The Economics of Carbon Border Adjustment Mechanisms for Lower-Income Countries

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How will carbon border adjustment mechanisms (CBAMs) affect lower-income countries? We study the welfare implications of proposed CBAM policies in the context of the global aluminum industry. We find that the typical narrative, which emphasizes negative effects on lower income countries, does not necessarily hold in the data. First, we show descriptively that emission intensity is not strictly higher for aluminum producers in lower-income countries. Second, we use a quantitative equilibrium model to show that some producers in lower-income countries even benefit from a CBAM, which raises equilibrium prices and profits for cleaner producers.

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1 Introduction

As the European Union implements the first carbon border adjustment mechanism (CBAM), the world is experiencing an important new climate policy tool. Similar measures are already slated in the United Kingdom. When paired with domestic carbon regulation, CBAMs aim to level the playing field in two ways. First, CBAMs help domestic producers. Without a CBAM, domestic regulation imposes added costs on domestic producers relative to their foreign competitors. This competitiveness concern creates domestic political support for CBAM policies. Second, CBAMs reduce global emissions. Without a CBAM, domestic regulation encourages both production and consumption to substitute toward unregulated markets. This "leakage" concern undercuts the emission reductions from domestic regulation because foreign emissions rise as domestic emissions fall.[1] Competitive and leakage effects thus represent two key motivations for countries to impose CBAMs.

This paper emphasizes the global distributional impacts of CBAM policies. As the EU and UK implement these policies, they may place significant burden on their lower-income trading partners. We quantify these impacts in the context of the global aluminum industry, where we measure emissions that amount to 0.7 Gt of CO_2 in 2023 – roughly as much as the German economy (EDGAR 2024). We use detailed plant-level data to show that emission intensity is relatively low for many producers in lower-income countries. We highlight the case of Mozambique, a lower-income but green, hydropowered aluminum producer that derives roughly a quarter of its total export revenue from aluminum exports to the EU and UK. We then use a global equilibrium model of trade to evaluate the welfare implications of green comparative advantage.

First, we show descriptively that emission intensity is not strictly higher for aluminum producers in lower-income countries. We draw on plant-level data from Wood Mackenzie, a leading data provider for the energy sector. For the near-universe of aluminum smelters globally, we observe production quantities, costs, and emissions. We document a flat relationship between emissions per unit of production and country-

[1] Border rebates for exporters would further improve the competitiveness of domestic companies operating abroad. The EU and UK have not considered such rebates, and so we do not consider them here.

level GDP per capita. The reason is that emission intensity is convex in production, and producers in lower-income countries operate at smaller scale. Consequently, a CBAM does not place disproportionate burden on these producers. For Mozambique, a CBAM improves its competitiveness by penalizing its higher-emission competitors.

Second, we model the production, consumption, and trade of aluminum in world markets. We construct a global supply curve for aluminum by drawing directly on our plant-level data, and we use our model to evaluate the welfare effects of carbon regulation. We simulate climate coalitions that implement CBAMs alongside carbon taxation. We highlight two key forces – regulation and reallocation – that shape policy impact in equilibrium. On one hand, the regulation force helps lower-income countries in non-coalition markets: carbon taxation in coalition markets reduces the global supply of aluminum, raising prices and profits for producers in lower-income countries. On the other hand, the reallocation force hurts: a CBAM reallocates sales from coalition to non-coalition markets, reducing prices and profits for producers in lower-income countries. When the coalition includes the EU and UK, these forces balance. The result is minimal negative impact on net for lower-income trade partners.

2 Literature

Much of the prior literature has emphasized ways in which the EU CBAM may ultimately harm other countries, by shifting the burden of decarbonization policies toward tariffed countries and by lowering the market access of tariffed countries. But most studies employ neither detailed facility-level data nor a fully specified model of how world markets adapt in the face of a CBAM, both areas that our analysis implements below.

The EU CBAM intends to address leakage and competitiveness issues associated with the cost imposition of removing free allowances from the EU emissions trading system. Yet, while such competitiveness effects are important for energy-intensive and trade-exposed EU industries, there are reasons to think that impacts from the EU CBAM will be mild for many other countries.

A small handful of industries account for most industrial emissions, and many countries do not export large quantities of these products to jurisdictions that are

levying CBAMs.[2] Further, most studies suggest that emissions leakage is limited in practice (Grubb et al. 2022). As a consequence, the literature modeling CBAM impacts has often found only limited effects on emissions, production, or welfare (Böhringer et al. 2012, Devarajan et al. 2022, Irfanoglu et al. 2015, Branger and Quirion 2014).

Still, while effects for many countries may be small, there may be important exceptions. Many sources discuss how low- and middle-income countries may be harmed by CBAMs, particularly those countries that export large quantities of energy-intensive goods to CBAM destinations. Most analyses describe these concerns in general terms, including Lowe (2021), UNCTAD (2021), Branger and Quirion (2014), Simola (2021), He et al. (2022), Zhong and Pei (2022), and Böhringer et al. (2012, 2018, 2022). This research typically relies on either simple data analysis of existing trade patterns or computable general equilibrium modeling.[3] While California has done some limited border adjustment, there is no international experience to draw from.

Country characteristics, such as energy intensity of the relevant sectors as well as the pattern of their comparative advantage, determine whether countries will on net lose or perhaps even gain from the imposition of a CBAM on their exports. Countries have the potential to gain if they produce relatively cleanly, since the rise in price in the destination market can exceed losses due to CBAM payments. UNCTAD (2021) models trade and GDP effects, finding that most less developed countries lose (21 of 38) or break even (8 of 38), but 9 of 38 benefit.

Overland and Sabyrbekov (2022) develop a predictive CBAM opposition index based on countries' trade patterns, carbon intensity, climate opinions, WTO litigiousness, and innovation capacity, focusing on the countries that are top-50 destinations for EU exports (since such countries would have the most leverage in trade disputes). They conclude that a list of fossil fuel-abundant and manufacturing exporting coun-

[2] A 2021 European Commission analysis of the proposed carbon border adjustment mechanism indicated that four industries (iron and steel, cement and lime, fertilizer, and aluminum) account for more than half of EU industrial carbon-equivalent emissions, and 13 percent of total EU emissions. The EU CBAM has since expanded beyond these sectors.

[3] For example, He et al. (2022) use a dynamic CGE model to assess the impact of the CBAM on other countries, finding that the CBAM will reduce trade flows and on net harm welfare and growth in highly exposed countries. Modeling the current EU scope, they calculate the implied equivalent tariffs (which are typically single-digit) and the resulting loss in trade and welfare. The largest GDP effects are on Russia and Ukraine. Some work also uses other modeling methods, including a multi-regional Input-Output model (Zhong and Pei 2022).

tries are most likely to object, including China, the United States, Iran, India, Russia, and others. Note that this methodology does not necessarily capture the jurisdictions that are most harmed by the EU CBAM, but rather those most likely to be in opposition.

The EU's own analysis describes how the CBAM is expected to address leakage and competitiveness concerns, but they recognize that some low-income countries may be adversely affected (European Commission 2021). In addition to concerns regarding compliance costs in low-income countries, some country/industry pairs are particularly exposed, including the aluminum sector in Mozambique.

Other work has brought more detailed data and analysis to bear. The World Bank, for example, has developed a CBAM "exposure" index, which charts how countries compare in terms of exposure to the EU CBAM. They focus on the five key EU sectors: aluminum, cement, iron and steel, fertilizer, and electricity. The exposure index is the product of the share of GDP that is CBAM goods destined for the EU and the estimated carbon payment per dollar of exports relative to an average EU producer. Their analysis accounts for the fact that costs of production will also increase in the EU market as EU producers pay for emissions; thus, relatively clean exporters may gain competitiveness while relatively dirty exporters lose. They find that, on aggregate, the most exposed countries are Zimbabwe, Ukraine, Georgia, Mozambique, and India.

In a related blog post, Maliszewska et al. (2023) notes that the scope of emissions can have a big impact on the relative CBAM exposure, using aluminum in Mozambique as an example. Mozambique exports almost all their aluminum to the EU, but since it relies on hydropower, their scope 2 emissions are cleaner than their scope 1 emissions. Using scope 1, Mozambique is the most "exposed" country in the aluminum sector; but using both scope 1 and scope 2, Mozambique's rank is 8.

Magachado et al. (2022) investigate the impact of the EU CBAM on trading partners, considering the relationship between trade patterns, industry carbon intensity, and output and labor market impacts of CBAMs. They find a relatively low impact on Mozambique, due to the low carbon intensity of aluminum production in Mozambique. Revenues are less than one percent of the value of aluminum exports. However, if demand for Mozambique aluminum falls due to the CBAM, the potential

for negative impacts on output and employment remains large. Eicke et al. (2021) consider the impact of the EU CBAM on poorer countries, developing a risk index based on data on trade patterns, carbon intensity, and institutional capacities. Like many studies, they find that many countries are minimally affected by the EU CBAM, but there are important exceptions, and many of the countries exposed to greater risk are in Africa. They undertake a short qualitative analysis of Mozambique, finding that its risk is driven by difficulty proving lower emissions levels. They note that Mozambique missed several deadlines for reporting to the UNFCCC, suggesting limits in statistical capacity. The authors suggest the need for directed capacity building in this area.

Many have suggested altering CBAMs, or accompanying CBAMs with complementary policies, in order to make them more responsive to the needs of poorer countries, including Clausing and Wolfram (2023). More generous treatment of poorer countries can be justified on multiple grounds, including the fact that they bear the brunt of climate change consequences while bearing little responsibility for the existing stock of greenhouse gasses in the atmosphere (Carleton et al. 2022).

Tagliapietra and Goldthau (2022) suggest devoting CBAM revenues to climate finance, what they term an "international carbon dividend" as well as exemptions for both the least developed countries and small island developing states. UNCTAD (2021) and Brandi (2021) have similar recommendations of exemptions and CBAM revenue earmarking. Ianchovichina and Onder (2021) also suggest reducing trade barriers in clean goods, and working to ensure clean technology access.

Beaufils et al. (2023) explore international revenue redistribution schemes, finding that design features can help shift resources toward vulnerable countries. Perdana and Vielle (2022) compare policy tools that might complement CBAMs, ameliorating the negative effects on partners without unduly increasing leakage. Using a dynamic CGE model, they find that the most cost-effective policy consistent with reduced leakage is revenue-redistribution in a form that promotes energy efficiency.

While the EU has designed their CBAM to be non-discriminatory in the dual sense that is required by the WTO, neither discriminating between domestic and foreign producers, nor among foreign countries, such principles do not allow for the treatment based on "common but differentiated responsibility" that is foundational

in the climate context. To allow more generous treatment of poorer countries, a multilateral approach may ease the way forward, as argued in Sapir (2021). As one example, the Institute for Development Studies has put forward a multilateral carbon tax treaty text for discussion purposes that includes minimum carbon prices that would vary by stage of development (Falcão 2024). This proposal is compatible with tiered minimum carbon pricing, as suggested by Parry et al. (2021).

The literature has also investigated how countries might respond to CBAMs with domestic policy changes, including Clausing and Wolfram (2023). For example, jurisdictions with large carbon-intensive exports to CBAM countries may find adoption of carbon pricing, or increasing existing carbon prices, advantageous in order to lessen tariffs (Böhringer et al. 2016). Countries may also choose to retaliate in response (Böhringer et al. 2022).

Hsiao (2024) lays important groundwork for the analysis below.The author combines plot-level data on the palm oil industry with a quantitative equilibrium model of global trade to quantify the emission reductions from regulation in the form of domestic regulation, import tariffs, and a CBAM. We use similar techniques to study the equilibrium welfare effects of a CBAM on lower-income countries, with a focus on the aluminum sector.

3 Background

We provide institutional details on the global aluminum industry, including in Mozambique.

3.1 Aluminum

The global aluminum industry represents an important component of the world economy, driven by the demand for aluminum in sectors such as transportation, construction, packaging, and energy. Aluminum is a globally traded commodity, with its price determined by international markets like the London Metal Exchange (LME). Regional price variation is limited. For example, the LME lists one global contract and four regional "Premiums." The absolute values of the Premiums were on average less than 1% of the global contract price. The aluminum sector is also a focal point of

environmental discussions: estimates suggest that the sector accounts for about 2% percent of global greenhouse gas emissions.

The industry operates with two distinct production methods: primary production, which involves extracting aluminum from alumina, and secondary production, which involves recycling aluminum scrap. Primary aluminum production involves a highly energy-intensive process in which alumina, a compound of aluminum and oxygen, interacts with pure carbon to separate oxygen molecules from the aluminum, resulting in pure aluminum and carbon dioxide as a by-product. According to industry data, primary aluminum production has accounted for the majority of global aluminum output. Of the approximately 100 million metric tons (Mt) produced in 2023, 70 Mt was primary production.

There are two main sources of carbon emissions in primary aluminum production. First, the chemical reaction itself releases CO_2 as a byproduct. This reaction has a theoretical lower limit on the amount of CO_2 it can release: the production of 1 metric ton (t) of aluminum emits at least 1.22 t of CO_2, meaning that even with the most efficient processes, emissions from the reaction are inevitable.[4] Second, the electricity used in the production process can generate additional CO_2 emissions, depending on the energy mix used to supply a plant. If an aluminum smelter uses electricity that is primarily generated from coal or other fossil fuels, the carbon footprint of aluminum production is higher. In contrast, plants that rely on low- or zero-emissions electricity sources, such as hydroelectric power, can produce aluminum with much lower emissions. Some plants have their own onsite power generation, while most are connected to the grid.

Secondary aluminum production, on the other hand, involves recycling aluminum scrap, which requires significantly less energy and has no direct CO_2 emissions. Recycling aluminum consumes only 5-10% of the energy required to produce primary aluminum from raw materials. This substantial energy saving makes secondary production a critical strategy for reducing the aluminum industry's overall carbon footprint. However, given the high demand for aluminum, primary production remains necessary to meet market needs.

[4] Carbon-free aluminum production, using inert-anode technologies, is not yet commercially viable.

3.2 Mozambique

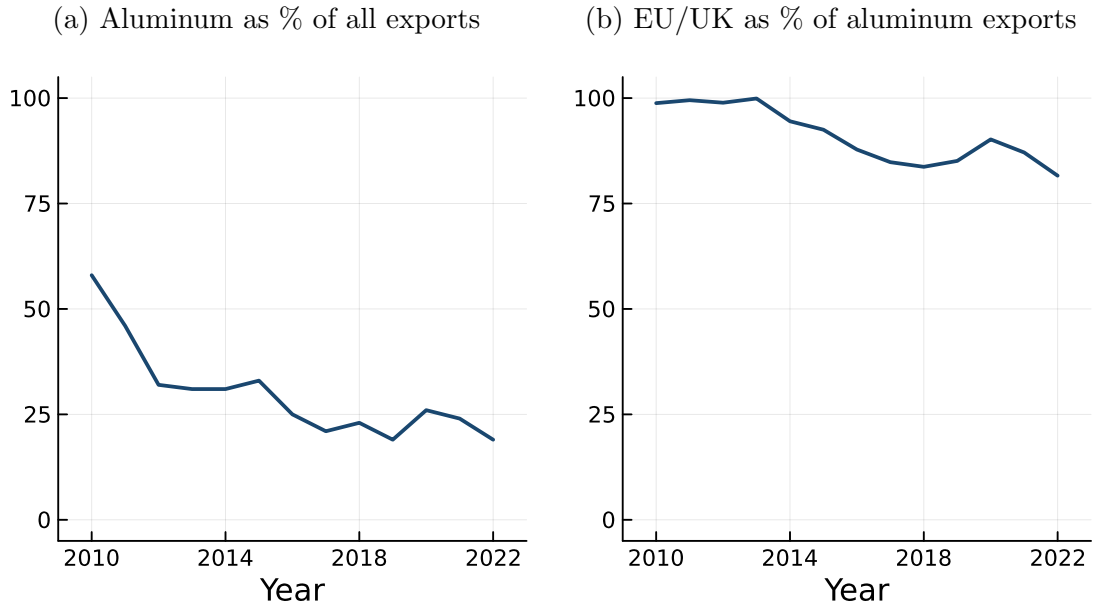
Mozambique is a key player in the global aluminum industry due to the presence of Mozal, the second-largest aluminum smelter in Africa. The project began in 1998 as part of a recovery program driven by the Mozambican government's active desire for foreign investment to help rebuild the nation after the 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.[5] 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. Figure 1 depicts aluminum as a share of Mozambique's total exports, which was over 50% in 2011 but fell to about 17% in 2022. It also shows the share of total aluminum exports going to the EU and UK, which has been above 95% but fell to about 75% in 2022. Even with these recent changes, aluminum exports to CBAM countries remain an important part of Mozambique's economy.

[5] 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.

Figure 1: Aluminum exports for Mozambique



Trade data on exports come from UN Comtrade.

4 Data

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

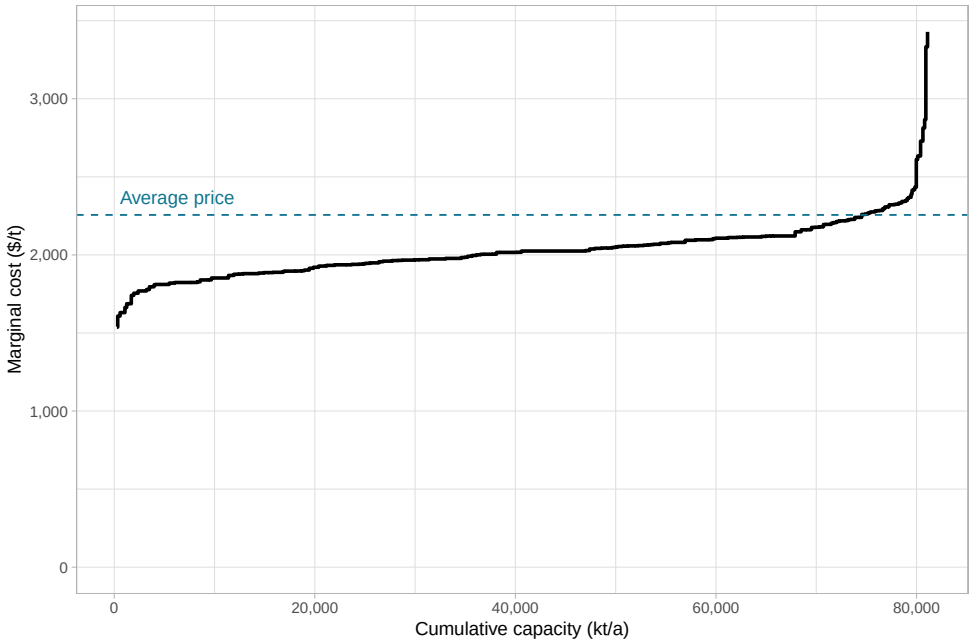
4.1 Production

We measure aluminum production at the firm level with detailed data from Wood Mackenzie (WoodMac), a leading data and analytics provider focused on energy industries and related sectors.[6] These data cover the near-universe of aluminum smelters globally: we observe 153 smelters that represent 100% percent of the world's active smelters in 2023. WoodMac specialists compile these data by combining public information with periodic site visits to each smelter.[7] We observe detailed information on plant capacity, annual production from 2000 to 2023, and operating and capital

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

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

Figure 2: Global supply of aluminum



Marginal costs and average price in 2023 USD. Cumulative capacity in kilotons per annum. Estimated costs are operating costs, defined as cash costs plus depreciation. Costs include any existing carbon pricing. Average price $2,256 from World Bank Commodity Pricing database.

costs, along with estimates of both Scope 1 and Scope 2 carbon emissions. Scope 1 emissions refer to the direct emissions from the smelting process itself, while Scope 2 emissions come from the electricity used in the production process. Costs include those from electricity, alumina, other raw materials, consumables, labor, maintenance, and freight, which we supplement with our own estimates of transport costs. Figure 2 plots these production costs, which collectively form a global supply curve.

We measure global production of 69.0 Mt in 2023. Table 1 lists the top ten producing countries, which together account for 61.8 Mt. China is a dominant producer and consumer of aluminum, accounting for about 60 percent of the primary aluminum market. These measures are consistent with country-level estimates from the United States Geological Survey. Lower-income countries account for 5.1 Mt of global production. In our production data, these countries include Cameroon, Egypt, Ghana, India, Mozambique, Tajikistan, and Venezuela. We define lower-income countries as those classified as low and lower-middle income by the World Bank.

Table 1: Aluminum production and consumption by country: 2023

(a) Top ten producers

Country	Mt
China	41.3
India	4.1
Russia	4.0
Canada	3.3
United Arab Emirates	2.7
Bahrain	1.6
Australia	1.6
Norway	1.3
Brazil	1.0
EU + UK	1.0
Rest of world	7.2

(b) Top ten consumers

Country	Mt
China	42.7
EU + UK	4.5
United States	3.6
India	2.6
Russia	2.3
United Arab Emirates	1.9
Bahrain	1.4
Norway	1.3
Turkey	1.2
Canada	1.1
Rest of world	6.4

The European Union includes 27 member countries. We measure production and consumption in units of one million metric tons.

4.2 Consumption

We construct aluminum consumption by combining the production data with country-level trade data for 2023 from UN Comtrade.[8] We focus on "Aluminium; unwrought, (not alloyed)" with HS code 760110. 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 1.0 Mt, imported 3.5 Mt, and exported less than 0.1 Mt to the rest of the world. The sum of production and net imports yields 4.5 Mt in EU and UK consumption. We repeat this calculation for other countries to identify the top ten consumers globally, as listed in table 1. These top consumers consume a total of 62.6 Mt. Assuming balanced trade, such that total production and consumption are equal at 69.0 Mt, we attribute the remaining 6.4 Mt of consumption to the rest of the world.

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

Table 2: Carbon pricing

	Prices ($/t)	
Country (Region)	Unadjusted	Adjusted
Argentina	2.35	2.35
Canada (British Columbia)	48.15	48.15
Canada (Quebec)	33.35	4.09
China (Hubei)	6.50	6.50
China (Sichuan)	9.62	9.62
France	91.79	37.99
Germany	91.79	51.03
Greece	91.79	38.27
Iceland	91.79	31.97
New Zealand	48.35	10.30
Norway	91.79	29.65
Romania	91.79	66.51
South Africa	8.62	1.29
Sweden	91.79	50.61
United Kingdom	66.59	28.06

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

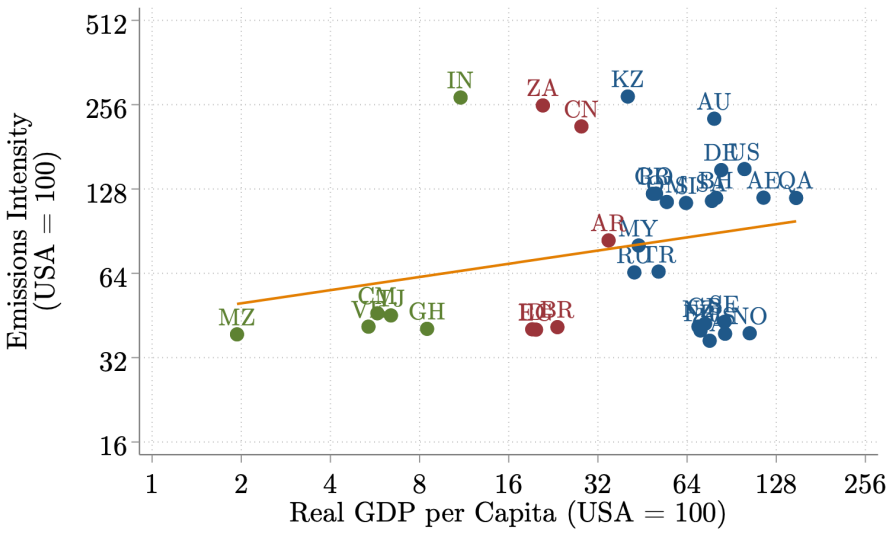
4.3 Regulation

We collect carbon prices for each country in 2023, accounting for regional markets where applicable. Information largely comes from the World Bank and regulatory documents from relevant country governments. For each smelter, we also collect data on the number of free allowances they receive within the carbon market to produce an adjusted carbon price for each plant. Smelters pay these lower, adjusted prices. Table 2 presents both sets of prices for countries with nonzero carbon prices in place.

4.4 Prices

We obtain data on world aluminum prices from the World Bank's Commodities Price dataset. The average world price for aluminum was 2,256 USD per ton in 2023.

Figure 3: Emission intensity vs. GDP



5 Stylized Facts

We report stylized facts on plant-level emissions. Producers in lower-income countries compare favorably to those in higher-income countries.

5.1 Lower-income countries have lower emission intensity

Figure 3 presents the relationship between the average emission intensity of aluminum production and real GDP per capita across countries. We have normalized the data so that the mean of emission intensity across facilities is set to 100. Real GDP per capita is normalized relative to that of the United States. We document a positive relationship between the emission intensity of aluminium production and real GDP per capita. While it is often assumed that higher-income countries produce more efficiently, our descriptive analysis shows that lower-income countries are not always at a disadvantage in terms of emission intensity.

5.2 Lower-income countries have smaller-scale production

Appendix figure A1 explores the empirical relevance of plant-level factors in explaining variation in the emission intensity of production. Producers in lower-income

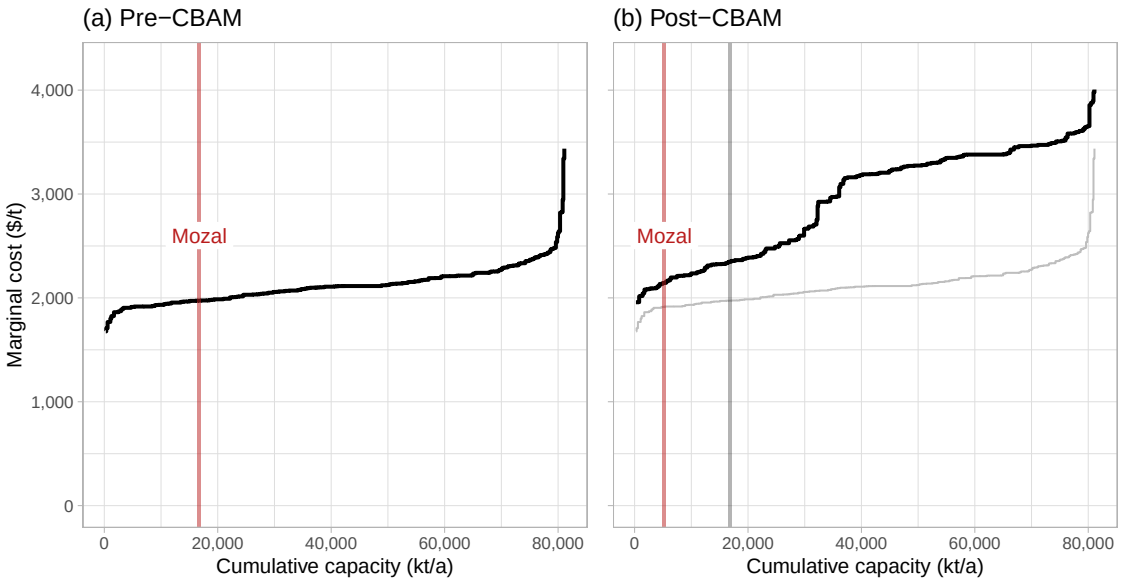
countries are less emission-intensive because they produce less (scale effects) and not because they have younger plants with more recent technology (technology effects). Panel (a) shows that emission intensity is positively associated with production. This relationship suggests that emissions are convex in production – a scale effect. Panel (b) shows that emission intensity is negatively associated with plant age. That is, younger plants produce with higher emission intensity. This finding contrasts with the idea that younger plants may use more recent, lower-carbon technologies – a technology effect. Panel (c) shows that, on average, younger plants are larger, suggesting that scale effects are more important than technology effects in this context. One possible reason is the relative importance of power emissions in the production process, as power-related emissions account for 78% of total emissions on average.

5.3 Lower-income countries can benefit from a CBAM

Figure 4 illustrates the case of Mozal, the primary aluminium smelter in Mozambique. We plot cumulative capacity in order of marginal cost for each facility and show that Mozal is in the left-tail of the distribution. Panel (b) simulates the introduction of a CBAM that introduces a flat \$85 fee per ton of CO_2, equivalent to the average ETS price in the EU and UK in 2023. Accounting for this carbon price results in a shift up in marginal costs for all smelters. However, given differences in the emission intensity of production across producers there are changes in position. Mozal shifts down the marginal cost curve, moving from the 29th most cost-effective smelter to the 16th. That is, Mozal shifts from the 78th percentile of cost-effectiveness to the 93rd percentile.

Appendix figure A2 explores more general patterns of variation in marginal cost rank under this CBAM simulation. We observe that there is little association between the change in marginal cost rank and real GDP per capita. The most important predictor is the emission intensity of production. Smelters with lower emissions intensities result in much larger reductions in marginal cost rank compared to smelters with higher emissions intensities. One of the most important predictors of emission intensity in this context is the carbon intensity of power emissions. Facilities that use clean power, like Mozal, have much lower emissions intensities and experience greater reductions in marginal cost rank.

Figure 4: Changes in marginal costs under a CBAM



Marginal costs are reported in 2023 USD. Cumulative capacity is in metric kilotons per annum. Estimated costs are operating costs, defined as cash costs plus depreciation. Costs include weighted average costs of shipping unwrought aluminum for each country to the European Union or United Kingdom. Estimated emissions include direct and indirect emissions including emissions from on- and off-site power generation. Estimated costs in pre-CBAM period include any existing carbon pricing. Estimated costs in post-CBAM period include flat $85 USD price per ton of CO2 equivalent emissions with no allowances, based on average 2023 ETS price in the EU and UK. Mozal moves up 13 positions from 29th most cost-effective smelter to 16th, up 14 percentiles from 79th percentile to 93rd percentile.

6 Model

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

6.1 Demand

Demand in each market is log-linear. For intercepts δ^m, elasticities ε^m, and prices P^m, demand is given by

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

We focus on primary aluminum, and we abstract for now from the consumption of recycled aluminum. World demand aggregates over markets.

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

6.2 Supply

Aluminum smelters $\mathcal{I}$ produce supply. A smelter i in market m has production capacity s_i, costs c_i, and emissions e_i, and they face a domestic carbon tax τ^m. We observe each quantity directly. Production is at either full or zero capacity. Capacity is in metric tons, while costs and emissions are per ton. We take each as given, noting that adjustment requires substantial investment that can be difficult in the short run. Domestic carbon taxes are per ton. Market H is more highly regulated, such that $\tau^H > \tau^L$. We study how a CBAM influences the impacts of regulation τ^H in equilibrium.

Carbon taxation

We consider domestic carbon taxation without a CBAM. In the absence of border taxes, prices equalize across markets, and smelters face a single world price P.

Accounting for domestic carbon taxes, smelters receive net prices

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

These prices vary by smelter because they depend on smelter-specific emissions. Smelters operate if prices exceed costs.

$$o_i^m = \mathbb{1}(p_i^m > c_i)$$

Production is given by capacity, conditional on operating, and world supply aggregates over smelters.

$$S = \sum_m \sum_{i \in \mathcal{I}^m} s_i o_i^m \tag{3}$$

Carbon border adjustment mechanism

When H pairs carbon taxation with a CBAM, it introduces a price wedge in the form of adjustment α^H.

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

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

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

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

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

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

Smelters choose their highest net price.

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

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

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

As before, production is given by capacity, conditional on operating. And smelters operate if prices exceed costs, such that $o_i^m = \mathbb{1}(p_i^m > c_i)$. Total supply to H aggregates over supply from both markets, as does total supply to L.

$$S^H = \sum_m \sum_{i \in \mathcal{I}^m} s_i o_i^m h_i^m, \quad S^L = \sum_m \sum_{i \in \mathcal{I}^m} s_i o_i^m \ell_i^m$$

6.3 Equilibrium

Without a CBAM, equilibrium prices P^* clear global markets. For world demand and supply as defined by equations 2 and 3,

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

Under a CBAM that imposes adjustment α^H, equilibrium prices (P^{H*}, P^{L*}) clear each market. The marginal producer is indifferent between selling to H or L.

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

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

6.4 Welfare

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

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

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

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

Emissions reflect per-ton emissions and production.

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

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

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

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

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

Smelters in L pay total tax τ^H on all exports to the regulated market, regardless of the size of domestic carbon tax τ^L. These smelters are thus indifferent to τ^L. It follows that regulators in L can collect revenue without distorting outcomes. Consider the extremes. When $\tau^L = 0$, exporters pay $\alpha^H = \tau^H$ and the revenue goes entirely to H. When $\tau^L = \tau^H$, exporters pay $\alpha^H = 0$ and the revenue goes entirely to L. Exporters pay the same total tax because $\tau^L + \alpha^H = \tau^H$ in both cases.

7 Counterfactuals

We construct empirical demand and supply curves for both regulated and unregulated markets. We study the impacts of carbon taxation by market H, both with and without a CBAM. Our simulations vary the intensity of carbon taxation and the coverage of market H. We evaluate welfare impacts across markets $\mathcal{M} \in \{H, L, LL\}$, which include high-regulation market H, low-regulation market L, and lower-income, low-regulation market LL, where LL is a strict subset of L.

7.1 Demand

We use country-level consumption data to construct demand. We simply calibrate the elasticities for now.

$$\varepsilon^H = \varepsilon^L = -0.25$$

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

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

We recover the intercepts by inverting equation 1. With data on consumption D^m and world price P, we compute

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

for each market. Counterfactuals will vary the set of countries in H.

7.2 Supply

We use firm-level production data to construct supply. We observe production quantities, and we assume that smelters operate at capacity to obtain capacities s_i. We observe average costs, and we assume constant marginal costs to obtain costs c_i. This assumption is as in Asker et al. (2019), who model production such that average and marginal costs are equal in order to conduct counterfactuals based on average-cost accounting data. We observe average emissions, and we again assume constant marginal emissions to obtain emissions e_i. Finally, we observe domestic carbon taxes τ^m that we take as baseline values.

In counterfactuals, we note that higher prices will increase producer surplus for smelters, but they will not raise production beyond observed levels. In our model, smelters are already operating at capacity. Data on potential capacity can relax this assumption. Nonetheless, our model remains well suited to evaluate responses to lower prices, as production falls below observed levels. Our model predicts that high-cost smelters will be the first to cease operations.

7.3 Policy

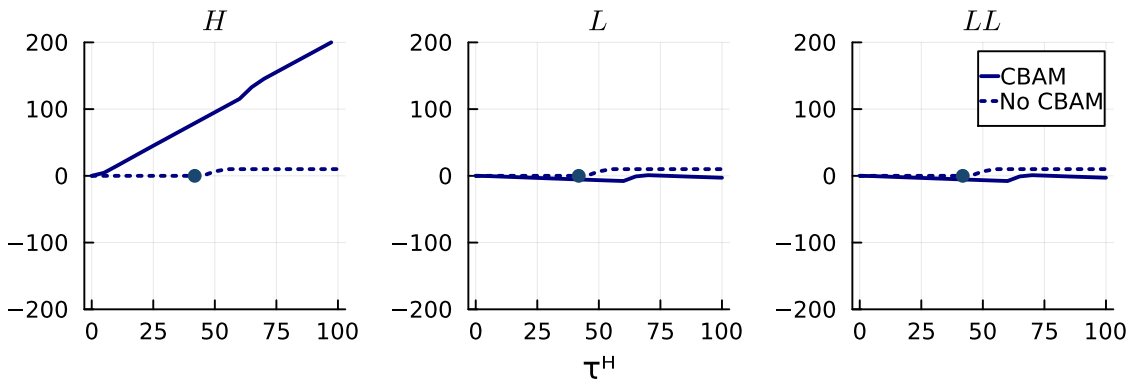
We evaluate carbon taxation and CBAMs of increasing intensity and scope. As a benchmark, we assess welfare under a business-as-usual scenario with zero carbon taxation, setting $\tau^H = \tau^L = 0$. We solve for equilibrium prices, and we compute consumer surplus, producer surplus, government revenue, and emissions. We study the role of intensity by increasing the intensity of carbon taxation τ^H in market H from zero to \$100 per ton CO_2, while maintaining $\tau^L = 0$ in market L. We do so both with and without a CBAM in place, and we compute welfare changes relative to business as usual. We study the role of scope by considering three regulatory coalitions. When market H includes the EU and UK, where CBAMs are slated for full implementation in 2026 and 2027, it covers 4.5 Mt (6.5%) of global consumption. When market H includes the EU, UK, and US, it covers 8.1 Mt (11.7%) of global consumption. When market H includes the EU, UK, and China, where the partnership with China is in place of that with the US, it covers 47.2 Mt (68.4%). We highlight the outsized role of China in both production and consumption.

7.4 Results

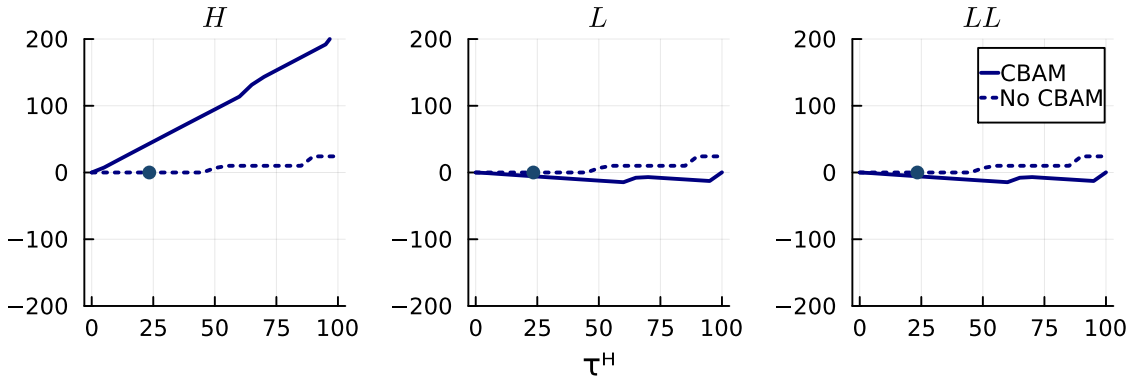
Figure 5 plots impacts on prices across markets H, L, and LL. We simulate CBAMs paired with carbon taxes of increasing intensity. Figure 5a treats the EU and UK as H and imposes domestic carbon taxes τ^H that range from \$0 to \$100 per ton of CO_2. We then broaden the regulatory coalition. Figure 5b adds the US to H, and figure 5c adds China in place of the US. Market L includes all countries not in H. Market LL is the countries in market L that the World Bank classifies as low and lower-middle income. The solid blue lines show price impacts under a CBAM, while the dashed blue lines show price impacts without a CBAM. The solid lines coincide across L and LL because LL is a subset of L. The dashed lines coincide

Figure 5: Change in prices ΔP^m ($/t)

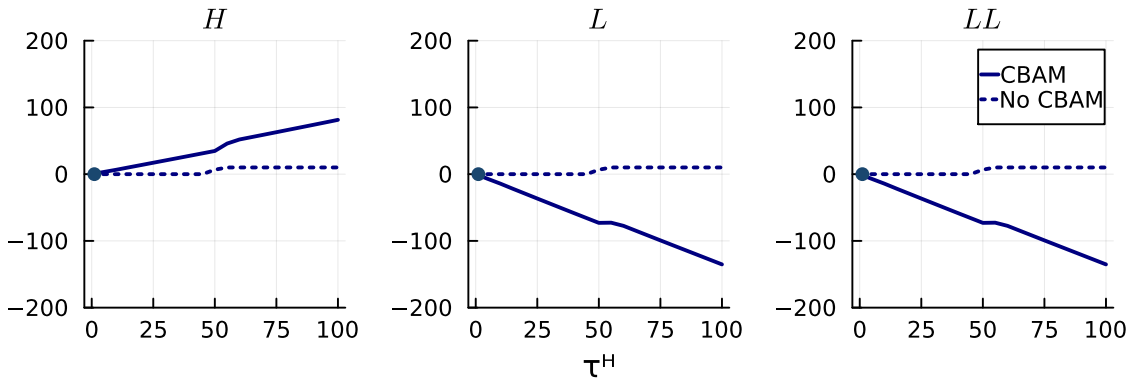
(a) EU/UK as market H



(b) EU/UK/US as market H



(c) EU/UK/China as market H



We compute changes in prices relative to business as usual with $\tau^H = \tau^L = 0$. We show impacts with and without a CBAM for high-regulation market H, low-regulation market L, and lower-income, low-regulation market LL. LL is a subset of L. Dots mark carbon taxation τ^H at current, observed levels: we measure carbon taxes for countries in markets H, and we compute production-weighted averages.

across H, L, and LL because prices equalize globally absent a border adjustment. Dots mark carbon taxation τ^H at current, observed levels, which we compute as production-weighted averages of carbon taxes for countries in H.

Price effects are governed by two forces: regulation and reallocation. Without a CBAM, we isolate the regulation force. Regulation in market H adds to production costs and shifts the global supply curve inward, resulting in higher prices globally. These price effects are attenuated if unregulated producers in L respond to higher prices with increased production. This "leakage" of production undercuts emission reductions in H. With a CBAM, the reallocation force emerges. Dirty producers in L seek to avoid the CBAM by reallocating sales away from H, reducing supply in H and raising supply in L. The result is higher prices in H and lower prices in L. These price effects are attenuated if unregulated consumers in L respond to lower prices with increased consumption. This "leakage" of consumption again undercuts emission reductions in H. Leakage is limited in our current modeling because our supply curve is inelastic beyond observed capacities, and our demand curve is relatively inelastic by assumption.

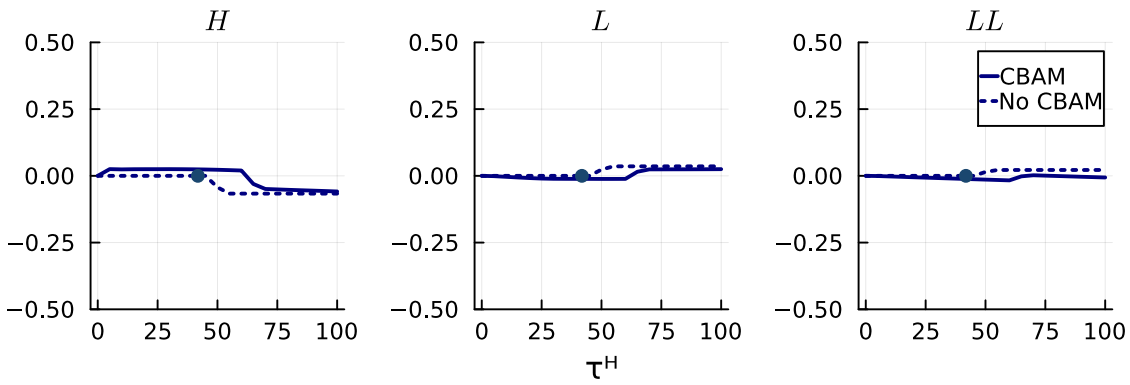
For market H, both regulation and reallocation lead to higher prices. The dashed line isolates the regulation force, and the difference between the solid and dashed lines gives the reallocation force. When H does not include China, extensive reallocation under the CBAM leads to much higher prices in H as regulation τ^H becomes more stringent. When H does include China, there is reduced scope for reallocation because L is small relative to the amount of production that producers seek to reallocate away from H. The result is much smaller price increases in response to regulation τ^H.

For markets L and LL, regulation leads to higher prices, while reallocation leads to lower prices. When H does include China, the reallocation force is large because consumption in L is small relative to the production reallocated away from H. The opposite holds when H does not include China, such that the reallocation force is weak. In this case, the regulation force can dominate and lead to higher prices on net, at least for some levels of regulation τ^H.

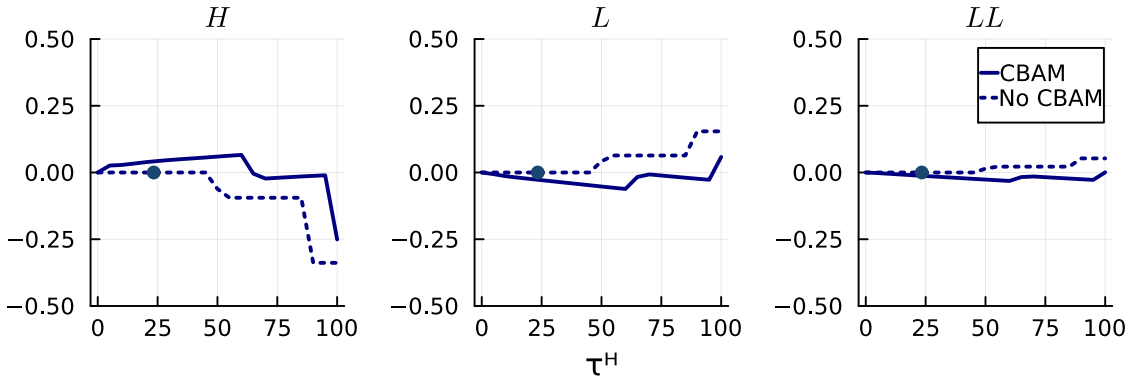
Figure 6 shows the resulting welfare impacts across markets. We first consider when market H includes the EU and UK. Appendix figure A3 shows the breakdown

Figure 6: Change in welfare ΔW^m (1B USD)

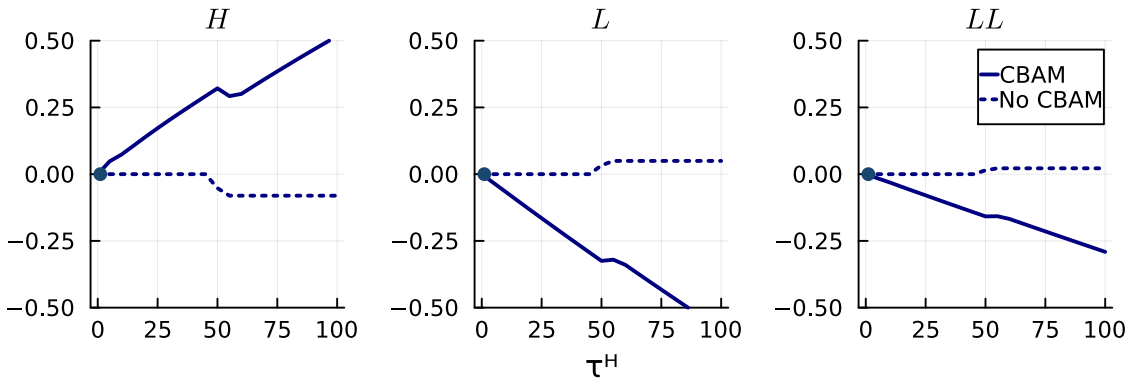
(a) EU/UK as market H



(b) EU/UK/US as market H



(c) EU/UK/China as market H



We compute changes in welfare relative to business as usual with $\tau^H = \tau^L = 0$. Welfare includes consumer surplus, producer surplus, and government revenue. We show impacts with and without a CBAM for high-regulation market H, low-regulation market L, and lower-income, low-regulation market LL. LL is a subset of L. Dots mark carbon taxation τ^H at current, observed levels: we measure carbon taxes for countries in markets H, and we compute production-weighted averages.

of consumer surplus, producer surplus, and government revenue in this case.[9] For H, the CBAM dominates in terms of overall welfare. Large price increases under the CBAM lead to large losses for consumers. But producers benefit from added protection from foreign competition, and the CBAM itself generates significant government revenue. For L and LL, the CBAM leads to worse welfare outcomes, but not especially so. Producers largely suffer because the CBAM represents more stringent regulation, except when prices rise on net because the regulation effect dominates for some levels of carbon regulation τ^H. When prices do decline, producer losses are offset by consumer benefits because consumers enjoy lower prices in L.

When market H includes the EU, UK, and US, the effects are somewhat magnified. When paired with a CBAM, we note that carbon taxation as high as $\tau^H \in [75, 95]$ can deliver emission reductions with limited welfare losses relative to business as usual. Appendix figure A4 breaks down the components of welfare. For H, losses for consumers and producers are offset by government revenue from the CBAM. For L and LL, price impacts are limited because the regulation and reallocation forces offset each other.

When market H includes the EU, UK, and China, the CBAM leads to large welfare gains in H but large welfare losses in L and LL. Appendix figure A5 again breaks down the components of welfare. For H, regulation itself leads to substantial government revenue, even without the CBAM in place. Indeed, this government revenue is on the order of tens of billions of dollars. Moreover, H is a dominant producer on the global stage. Regulation can be welfare-enhancing for H because it can exercise its market power and manipulate the terms of trade. But welfare gains in H are at cost to L.

[9] Appendix figure A6 provides a further breakdown of producer profits by smelter under carbon regulation τ^H at current, observed levels, both with and without a CBAM. A CBAM reduces profit losses to some extent for smelters in H, while imposing profit losses on smelters in L and LL. At the same time, regulation still binds for the dirtiest smelters in H. Furthermore, many smelters in L and LL are relatively clean, and so their profit losses remain limited.

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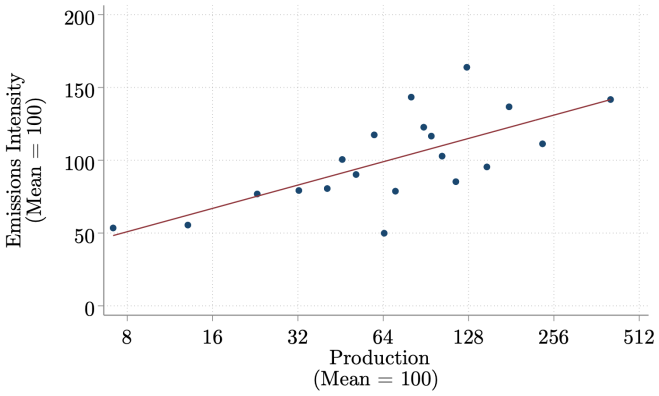
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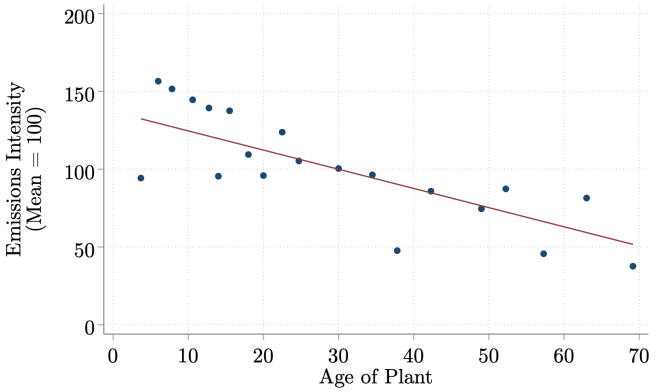
Appendix

Figure A1: Emission intensity, production, and plant age

(a) Emission intensity vs. production



(b) Emission intensity vs. plant age



(c) Production vs. plant age

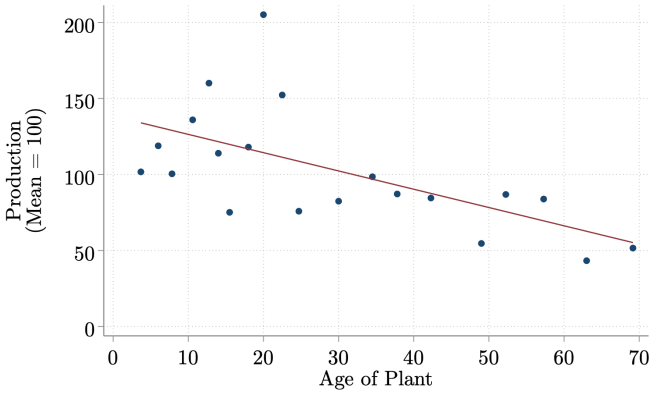
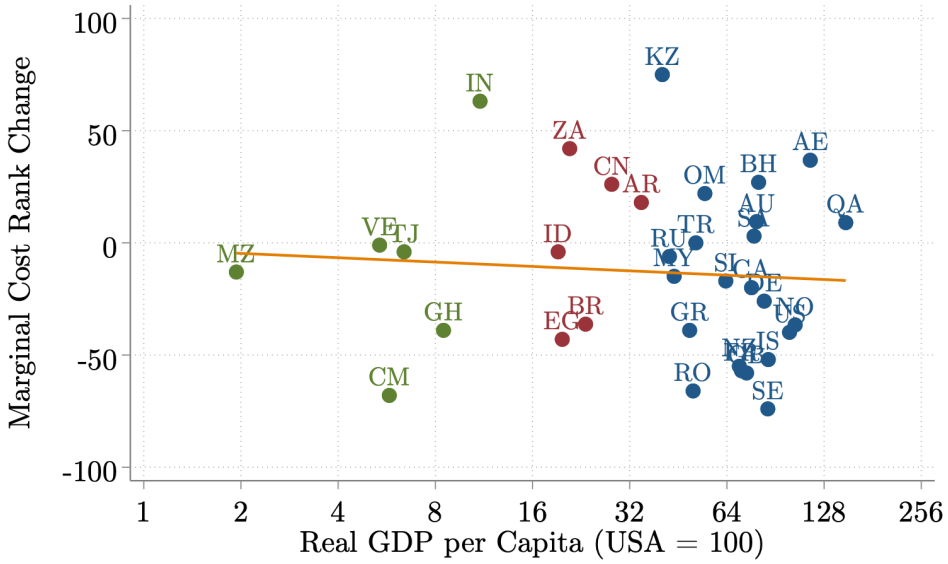


Figure A2: Heterogeneity in changes in marginal costs under a CBAM

(a) Rank changes vs. real GDP per capita



(b) Rank changes vs. emission intensity

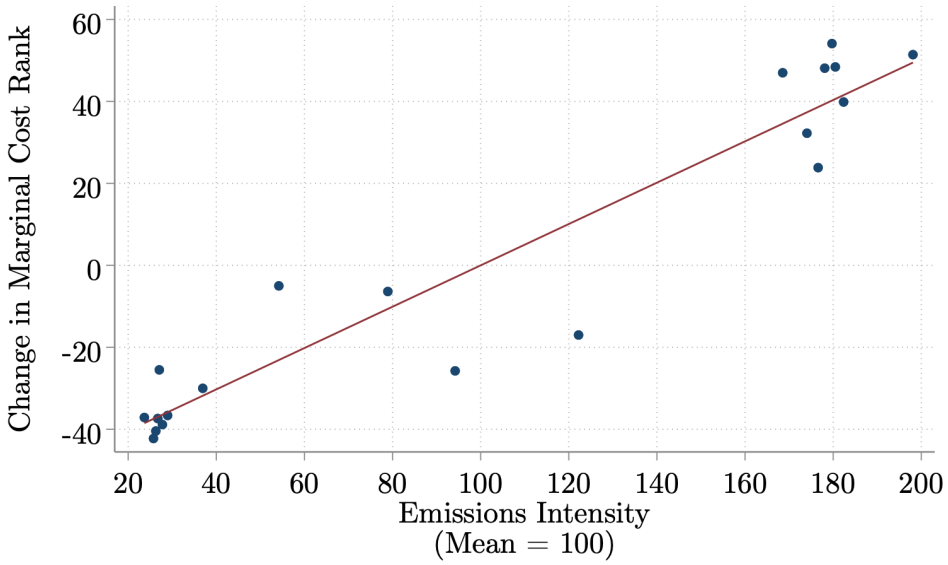
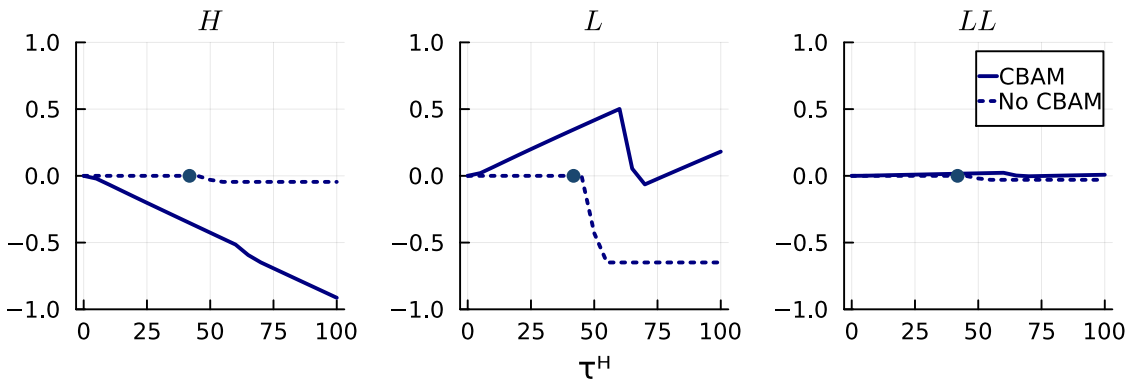
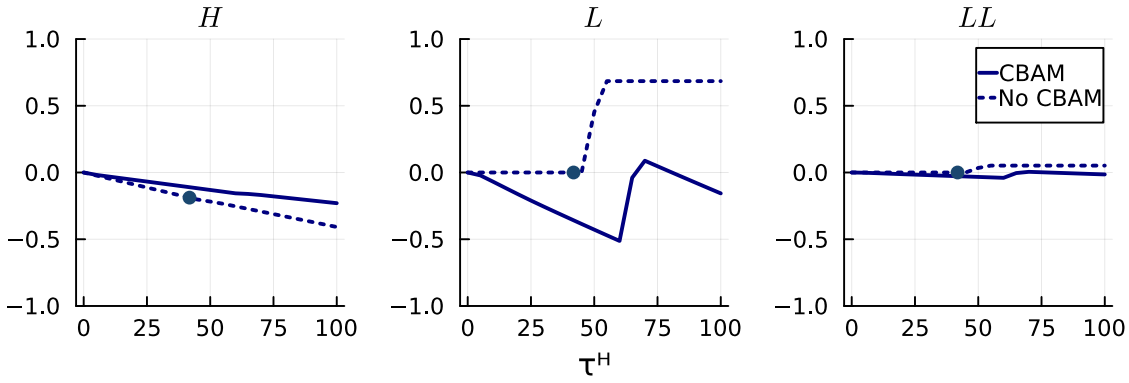


Figure A3: Change in welfare for EU/UK as market H (1B USD)

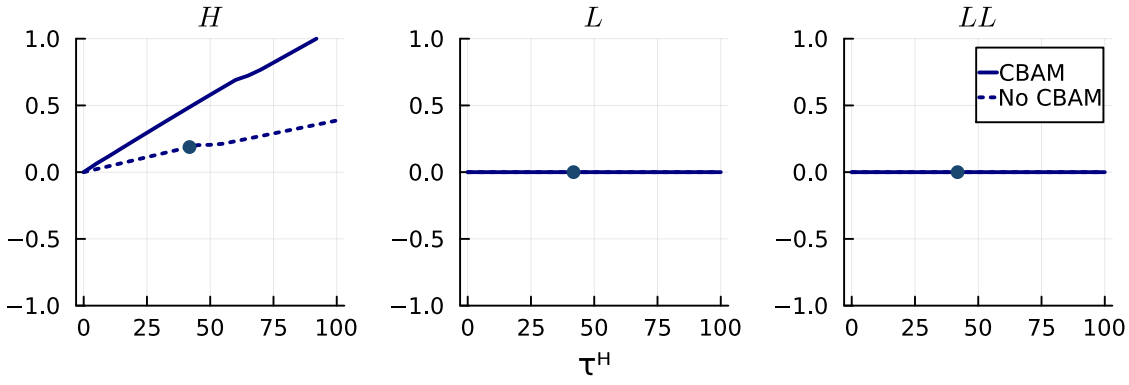
(a) Consumer surplus ΔCS^m



(b) Producer surplus ΔPS^m



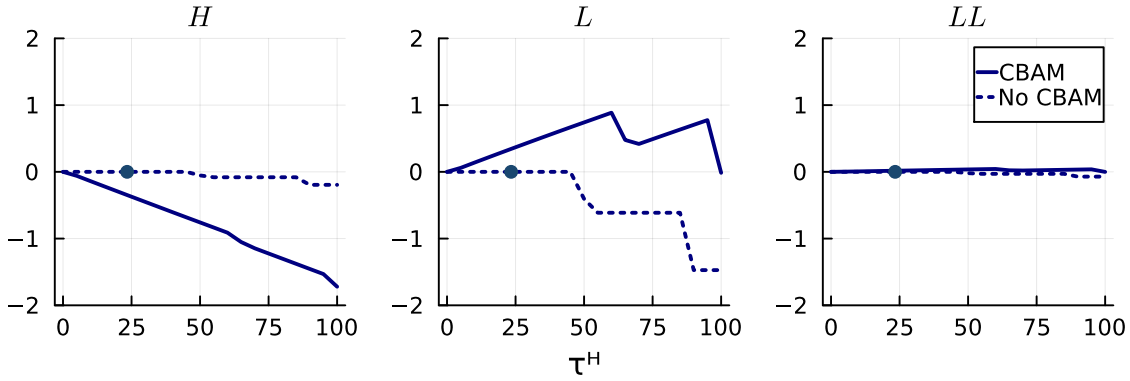
(c) Government revenue ΔG^m



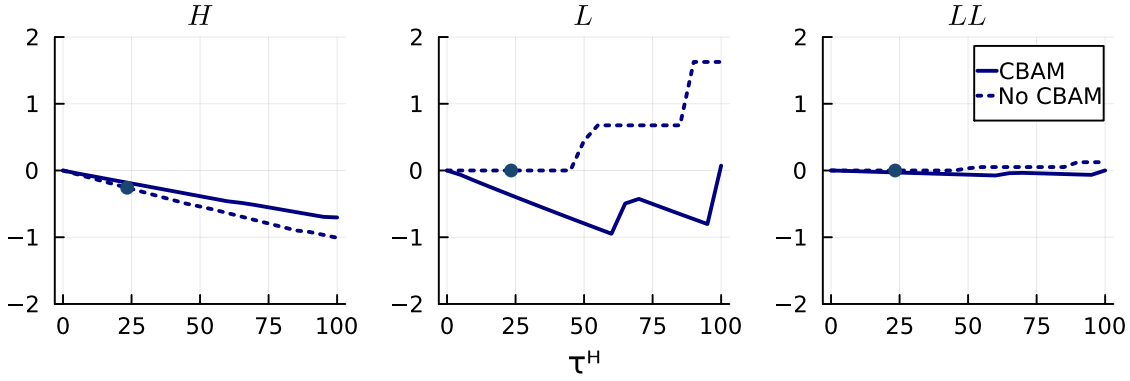
We compute changes in consumer surplus, producer surplus, and government revenue relative to business as usual with $\tau^H = \tau^L = 0$. We show impacts with and without a CBAM for high-regulation market H, low-regulation market L, and lower-income, low-regulation market LL. H is the EU and UK. LL is a subset of L. Dots mark carbon taxation τ^H at current, observed levels: we measure carbon taxes for countries in market H, and we compute the production-weighted average.

Figure A4: Change in welfare for EU/UK/US as market H (1B USD)

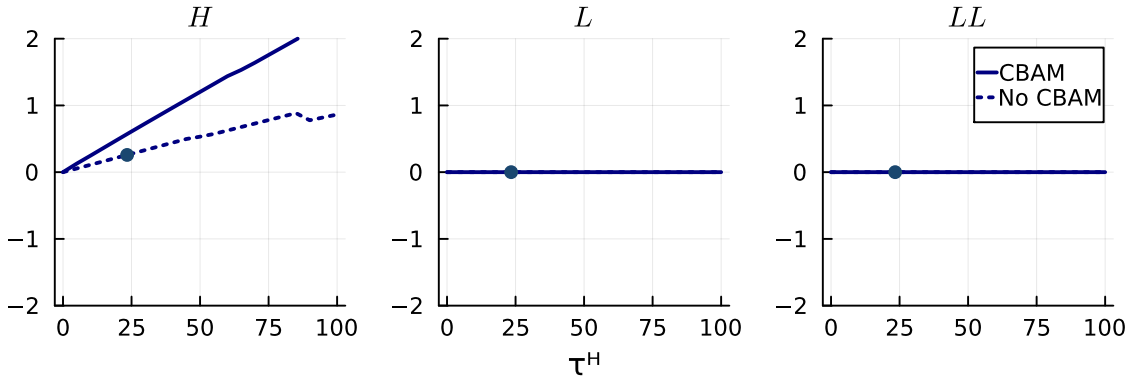
(a) Consumer surplus ΔCS^m



(b) Producer surplus ΔPS^m



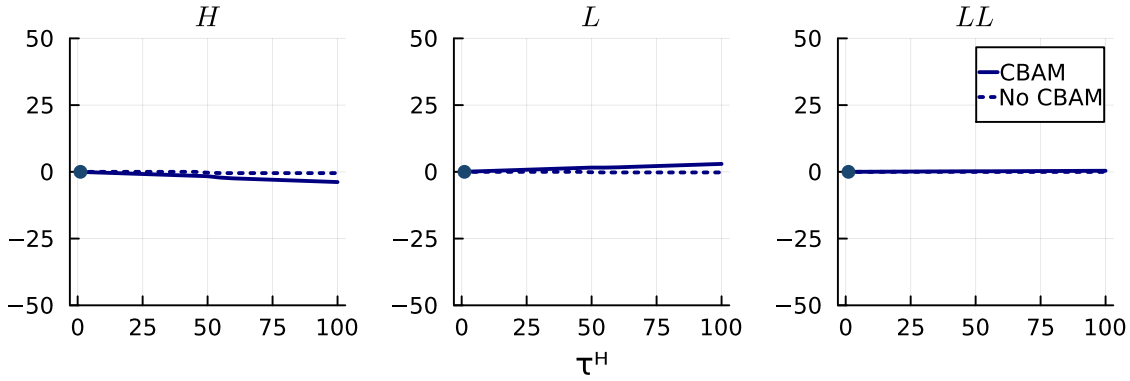
(c) Government revenue ΔG^m



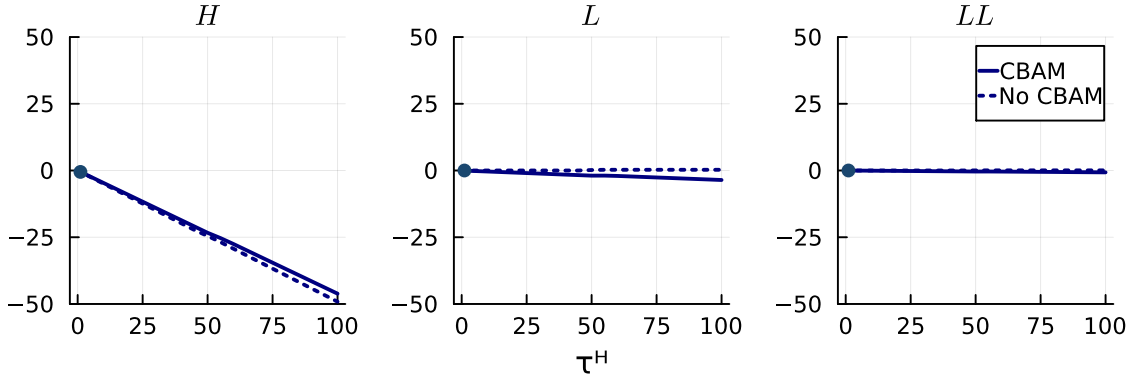
We compute changes in consumer surplus, producer surplus, and government revenue relative to business as usual with $\tau^H = \tau^L = 0$. We show impacts with and without a CBAM for high-regulation market H, low-regulation market L, and lower-income, low-regulation market LL. H is the EU, UK, and US. LL is a subset of L. Dots mark carbon taxation τ^H at current, observed levels: we measure carbon taxes for countries in market H, and we compute the production-weighted average.

Figure A5: Change in welfare for EU/UK/China as market H (1B USD)

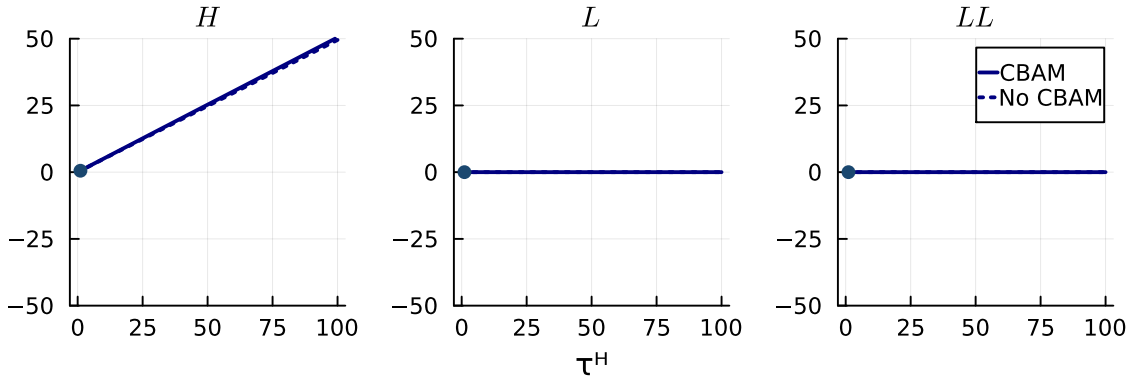
(a) Consumer surplus ΔCS^m



(b) Producer surplus ΔPS^m



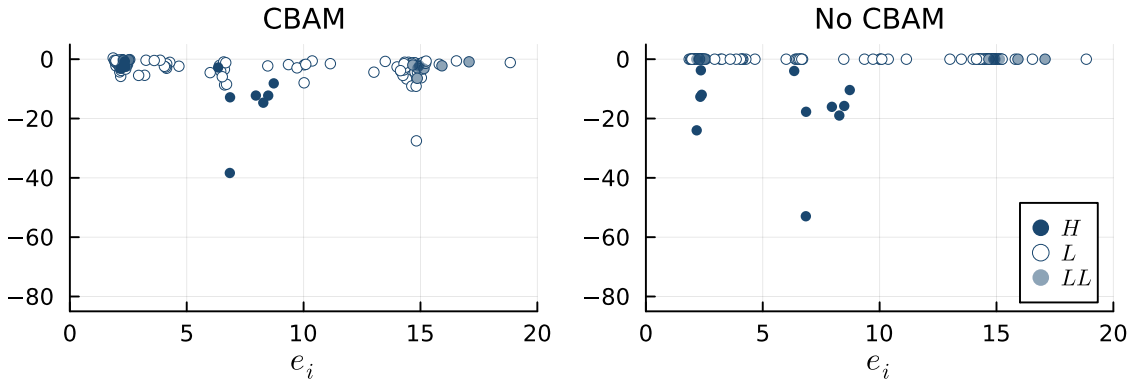
(c) Government revenue ΔG^m



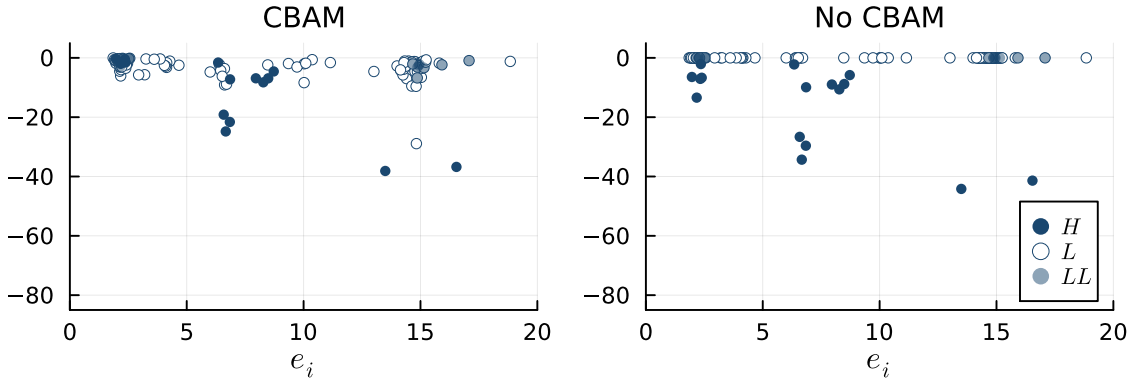
We compute changes in consumer surplus, producer surplus, and government revenue relative to business as usual with $\tau^H = \tau^L = 0$. We show impacts with and without a CBAM for high-regulation market H, low-regulation market L, and lower-income, low-regulation market LL. H is the EU, UK, and China. LL is a subset of L. Dots mark carbon taxation τ^H at current, observed levels: we measure carbon taxes for countries in market H, and we compute the production-weighted average.

Figure A6: Change in producer profits $\Delta\pi_i$ under observed τ^H (1M USD)

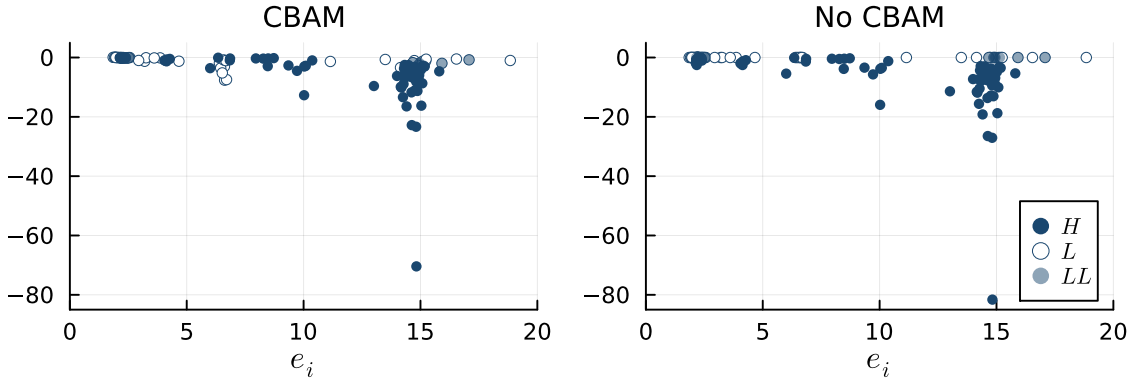
(a) EU/UK as market H



(b) EU/UK/US as market H



(c) EU/UK/China as market H



We compute changes in producer profits, net of carbon taxes and border taxes, relative to business as usual with $\tau^H = \tau^L = 0$. We show impacts with and without a CBAM for high-regulation market H, low-regulation market L, and lower-income, low-regulation market LL. LL is a subset of L. We evaluate carbon taxation τ^H at current, observed levels: we measure carbon taxes for countries in markets H, and we compute production-weighted averages. Each dot is one smelter.