Online Technical Appendix

Building a Climate Coalition: Aligning Carbon Pricing, Trade, and Development
Flagship Report of the Global Climate Policy Project (GCPP) Working Group on Climate Coalitions
(the "Report")

Introduction

This online appendix describes the framework and assumptions used to generate the simulation results in the Report. We employ two complementary models to enhance the robustness of our findings. Both models simulate the same scenarios and assume that carbon pricing in a climate coalition applies to four emissions-intensive industries: steel, aluminum, cement, and fertilizers.

There are several assumptions that are shared across both models and apply in each coalition scenario (*Uniform Price* and *Graduated Price)* as well as the *Current Policy Baseline* scenario. Carbon pricing policy is at the country-level. We assume that each country can have a carbon tax or an emissions trading system. For ease of modeling, we assume that there are no free allowances, so that the domestic revenue accrued from an emissions trading system or carbon tax would be equivalent, given the resulting allowance trading price is equal to the level of the carbon tax. We assume that auction reserve prices can keep the carbon price generated by an emissions trading system at or above the level of the price floors for each scenario. For ease of modeling, we assume that carbon prices are equal to the price floor for each scenario, and not above it. We assume that carbon prices cover both Scope 1 emissions (from fuel combustion and chemical processes) and Scope 2 emissions (from electricity used in production).

Table OA1 below is included as Table 2 in the Report and summarizes key assumptions in the two coalition scenarios and the *Current Policy Baseline* scenario. It is copied below.

Table OA1 Overview of coalition scenarios

	Current Policy Baseline	Uniform Price	Graduated Price
Country membership	European Union, United Kingdom, Iceland, Norway, Switzerland, Liechtenstein	Algeria, Australia, Brazil, Cameroon, Canada, China, Egypt, European Union, Ghana, Iceland, India, Indonesia, Kenya, Liechtenstein, Mozambique, Norway, Switzerland, Thailand, Togo, United Kingdom, Uganda, Zambia	
Carbon price floor	\$75/t	\$50/t	HIC: \$75/t UMIC: \$50/t LMIC/LIC: \$25/t
Border adjustment	\$75/t	\$50/t	\$75/t
Free allowances	No	No	No

Notes: In the *Graduated Price* scenario, all countries set the border adjustment to the same value, \$75/t, while varying the level of their domestic carbon prices.

Importantly, we carry the broad assumption that countries that are not in the coalition have a carbon price of \$0. We also calculate a “zero-regulation” baseline that assumes that every country has a carbon price of \$0. We do this to standardize a reference baseline between both models and as the basis for estimating the impacts of the *Current Policy Baseline*. Although there are many jurisdictions that have existing carbon prices, average price levels remain low due to high free allowance allocations. The following table shows the average carbon prices paid in 2023 in steel-producing countries after accounting for free allowances. Countries highlighted in blue are those that are included as coalition members in the *Current Policy Baseline.*

Table OA2 Carbon prices on steel production in 2023

	Prices (\$/t)	
Country (Region)	Unadjusted	Adjusted
Argentina	3.27	3.27
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
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
New Zealand	34.20	34.20
Singapore	3.77	3.77
South Africa	8.93	2.23
South Korea	11.24	3.49
Ukraine	0.82	0.82

Austria	96.29	43.29
Belgium	96.29	11.23
Bulgaria	96.29	33.60
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
Netherlands	96.29	44.17
Norway	96.29	0.00
Poland	96.29	53.00
Portugal	96.29	0.18
Romania	96.29	23.36
Slovakia	96.29	43.43
Slovenia	96.29	15.91
Spain	96.29	3.11
Sweden	96.29	32.17
Switzerland	93.81	0.00
United Kingdom	88.13	20.78

Notes: 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. Countries highlighted in blue are included in the Current Policy Baseline.

Both models are static: they represent each policy scenario as a new equilibrium with the policy fully in place and all changes already realized. These models are designed to capture differences between counterfactual scenarios in static equilibrium states; they do not address the timeline for implementation nor how long it would take for the changes between states to take place. For each scenario and the zero-regulation baseline, we calculate prices, emissions, production, producer revenue (price multiplied by production), domestic carbon tax revenue, and border carbon adjustment fee revenue. Of course, the government revenue is $0 in the zero-regulation baseline. For the coalition scenarios (*Uniform Price* and *Graduated Price*), we report output and price changes as percentage changes from the *Current Policy Baseline.* We calculate domestic carbon tax revenue at the country level as the sum of carbon price payments that are made from all the domestic producers in that country. Domestic carbon tax revenue is not reported (see Figure ES2 and Figure 4 and Figure 5) relative to another scenario; the Figures represent all the revenue that is generated from regulated producers versus if there were no carbon price at all. Emissions changes are calculated from a zero-regulation baseline, and we assume the emissions level for the zero-regulation baseline align with actual 2023 emissions. Therefore, the reported emissions changes reflect the full modeled abatement impacts of the price floors (not the abatement impacts of the price floors relative to the abatement impacts of existing carbon prices). This is a broad assumption made for the ease of modeling.

Literature

Both models build on a growing body of work that studies the environmental effects of trade policy, specifically border carbon adjustment mechanisms (BCAs), including but not restricted to Ismer & Neuhoff (2007); Elliot et al. (2010); Böhringer et al. (2012); Fischer & Fox., (2012);

Schinko et al. (2014); Fowlie et al. (2016); Kortum & Weisbach (2017); Mehling et al. (2019); Böhringer et al. (2021); Böhringer et al. (2022); Fowlie & Reguant (2022); Grubb et al. (2022); Perdana & Vielle (2022); Zhong & Pei (2022); Clausing and Wolfram (2023); Bellora & Fontagné (2023); Lin & Zhao (2023); Rorke et al. (2023); Coster et al. (2024); Perdana et al. (2024); Takeda & Arimura (2024); Magacho et al. (2024); Clausing et al. (2025); Tanaka & Nagashima (2025); Walczak et al. (2025). The *Model Without Trade Frictions* builds on the model in Clausing et al. (2025) and lies in the realm of quantitative microeconomic trade models tied to the field of empirical industrial organization that leverage firm-level data on individual industries (Bernard et al., 2003; Demailly & Quirion, 2006; De Loecker, 2011; Eaton et al., 2011; Ryan, 2012; Collard-Wexler & De Loecker. 2015; Roberts et al., 2018; Shapiro & Walker, 2018). The *Model with Trade Frictions* builds on the body of Armington style computable general equilibrium models as examined in Arkolakis (2012) including those used for evaluating climate and trade policy such as in Casey et al. (2025). Leveraging both models helps bound our results and the consistency between the results of the model provides robustness to our analysis. Overall, in line with general trends in the economic trade literature, these models put more emphasis on transparency and less emphasis on capturing all features of the relevant markets. They are designed to be powerful enough to capture first-order features of the data, like the role of country size and emissions intensity, but simple enough that we can credibly identify the crucial parameters and see how changing them shifts the policy predictions.

The following sections outline the methodology and critical assumptions of each model.

Model without Trade Frictions

Data

Production

We use detailed, plant-level data on production, capacity, costs, and emissions for four industries: steel, aluminum, cement, and fertilizers. We use the ammonia industry as a proxy for fertilizers due to data limitations and as ammonia production accounts for the majority of carbon dioxide emissions associated with manufacturing nitrogenous fertilizers. The exclusion of potassium and phosphorous fertilizers is due to data limitations but also follows the EU CBAM's focus on nitrogenous fertilizers, which are relatively more emissions intensive than other types of fertilizers, as they primarily use natural gas or coal as a feedstock rather than a mined natural mineral (like phosphate or potash). Data for primary aluminum are from Wood Mackenzie, a leading data provider for the energy sector. Data for secondary aluminum are from the World Bureau of Metal Statistics from the London Stock Exchange Group. Data for steel, cement, and ammonia are from Climate TRACE (Tracking Real-time Atmospheric Carbon Emissions), an independent non-profit that monitors and reports global greenhouse gas emissions. The data are from 2023 and include 892 steel plants, 163 aluminum plants, 2,241 cement plants, and 223 ammonia plants. Steel production includes primary steel (produced in a basic oxygen furnace) and secondary steel (produced in an electric arc furnace). Aluminum production includes primary aluminum (from mined bauxite ore which is refined to alumina and then reduced via the Hall-Héroult process to yield aluminum) and secondary aluminum (produced from recycled aluminum scrap). We treat primary and secondary materials as perfect substitutes.

Consumption

We estimate consumption as production plus net imports, using 2023 country-level trade data from UN Comtrade (except for Russia where we use 2021 data due to availability). The HS codes for steel are those that are targeted by the EU CBAM: HS codes 7201, 720211, 720219, 720241, 720249, 720260, 7303, and 7205 through 7220. The HS code for aluminum is 7601, "Aluminum; unwrought." The HS code for cement is 2523, and for ammonia is 2814. 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 global prices in 2023.

Prices

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, cement, and ammonia are not widely traded on exchanges, and so we calculate a global price as the weighted average of export prices for each product. The average steel price was 1,011 USD per ton in 2023, the average cement price was 76 USD per ton, and the average ammonia price was 577 USD per ton.

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 plants are spread across jurisdictions with 27 different carbon pricing schemes: 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.

Model

Structure

We combine our microdata with a quantitative equilibrium model of global trade. For each scenario and the zero-regulation baseline, we model carbon pricing and a border carbon adjustment (BCA) in a world commodity market. The model considers two markets. The first consists of coalition member countries, all of which impose carbon prices on domestic production and border carbon fees on imports from non-member trading partners in each of the coalition scenarios (in the *Current Policy Baseline,* only a subset of the coalition countries implement these policies). The second comprises the rest of the world where carbon emissions are not priced. We also calculate a zero-regulation baseline where there are no carbon prices. For each market, we use our country-level consumption data and specify log-linear demand with a constant price elasticity of demand of -0.25, which is consistent with low empirical estimates for these sorts of primary commodities (Söderholm and Ekvall, 2020). We aggregate across countries to measure consumption by market. We obtain empirical demand curves that identify how demand in each market responds to prices. Global demand is the sum of demand across each market. Goods from each industry are assumed to be homogenous and are treated as perfect substitutes across countries (e.g., a consumer values a ton of aluminum from the United States the same as a ton of aluminum from China, regardless of where the consumer is located, all else equal).

We use our plant-level data to construct supply. Each producer has a fixed capacity and a constant marginal cost that are observed in the data; we assume that changes in capacity and cost require significant investment that is challenging in the short run. Assuming constant marginal costs allows us to read costs from our plant-level data akin to Asker et al. (2019). We use observed production and capacity to compute capacity utilization, and we observe that capacity utilization is highest for low-cost producers and lowest for high-cost producers. We allow production and prices to respond endogenously to regulation. We assume that each producer has a collection of production lines that can be "on" or "off" and we model the utility of operating a production line. We use the capacity utilization, price, and cost data to estimate a profit coefficient that captures how producers value profits in utility terms and governs how changes in prices or costs translate to changes in production. For a given producer, production lines have common observed costs, common unobserved costs, and idiosyncratic unobserved costs, which we assume are logit distributed. We model producer choices at the production line level; a producer will operate a line when its profit plus the idiosyncratic unobserved cost is positive. We interpret the fraction of lines that will operate as capacity utilization. Capacity utilization increases when a producer's per-unit profits (the market price minus the per-unit production cost including any carbon prices) increase and falls when per-unit profits decrease. Thus, there is a smooth, extensive-margin supply response: small price or cost changes shift utilization continuously up to a plant's capacity. Output at the producer level is capacity multiplied by capacity utilization. World supply is the sum of output across all producers.

Carbon policy enters through the producer's per-unit profits. If a market levies a domestic carbon tax, per-unit profits are reduced in proportion to the producer's emissions intensity. Producers abate in response. The model allows producers emissions per ton to fall when the carbon cost is higher, using a fixed elasticity of 0.3 per dollar of carbon price, 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. This abatement channel partially offsets the reduction in profits from the carbon price itself.

A BCA is modeled as a price wedge equal to the regulated market's carbon price floor. The price wedge is an adjustment such that all consumption in the regulated market is subject to a price floor. Goods produced in the regulated market face a price floor during production, while goods imported from the unregulated market face the price floor at the border. Prices no longer equalize across markets, and so we distinguish between prices in the regulated market and prices in the unregulated market. Producers decide which market to serve, and so regulation affects trade. Producers in the regulated market can choose among the two prices, but they are always subject to the domestic carbon price floor; they do not receive a tax refund when exporting to the unregulated market. We define net prices less the carbon price floor for regulated producers who sell into the regulated market and who sell into the unregulated market. We also define net prices for producers in the unregulated market which experience a carbon price only when exporting to the regulated market. Producers choose their highest net price—they sell into the regulated market when net prices in the regulated market dominate, otherwise they serve the unregulated market. Producers do not face increased costs for adjusting exports across markets and can immediately redirect their production to more profitable destinations in response to policy changes. Under these assumptions, even small changes in relative prices or trade costs because of carbon pricing policy can lead to adjustments in trade flows between markets.

Without a climate coalition—as in our zero-regulation baseline—equilibrium prices clear global markets, so we see a single global price per industry (which we observe in the data). Under a climate coalition with a BCA, there is a price wedge. In equilibrium, the price in the unregulated market and the price in the regulated market clear each market separately so we see two prices per industry—one for each market. The marginal producer will be indifferent between selling to the regulated market or the unregulated market.

When the regulated market imports from the unregulated market**,** then the regulated market's price ends up higher than the unregulated because selling into the regulated market requires paying the higher carbon price. Clean plants (with a low emissions intensity in our data) can profitably access the higher price in R and redirect shipments there, moderating the regulated market's price increase with increased supply while dirtier exporters are pushed toward the unregulated market, which expands supply and puts downward pressure on the unregulated market's price.

Estimation

Using our country-level consumption data and plant-level production data described above, we construct empirical supply and demand curves for both markets (unregulated and regulated) for each of the four industries. We solve each industry separately and thus the *Model without Trade Frictions* does not capture any spillover effects between industries. We vary the levels of carbon taxation and market membership according to the three scenarios (*Uniform Price, Graduated Price,* and *Current Policy Baseline*) as well as a zero-regulation baseline. For the *Graduated Price* scenario, we evaluate impacts on the regulated market divided into high-income countries (HIC), upper-middle-income countries (UMIC) and lower-middle-income and low-income countries (LMIC/LIC). We vary the level of domestic carbon pricing for these submarkets but not the BCA fee. We report equilibrium prices, emissions, production, producer revenue (price multiplied by production), domestic carbon tax revenue, and border carbon adjustment fee revenue.

Model with Trade Frictions

Data

EXIOBASE

We use EXIOBASE v3.9, a multi-region input-output (MRIO) database, for bilaterial trade data (Stadler et al., 2018). EXIOBASE provides 200 product groups with 44 individual countries (the 27 EU members plus 17 major economies) and five rest-of-world (RoW) regions. We aggregate the EU into a single region and keep the 17 non-EU countries and the five RoW regions, yielding 23 total regions. Because the EU is modeled as one region, we drop intra-EU trade and aggregate all EU members to "EU" on both exporter and importer sides. Although EXIOBASE extends its time series ("nowcasts") to 2022 using Comtrade trade data and macro indicators from the IMF, we adopt the recommended 2020 benchmark (v3.9.4) to avoid COVID-era nowcasting artifacts.[1] We work at the EXIOBASE product level. We convert monetary values from million EUR to million USD using 2020 IRS exchange rates. We aggregate final demand categories in EXIOBASE and add them to inter-industry flows, so the bilateral trade matrices used by the model include both intermediate and final uses. For numerical stability, we remove any product with zero trade across all sectors. The regulated EXIOBASE products include "iron and steel," "aluminum and aluminum products," "cement," and "N-fertilizer."

Elasticities

Armington elasticities come from Ossa (2015) which reports substitution elasticities for 251 SITC Rev.3 product categories. We construct a crosswalk from EXIOBASE products to SITC3 and merge the elasticities onto the EXIOBASE product list. When an EXIOBASE product maps to multiple SITC3 codes, we take the unweighted mean of the available elasticities.

Emissions

Emissions intensities for the covered industries come from the same plant-level microdata used in the *Model without Trade Frictions.* We collapse emissions intensities to the EXIOBASE product-country level using production-weighted averages. These intensities are used to calculate carbon-policy shocks for the regulated industries (both domestic carbon pricing and BCAs).

Prices

We attach product-level prices (USD per ton) for each EXIOBASE product using country-level weighted-average UN Comtrade 2023 export values and a crosswalk between EXIOBASE sectors and HS codes.

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[1] In the Report, we followed Exiobase's recommendation to use 2020 data as the latest available year. As an additional robustness check, we ran the analysis using 2019 trade data. Results for carbon pricing revenues, price changes, and emissions did not change significantly. CBAM revenue decreases by $700 million in the Uniform Price scenario and $900 billion in the Graduated Price scenario, closer to the lower estimates in the *Model without Trade Frictions* (Figure 4 in the Report).

Together, the EXIOBASE 2020 bilateral trade flows, Ossa (2015) elasticities, emissions intensities from WoodMac and Climate Trace, and 2023 prices per ton from UN Comtrade form a consistent dataset for estimating the *Model with Trade Frictions*.

Model

Structure

A gravity model such as the *Model with Trade Frictions* is part of an important class of Armington-style models described in Arkolakis et al. (2012). The Armington model is considered one of the simplest models in the economic trade literature. The *Model with Trade Frictions* extends from the Armington model as a multi-country, multi-sector general-equilibrium trade framework with the assumption that goods are differentiated by country and are imperfect substitutes. (e.g., U.S. steel and Chinese steel are treated as distinct products despite identical physical properties). Consumers can substitute between products from different countries, but their willingness to do so varies for different products—for example, consumers may view steel from different countries as nearly identical but consider automobiles from different countries as quite distinct. As previously stated, the model captures this substitution behavior based on empirical elasticity estimates from Ossa (2015).

Within each country, households spend a fixed share of their total expenditure on each sector (Cobb-Douglas across sectors). Labor moves freely across sectors inside a country but not across countries. Because all households in a country face the same prices, nominal and real wages are equalized across that country's sectors.

Production is perfectly competitive with constant returns to scale. Each country-sector produces an origin-specific product variety using domestic labor and sector-country productivity; the local sectoral final good is a CES aggregate over these origin-specific varieties with sector-specific elasticities of substitution. Consumers value the same sectoral product differently depending on where it was made (e.g., "U.S. steel" vs. "Chinese steel"), with a sector-specific elasticity of substitution (from Ossa, 2015) governing how easily buyers switch between foreign and domestic products.

Trade is subject to iceberg costs: shipping a good from country i to j requires more than one unit of the good to deliver one unit of the good. Domestic shipments have no such cost. The ratio of number of units required to deliver one unit international is the iceberg factor. Perfect competition implies that the delivered price a buyer sees equals the origin price times the iceberg factor. Combining this structure with the demand function for the local sectoral final good yields a standard gravity expression for trade shares that depends on (i) bilateral trade costs, (ii) each origin's production price and productivity, and (iii) preference weights (captured by baseline trade shares). The model is therefore able to determine how each destination's sectoral expenditure is split across origins. It also computes a CES sectoral price index for each country.

The two equilibrium conditions are a market-clearing condition and a gravity equation. First, in each country and sector, labor income equals labor's share of total spending on that country-sector's goods (a sector-specific labor share maps revenue into wages and employment). Second, bilateral trade flows must follow the gravity equation described above. Solving these two systems jointly yields wages by country, output by country-sector, bilateral trade flows by sector, and sectoral price indices by country. The model keeps current-account deficits fixed as is standard practice in these static models (see e.g. Dekle et al. (2008), so total expenditure equals income plus the pre-policy deficit. Because sectoral preferences are Cobb-Douglas, shifts in sectoral expenditures track shifts in total expenditure.

Carbon policy enters through two channels and is applied to the four covered products. A domestic carbon tax acts like raising the effective cost of production and is implemented as a reduction in sectoral productivity or taxed country-sectors. A BCA (import tariff) is modeled as an increase in bilateral iceberg trade costs applied by the importing country on the embodied emissions of the exporter's product. Intra-coalition imports are not subject to the BCA. In both cases, an abatement elasticity of 0.3 per dollar of carbon tax is applied in a similar manner as the *Model without Trade Frictions.* Both levers shift relative prices and hence trade shares, sectoral price indices, and real wages. After computing comparative statics for sectoral quantities, we can estimate emissions changes using baseline emissions intensities and abatement responses parametrized by the abatement elasticity. The model does not capture spillovers in fossil fuel markets. However, from the data we estimate that over half of the energy input across the four sectors is coking coal for steelmaking. This type of steel is used almost exclusively for steelmaking, and a distinct type of coal—thermal coal—is used in power plants to generate electricity. So it may not be unrealistic to assume that there will not be significant spillovers in the fossil fuel market that will affect non-regulated industries.

Estimation

Together, the EXIOBASE 2020 bilateral trade flows, Ossa (2015) elasticities, emissions intensities from WoodMac and Climate Trace, and 2023 prices per ton from UN Comtrade form a consistent dataset for estimating the *Model with Trade Frictions*. For each scenario (*Uniform Price, Graduated Price,* and *Current Policy Baseline*) and the zero-regulation baseline, we vary country-level domestic carbon prices and BCA fees. After prices and quantities adjust in accordance with the market clearing conditions described above, emissions changes are computed in post-processing from sectoral quantity changes, baseline emissions intensities, and abatement responses according to the abatement elasticity. Comparative statics are computed in "changes." Rather than re-solving levels from scratch, the model takes observed baseline data (wages, trade shares, expenditures, deficits, etc.) and solves for percentage changes in all variables between the baseline equilibrium (which is a zero-regulation baseline with no carbon prices) and a policy scenario equilibrium. This "solve-in-hats" approach was popularized by Dekle et al. (2008) and makes it straightforward to apply carbon price shocks (domestic and at the border) and read off the implied percentage changes in wages, outputs, trade shares, sectoral price indices, and emissions. We aggregate country-level impacts up to the level of the coalition and coalition subgroups of high-income countries (HIC), upper-middle-income countries (UMIC) and lower-middle-income and low-income countries (LMIC/LIC). We vary the level of domestic carbon pricing for these subgroups but not the BCA fee. We report equilibrium prices, emissions, production, producer revenue (sectoral price multiplied by production), domestic carbon tax revenue, and border carbon adjustment fee revenue.

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