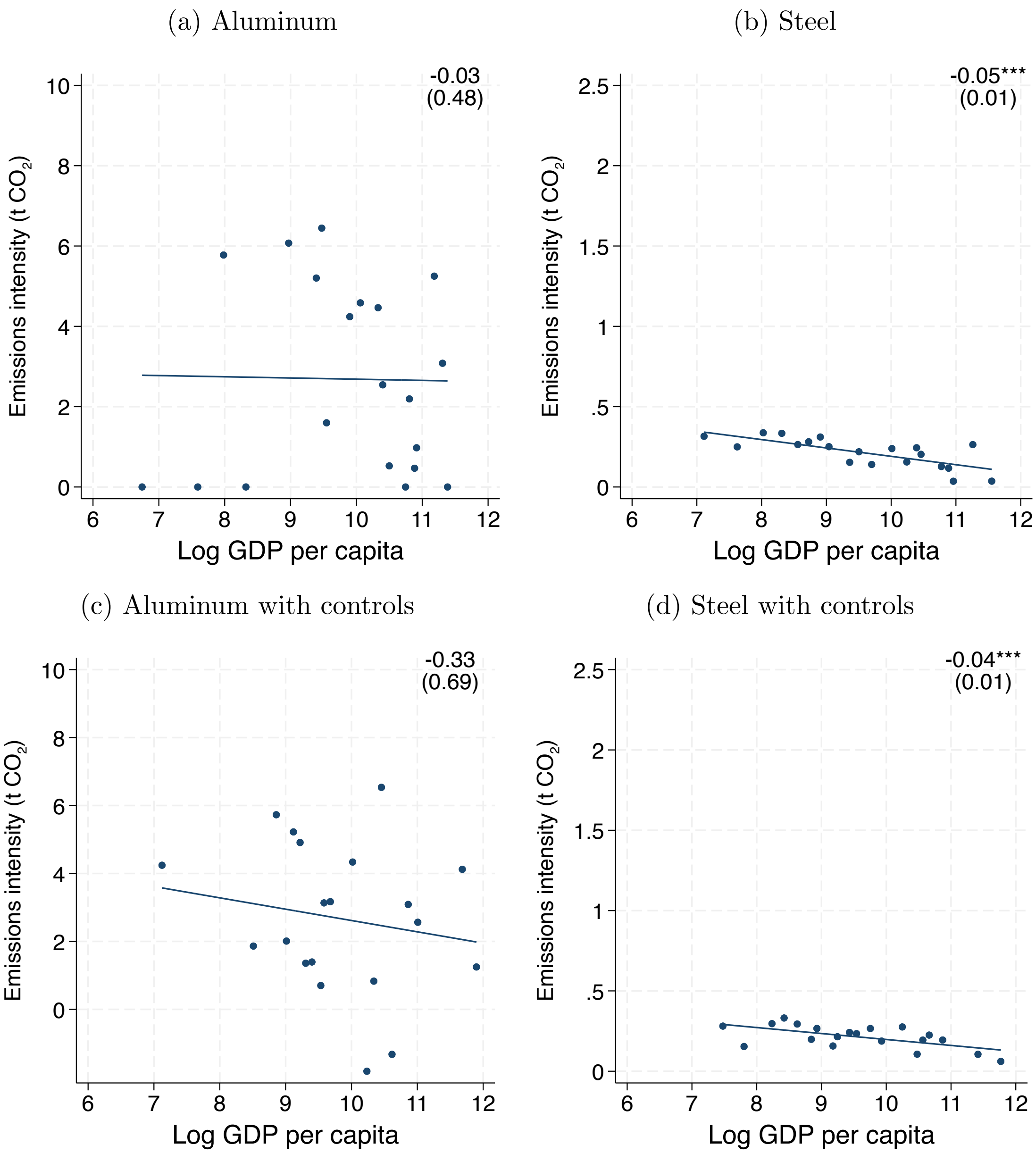
Each point is an equal-size bin of plants based on emissions intensity. The y-axis is the bin-level average change in the marginal cost percentile, determined from the cumulative capacity ranking of plant marginal costs before and after the introduction of a CBAM. We simulate a CBAM with a carbon tax of \$96 per ton of CO_2. Plants with lower marginal costs are in lower cost percentiles. The x-axis is the bin-level average emissions intensity of production, normalized such that the mean emissions intensity is 100.

Figure A2: Scope 1 emissions intensity by GDP per capita



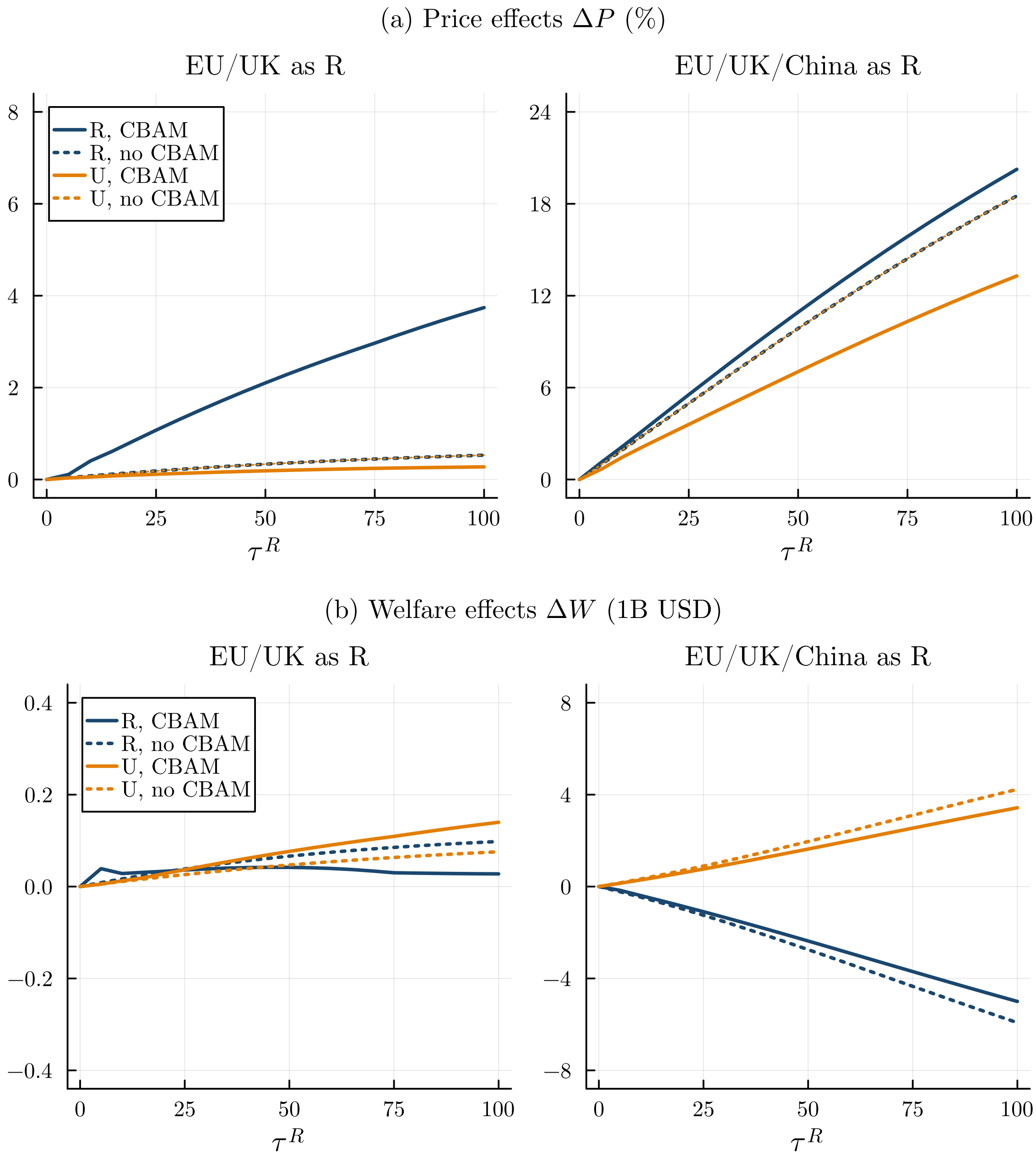
Each figure is a binned scatter plot. Each observation is a country. Emissions intensity is tons of CO_2 emitted per ton of production. Scope 1 emissions are direct production emissions. Controls include primary production (%), average production (Mt), state ownership (%), and foreign ownership (%). Primary production refers to primary aluminum and BOF steel. State ownership is whether the majority-stakeholder parent company is a state-owned enterprise. Foreign is whether the majority-stakeholder parent company is headquartered in a different country from a given plant. We compute the production-weighted average across plants within each country. Average production is the average across plants within a country. We report the slope and standard error of the fitted line in the top-right corner of each figure.

Figure A3: Scope 2 emissions intensity by GDP per capita



Each figure is a binned scatter plot. Each observation is a country. Emissions intensity is tons of CO_2 emitted per ton of production. Scope 2 emissions are those from the electricity used in production. Controls include primary production (%), average production (Mt), state ownership (%), and foreign ownership (%). Primary production refers to primary aluminum and BOF steel. State ownership is whether the majority-stakeholder parent company is a state-owned enterprise. Foreign is whether the majority-stakeholder parent company is headquartered in a different country from a given plant. We compute the production-weighted average across plants within each country. Average production is the average across plants within a country. We report the slope and standard error of the fitted line in the top-right corner of each figure.

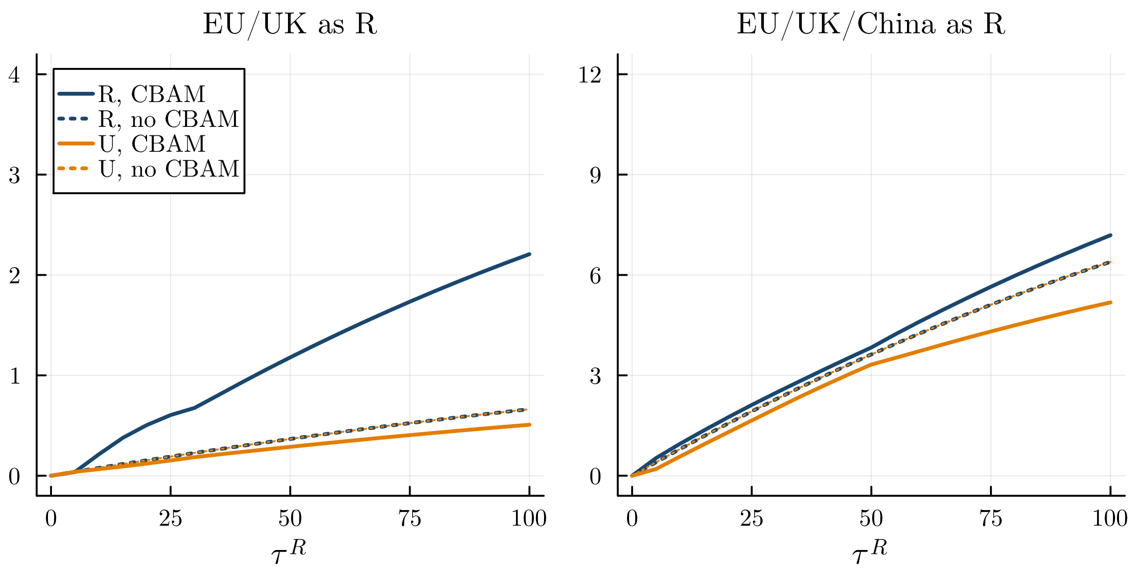
Figure A4: Carbon taxation with border adjustment, aluminum only



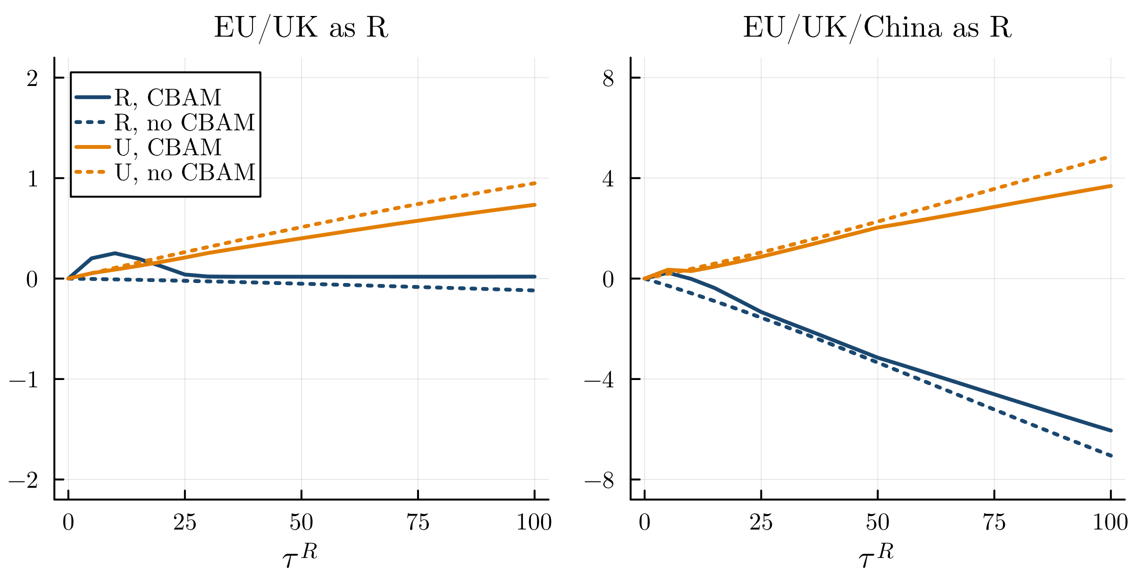
For aluminum, we simulate carbon regulation $\tau^R > 0$ in regulated market R, imposing $\tau^U = 0$ in unregulated market U. We compute effects relative to a zero-regulation benchmark with $\tau^R = \tau^U = 0$. We simulate regulation with and without a CBAM, and we compute effects separately for markets R and U.

Figure A5: Carbon taxation with border adjustment, steel only

(a) Price effects ΔP (%)



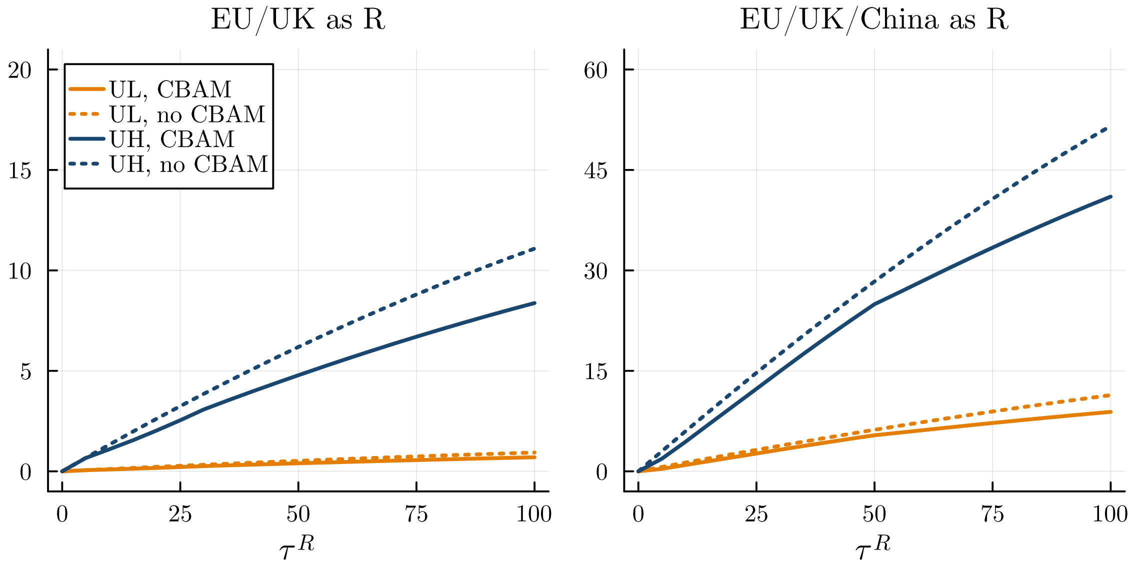
(b) Welfare effects ΔW (1B USD)



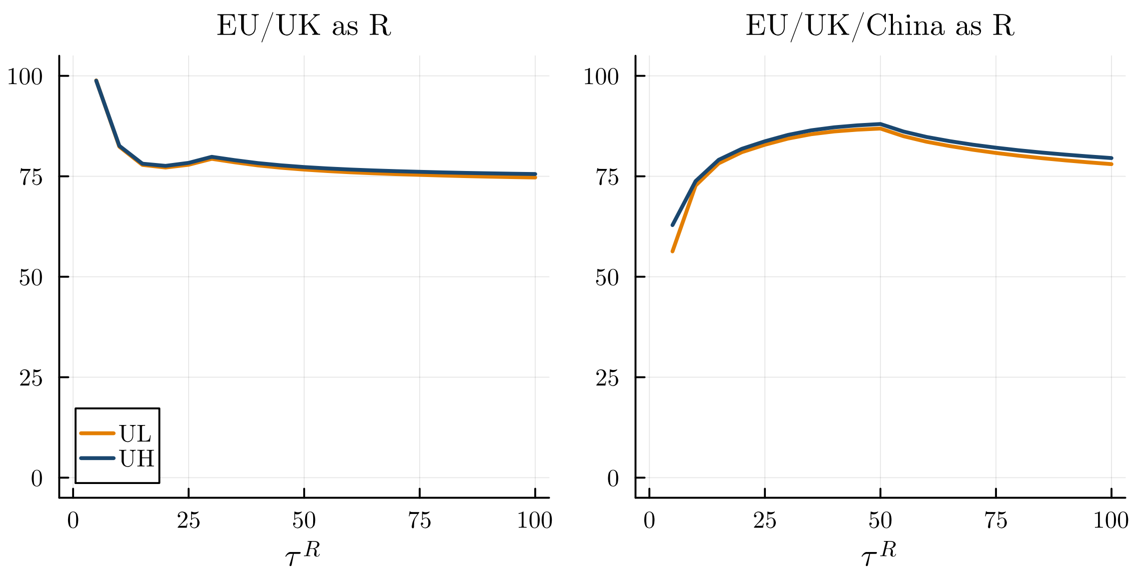
For steel, we simulate carbon regulation $\tau^R > 0$ in regulated market R, imposing $\tau^U = 0$ in unregulated market U. We compute effects relative to a zero-regulation benchmark with $\tau^R = \tau^U = 0$. We simulate regulation with and without a CBAM, and we compute effects separately for markets R and U.

Figure A6: Foreign competitiveness

(a) Producer surplus effects ΔPS (1B USD)



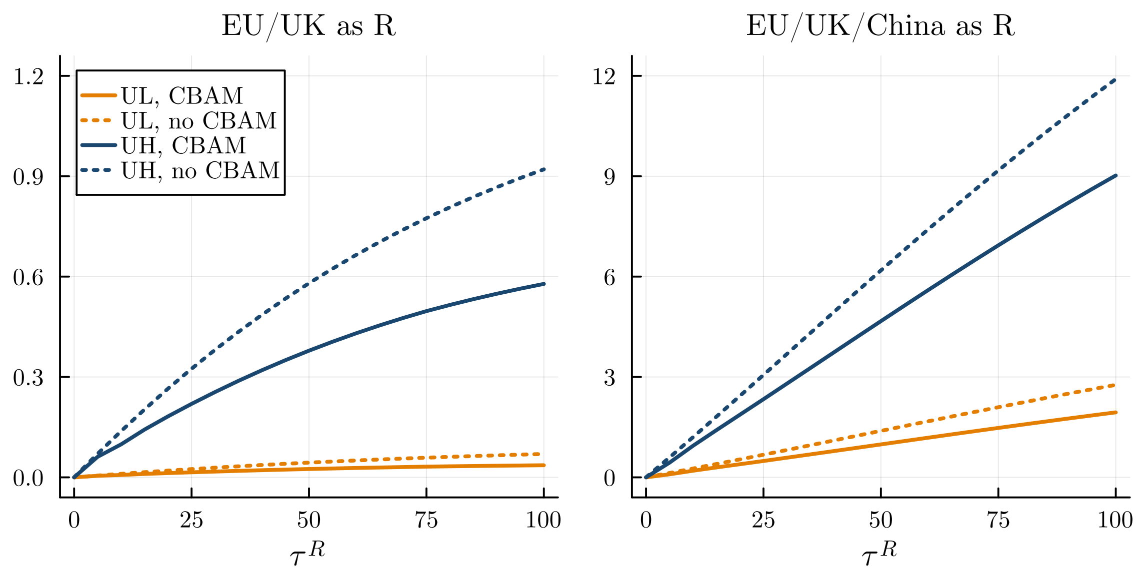
(b) CBAM vs. no CBAM ratio (%)



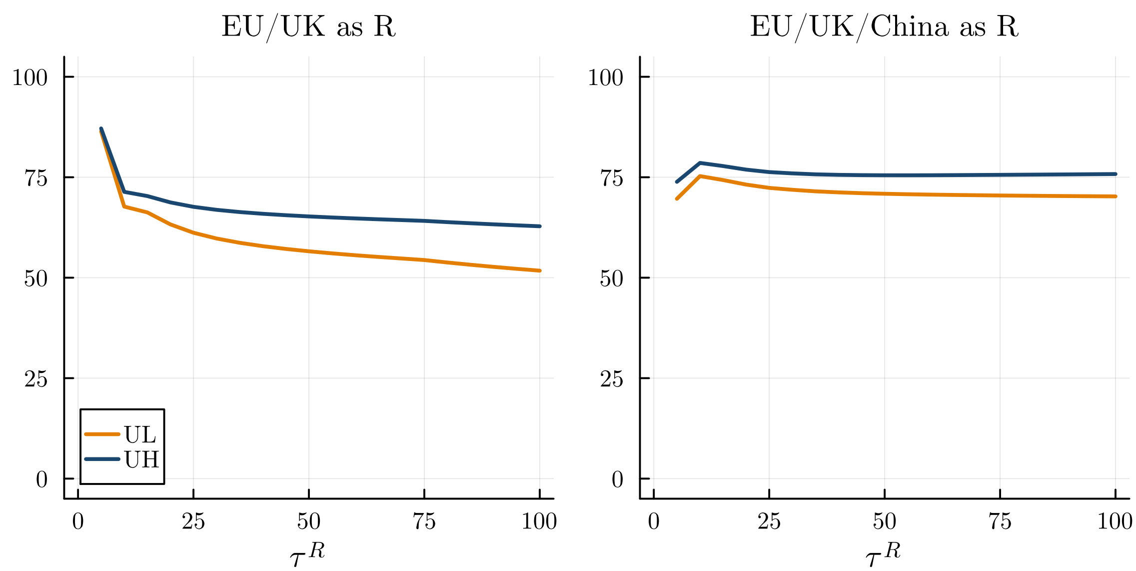
We simulate carbon regulation $\tau^R > 0$ in regulated market R, imposing $\tau^U = 0$ in unregulated market U. We compute effects relative to a zero-regulation benchmark with $\tau^R = \tau^U = 0$. We simulate regulation with and without a CBAM, and we compute effects separately for markets UL and UH, which divide U into lower- and higher-income countries based on World Bank income groups. In the top panel, producer surplus effects sum over aluminum and steel. In the bottom panel, we divide producer surplus effects under a CBAM by producer surplus effects without a CBAM.

Figure A7: Foreign competitiveness, aluminum only

(a) Producer surplus effects ΔPS (1B USD)



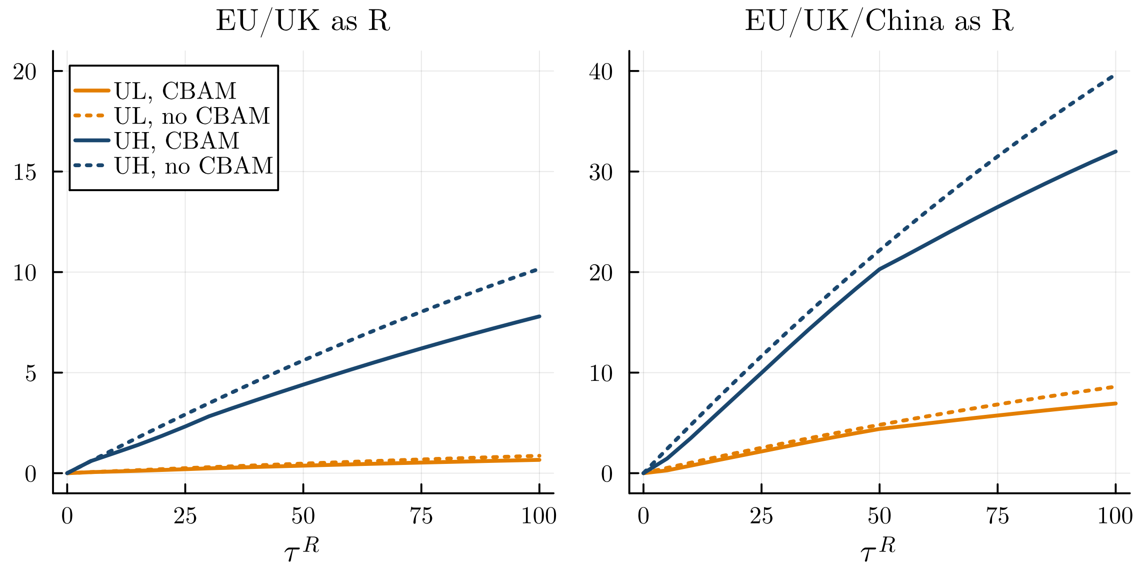
(b) CBAM vs. no CBAM ratio (%)



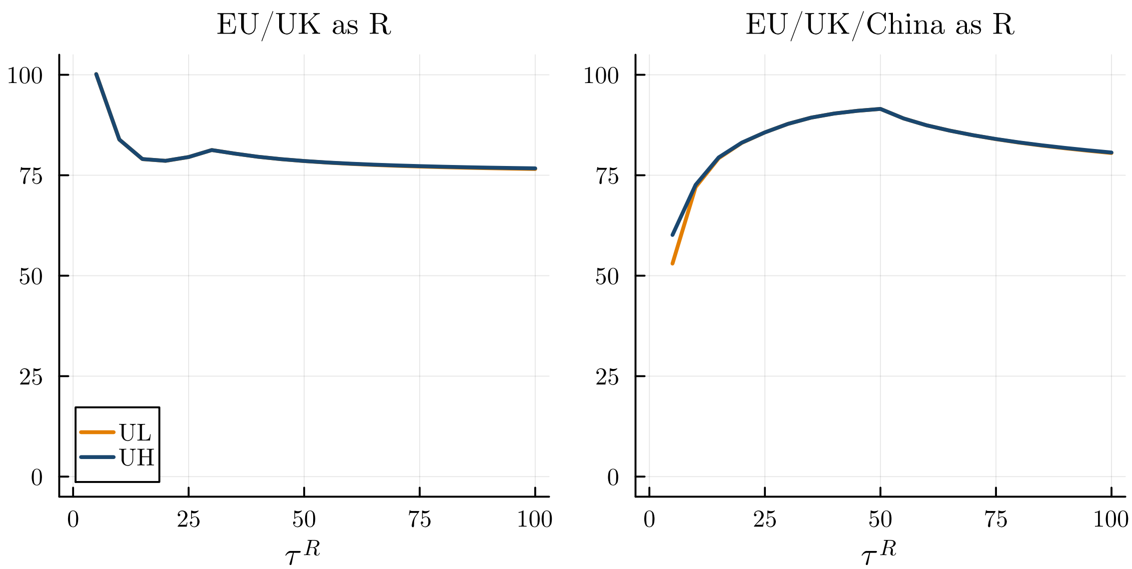
For aluminum, we simulate carbon regulation $\tau^R > 0$ in regulated market R, imposing $\tau^U = 0$ in unregulated market U. We compute effects relative to a zero-regulation benchmark with $\tau^R = \tau^U = 0$. We simulate regulation with and without a CBAM, and we compute effects separately for markets UL and UH, which divide U into lower- and higher-income countries based on World Bank income groups. In the bottom panel, we divide producer surplus effects under a CBAM by producer surplus effects without a CBAM.

Figure A8: Foreign competitiveness, steel only

(a) Producer surplus effects ΔPS (1B USD)



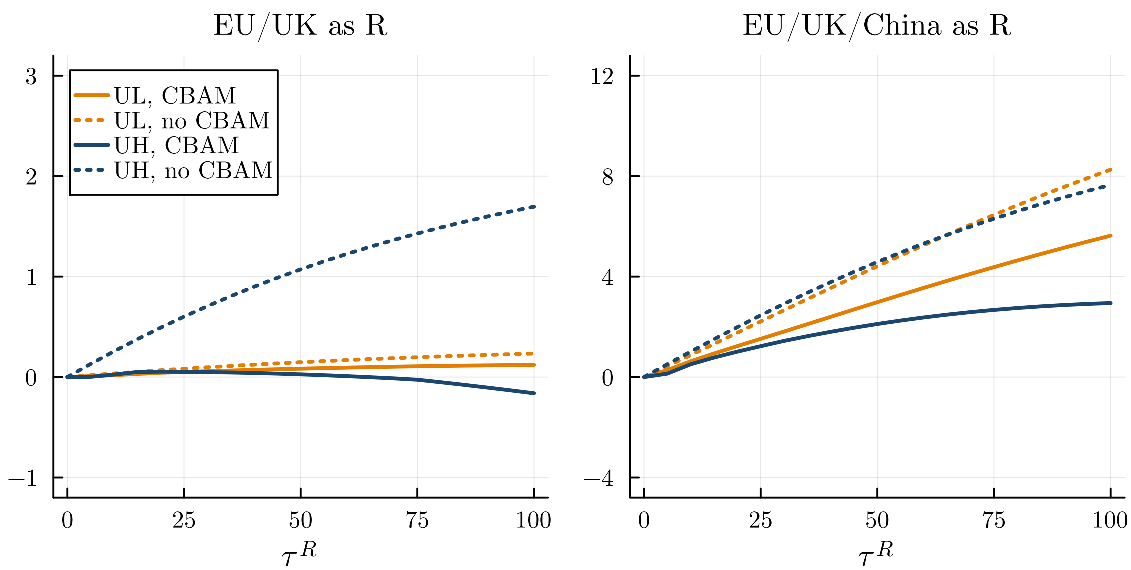
(b) CBAM vs. no CBAM ratio (%)



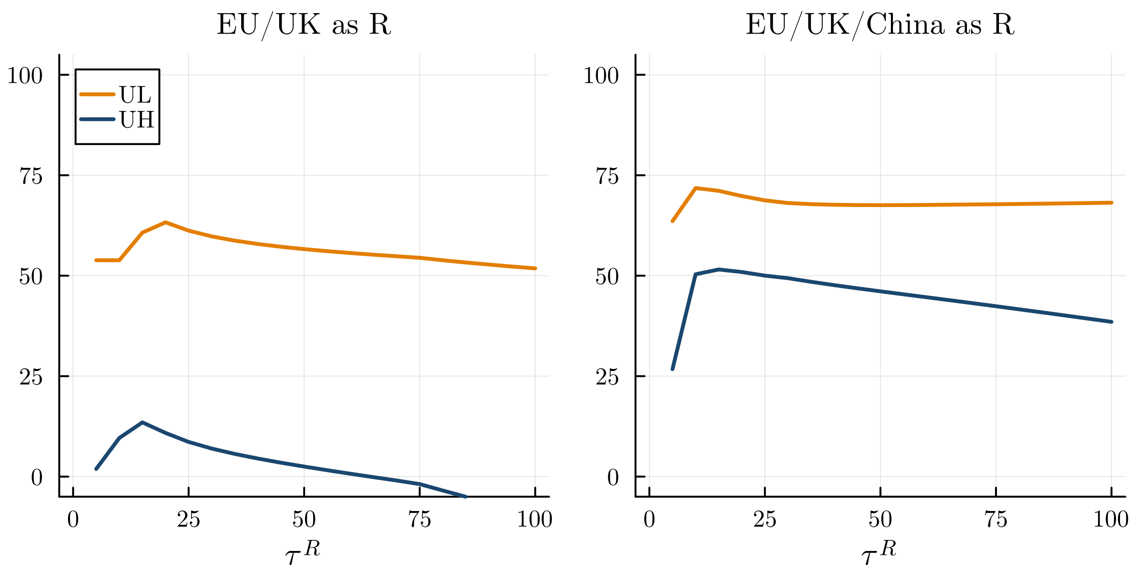
For steel, we simulate carbon regulation $\tau^R > 0$ in regulated market R, imposing $\tau^U = 0$ in unregulated market U. We compute effects relative to a zero-regulation benchmark with $\tau^R = \tau^U = 0$. We simulate regulation with and without a CBAM, and we compute effects separately for markets UL and UH, which divide U into lower- and higher-income countries based on World Bank income groups. In the bottom panel, we divide producer surplus effects under a CBAM by producer surplus effects without a CBAM.

Figure A9: Carbon leakage, aluminum only

(a) Emissions effects ΔE (Mt CO_2)



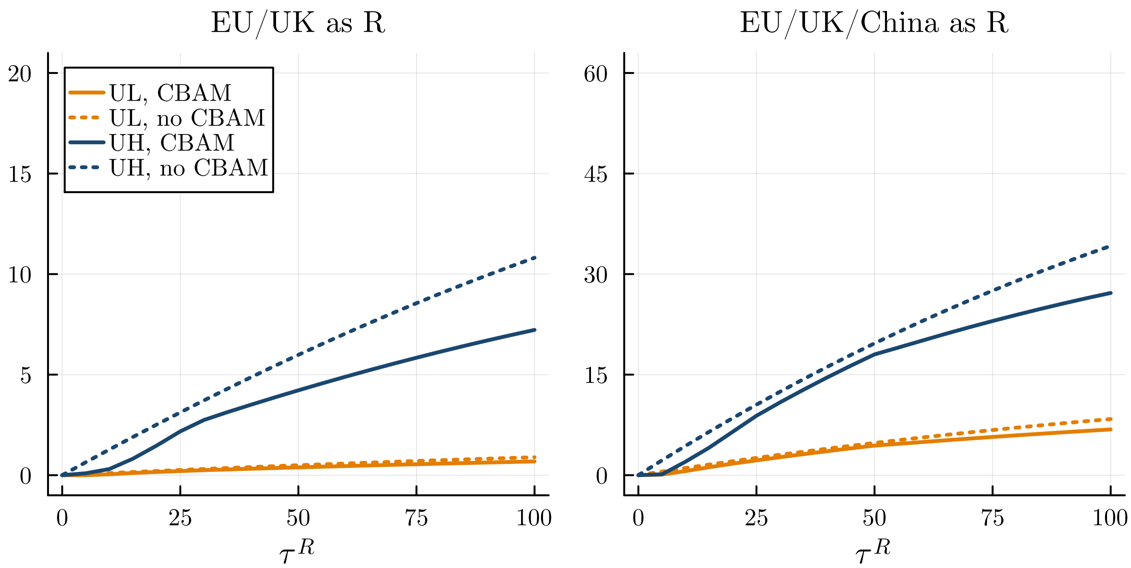
(b) CBAM vs. no CBAM ratio (%)



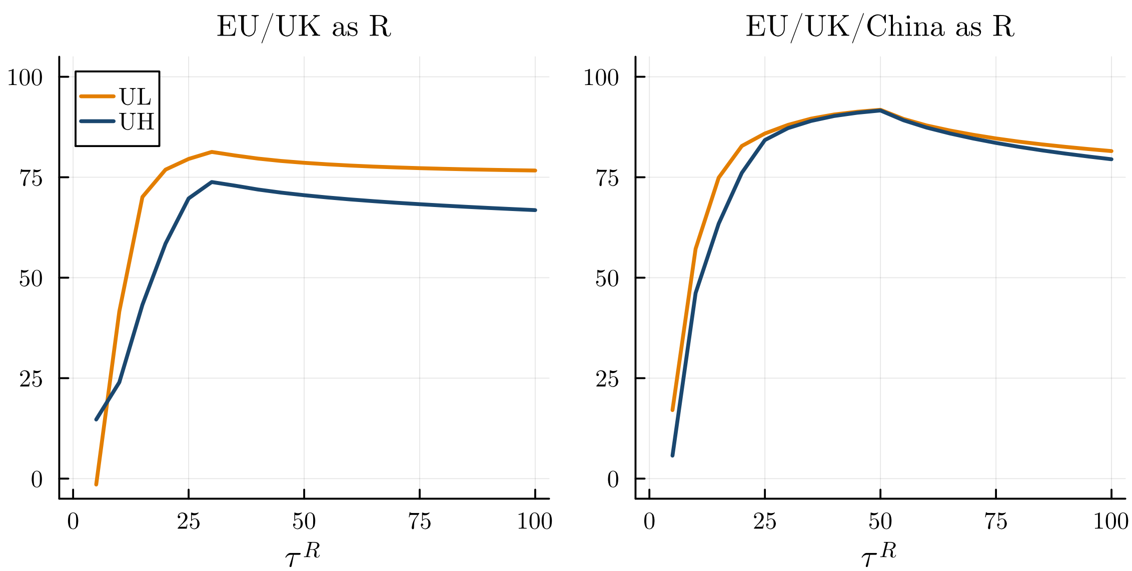
For aluminum, we simulate carbon regulation $\tau^R > 0$ in regulated market R, imposing $\tau^U = 0$ in unregulated market U. We compute effects relative to a zero-regulation benchmark with $\tau^R = \tau^U = 0$. We simulate regulation with and without a CBAM, and we compute effects separately for markets UL and UH, which divide U into lower- and higher-income countries based on World Bank income groups. In the bottom panel, we divide emissions effects under a CBAM by emissions effects without a CBAM.

Figure A10: Carbon leakage, steel only

(a) Emissions effects ΔE (Mt CO_2)



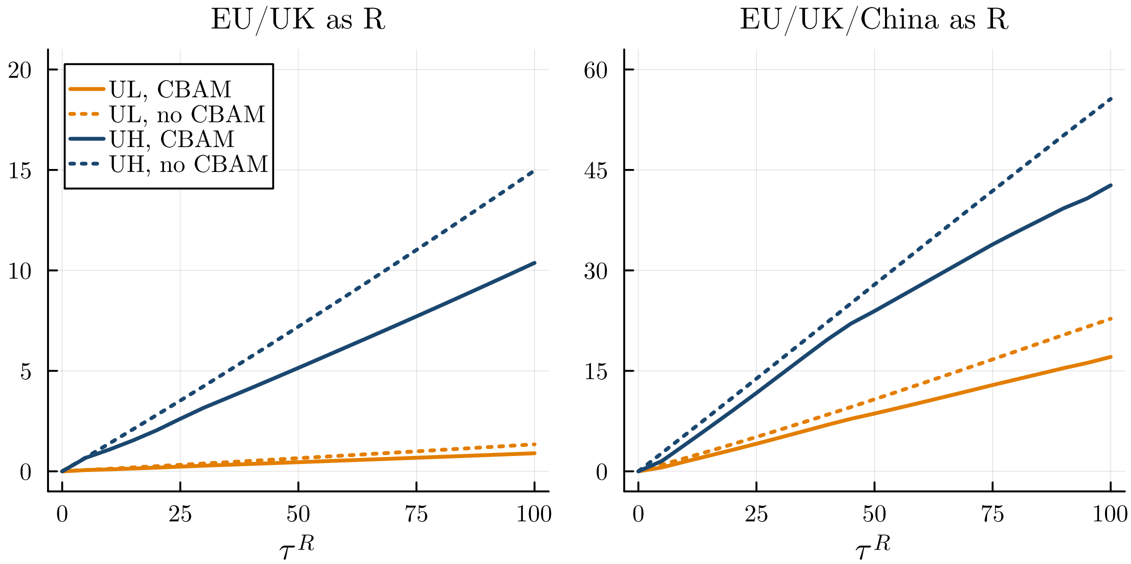
(b) CBAM vs. no CBAM ratio (%)



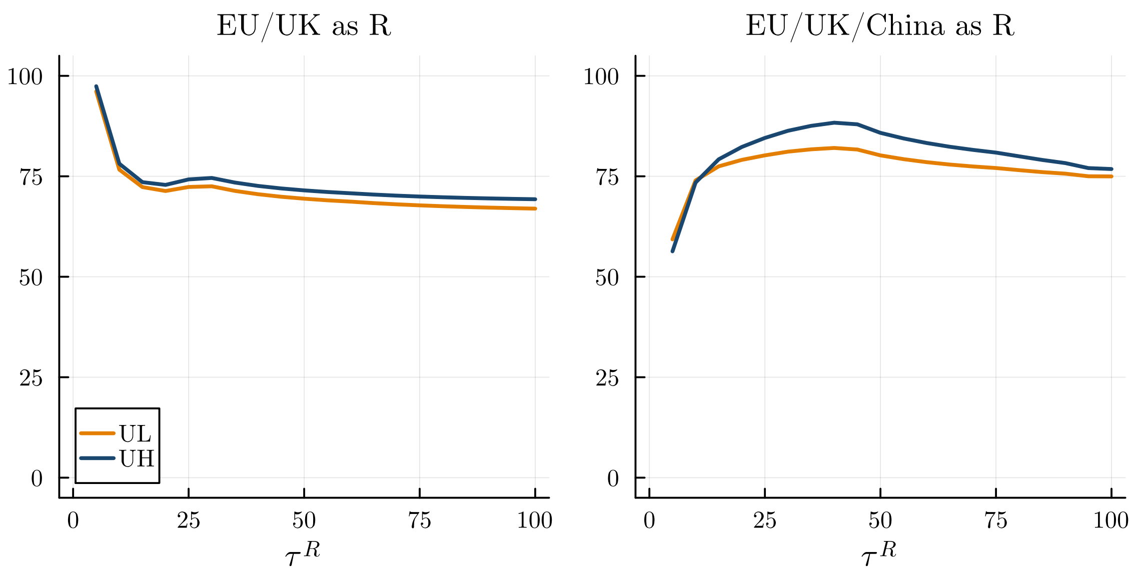
For steel, we simulate carbon regulation $\tau^R > 0$ in regulated market R, imposing $\tau^U = 0$ in unregulated market U. We compute effects relative to a zero-regulation benchmark with $\tau^R = \tau^U = 0$. We simulate regulation with and without a CBAM, and we compute effects separately for markets UL and UH, which divide U into lower- and higher-income countries based on World Bank income groups. In the bottom panel, we divide emissions effects under a CBAM by emissions effects without a CBAM.

Figure A11: Abatement technology

(a) Emissions effects ΔE (Mt CO_2) without abatement ($\gamma = 0$)



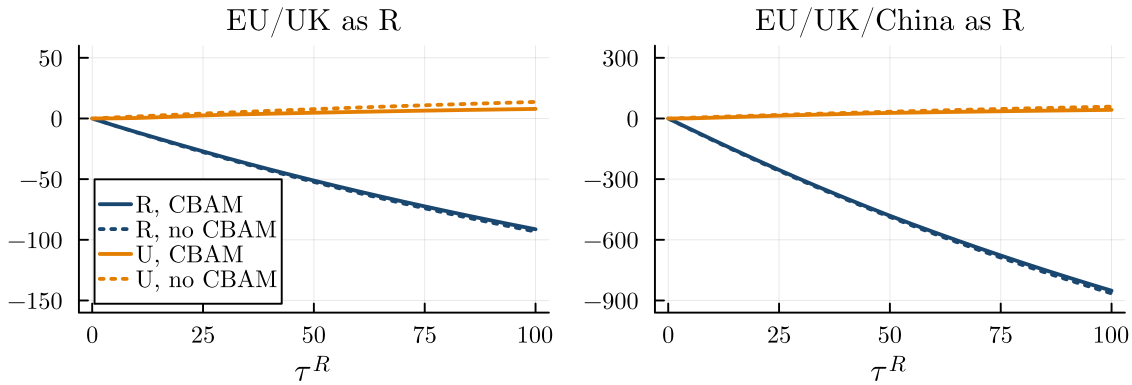
(b) CBAM vs. no CBAM ratio (%) without abatement ($\gamma = 0$)



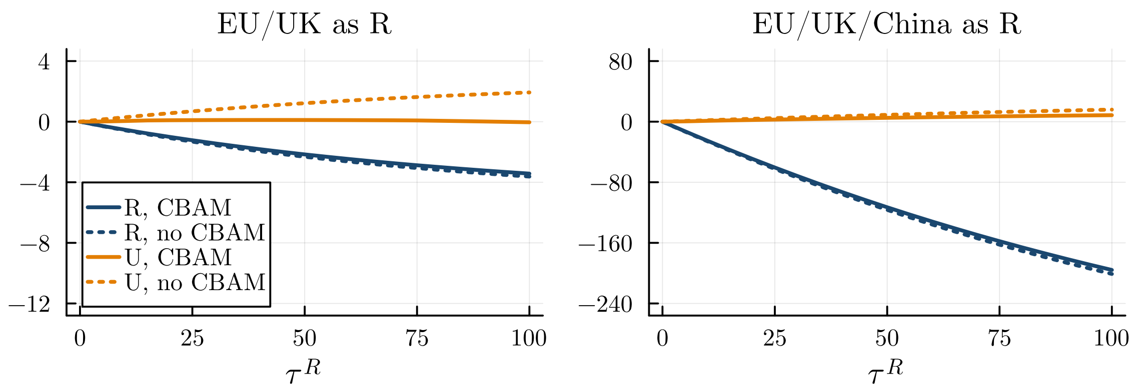
We eliminate the ability of firms to curb emissions in response to carbon taxation, imposing $\gamma = 0$ in place of baseline $\gamma = 0.3$. We simulate carbon regulation $\tau^R > 0$ in regulated market R, imposing $\tau^U = 0$ in unregulated market U. We compute effects relative to a zero-regulation benchmark with $\tau^R = \tau^U = 0$. We simulate regulation with and without a CBAM, and we compute effects separately for markets UL and UH, which divide U into lower- and higher-income countries based on World Bank income groups. In the top panel, emissions effects sum over aluminum and steel. In the bottom panel, we divide emissions effects under a CBAM by emissions effects without a CBAM.

Figure A12: Carbon taxation with border adjustment, emissions

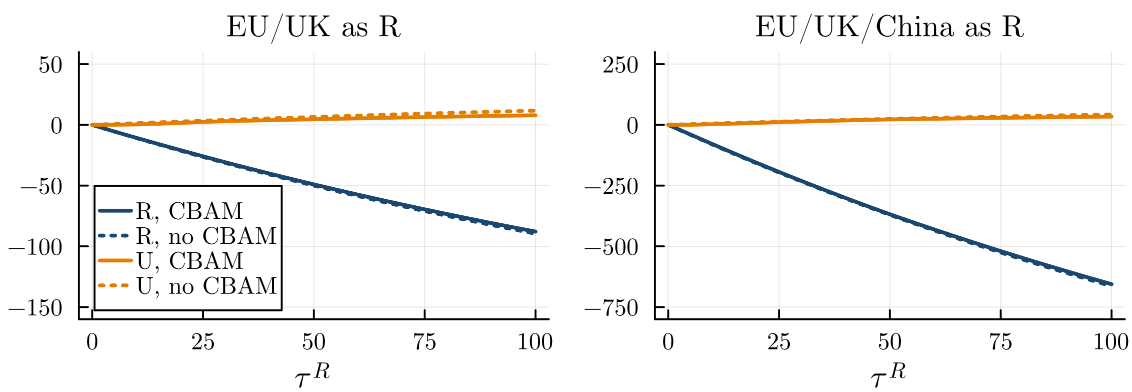
(a) Total emissions effects ΔE (Mt CO_2)



(b) Aluminum emissions effects ΔE (Mt CO_2)



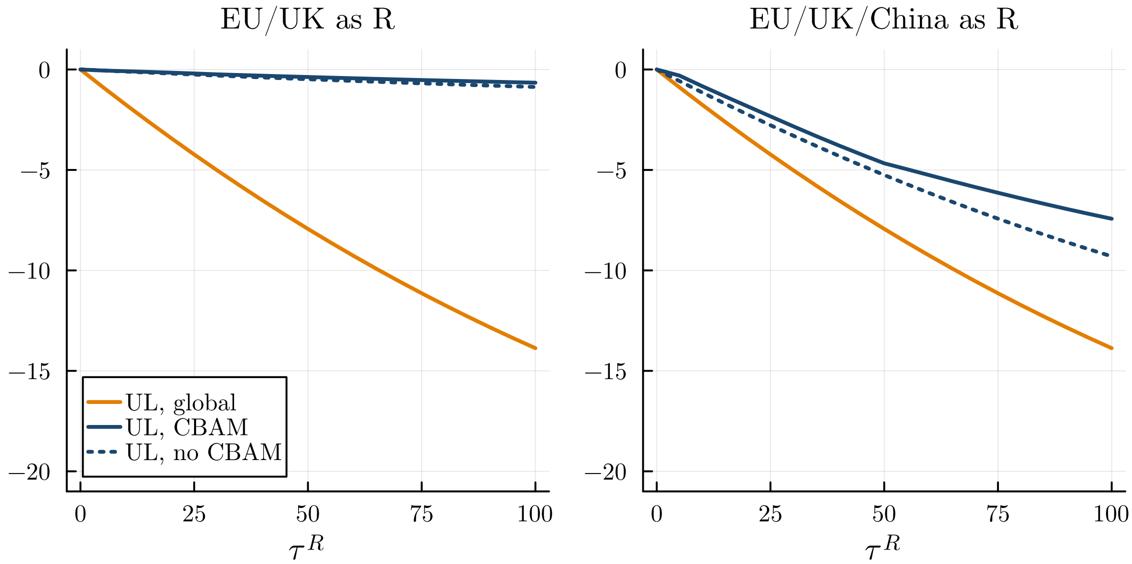
(c) Steel emissions effects ΔE (Mt CO_2)



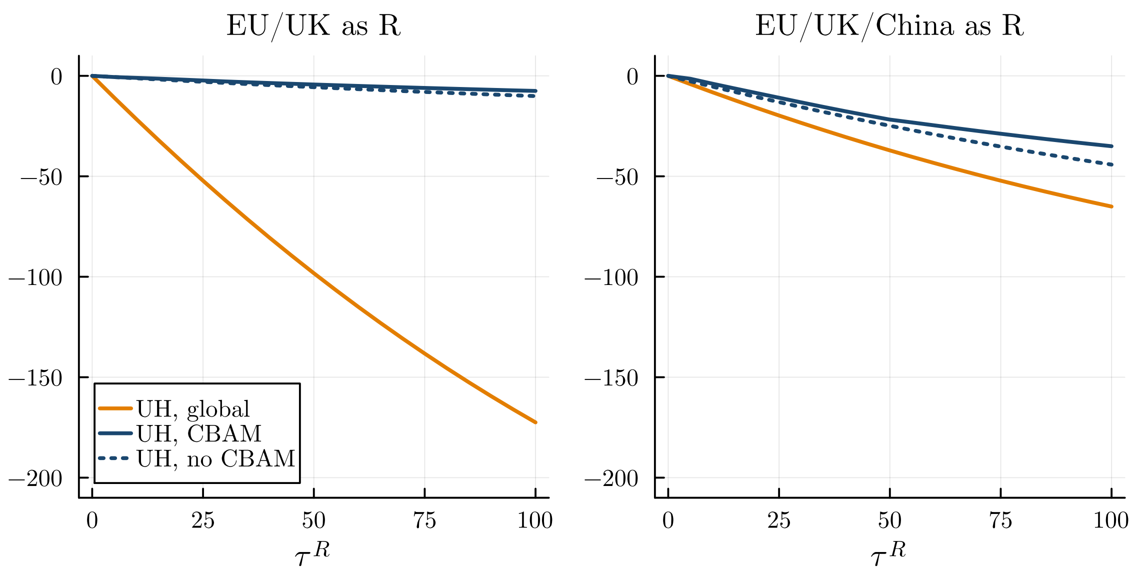
We simulate carbon regulation $\tau^R > 0$ in regulated market R, imposing $\tau^U = 0$ in unregulated market U. We compute effects relative to a zero-regulation benchmark with $\tau^R = \tau^U = 0$. We simulate regulation with and without a CBAM, and we compute effects separately for markets R and U. Total emissions effects sum over aluminum and steel.

Figure A13: Policy spillovers, consumer surplus

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



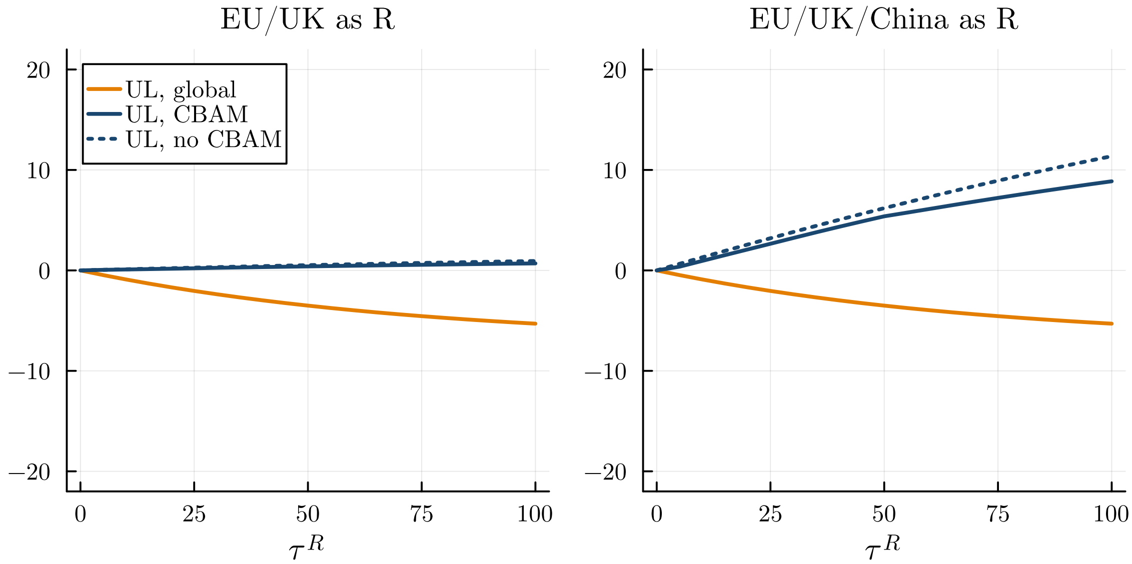
(b) Consumer surplus effects ΔCS for market UH (1B USD)



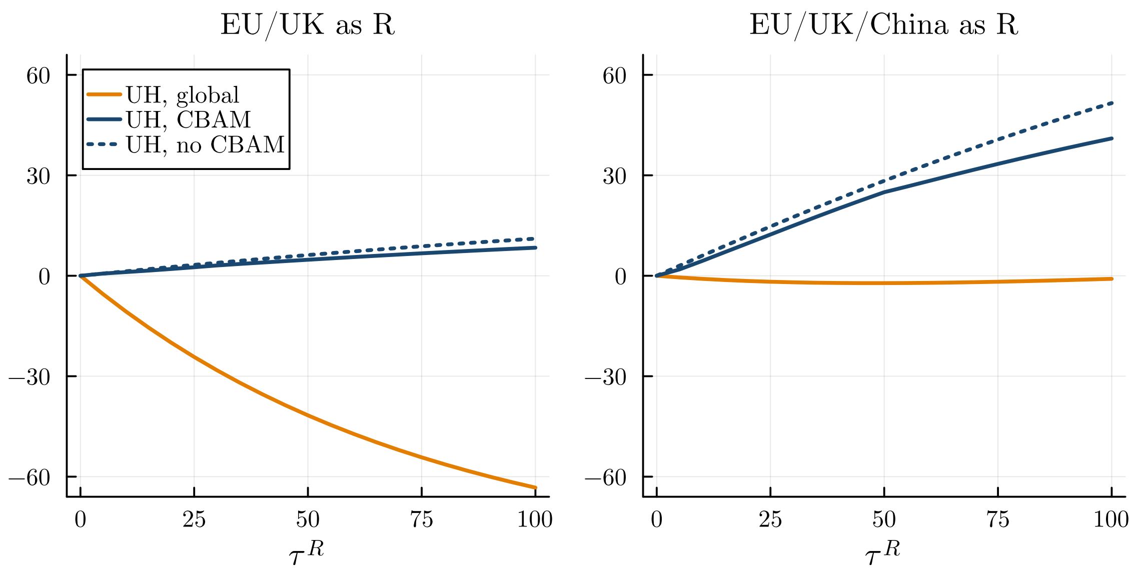
We simulate carbon regulation in three forms. Global regulation $\tau = \tau^R = \tau^U$ is uniform across regulated and unregulated markets R and U. CBAM regulation involves carbon regulation $\tau^R > 0$ and border adjustment in R, imposing $\tau^U = 0$ in U. No-CBAM regulation involves carbon regulation $\tau^R > 0$ in R, imposing $\tau^U = 0$ in U. We compute effects relative to a zero-regulation benchmark with $\tau^R = \tau^U = 0$. We compute effects separately for markets UL and UH, which divide U into lower- and higher-income countries based on World Bank income groups. Consumer surplus effects sum over aluminum and steel.

Figure A14: Policy spillovers, producer surplus

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



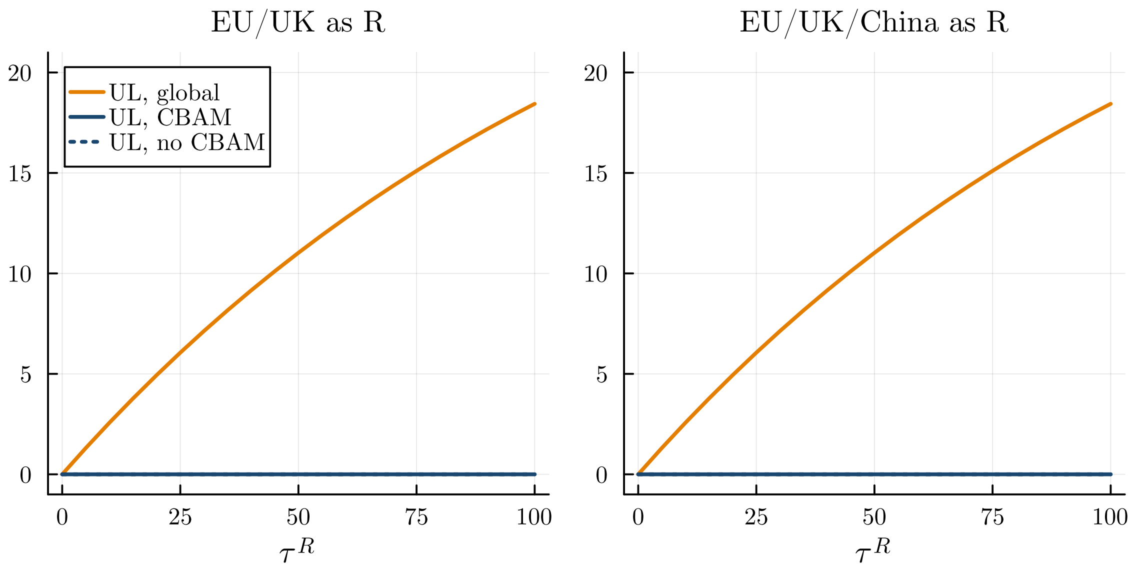
(b) Producer surplus effects ΔPS for market UH (1B USD)



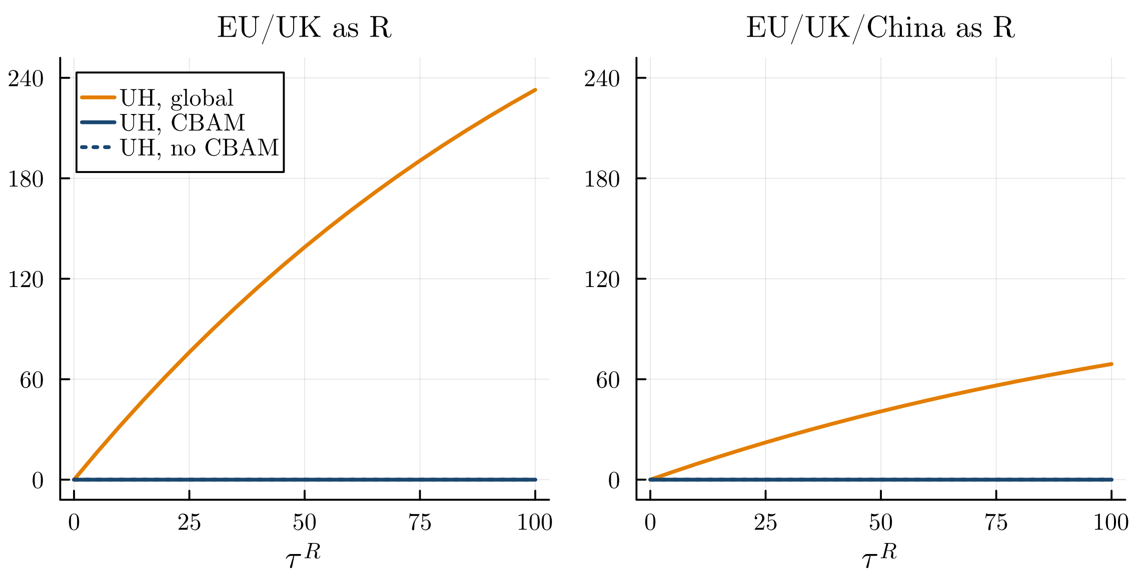
We simulate carbon regulation in three forms. Global regulation $\tau = \tau^R = \tau^U$ is uniform across regulated and unregulated markets R and U. CBAM regulation involves carbon regulation $\tau^R > 0$ and border adjustment in R, imposing $\tau^U = 0$ in U. No-CBAM regulation involves carbon regulation $\tau^R > 0$ in R, imposing $\tau^U = 0$ in U. We compute effects relative to a zero-regulation benchmark with $\tau^R = \tau^U = 0$. We compute effects separately for markets UL and UH, which divide U into lower- and higher-income countries based on World Bank income groups. Producer surplus effects sum over aluminum and steel.

Figure A15: Policy spillovers, government revenue

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



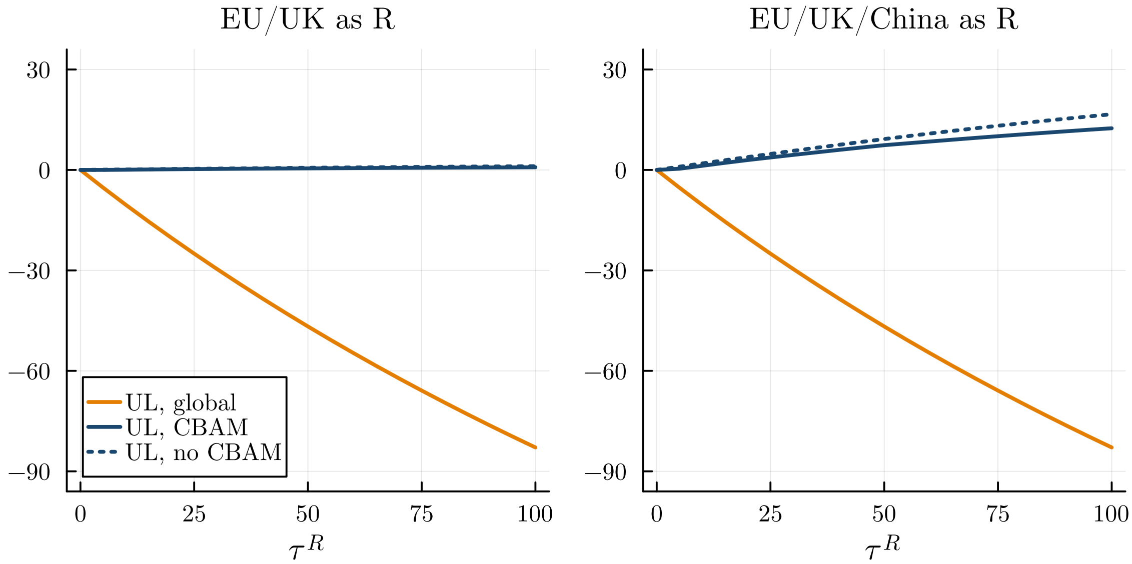
(b) Government revenue effects ΔG for market UH (1B USD)



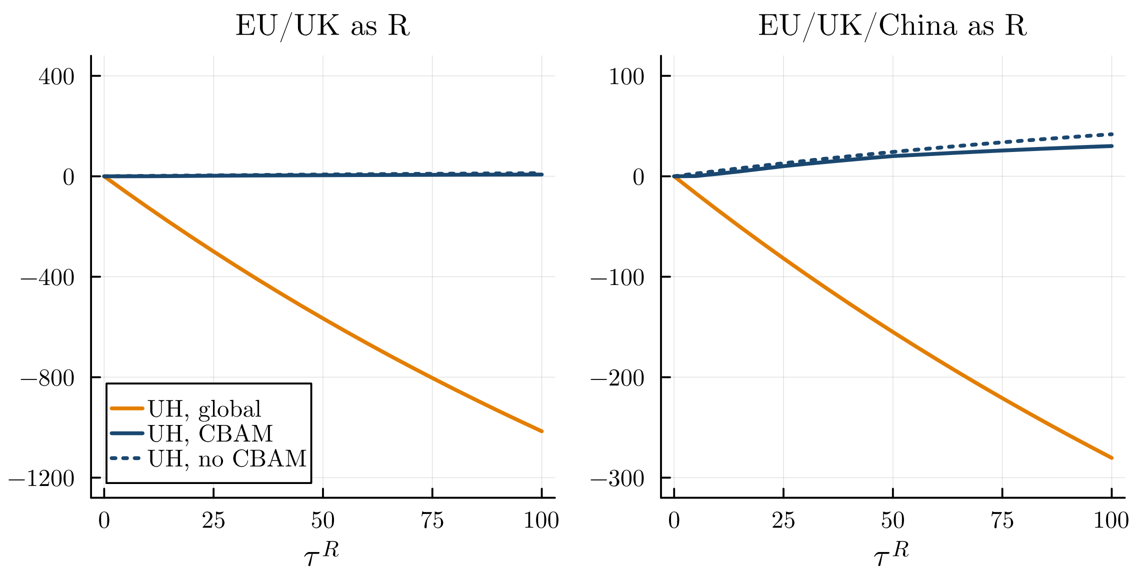
We simulate carbon regulation in three forms. Global regulation $\tau = \tau^R = \tau^U$ is uniform across regulated and unregulated markets R and U. CBAM regulation involves carbon regulation $\tau^R > 0$ and border adjustment in R, imposing $\tau^U = 0$ in U. No-CBAM regulation involves carbon regulation $\tau^R > 0$ in R, imposing $\tau^U = 0$ in U. We compute effects relative to a zero-regulation benchmark with $\tau^R = \tau^U = 0$. We compute effects separately for markets UL and UH, which divide U into lower- and higher-income countries based on World Bank income groups. Government revenue effects sum over aluminum and steel.

Figure A16: Policy spillovers, emissions

(a) Emissions effects ΔE for market UL (Mt CO_2)



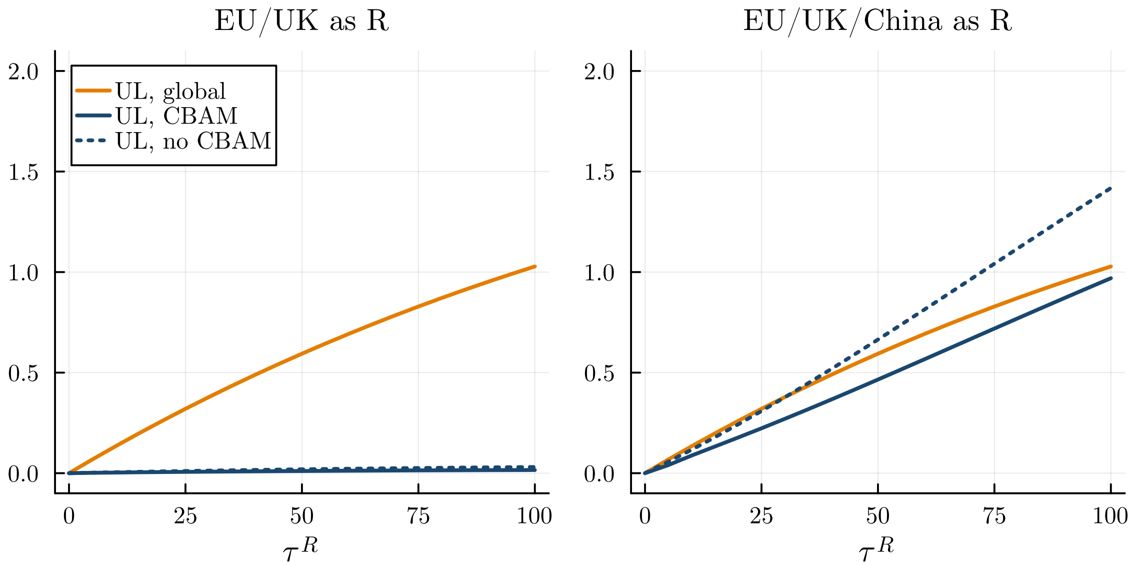
(b) Emissions effects ΔE for market UH (Mt CO_2)



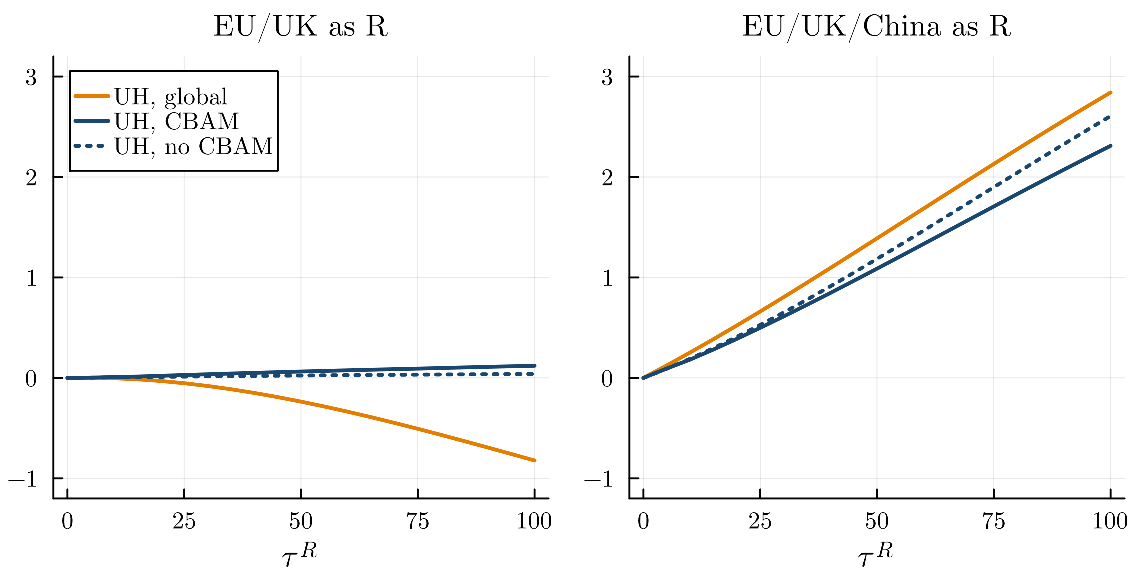
We simulate carbon regulation in three forms. Global regulation $\tau = \tau^R = \tau^U$ is uniform across regulated and unregulated markets R and U. CBAM regulation involves carbon regulation $\tau^R > 0$ and border adjustment in R, imposing $\tau^U = 0$ in U. No-CBAM regulation involves carbon regulation $\tau^R > 0$ in R, imposing $\tau^U = 0$ in U. We compute effects relative to a zero-regulation benchmark with $\tau^R = \tau^U = 0$. We compute effects separately for markets UL and UH, which divide U into lower- and higher-income countries based on World Bank income groups. Emissions effects sum over aluminum and steel.

Figure A17: Policy spillovers, aluminum only

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



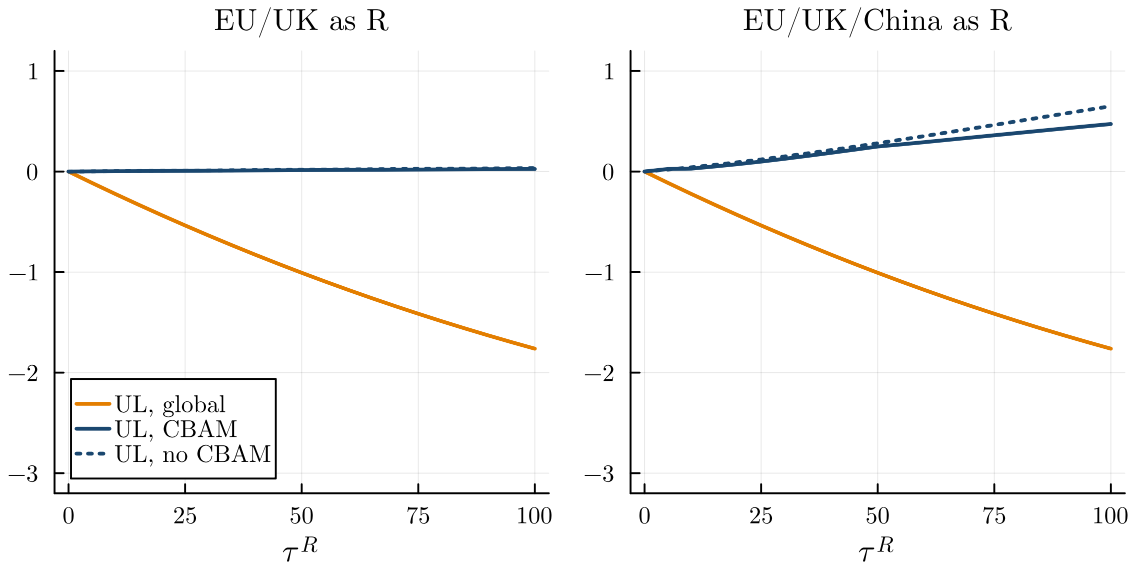
(b) Welfare effects ΔW for market UH (1B USD)



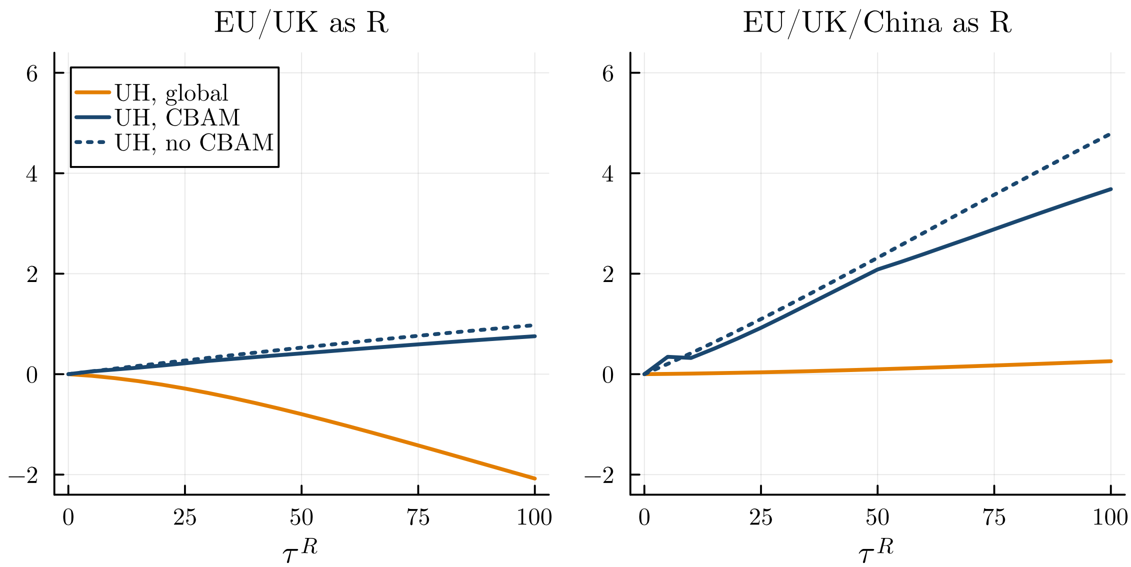
For aluminum, we simulate carbon regulation in three forms. Global regulation $\tau = \tau^R = \tau^U$ is uniform across regulated and unregulated markets R and U. CBAM regulation involves carbon regulation $\tau^R > 0$ and border adjustment in R, imposing $\tau^U = 0$ in U. No-CBAM regulation involves carbon regulation $\tau^R > 0$ in R, imposing $\tau^U = 0$ in U. We compute effects relative to a zero-regulation benchmark with $\tau^R = \tau^U = 0$. We compute effects separately for markets UL and UH, which divide U into lower- and higher-income countries based on World Bank income groups.

Figure A18: Policy spillovers, steel only

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



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



For steel, we simulate carbon regulation in three forms. Global regulation $\tau = \tau^R = \tau^U$ is uniform across regulated and unregulated markets R and U. CBAM regulation involves carbon regulation $\tau^R > 0$ and border adjustment in R, imposing $\tau^U = 0$ in U. No-CBAM regulation involves carbon regulation $\tau^R > 0$ in R, imposing $\tau^U = 0$ in U. We compute effects relative to a zero-regulation benchmark with $\tau^R = \tau^U = 0$. We compute effects separately for markets UL and UH, which divide U into lower- and higher-income countries based on World Bank income groups.

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 emissions allowances based on 2023 emissions 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 emissions allowances based on 2023 emissions estimates and production volumes.

Table B3: Carbon pricing for 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 emissions allowances based on 2023 emissions estimates and production volumes.

Table B4: Changes in aluminum production marginal cost percentiles

Country	Capacity (Mt/a)	Cost Percentile (Pre)	Cost Percentile (Post)	Difference
Low income				
Mozambique	0.6	18	6	-12
Subtotal	0.6	18	6	-12
Lower middle income				
India	6.1	62	84	22
Tajikistan	0.4	15	6	-9
Venezuela	0.4	3	2	-1
Egypt	0.3	54	18	-36
Ghana	0.2	39	13	-26
Cameroon	0.1	83	42	-41
Subtotal	7.6	55	70	15
Upper middle income				
China	55.1	50	60	10
Brazil	2.3	73	24	-49
Malaysia	1.1	49	25	-24
South Africa	0.7	39	67	28
Argentina	0.5	3	14	11
Indonesia	0.3	12	5	-7
Kazakhstan	0.3	0	53	53
Turkey	0.1	0	1	1
Subtotal	60.3	50	58	8
High income				
United States	4.8	95	54	-41
Russian Federation	4.4	26	18	-8
Canada	3.4	21	6	-15
United Arab Emirates	2.7	15	31	16
Norway	1.8	46	13	-33
Australia	1.7	70	78	8
Bahrain	1.6	22	32	10
Germany	1.4	97	53	-44
Iceland	0.9	46	14	-32
Italy	0.8	71	11	-60
Japan	0.8	80	25	-55
Saudi Arabia	0.8	43	43	0
Korea, Republic of	0.6	74	19	-55
Qatar	0.6	40	43	3
Taiwan	0.5	99	54	-45
France	0.4	68	20	-48
New Zealand	0.4	67	23	-44
Oman	0.4	61	45	-16
Romania	0.3	99	56	-43
Greece	0.2	94	49	-45
Slovenia	0.1	95	49	-46
Sweden	0.1	92	42	-50
United Kingdom	0.0	81	29	-52
Subtotal	28.9	53	33	-20

Countries with lower marginal costs have lower cost percentiles. A CBAM shifts more carbon-intensive producers into higher percentiles. Data on primary aluminum capacity, emissions, and costs are from WoodMac. Secondary aluminum capacity is the maximum production over the last 10 years from the World Bureau of Metal Statistics, and scrap input prices are from UN Comtrade. Shipping data are from UNCTAD. Pre-CBAM costs include existing carbon prices based on data from the World Bank Carbon Pricing Dashboard and regulatory documents. Post-CBAM costs apply carbon taxes that bring all producers to \$96 per ton of CO_2.

Table B5: Changes in steel production marginal cost percentiles

Country	Capacity (Mt/a)	Cost Percentile (Pre)	Cost Percentile (Post)	Difference
Low income				
Uganda	0.4	80	30	-50
Subtotal	0.4	80	30	-50
Lower middle income				
India	108.8	6	23	17
Vietnam	25.3	38	43	5
Egypt	14.5	17	19	2
North Korea	8.0	84	59	-25
Venezuela	5.1	23	22	-1
Morocco	3.5	15	8	-7
Bangladesh	3.0	7	3	-4
Syria	2.2	18	10	-8
Philippines	1.3	100	100	0
Kenya	1.0	80	35	-45
Nigeria	1.0	63	33	-30
Uzbekistan	1.0	86	38	-48
Pakistan	0.9	9	2	-7
Ghana	0.8	70	28	-42
Subtotal	176.3	18	27	9
Upper middle income				
China	1,177.2	52	57	5
Turkey	56.1	25	20	-5
Iran	44.7	24	27	3
Brazil	44.1	52	48	-4
Ukraine	33.2	46	57	11
Mexico	27.3	23	21	-2
Indonesia	18.2	73	57	-16
Malaysia	15.5	67	45	-22
Thailand	8.2	68	26	-42
Algeria	8.1	14	19	5
South Africa	7.8	45	55	10
Argentina	7.5	42	37	-5
Kazakhstan	6.8	81	83	2
Belarus	3.0	25	9	-16
Peru	2.9	79	30	-49
Serbia	2.7	75	76	1
Iraq	2.6	18	10	-8
Bosnia & Herzegovina	1.9	81	59	-22
Libya	1.6	9	17	8
Azerbaijan	1.0	54	22	-32
Moldova	1.0	24	13	-11
Albania	0.7	44	12	-32
North Macedonia	0.6	47	19	-28
Guatemala	0.5	81	30	-51
Subtotal	1,473.2	50	53	3
High income				
United States	120.7	30	27	-3
Japan	117.0	92	82	-10
Russia	89.4	5	22	17
South Korea	83.7	64	49	-15
Germany	50.5	98	83	-15
Italy	32.9	92	54	-38
Taiwan	23.6	65	55	-10
Spain	19.4	59	21	-38
France	19.1	73	56	-17
Canada	15.7	48	39	-9
United Kingdom	13.1	76	59	-17
Saudi Arabia	10.8	16	22	6
Poland	9.7	80	55	-25
Belgium	8.0	75	58	-17

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

Country	Capacity (Mt/a)	Cost Percentile (Pre)	Cost Percentile (Post)	Difference
Austria	7.6	97	89	-8
Netherlands	7.5	96	86	-10
Czechia	6.4	88	54	-34
Australia	5.9	38	44	6
Romania	5.3	81	61	-20
Sweden	4.8	89	60	-29
Slovakia	4.5	98	89	-9
Finland	4.4	81	60	-21
Oman	4.3	13	14	1
Greece	4.1	58	18	-40
United Arab Emirates	3.6	15	23	8
Qatar	3.5	7	13	6
Luxembourg	3.0	40	9	-31
Hungary	2.2	83	67	-16
Chile	2.0	62	53	-9
Portugal	1.7	34	9	-25
Bulgaria	1.4	46	11	-35
Switzerland	1.4	44	10	-34
Kuwait	1.2	24	12	-12
Bahrain	1.1	36	30	-6
Norway	0.8	28	6	-22
Singapore	0.8	81	31	-50
New Zealand	0.7	98	50	-48
Slovenia	0.7	50	13	-37
Subtotal	692.5	59	49	-10

Countries with lower marginal costs have lower cost percentiles. A CBAM shifts more carbon-intensive producers into higher percentiles. Steel capacity and emissions are from Climate TRACE, and costs are from TransitionZero's Global Steel Cost Tracker. Shipping data are from UNCTAD. Pre-CBAM costs include existing carbon prices based on data from the World Bank Carbon Pricing Dashboard and regulatory documents. Post-CBAM costs apply carbon taxes that bring all producers to \$96 per ton of CO_2.

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_2)	169	156
Scope 1 and 2 Emissions (Mt CO_2)	687	676
Number of Countries	36	34
Number of Smelters	148	153

Data for both sources is for 2023.

Table B7: Aluminum smelter ownership

Country	State ownership %	Foreign ownership %	Global production %
China	39	0	58
India	11	57	6
EU + UK	35	48	5
USA	0	18	5
Russia	4	0	5
Canada	0	100	4
UAE	100	0	3
Brazil	44	68	2
Bahrain	50	0	2
Australia	0	100	2
Rest of world	67	44	8

The EU + UK include 27 EU member countries plus Norway, Iceland, Switzerland, Liechtenstein, and the United Kingdom. State ownership is whether the majority-stakeholder parent company is a state-owned enterprise. Foreign is whether the majority-stakeholder parent company is headquartered in a different country from a given plant. We compute the production-weighted average across plants within each country. Global production is the share of global production.

Table B8: Steel mill ownership

Country	State ownership %	Foreign ownership %	Global production %
China	10	0	51
EU + UK	11	11	9
Japan	0	0	5
USA	2	17	5
India	39	10	5
Russia	0	8	4
South Korea	28	0	4
Turkey	9	4	2
Brazil	0	41	2
Iran	62	0	2
Rest of world	22	24	11

The EU + UK include 27 EU member countries plus Norway, Iceland, Switzerland, Liechtenstein, and the United Kingdom. State ownership is whether the majority-stakeholder parent company is a state-owned enterprise. Foreign is whether the majority-stakeholder parent company is headquartered in a different country from a given plant. We compute the production-weighted average across plants within each country. Global production is the share of global production.

Table B9: 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 B10: Emissions intensity by GDP per capita

	Aluminum		Steel	
	(1)	(2)	(3)	(4)
Log GDP per capita	-0.208	-0.365	0.0843	-0.0697*
	(0.488)	(0.672)	(0.0642)	(0.0355)
Primary production (%)		4.460***		1.489***
		(1.214)		(0.197)
Average production (Mt)		3.791**		0.166*
		(1.549)		(0.0883)
State ownership (%)		-1.391		0.431***
		(1.542)		(0.153)
Foreign ownership (%)		1.802		-0.257
		(2.007)		(0.204)
Observations	38	38	77	77

Each observation is a country. Emissions intensity is tons of CO_2 emitted per ton of production. Primary production refers to primary aluminum and BOF steel. State ownership is whether the majority-stakeholder parent company is a state-owned enterprise. Foreign is whether the majority-stakeholder parent company is headquartered in a different country from a given plant. We compute the production-weighted average across plants within each country. Average production is the average across plants within a country. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

Table B11: Global carbon taxation

(R)	EU/UK			EU/UK/China		
(τ)	25	50	100	25	50	100
Market R						
Price (%)	3.70	7.03	12.5	3.70	7.03	12.5
Emissions (Mt CO_2)	-23.8	-45.2	-82.0	-241	-456	-817
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
Market U						
Price (%)	3.70	7.03	12.5	3.70	7.03	12.5
Emissions (Mt CO_2)	-324	-613	-1098	-107	-202	-363
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
Market UL						
Price (%)	3.70	7.03	12.5	3.70	7.03	12.5
Emissions (Mt CO_2)	-25.0	-46.7	-82.9	-25.0	-46.7	-82.9
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
Market UH						
Price (%)	3.70	7.03	12.5	3.70	7.03	12.5
Emissions (Mt CO_2)	-299	-566	-1015	-81.7	-155	-280
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

We simulate global carbon taxation $\tau = \tau^R = \tau^U$ across regulated and unregulated markets R and U. We compute effects relative to a zero-regulation benchmark with $\tau^R = \tau^U = 0$. We report effects separately by market, where markets UL and UH divide U into lower- and higher-income countries based on World Bank income groups. Price effects average over aluminum and steel, weighting by observed revenues. Emissions, welfare, surplus, and revenue effects sum over aluminum and steel. We consider carbon taxation τ of \$25, \$50, and \$100 per ton CO_2.

Table B12: Unilateral carbon taxation with border adjustment (CBAM)

(R)	EU/UK			EU/UK/China		
(τ^R)	25	50	100	25	50	100
Market R						
Price (%)	0.70	1.36	2.52	2.80	5.26	9.81
Emissions (Mt CO_2)	-27.1	-51.2	-91.3	-255	-481	-852
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
Market U						
Price (%)	0.14	0.27	0.46	2.04	4.07	6.81
Emissions (Mt CO_2)	2.48	4.72	7.87	13.8	27.5	42.6
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
Market UL						
Price (%)	0.14	0.27	0.46	2.04	4.07	6.81
Emissions (Mt CO_2)	0.26	0.47	0.80	3.73	7.40	12.5
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
Market UH						
Price (%)	0.14	0.27	0.46	2.04	4.07	6.81
Emissions (Mt CO_2)	2.23	4.25	7.06	10.1	20.1	30.1
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

We simulate unilateral domestic carbon regulation $\tau^R > 0$ in regulated market R, paired with border adjustment $\alpha^R = \tau^R - \tau^U$, holding fixed $\tau^U = 0$ in unregulated market U. We compute effects relative to a zero-regulation benchmark with $\tau^R = \tau^U = 0$. We report effects separately by market, where markets UL and UH divide U into lower- and higher-income countries based on World Bank income groups. Price effects average over aluminum and steel, weighting by observed revenues. Emissions, welfare, surplus, and revenue effects sum over aluminum and steel. We consider carbon taxation τ^R of \$25, \$50, and \$100 per ton CO_2.

Table B13: Unilateral carbon taxation (no CBAM)

(R)	EU/UK			EU/UK/China		
(τ^R)	25	50	100	25	50	100
Market R						
Price (%)	0.19	0.36	0.64	2.53	4.88	8.83
Emissions (Mt CO_2)	-27.7	-52.3	-93.2	-259	-487	-865
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
Market U						
Price (%)	0.19	0.36	0.64	2.53	4.88	8.83
Emissions (Mt CO_2)	4.06	7.70	13.6	17.8	33.5	58.5
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
Market UL						
Price (%)	0.19	0.36	0.64	2.53	4.88	8.83
Emissions (Mt CO_2)	0.34	0.64	1.12	4.78	9.22	16.6
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
Market UH						
Price (%)	0.19	0.36	0.64	2.53	4.88	8.83
Emissions (Mt CO_2)	3.72	7.06	12.5	13.0	24.2	41.9
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

We simulate unilateral domestic carbon regulation $\tau^R > 0$ in regulated market R, holding fixed $\tau^U = 0$ in unregulated market U. We compute effects relative to a zero-regulation benchmark with $\tau^R = \tau^U = 0$. We report effects separately by market, where markets UL and UH divide U into lower- and higher-income countries based on World Bank income groups. Price effects average over aluminum and steel, weighting by observed revenues. Emissions, welfare, surplus, and revenue effects sum over aluminum and steel. We consider carbon taxation τ^R 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, as reported in the UN Trade and Development (UNCTAD) trade and transport dataset.

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 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 steel. We observe 357 BF-BOF plants and 535 EAF plants. We include weighted average costs of shipping steel for each country to the European Union or United Kingdom, as reported in the UN Trade and Development (UNCTAD) trade and transport dataset. We estimate average carbon prices paid for emissions from steel production as described in Section 3.3 and as shown in appendix table B3.

C.3 State and foreign ownership

We define state and foreign ownership based on majority-stakeholder parent companies. For aluminum, we manually code this ownership for 74 unique parent companies. For steel, we draw state ownership from the Climate TRACE data, which code parent companies as fully or partially state-owned. We assume 50% state ownership for those that are partially state-owned. We determine foreign ownership by examining where each parent company produces across its potentially multiple plants. Roughly 90% produce in only one country, and we assume these companies operate in those countries. We otherwise assign parent companies to where they produce the most. There are seven parent companies that produce in multiple countries, but with less than 50% of their production in any given country. We code these companies manually. Appendix tables B7 and B8 present ownership by country, production-weighting across plants within each country.

C.4 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[28] and bilateral distances for each trade flow from the CEPII GeoDist dataset.[29] We calculate shipping emissions as

$$CO_2 \text{ emissions (kg)} = \text{Trade Volume (mt)} \times \text{Bilateral Distacnce} \times \text{Emissions Factor.}$$

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

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

We use an emissions factor for maritime shipping of 0.01923 kg CO_2 per ton-kilometer, as in Mundaca et al. (2021). Appendix table B9 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.

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.[30] 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.

[30] 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.