Carbon Border Adjustment Mechanism and Trade Policy: A Quantitative Analysis*

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Abstract

The European Union (EU) has introduced the Carbon Border Adjustment Mechanism (CBAM) to curb carbon leakage and incentivize global climate policy alignment. We develop a multi-country, multi-sector general equilibrium model featuring input–output linkages, carbon supply chains, and global emission externalities to evaluate the environmental and economic impacts of the EU's CBAM. Our results show that unilateral implementation modestly reduces global emissions due to carbon leakage through global energy markets. Global welfare improves marginally when environmental benefits are accounted for. When other countries respond optimally, strategic carbon policy adjustments under a non-cooperative Nash equilibrium enhance global emission reductions by mitigating both carbon leakage and free-riding. Under a cooperative equilibrium with Nash bargaining, multilateral negotiations yield substantial welfare and environmental gains, with the CBAM functioning as an effective enforcement device that raises the cost of disagreement and fosters deeper global climate cooperation.

Keywords: border adjustment, carbon tax, carbon tariff, quantitative trade policy
JEL codes: F13, F18, F64, H23, Q56

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1 Introduction

A central policy prescription for mitigating global climate change is to establish sufficiently high carbon prices globally that internalize the externality of greenhouse gas emissions (Coster et al., 2024). In practice, however, the adoption of carbon pricing remains limited and highly heterogeneous. According to OECD (2024), fewer than half of the world's countries had implemented a carbon pricing instrument by 2023. Among these adopters, carbon prices vary widely, from below \$1/tCO_2 in Kazakhstan to as high as \$158/tCO_2 in Uruguay, reflecting stark differences in climate governance ambition across countries.[1] Moreover, most initiatives, such as carbon taxes and emissions trading systems (ETS), are implemented unilaterally. Two primary challenges undermine the effectiveness of such unilateral efforts in reducing global emissions. The first is the risk of *carbon leakage*. Direct leakage occurs when emissions-intensive production relocates to jurisdictions with less stringent environmental regulations. Indirect leakage arises through global energy markets, where reduced demand in regulated regions depresses fossil fuel prices and stimulates energy consumption elsewhere (Copeland et al., 2022). The second challenge is the problem of *free-riding*. Because climate change is a global externality, countries may rely on others' mitigation efforts without undertaking proportionate abatement themselves (Nordhaus, 2015).

To curb carbon leakage and incentivize global climate policy alignment, the European Union (EU) introduced the Carbon Border Adjustment Mechanism (CBAM) in 2023, set to take effect in 2026. The CBAM imposes tariffs on EU imports based on their embedded emissions and initially targets carbon-intensive sectors that account for over half of the emissions covered by the EU's ETS (European Commission, 2023). As the first large-scale cross-border initiative integrating trade and climate policy, the CBAM has generated intense scrutiny regarding its economic and environmental impacts.[2] In this paper, we examine three core research questions. First, to what extent does the EU's CBAM reduce global carbon emissions, and at what economic cost? Second, given that the CBAM's effectiveness hinges on the responses of regulated parties, how do non-EU countries strategically adjust their policies, and what are the resulting consequences? Third, as the CBAM may reshape countries' incentives in multilateral negotiations, what are its implications for global cooperation on climate governance? Answers to these questions not only advance academic understanding of the trade–climate policy nexus, but also carry significant policy relevance.

[1] Data source: World Bank Carbon Pricing Dashboard.

[2] For example, Russia has initiated a WTO dispute against the EU's CBAM and emissions trading on 19 May 2025 (`https://www.wto.org/english/news_e/news25_e/ds639rfc_19may25_e.htm`). Critics have also raised concerns about the CBAM's disproportionately negative impact on developing countries (`https://www.reuters.com/sustainability/boards-policy-regulation/comment-eus-carbon-border-tax-is-blow-climate-justice-heres-how-fix-it-2023-11-15/`).

To address these questions, we begin with a multi-country, multi-sector quantitative general equilibrium trade model featuring global input-output linkages, sectoral heterogeneity, and intermediate goods trade, as in Caliendo and Parro (2015). We extend this framework along three dimensions to capture the environmental and economic mechanisms central to evaluating the CBAM. First, fossil fuel and carbon supply chains are explicitly incorporated into intermediate goods production through input-output relationships. We distinguish between primary extractive sectors (e.g., coal, oil, gas) and secondary energy sectors (e.g., refined petroleum, electricity), thereby capturing heterogeneity in energy use and emissions intensity across downstream industries. Second, we count CO_2 emissions generated from both direct energy production and indirect energy consumption. Following Farrokhi and Lashkaripour (2025), households experience disutility from global carbon emissions with country-specific valuations of climate damage, which is modeled as a pure externality. Third, in line with the EU's CBAM design, we model border carbon adjustments as import tariffs levied on embodied emissions in CBAM-targeted sectors. The carbon tariff rates are endogenously determined through national policy-making, allowing for strategic interactions across countries and alternative policy instrument implementations.

In our model, the CBAM affects economic and environmental outcomes through several key channels. First, as a border taxation, carbon tariffs alter global trade flows and reshape industrial composition across countries. Second, regulated countries face trade-offs when adjusting carbon policies in response to the CBAM. Raising domestic carbon taxes alleviates trade penalties but increases production costs, weakening competitiveness in all the markets. In the presence of climate externalities, stricter regulation also lowers energy use and emissions, generating environmental benefits that partially compensate for the associated income losses from higher carbon pricing. These interrelated forces render the aggregate effects ambiguous, necessitating a comprehensive quantitative evaluation of the CBAM and the strategic behaviors it may provoke. We further derive analytical decompositions of changes in real income and emissions to isolate the contribution of each channel.

We calibrate the model to a global economy comprising thirteen major regions, with three primary extractive sectors, three secondary energy sectors, and eighteen non-energy industries. We use data from the GTAP 11 database for global input-output linkages and bilateral trade flows in 2017, complemented by carbon emissions data from the GTAP-E extension. To infer countries' perceived valuations of climate externalities, we exploit revealed preferences in setting carbon taxes. Specifically, we calibrate the disutility parameters to exactly match the model-predicted unilateral optimal carbon taxes with the observed carbon prices. The calibration reveals substantial cross-country heterogeneity in the perceived cost of carbon emissions: Russia and India place low value on emissions, while Canada, Japan, and the EU assign larger weights to environmental costs.

We begin our quantitative analysis by simulating the introduction of the EU's CBAM in its initial targeted sectors (Chemicals, Minerals, and Metals), while assuming other countries remain passive. On average, global carbon tariffs amount to 3.25%, with the steepest rates levied on exports from Russia and India. The policy induces notable trade diversion: trade volume between the EU and non-EU countries falls by 1.60%, particularly in the CBAM-targeted sectors, while trade among non-EU countries expands. Environmentally, CBAM reduces direct carbon leakage by shifting carbon-intensive production away from high-emission countries and encourages greener industrial reallocation toward less carbon-intensive sectors in foreign economies. However, reduced energy demand depresses energy prices, inducing indirect leakage through global energy markets. As a result, global emissions decline only modestly by 0.071%. The EU gains in real income through improved terms of trade, while most other countries suffer consumption losses from the carbon tariffs. Nevertheless, global welfare rises marginally when environmental benefits are accounted for.

We next examine whether extending the CBAM to cover all tradable sectors would achieve greater emission reductions, as envisioned in potential post-2030 expansions. Surprisingly, broader sectoral coverage results in a smaller emissions decline of 0.065%. The reasons are twofold. First, the stronger contraction in energy demand exacerbates indirect leakage via international energy price channel. Second, eliminating sectoral variation in carbon tariffs weakens incentives for industrial reallocation. Under the initial scope, CBAM induces substitution from carbon-intensive exports toward cleaner alternatives by differentiating carbon tariffs across sectors. Once all sectors are covered, however, this adjustment margin narrows considerably, dampening the environmental performance of CBAM.

To assess how countries' optimal responses interact with the CBAM and to quantify the impact of such strategic behavior on CBAM's environmental effectiveness beyond the passive scenario, we then simulate a non-cooperative Nash equilibrium in which each government sets its welfare-maximizing carbon tax, taking other countries' optimal policies as given. We solve this equilibrium using the mathematical programming with equilibrium constraints (MPEC) approach popularized by Su and Judd (2012). In equilibrium, the EU raises its carbon price by \$13.79/tCO_2, the largest increase among all regions. This stringent regulation reinforces trading partners' incentives to mirror EU carbon pricing: since CBAM tariffs depend on carbon price differentials, foreign exporters face higher trade penalties unless they also raise domestic taxes. Consequently, all countries increase carbon prices, demonstrating how CBAM reduces free-riding behavior that typically limits unilateral climate action. Strategic responses substantially enhance CBAM's environmental effectiveness, reducing global emissions by 1.44%. Crucially, the CBAM also contributes to mitigating indirect carbon leakage as rising global carbon taxes offset falling energy prices and lowers emission intensity across countries. The climate gains come at the cost of modest real income losses, and climate-adjusted global welfare rises by 0.04%.

Finally, to explore how the CBAM facilitates global decarbonization through coordination of climate action, we simulate a cooperative equilibrium in which countries jointly determine carbon taxes through multilateral negotiations, conditional on the EU's CBAM implementation. Using a Nash bargaining protocol, we solve for the set of cooperative carbon taxes that maximizes collective welfare. The agreement raises the global average carbon price to \$36.07/tCO_2 and reduces global emissions by 6.05%. The resulting decline exceeds the total annual baseline emissions from the global textile, electronics, machinery, and transport equipment sectors, and increases global welfare by 0.17%. Decomposition shows that cooperative pricing drives greener industrial reallocation globally and further mitigate indirect leakage by lowering emission intensities in most regions. By contrast, multilateral coordination starting from the pre-CBAM factual equilibrium results in a lower global average carbon price of \$32.13/tCO_2 and achieves only 64.57% of the emissions reduction attainable with CBAM in place. This comparison highlights the role of CBAM as an effective enforcement mechanism in international climate negotiations: by credibly raising the cost of disagreement, especially for carbon-intensive exporters, CBAM strengthens cross-country incentives for environmental policy alignment and fosters deeper global cooperation on climate governance to achieve higher carbon prices.

Related Literature. Our work relates to several strands of literature. First, it builds on a growing body of research that integrates environmental dimensions into quantitative general equilibrium trade and macro models, such as Babiker (2005); Elliott et al. (2010); Egger and Nigai (2015); Shapiro (2016, 2021); Shapiro and Walker (2018); Duan et al. (2021); Larch and Wanner (2024); Caliendo et al. (2024); Coster et al. (2024), and as reviewed by Copeland et al. (2022). These studies provide rich structural foundations for understanding the interaction between trade and emissions in open economies, but they generally do not consider the design of optimal policy. A notable exception is Farrokhi and Lashkaripour (2025), who analytically derive the optimal structure of border taxes in a general equilibrium setting to study climate clubs à la Nordhaus (2015), in which border taxes are used to deter free-riding. We contribute to this literature by quantifying optimal policies for both regulators and regulated regions in a globally interconnected climate–trade system to evaluate the economic and environmental impacts of the CBAM. Our paper highlights how CBAM can address global climate externalities by lowering both direct and indirect carbon leakage and by curbing free-riding through trade penalties that raise the cost of noncompliance.

Second, our paper is closely related to studies evaluating the effectiveness of border carbon adjustments (BCAs), including Böhringer et al. (2012); Fischer and Fox (2012); Keen and Kotsogiannis (2014); Böhringer et al. (2016); Larch and Wanner (2017); Bellora and Fontagné (2023), which often impose exogenous policies to simulate unilateral or stylized BCA scenarios. Our analysis endogenizes policy-making across countries and explicitly characterizes strategic interactions under both non-cooperative and cooperative regimes. Our results provide a benchmark for assessing the full potential of BCAs in reducing global emissions and for illustrating their institutional role in facilitating international coordination on climate action. In addition, much of the existing work employs large-scale computational general equilibrium (CGE) models, which have been criticized for their "black-box" nature. The tractability of our framework allows analytical decomposition of welfare and emissions outcomes, thereby offering transparent insights into the underlying economic mechanisms.

Lastly, our research contributes to the broader literature on the design of trade and environmental policy in the presence of international externalities. Foundational theoretical studies, such as (Copeland, 1996; Hoel, 1996; Kortum and Weisbach, 2022; Weisbach et al., 2023), analyze optimal carbon policies under trade leakages but typically rely on partial-equilibrium or two-country settings. We advance this line of inquiry by embedding these theoretical insights into a multi-country, multi-industry general equilibrium framework that enables detailed counterfactual evaluation of both unilateral and multilateral policy regimes. Another related strand of research examines strategic trade policy interactions using quantitative methods (Ossa, 2014; Mei, 2020; Bagwell et al., 2021; De Souza et al., 2024; Mei, 2024). We integrate this strategic dimension into a comprehensive evaluation of CBAM at the intersection of international trade, environmental outcomes, and policy design, advancing academic understanding of the interplay between climate and trade policy.

The remainder of the paper is structured as follows. Section 2 provides the background on carbon leakage and the CBAM. Section 3 presents our quantitative general equilibrium framework and decomposition tools. After describing data and calibration strategies in Section 4, we present the simulation results in Section 5. Finally, Section 6 concludes.

2 Background

2.1 Carbon Emissions and Carbon Leakage

Carbon dioxide (CO_2), which stems primarily from fossil fuel combustion and industrial production processes, accounts for the largest share of anthropogenic GHG emissions. Since 1850, human activities have increased atmospheric CO_2 concentrations from approximately

285.5 parts per million (ppm) to over 420 ppm in 2024.[3] This rise in CO_2 has been associated with a 1.1°C increase in global surface temperatures relative to the late 19th-century pre-industrial average (Intergovernmental Panel On Climate Change, 2023).

On the one hand, climate change has caused severe ecological disruptions, including intensified heatwaves, melting polar ice, and biodiversity loss. On the other hand, its substantial economic costs are well documented in the literature, encompassing declines in agricultural and industrial output, reductions in labor productivity, adverse health outcomes, and heightened risks of political instability and inequality (Dell et al., 2012, 2014; Carleton and Hsiang, 2016; Diffenbaugh and Burke, 2019). As a result, reducing CO_2 emissions has become a central policy objective for many governments. The 2015 Paris Agreement, for example, ratified by 196 nations, aims to limit global warming to well below 2°C, preferably 1.5°C, above pre-industrial levels by achieving net-zero emissions by mid-century.

Despite ambitious international commitments, carbon leakage remains a major challenge in climate policy, a phenomenon in which carbon emissions increase in one country as a result of emissions reductions in another country with more stringent environmental regulations. As reviewed by Copeland et al. (2022), carbon leakage from unilateral carbon policies arises mainly through the *direct trade channel* and the *indirect international energy price channel.*

The direct channel stems from increased production costs due to strict carbon policy, which incentivize firms to shift production towards other jurisdictions with weaker environmental standards via trade reallocation, offshoring, or foreign direct investment. This direct carbon leakage is particularly pronounced in energy-intensive and trade-exposed (EITE) sectors such as steel, cement, and chemicals (Böhringer et al., 2017). The indirect channel is caused by the effects of carbon policy on the international energy prices. Reduced demand for energy resources in regulated regions depresses global energy prices, thereby stimulating fuel consumption and emissions in unregulated economies. Carbon leakage not only undermines the environmental effectiveness of unilateral climate action, but also raises concerns about industrial competitiveness and labor market displacement in countries with stringent climate policies (Böhringer et al., 2012; Fontagné and Schubert, 2023).

2.2 Carbon Border Adjustment Mechanism

To address carbon leakage and the free-riding problem associated with fragmented environment policies, economists have long advocated for border carbon adjustments (BCAs), which impose carbon tariffs on imported goods based on their embedded carbon emissions (Elliott et al., 2010; Fischer and Fox, 2012; Keen and Kotsogiannis, 2014; Larch and Wan-

[3] Source for 1850 level: `https://data.giss.nasa.gov/modelforce/ghgases`. Source for 2024 level: `https://climate.nasa.gov/vital-signs/carbon-dioxide`.

ner, 2017). BCAs aim to equalize the carbon costs faced by domestic and foreign producers, thereby preserving the effectiveness of domestic carbon pricing instruments while reducing incentives for firms to reallocate production to weaker-regulation countries. BCAs restore a level playing field in the domestic market and correct for the emission externality associated with production. Furthermore, by ensuring that imported goods face comparable carbon costs, BCAs promote foreign producers to adopt cleaner, less-carbon-intensive production technologies, contributing to emissions reductions on a global scale.

In response to environmental concerns, the European Union introduced the Carbon Border Adjustment Mechanism (CBAM) in 2023 as part of its long-term goal of achieving climate neutrality by 2050. Specifically, CBAM is designed to complement the EU Emissions Trading System (ETS) by imposing carbon tariffs on imports from carbon-intensive sectors, thereby ensuring that foreign producers face similar carbon costs comparable to those borne by EU firms operating under the ETS (European Commission, 2021). The mechanism initially targets a selected group of product categories, including iron and steel, cement, fertilizers, aluminum, electricity, and hydrogen. These sectors are characterized by high carbon intensities, large trade exposure, and substantial energy consumption, making them particularly vulnerable to carbon leakage (European Commission, 2023). Additionally, the scope of CBAM may be expanded in the future to cover more sectors if deemed feasible.

The implementation of the EU's CBAM follows a phased approach.[4] The transitional phase, which began in October 2023, requires importers to report direct and indirect embedded emissions in their goods, but without financial obligations. Full implementation is scheduled for 2026, at which point importers will be required to purchase CBAM certificates, priced according to the EU ETS auction rate, to offset emissions embodied in their imports.[5]

By incorporating CBAM into its climate policy architecture, the EU seeks to reduce carbon leakage while encouraging global trading partners to strengthen their own carbon pricing frameworks. However, the mechanism's trade implications, distributional consequences, and compliance challenges remain subjects of ongoing debate in both academic and policy circles. In the subsequent section, we develop a quantitative general equilibrium model incorporating carbon emissions and border adjustments to analyze the economic and environmental consequences of the EU's CBAM implementation.

[4] Source: `https://taxation-customs.ec.europa.eu/carbon-border-adjustment-mechanism_en`

[5] If importers can prove that a carbon price has already been paid during the production of the imported goods, the corresponding amount can be deducted. For example, if a steel producer in China has paid a carbon tax of €10 per tonne of CO_2, while the EU ETS price is €90, the importer needs to purchase CBAM certificates covering the €80 difference, multiplied by the product's embedded emissions. To ensure compliance, the EU mandates third-party verification of reported emissions data, allowing for default emission values if foreign producers lack reliable reporting systems.

3 Model

In this section, we develop a multi-country, multi-industry quantitative general equilibrium trade model that incorporates global supply chains of carbon, emission externalities, national carbon taxes, and border adjustment mechanisms. The global economy consists of N countries indexed by $i, j \in \{1, \cdots, N\}$. Each country comprises three types of sectors: primary extractive energy sectors $s \in \mathbb{E}_1$, secondary energy sectors $s \in \mathbb{E}_2$, and non-energy sectors $s \in \mathbb{G}$, with $\mathbb{E} \equiv \mathbb{E}_1 \cup \mathbb{E}_2$ denoting all energy sectors and $\mathbb{S} \equiv \mathbb{E} \cup \mathbb{G}$ denoting the full set of sectors.[6,7] A continuum of firms with heterogeneous productivity in each sector produces intermediate goods by demanding labor and composite intermediate inputs with input-output linkages as in Caliendo and Parro (2015). Additionally, production in primary extractive energy sectors requires natural resources, which are assumed to be exogenously given and non-tradable within each country, as a sector-specific input.[8] All markets are assumed to be perfectly competitive.

Carbon emission content is embedded in the outputs of both primary extractive and secondary energy sectors. Each national government imposes a carbon tax levied on the use of energy sector composites. We count CO_2 emissions when energy inputs are employed in the production of non-energy intermediate goods.[9] Households experience disutility from global carbon emissions, which we model as a pure climate externality following Farrokhi and Lashkaripour (2025).

In what follows, we first describe the main quantitative framework, detailing the optimization problems of representative households and firms in each country and sector. We then outline the set of equations characterizing the general equilibrium and its representation in relative changes. Finally, we present the welfare with climate externality and derive analytical decompositions of changes in real income and emissions to quantify the contribution of distinct economic forces.

[6] Examples of primary extractive energy sectors include coal, crude oil, and natural gas; secondary energy sectors include refined petroleum, electricity, and gas manufacture and distribution; non-energy sectors include textile, machinery, and chemicals.

[7] By distinguishing between primary and secondary energy sectors, our model captures the empirical heterogeneity in energy consumption across sectors, particularly in cost shares and emission intensities along the supply chain. Primary energy inputs account for a substantial share of production costs in secondary energy sectors, for instance, crude oil in refined petroleum and coal in electricity. In contrast, downstream industries such as textiles and machinery predominantly rely on secondary energy of electricity.

[8] Natural resources can be interpreted as coal mines for coal extraction, oil fields for crude oil, or gas deposits for natural gas, among others.

[9] This modeling approach avoids double counting of emissions, as emissions generated during energy production are attributed to indirect emissions in downstream production.

3.1 Households

Each country j is endowed with a fixed population mass L_j of households, who are perfectly mobile across sectors within a country but cannot move across borders. Households are assumed to own all production factors in a country and supplies one unit of labor inelastically at the wage rate w_j. Following Farrokhi and Lashkaripour (2025), the utility of a representative household in country j consists of the utility from consumption net of disutility from global CO_2 emissions. Specifically, preferences are given by

$$U_j = \prod_{s \in \mathbb{S}} \left(C_j^s\right)^{\alpha_j^s} - \lambda_j Z_w,$$

where C_j^s is the consumption of final goods from sector s in country j, and α_j^s is the final consumption expenditure share, with $\sum_{s \in \mathbb{S}} \alpha_j^s = 1$. The term λ_j is the disutility parameter that represents the utility loss per unit of global CO_2 emissions experienced by households in country j. We denote $Z_w \equiv \sum_{j=1}^{N} Z_j$ as global emissions, which aggregates national carbon emissions across all countries.

Because emissions are treated as a pure externality, households take Z_w as given and do not internalize the environmental consequences of their consumption decisions. Therefore, the representative household chooses a consumption bundle $\{C_j^s\}_{s \in \mathbb{S}}$ to maximize its utility from final consumption subject to the budget constraint:

$$I_j = \sum_{s \in \mathbb{S}} P_j^s C_j^s,$$

where I_j denotes household income, which will be discussed in more detail later on, and P_j^s is the ideal price index of final goods from sector s in country j. The corresponding aggregate consumption price index in country j is given by

$$P_j = \prod_{s \in \mathbb{S}} \left(\frac{P_j^s}{\alpha_j^s}\right)^{\alpha_j^s}. \tag{1}$$

3.2 Production

The production technology in non-energy sectors closely follows Caliendo and Parro (2015). A continuum of intermediate goods $\omega^s \in [0, 1]$ in each sector $s \in \mathbb{S}$ is produced by heterogeneous firms with different productivities φ_j^s. Final goods are assembled using intermediate varieties sourced from the lowest-cost suppliers across countries. In non-tradable sectors, final goods are produced solely using domestic intermediates.

3.2.1 Intermediate Goods Producers

In primary extractive energy sectors $s \in \mathbb{E}_1$, firms with productivity φ_j^s employ labor, natural resources, and composite intermediate inputs (also referred to as materials) to extract energy resources ω^s with a constant returns to scale technology. Specifically, the production function is given by

$$q_j^s(\omega_s) = \varphi_j^s(\omega^s)\left[l_j^s(\omega^s)\right]^{\beta_j^{s,L}}\left[R_j^s(\omega^s)\right]^{\beta_j^{s,R}}\prod_{s' \in \mathbb{S}}\left[m_j^{s's}(\omega^s)\right]^{\gamma_j^{s's}}, \quad s \in \mathbb{E}_1$$

where l_j^s and R_j^s denote the demands for labor and sector-specific natural resources, respectively. $m_j^{s's}$ denotes the demand for materials from sector s' used in sector s production. The parameters $\beta_j^{s,L}$ and $\beta_j^{s,R}$ represent the value-added shares of labor and natural resources in output, and $\gamma_j^{s's} \geq 0$ is the share of composite intermediate goods from sector s' used in the production of sector s. The production function exhibits constant returns to scale; therefore $\sum_{s'=1}^{\mathbb{S}} \gamma_j^{s's} = 1 - \beta_j^{s,L} - \beta_j^{s,R}$.

In secondary energy and non-energy sectors $s \in \mathbb{E}_2 \cup \mathbb{G}$, production differs from primary energy production in that only uses labor and material inputs without natural resources, namely, $\beta_j^{s,R} = 0$. The corresponding production function becomes

$$q_j^s(\omega_s) = \varphi_j^s(\omega^s)\left[l_j^s(\omega^s)\right]^{\beta_j^{s,L}}\prod_{s' \in \mathbb{S}}\left[m_j^{s's}(\omega^s)\right]^{\gamma_j^{s's}}, \quad s \in \mathbb{E}_2 \cup \mathbb{G}$$

3.2.2 Final Goods Producers

Final goods in sector s and country j are produced by aggregating a continuum of intermediate varieties $\omega^s \in [0, 1]$ sourced from the lowest-cost suppliers around the world. The production technology is a constant elasticity of substitution (CES) aggregator:

$$Q_j^s = \left[\int q_j^s(\omega^s)^{\frac{\sigma^s - 1}{\sigma^s}} d\omega^s\right]^{\frac{\sigma^s}{\sigma^s - 1}},$$

where $q_j^s(\omega^s)$ is the demand for intermediate goods ω^s, and σ^s is the elasticity of substitution across intermediate varieties within sector s. For non-tradable sectors, all intermediates are sourced domestically.

3.3 Carbon Policy Wedges

As mentioned earlier, the combustion of all forms of energy, primary or secondary, is subject to a national carbon tax levied on carbon emissions generated during the production of intermediate goods. The after-tax price of material input from energy sector $s' \in \mathbb{E}$ faced by firms in sector $s \in \mathbb{S}$ and country j is

$$\tilde{P}_j^{s's} = P_j^{s'} + t_j^E v_j^{s's} \tag{2}$$

where t_j^E is the carbon tax rate per tonne of CO_2 emissions. $v_j^{s's}$ denotes the exogenously given carbon emission coefficient, which is defined as the amount of CO_2 emissions generated per unit of energy input from energy sector s' used in sector s and country j. This parameter reflects the emission efficiency or "greenness" of energy use across different sector–energy input combinations within a country.

Given the assumption of perfect competition, firms in sector s and country j set prices equal to unit costs, $c_j^s / \varphi_j^s(\omega^s)$. The cost of an input bundle c_j^s is given by

$$\begin{aligned} c_j^s &= B_j^s (w_j)^{\beta_j^{s,L}} \left(r_j^s\right)^{\beta_j^{s,R}} \prod_{s' \in \mathbb{S}} \left(\tilde{P}_j^{s's}\right)^{\gamma_j^{s's}}, \quad s \in \mathbb{E}_1 \\ c_j^s &= \tilde{B}_j^s (w_j)^{\beta_j^{s,L}} \prod_{s' \in \mathbb{S}} \left(\tilde{P}_j^{s's}\right)^{\gamma_j^{s's}}, \quad s \in \mathbb{E}_2 \cup \mathbb{G} \end{aligned} \tag{3}$$

where r_j^s is the rental rate of natural resources in sector s and country j. The two constants are given by $B_j^s = (\beta_j^{s,L})^{-\beta_j^{s,L}} (\beta_j^{s,R})^{-\beta_j^{s,R}} \prod_{s' \in \mathbb{S}} (\gamma_j^{ss'})^{-\gamma_j^{ss'}}$ and $\tilde{B}_j^s = (\beta_j^{s,L})^{-\beta_j^{s,L}} \prod_{s' \in \mathbb{S}} (\gamma_j^{ss'})^{-\gamma_j^{ss'}}$. Note that since the use of non-energy materials does not generate carbon emissions, carbon taxes do not apply in this case and $\tilde{P}_j^{s's} = P_j^{s'}$ for $s' \in \mathbb{G}$.

3.4 Carbon Emissions

We count carbon emissions when energy is used in downstream production of intermediate goods à la Farrokhi and Lashkaripour (2025). Specifically, CO_2 emissions generated by the use of energy input from sector $s' \in \mathbb{E}$ in sector $s \in \mathbb{S}$ and country j are given by

$$Z_j^{s's} = v_j^{s's} Q_j^{s's}, \tag{4}$$

where $Q_j^{s's} = \int q_j^{s's}(\omega^s) d\omega^s$ is the sectoral demand for energy s' in sector s in country j. Carbon emissions in sector s and country j sum across all energy types:

$$Z_j^s = \sum_{s' \in \mathbb{E}} Z_j^{s's}.$$

National carbon emissions in country j are the sum of carbon emissions over sectors:

$$Z_j = \sum_{s \in \mathbb{S}} Z_j^s,$$

and lastly, global CO_2 emissions aggregate national carbon emissions across countries:

$$Z_w = \sum_{j=1}^{N} Z_j.$$

3.5 International Trade, CBAM, and Prices

International trade in intermediate goods incurs three types of costs, including (i) iceberg-type shipping costs, (ii) import tariffs, and, where applicable, (iii) carbon tariffs. The first two cost components are standard in the trade literature. Let $d_{ij}^s \geq 1$ denote the iceberg-type shipping cost for trade in intermediates in sector s from country i to country j, with $d_{ii}^s = 1$. Additionally, importers in country j that source goods from country i face a standard ad valorem import tariff denoted by $t_{ij}^{s,G}$, with $t_{ii}^{s,G} = 0$.

Turning to carbon tariffs, as discussed in Section 2, under the implementation of CBAM in country j, imports of covered goods from country i are subject to the purchase of CBAM certificates for their embedded carbon emissions. The price of CBAM certificates equals the carbon price differential between the regulator j and the regulated exporter i, provided that the origin country has a lower carbon price. Specifically, the price of CBAM certificates per unit of carbon emission is given by

$$P_{ij}^{CBAM} = \left(t_j^E - t_i^E\right) \mathbb{1}_{\left\{t_j^E \geq t_i^E\right\}}, \tag{5}$$

where $\mathbb{1}_{\{\cdot\}}$ is the indicator function. The resulting ad valorem carbon tariff rate for covered goods from country i to country j in sector s equals

$$t_{ij}^{s,E} = \chi_i^s P_{ij}^{CBAM} \mathbb{1}_{\left\{(j,s) \in \Lambda_{CBAM}^{N,S}\right\}}, \tag{6}$$

where $\Lambda_{CBAM}^{N,S}$ is the set of regulation countries and CBAM-targeted sectors. The term $\chi_i^s \equiv \sum_{s' \in \mathbb{E}} v_i^{s's} \gamma_i^{s's} / \tilde{P}_i^{s's}$ denotes the carbon emission intensity, which is defined as the amount of CO_2 emissions generated per dollar of output in sector s and in exporting country i.

Combining all sources of cost incurring, we denote the total trade cost for goods from country i to country j in sector s by κ_{ij}^s, satisfying that

$$\kappa_{ij}^s = \left(1 + t_{ij}^s\right) d_{ij}^s, \tag{7}$$

where $t_{ij}^{s}=t_{ij}^{s,G}+t_{ij}^{s,E}$ is the total ad valorem tariff rate, comprising both standard import tariffs and carbon tariffs. For notational convenience, we define $\tau_{ij}^{s}=1+t_{ij}^{s}$. In non-tradable sectors, we assume infinite trade costs.

Since final goods producers source intermediate varieties from the lowest-cost supplier across all locations, the after-tax price of variety ω^s in country j is given by

$$p_j^s\left(\omega^s\right)=\min_{i\in\{1,\cdots,N\}}\left\{\frac{c_i^s\kappa_{ij}^s}{\varphi_i^s\left(\omega^s\right)}\right\}.$$

Following Eaton and Kortum (2002), each firm in sector s and country j draws its productivity $\varphi_j^s\left(\omega^s\right)$ independently from a Fréchet distribution with shape parameter θ^s and location parameter T_j^s. The sectoral price index for final goods in sector s and country j is then

$$P_j^s=\left[\Gamma(\frac{1-\sigma^s}{\theta^s}+1)\right]^{1/(1-\sigma^s)}\left[\sum_{i=1}^{N}T_i^s\left(c_i^s\kappa_{ij}^s\right)^{-\theta^s}\right]^{-\frac{1}{\theta^s}},\tag{8}$$

where $\Gamma(\cdot)$ is the Gamma function.

Let $X_j^s=P_j^sQ_j^s$ denote total expenditure on sector s goods in country j, and X_{ij}^s the expenditure on sector s goods imported from country i in country j. Using the properties of the Fréchet probabilistic representation of technologies, the bilateral expenditure share, denoted by $\pi_{ij}^s=X_{ij}^s/X_j^s$, is given by

$$\pi_{ij}^s=\frac{T_i^s\left[c_i^s\kappa_{ij}^s\right]^{-\theta^s}}{\sum_{i'=1}^{N}T_{i'}^s\left[c_{i'}^s\kappa_{i'j}^s\right]^{-\theta^s}}.\tag{9}$$

3.6 Market Clearing Conditions

Total expenditure on final goods of sector s in location j is the sum of the expenditure on materials by firms and final consumption by households:

$$X_j^s=\alpha_j^sI_j+\sum_{s'\in\$}\gamma_j^{ss'}Y_j^{s'},\tag{10}$$

where $Y_j^s=\sum_{i=1}^{N}\pi_{ji}^sX_i^s/\tau_{ji}^s$ is the total output of sector s in country j. I_j denotes the national income in country j, which is the sum of labor income, natural resource revenues, carbon tax revenues, tariff revenues, and trade deficit:

$$I_j=w_jL_j+\sum_{s\in\mathbb{E}_1}r_j^sR_j^s+\sum_{s\in\$}t_j^EZ_j^s+\sum_{i=1}^{N}\sum_{s\in\$}t_{ij}^s\frac{\pi_{ij}^sX_j^s}{\tau_{ij}^s}+D_j,\tag{11}$$

where D_j denotes the trade deficit of country j. In particular, we denote country j's imports of sector s goods from country i by $M_{ij}^s = \pi_{ij}^s X_j^s / \tau_{ij}^s$ and country j's exports of sector s goods to country i by $E_{ij}^s = \pi_{ji}^s X_i^s / \tau_{ji}^s$. Then, the sectoral trade deficit in sector s and country j is given by $D_j^s = \sum_{i=1}^N \left(M_{ij}^s - E_{ij}^s \right)$ and the total national trade deficit is $D_j = \sum_{s \in \mathbb{S}} D_j^s$.[10]

Market clearing for natural resources requires

$$r_j^s R_j^s = \beta_j^{s,R} Y_j^s, \quad s \in \mathbb{E}_1 \tag{12}$$

and lastly, labor market clearing condition in each country j is

$$w_j L_j = \sum_{s \in \mathbb{S}} \beta_j^{s,L} Y_j^s. \tag{13}$$

3.7 General Equilibrium

The general equilibrium of the quantitative trade framework with emission externality, carbon taxes, and CBAM is defined as follows:

General Equilibrium. Given exogenous variables $\{L_j, R_j^s, D_j\}$ and exogenous model parameters $\{\lambda_j, \alpha_j^s, \beta_j^{s,L}, \beta_j^{s,R}, \gamma_j^{s's}, \upsilon_j^{s's}, \sigma^s, d_{ij}^s, \theta^s, T_j^s\}$, an equilibrium under a policy structure $\boldsymbol{\Psi}$, comprising carbon taxes $\{t_j^E\}$, tariffs $\{t_{ij}^{s,G}\}$, and CBAM implementation $\{\Lambda_{CBAM}^{N,S}\}$, is a set of wages $\{w_j\}$, resource rental rates $\{r_j^s\}$, and sectoral price indices $\{P_j^s\}$ that satisfies equilibrium conditions (1) to (13) for all sectors s and all countries j.

In practice, we solve for changes in equilibrium variables using the exact-hat algebra approach à la Dekle et al. (2007) to avoid calibrating unchanged underlying parameters. Specifically, let x denote an endogenous variable in the initial equilibrium under policy $\boldsymbol{\Psi}$, and x' its value in the counterfactual equilibrium under policy $\boldsymbol{\Psi}'$. We define $\hat{x} = x'/x$ as the relative change in any variable x after a policy structure change.

Equilibrium in Relative Changes. After changing from the structure of policies $\boldsymbol{\Psi}$ to another structure of policies $\boldsymbol{\Psi}'$, the equilibrium conditions in relative changes satisfy:

[10] Following Caliendo and Parro (2015), we assume that each country's total trade deficit is exogenously given, and that global trade is balanced in the aggregate. Sectoral trade imbalances are endogenously determined in equilibrium. In particular, we follow the approach in Dekle et al. (2007) to construct a trade flow matrix for 2017 without national trade deficits as the baseline.

Cost of the input bundle:

$$\begin{aligned}
\hat{c}_j^s &= (\hat{w}_j)^{\beta_j^{s,L}} \left(r_j^s\right)^{\beta_j^{s,R}} \prod_{s' \in \$} \left(\hat{\tilde{P}}_j^{s's}\right)^{\gamma_j^{s's}}, \quad s \in \mathbb{E}_1 \\
\hat{c}_j^s &= (\hat{w}_j)^{\beta_j^{s,L}} \prod_{s' \in \$} \left(\hat{\tilde{P}}_j^{s's}\right)^{\gamma_j^{s's}}, \quad s \in \mathbb{E}_2 \cup \mathbb{G}
\end{aligned} \tag{14}$$

Price index:

$$\hat{P}_j^s = \left[\sum_{i=1}^N \pi_{ij}^s \left(\hat{c}_i^s \hat{\tau}_{ij}^s\right)^{-\theta^s}\right]^{-1/\theta^s}, \tag{15}$$

Output:

$$\hat{Y}_j^s = \sum_{i=1}^N \frac{\xi_{ji}^s \left(\hat{c}_j^s \hat{\tau}_{ji}^s\right)^{-\theta^s}}{\sum_{j'=1}^N \pi_{j'i}^s \left(\hat{c}_{j'}^s \hat{\tau}_{j'i}^s\right)^{-\theta^s}} \frac{\hat{X}_i^s}{\hat{\tau}_{ji}^s}, \tag{16}$$

Total sectoral expenditure:

$$\begin{aligned}
\hat{X}_j^s = \frac{\alpha_j^s}{X_j^s} \Bigg[& \hat{w}_j w_j L_j + \sum_{s \in \mathbb{E}_1} \hat{r}_j^s r_j^s R_j^s + \sum_{s \in \$} \hat{t}_j^E t_j^E \hat{Y}_j^s Y_j^s \hat{\chi}_j^s \chi_j^s \\
& + \sum_{i=1}^N \sum_{s \in \$} t_{ij}^s \frac{\pi_{ij}^s X_j^s}{\tau_{ij}^s} \frac{\hat{t}_{ij}^s \left(\hat{c}_i^s \hat{\tau}_{ij}^s\right)^{-\theta^s}}{\sum_{i'=1}^N \pi_{i'j}^s \left(\hat{c}_{i'}^s \hat{\tau}_{i'j}^s\right)^{-\theta^s}} \frac{\hat{X}_j^s}{\hat{\tau}_{ij}^s} + D_j \Bigg] + \frac{1}{X_j^s} \sum_{s' \in \$} \gamma_j^{ss'} \hat{Y}_j^{s'} Y_j^{s'},
\end{aligned} \tag{17}$$

Natural resource market clearing:

$$\hat{r}_j^s = \hat{Y}_j^s, \quad s \in \mathbb{E}_1 \tag{18}$$

Labor market clearing:

$$\hat{w}_j = \sum_{s \in \$} \mu_j^s \hat{Y}_j^s, \tag{19}$$

where the relative changes in after-tax energy input prices and carbon emission intensity, and auxiliary parameters are given by

$$\hat{\tilde{P}}_j^{s's} = \frac{\hat{P}_j^s P_j^s + \hat{t}_j^E t_j^E v_j^{s's}}{P_j^{s's}}, \ \hat{\chi}_j^s = \frac{1}{\chi_j^s} \sum_{s' \in \mathbb{E}} \frac{v_j^{s's} \gamma_j^{s's}}{\hat{\tilde{P}}_j^{s's} \tilde{P}_j^{s's}}, \ \xi_{ji}^s = \frac{\pi_{ji}^s X_i^s / \tau_{ji}^s}{\sum_{i'=1}^N \pi_{ji'}^s X_{i'}^s / \tau_{ji'}^s}, \ \mu_j^s = \frac{\beta_j^{s,L} Y_j^s}{\sum_{s'=1}^S \beta_j^{s',L} Y_j^{s'}}.$$

3.8 Welfare with Emissions

As discussed earlier, representative households in each country do not internalize the global emission externality in their consumption decisions. The government, however, is assumed to optimally choose policy instruments to maximize national welfare with emission externality, defined as real income net of the disutility from global carbon emissions:

$$W_j = \frac{I_j}{P_j} - \lambda_j Z_w, \tag{20}$$

where I_j/P_j represents real income in country j, and λ_j denotes the disutility parameters per unit of global emissions for households in country j.

To disentangle the mechanisms through which changes in policy changes across countries affect welfare, we decompose the real income effects and the emission effects by taking total differentiation of the equilibrium conditions.

Decomposition of Real Income Effects. The decomposition of changes in real income is given by[11]

$$\begin{aligned} d\ln\frac{I_j}{P_j} = {} & \frac{1}{I_j}\sum_{i=1}^{N}\sum_{s\in\$}\underbrace{\left(E_{ij}^s d\ln c_j^s - M_{ij}^s d\ln c_i^s\right)}_{\text{terms of trade}} + \frac{1}{I_j}\sum_{i=1}^{N}\sum_{s\in\$}\underbrace{t_{ij}^s M_{ij}^s\left(d\ln M_{ij}^s - d\ln c_i^s\right)}_{\text{volume of trade}} \\ & + \frac{1}{I_j}\sum_{s\in\$}\underbrace{t_j^E Z_j^s\left(d\ln Y_j^s + d\ln\chi_j^s\right)}_{\text{volume of emission}}, \end{aligned} \tag{21}$$

where the first and second terms measure the multilateral and multisectoral *terms-of-trade* and *volume-of-trade* effects, respectively, as in Caliendo and Parro (2015). The third term measures the multisectoral *volume-of-emission* effect unique to the present framework, where emissions are explicitly incorporated.

In particular, the term-of-trade effect quantifies real income gains from an improvement in exporter prices relative to the change in importer prices, weighted by bilateral export and import values at the sector level.

The volume-of-trade effect measures the contribution of tariff revenue changes arising from changes in import values, adjusted by import prices, with weights determined by initial tariffs and import volumes across sectors.

The volume-of-emission effect reflects the change in domestic carbon tax revenue associated with adjustments in sectoral output and carbon emission intensity. Each sector's contribution depends on the initial domestic carbon tax rate and sectoral carbon emissions across energy types.

Decomposition of Emission Effects. Similarly, total differentiation yields the decomposition of changes in global carbon emissions, which are the weighted average of national

[11]The decomposition summarizes the first-order effects of policy changes on real income. Detailed derivations are provided in Appendix A.1.

emission changes:

$$d\ln Z_w = \sum_{j=1}^{N} \frac{Z_j}{Z_w} d\ln Z_j, \tag{22}$$

where the weights are given by each country's initial emission share Z_j/Z_w. Following the concepts introduced in Grossman and Krueger (1991) and Copeland and Taylor (1994), we can further decompose changes in country j's CO_2 emissions as:[12]

$$d\ln Z_j = \frac{1}{Z_j} \underbrace{\bar{\chi}_j Y_j d\ln Y_j}_{\text{scale effect}} + \frac{1}{Z_j} \sum_{s\in\mathbb{S}} \underbrace{\chi_j^s Y_j^s d\ln \frac{Y_j^s}{Y_j}}_{\text{composition effect}} + \frac{1}{Z_j} \sum_{s\in\mathbb{S}} \underbrace{\chi_j^s Y_j^s d\ln \chi_j^s}_{\text{technique effect}}, \tag{23}$$

where the three components represent the *scale*, *composition*, and *technique* effects, respectively. Here, $\bar{\chi}_j \equiv \sum_{s\in\mathbb{S}} \chi_j^s Y_j^s / Y_j$ denotes country j's average carbon emission intensity, capturing the amount of CO_2 emissions per dollar of output at the country level.

The scale effect quantifies changes in total emissions resulting from national output expansion or contraction, while holding the composition of goods produced, production technologies, and national average carbon emission intensity constant.

The composition effect captures changes in total emissions due to shifts in sectoral output shares following policy changes. Holding all else fixed, reallocating production toward carbon-intensive sectors will generate higher aggregate emissions, with each sector's contribution weighted by its initial emission level.

Lastly, because emission intensities are endogenously determined by energy prices, the technique effect measures changes in total emissions arising from changes in emission intensities across sectors, weighted by sectoral carbon emission intensities and output levels in the baseline equilibrium.

Consumption-Equivalent Welfare Change. In the subsequent quantitative exercises, instead of reporting the "exact-hat-algebra" measure of welfare change $\hat{W}_j = W_j'/W_j$, we adopt the concept of *consumption-equivalent welfare*, which measures the amount of consumption that an individual in the baseline economy would be willing to forgo in exchange for the implementation of a new policy. Formally, we define the consumption-equivalent welfare change from a policy structure $\mathbf{\Psi}$ to an alternative $\mathbf{\Psi}'$ as

$$\hat{W}_j^{CE} = \frac{\hat{I}_j}{\hat{P}_j} - \frac{\tilde{\lambda}_j}{I_j}\left(Z_w' - Z_w\right), \tag{24}$$

[12] The decomposition summarizes the first-order effects of policy changes on emissions. Detailed derivations are provided in Appendix A.2.

where $\tilde{\lambda}_j = P_j \lambda_j$ denotes country j's price-adjusted disutility parameter from global carbon emissions. This metric captures both the change in real consumption, relative to the status quo, and the change in environmental disutility associated with the policy shift from $\mathbf{\Psi}$ to $\mathbf{\Psi'}$, evaluated in units of real consumption at the baseline equilibrium.

4 Taking the Model to the Data

In this section, we first describe the data sources and procedures with which we discipline our model. Then, we illustrate the estimation strategy for the key structural parameters of our model, including input shares $\beta_j^{s,L}, \beta_j^{s,R}, \gamma_j^{s's}$, final consumption shares α_j^s, carbon emission coefficients $v_j^{s's}$ and χ_j^s, disutility parameters $\tilde{\lambda}_j$, and trade elasticities θ^s.

4.1 Data

Trade, Production, and Expenditure. Our primary data source is the Global Trade Analysis Project (GTAP) version 11 for the year 2017, which provides multi-regional input-output tables and bilateral international trade flow matrices, covering 141 regions and 65 sectors. We directly obtain data on trade volumes, production output, and expenditure values from the GTAP database.

For our quantitative analysis, we focus on twelve major economies: the Association of Southeast Asian Nations (ASEAN), Australia, Canada, China, India, Japan, South Korea, Mexico, Russia, Turkey, the United States (US), and the European Union (EU).[13] All remaining countries are aggregated into a single entity labeled the Rest of the World (ROW). Additionally, we structure our sample into three primary extractive energy sectors (Coal, Crude Oil, and Natural Gas), three secondary energy sectors (Refined Petroleum, Electricity, and Gas Manufacture and Distribution), and eighteen non-energy ISIC-level industries, of which fourteen are tradable and four are non-tradable. Tables 1 and 2 provide an overview of the countries and sectors included in our sample.

As highlighted in Ossa (2014), the presence of aggregate trade imbalances between countries can lead to extreme general equilibrium adjustments in response to trade policy changes. To address this concern, we follow the approach in Dekle et al. (2007) to construct a balanced

[13] We define the ASEAN as comprising its ten member states: Brunei, Cambodia, Indonesia, Laos, Malaysia, Myanmar, the Philippines, Singapore, Thailand, and Vietnam. Since the United Kingdom (UK) officially withdrew from the EU on 31 January 2020, the EU in our analysis consists of its current twenty-seven members, including Austria, Belgium, Bulgaria, Croatia, Republic of Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, Netherlands, Poland, Portugal, Romania, Slovakia, Slovenia, Spain, and Sweden.

trade flow matrix for 2017 without cross-country trade imbalances. As a robustness check, we also consider an alternative calibration that retains the observed 2017 trade imbalances.

Carbon Emissions. Country-sectoral CO_2 emissions data for the year 2017 are obtained from GTAP-E extension. Following Farrokhi and Lashkaripour (2025), we measure CO_2 emissions at the final stage when the energy output of the energy sectors ($s \in \mathbb{E}$) is used by downstream producers in non-energy sectors ($s \in \mathbb{G}$) and count emissions generated from both direct and indirect energy use.

In particular, we classify energy resources into four types: coal, oil, natural gas, and electricity. For a non-energy sector s in country n, direct emissions stem from its combustion of energy inputs during production, which can be directly observed in GTAP. Indirect emissions arise from carbon released during energy production, which are computed based on energy input-output flows from GTAP. The total CO_2 emissions associated with sector s in country n are then the sum of direct and indirect emissions. For instance, the direct emissions of the machinery sector stem from electricity use in production, while its indirect emissions are attributable to the upstream generation of electricity, which may involve burning coal and any other energy sources.

Baseline Taxes. Baseline bilateral tariff rates are calculated based on the GTAP data. Specifically, we compute applied tariffs by dividing the values of tariff duties by the sum of bilateral import values and transportation margins, i.e., the cost, insurance, and freight (CIF) values of imports as reported in GTAP.

To obtain a harmonized measure of carbon taxation across countries, we interpret national carbon taxes as the shadow prices of all existing regulations and levies on carbon emissions, following the spirit of Farrokhi and Lashkaripour (2025). In particular, We draw carbon pricing data from two sources. The primary source is the World Bank's Carbon Pricing Dashboard, which provides comprehensive information on carbon pricing schemes, including attributes such as coverage, rates, and revenue. For countries not covered in this database, we use the nearest available observations from the OECD Net Effective Carbon Rates dataset, which reports information on fuel excise taxes, carbon taxes, and tradable permits that effectively price carbon emissions. For ROW, we assign the global average carbon price across countries as reported by the International Monetary Fund (IMF).

4.2 Estimation of Structural Parameters

Input Shares. We recover input shares for both energy and non-energy sectors using GTAP data on value added by each factor of production and sectoral input expenditures.

Specifically, the labor shares $\beta_j^{s,L}$ and the composite intermediate goods shares $\gamma_j^{s's}$ are calculated by dividing the value added from labor and intermediate inputs expenditures by gross output, respectively. In addition, natural resource shares $\beta_j^{s,R}$ in primary extractive energy sectors are obtained by dividing the reported natural resources expenditures by the total output of the three primary energy sectors for each country.

Final Consumption Shares. By inverting the expression for total expenditure on final goods in (10), we compute the final consumption share of each sector in each country as

$$\alpha_j^s = \frac{1}{I_j}(X_j^s - \sum_{s' \in \mathbb{S}} \gamma_j^{ss'} Y_j^{s'}).$$

However, in some sectors, the implied intermediate input expenditures exceed sectoral gross output, leading to negative final consumption shares. To address this issue, we follow the normalization procedure in Bagwell et al. (2021) and calibrate $\gamma_j^{ss'}$ and α_j^s jointly to ensure that all final consumption shares remain non-negative. Specifically, we slightly adjust the input-output coefficients to minimize the sum of squared deviations from the values obtained from GTAP data, subject to the constraint that all recovered α values are strictly positive.

Carbon Emission Coefficients. We calibrate carbon emission coefficients $v_j^{s's}$, defined as the amount of CO_2 emitted per unit of energy input from sector s' used by sector s in country j, by dividing sectoral emissions from the combustion of each energy resource by its corresponding energy input use. This calculation requires data on energy prices by type and country, which we manually collect from the World Bank, OECD, the International Energy Agency (IEA), and CEIC database, using annual average prices in 2017. We then convert these prices into U.S. dollar per metric ton of CO_2 ($\$/tCO_2$ for short hereafter), based on emission factors from the U.S. Environmental Protection Agency (EPA). Carbon emission intensities are finally computed as $\chi_j^s = \sum_{s' \in \mathbb{E}} v_j^{s's} \gamma_j^{s's} / (P_j^{s'} + t_j^E v_j^{s's})$ by definition. Country-level and sector-level average emission intensities are reported in Tables 1 and 2, respectively.

Perceived Disutility from Carbon Emissions. As discussed earlier, infinitesimally small households and firms do not take into account the externalities of carbon emissions from their consumption and production decisions. Government, however, can directly affect carbon emissions through policy interventions that internalize these climate externalities. Accordingly, $\tilde{\lambda}_j$ represents the perceived disutility of global emissions from the perspective of government j, up to the country's price index in the baseline.[14]

We infer the perceived disutility parameters by exploiting governments' revealed preferences in setting carbon taxes. The intuition is that, holding other factors constant, a government that places a higher weight on emissions externalities is expected to impose a higher carbon tax. Formally, we calibrate $\tilde{\lambda}_j$ by minimizing the distance between observed carbon taxes and model-predicted unilateral optimal carbon taxes. In practice, we solve the following problem for each country:

$$\min_{\tilde{\lambda}_j > 0} \left(t_j^{E,data} - t_j^E(\tilde{\lambda}_j) \right)^2,$$

where $t_j^{E,data}$ is the factual carbon tax observed and $t_j^E(\tilde{\lambda}_j)$ is the model-implied optimal carbon tax that maximizes country j's welfare given $\tilde{\lambda}_j$. We report the calibrated values of $\tilde{\lambda}_j$ in Table 1 for each country.[15] Because all countries unilaterally maximize their own welfare given other's optimal policies, our calibration procedure implies that the factual equilibrium in our baseline corresponds to a Nash equilibrium in the absence of CBAM.

Trade Elasticities. The trade elasticities and the Fréchet shape parameters, θ^j, are estimated using the gravity-based approach developed by Fontagné et al. (2022), which exploits variation in bilateral tariffs for each product category across country pairs over time. Specifically, we use panel data on bilateral trade flows and applied tariffs at the most disaggregated HS6-digit level from Fontagné et al. (2022) covering the period of 2001–2016. Then, by inverting the expenditure share equation in (9), we obtain the standard structural gravity equation for estimating sector-level trade elasticities:[16]

$$X_{ij,HS6,t}^s = \exp\left[\theta^s \ln\left(1 + \tau_{ij,HS6,t}^s\right) + \delta_{i,HS6,t} + \delta_{j,HS6,t} + \delta_{i\leftrightarrow j}\right] \times \epsilon_{ij,HS6,t}, \tag{25}$$

[14] The literature, such as Caliendo et al. (2024) and Farrokhi and Lashkaripour (2025), typically uses the global social cost of CO_2 reported by the EPA to normalize the aggregate disutility across countries. The approach captures the *objective* monetary value of all future climate change impacts, including declines in agricultural productivity, human health risks, the frequency and severity of natural disasters, and climate-induced migration. In contrast, our calibrated $\tilde{\lambda}_j$, derived by matching observed carbon taxes in each country, reflects the *subjective* valuation of carbon damages as perceived by national governments. Nevertheless, our estimates imply a global social cost of \$126.33/tCO_2, which is broadly consistent with benchmark values in the literature.

[15] As shown in (24), the price-adjusted disutility parameters $\tilde{\lambda}_j = P_j \lambda_j$ are identified using the exact-hat algebra in our estimation strategy. Recovering λ_j would require additional information on baseline price levels. Nevertheless, $\tilde{\lambda}_j$ is sufficient for all subsequent quantitative exercises.

[16] As noted by Fontagné et al. (2022), under this specification, the sectoral elasticity corresponds to the average across HS6 products within each sector. This approach avoids composition bias that may arise when aggregating trade flows and averaging tariffs across heterogeneous products within a sector.

Table 1: Country-Level Statistics

Country	Output Share	CO_2 Emission Share	Population Share	Emission Intensity	Price-Adjusted Disutility
ASEAN	3.95%	4.46%	8.40%	2.58	1.52
Australia	1.62%	1.27%	0.32%	1.80	2.09
Canada	1.83%	1.47%	0.48%	1.84	34.01
China	19.30%	30.01%	18.34%	3.55	2.29
India	3.16%	6.95%	17.79%	5.03	0.24
Japan	6.10%	3.24%	1.67%	1.21	14.80
Korea	2.24%	1.81%	0.67%	1.84	6.29
Mexico	1.27%	1.29%	1.61%	2.34	1.17
Russia	1.93%	5.07%	1.91%	5.99	0.56
Turkey	1.02%	1.16%	1.05%	2.61	3.71
US	20.96%	13.89%	4.27%	1.52	8.40
EU	18.15%	7.94%	5.86%	1.00	42.03
ROW	18.47%	21.45%	37.62%	2.65	9.22

Notes: This table presents the characteristics of each country. The first three columns report each country's share of global output, CO_2 emissions, and population, respectively. The fourth column shows national emission intensity, defined as carbon emissions generated per dollar of output, normalized by the level of the EU. The final column reports our estimated price-adjusted disutility parameters from carbon emissions.

where $X^s_{ij,HS6,t}$ and $\tau^s_{ij,HS6,t}$ denote, respectively, the trade value and the applied tariff rate for an HS6 product within sector s exported from country i to j in year t. The terms $\delta_{i,HS6,t}$ and $\delta_{j,HS6,t}$ are exporter-HS6-year and importer-HS6-year fixed effects, which fully account for the multilateral resistance terms. We also include symmetric, time-invariant country-pair fixed effects $\delta_{i\leftrightarrow j}$ to control for persistent bilateral factors of a country pair, such as geographic distance, historical ties, and common language. To address heteroskedasticity in the error term $\epsilon_{ij,HS6,t}$ and the issue of zero trade flows, we follow Silva and Tenreyro (2006) and employ the Poisson Pseudo Maximum Likelihood (PPML) estimator to estimate trade elasticities θ^s in equation (25).

The detailed estimation results are reported in Appendix Table B.1, with sector-level point estimates replicated in the last column of Table 2. For non-tradable sectors, due to the lack of information on applied tariffs, we set the Fréchet shape parameters equal to the average value across tradable sectors. For energy sectors, we adopt the elasticity estimates from Farrokhi et al. (2025), which summarize average values based on the reported estimates in prior empirical studies. Across sectors, our estimated trade elasticities have a simple mean of 4.99, which falls within the range of previous findings in the literature.[17]

4.3 Stylized Facts

Country Level. The country-level statistics in Table 1 reveal several key stylized facts regarding the distribution of economic output, carbon emissions, and perceived disutility from global emissions.

First, there is substantial heterogeneity in both output and emissions across countries. The U.S. and the EU together account for nearly 40% of global output but only 21.83% of total carbon emissions, whereas countries such as China, India, and Russia exhibit significantly higher CO_2-to-GDP ratios than the global average.

Second, emission intensity, measured as CO_2 emissions per unit of output, varies widely across regions. Russia exhibits the highest national emission intensity at 5.99, followed by India and China, reflecting a heavier reliance on carbon-intensive production processes. In contrast, Japan and the EU have the lowest emission intensities at the aggregate level, reflecting more energy-efficient production structures.

Third, the estimated price-adjusted disutility parameters, which capture each government's valuation of the welfare loss from global carbon emissions, also vary substantially. India and Russia display lower disutility values, suggesting a relatively low perceived cost of environmental damage. In contrast, Canada, Japan, and the EU exhibit higher disutility values, indicating a greater willingness to internalize the climate externalities. The stark cross-country heterogeneity reveals the difficulties in global coordination on climate action, leaving the effectiveness of CBAM in tackling global climate change ambiguous.

Industry Level. The industry-level statistics in Table 2 highlight several stylized facts regarding sectoral output and carbon emissions.

First, the sample spans a wide spectrum of sector sizes and emission intensities, allowing our quantitative analysis to capture heterogeneity along both dimensions when assessing the the environmental and economic effects of CBAM.

Second, sectors initially targeted by the EU's CBAM, i.e., Chemicals, Metals, and Minerals, disproportionately account for 31.29% of global carbon emissions while contributing only 9.20% to global output. These sectors also rely heavily on energy inputs and exhibit

[17] For example, Broda and Weinstein (2006) report an average trade elasticity of 6.6. In their survey of 744 coefficients obtained from 32 studies, Head and Mayer (2014) find a median estimate of 5.03. Ossa (2014) reports an average trade elasticity of 3.42, while Caliendo and Parro (2015) estimate an aggregate elasticity of 4.55, with values ranging from 0.37 to 50.01. Soderbery (2018) finds a global average of 3.41. Nevertheless, we also incorporate the estimates from Farrokhi et al. (2025) as a robustness check.

Table 2: Industry-Level Statistics

Sector	Output Share	CO_2 Emission Share	Energy Input Share	Emission Intensity	Trade Elasticity
Tradable					
Agriculture	3.55%	3.72%	0.028	1.00	3.88
Other Mining	0.87%	1.98%	0.056	2.17	8.95
Food	5.10%	3.14%	0.014	0.59	4.15
Textile	1.93%	1.62%	0.018	0.80	3.25
Wood	0.49%	0.52%	0.027	1.01	7.90
Paper	1.15%	1.96%	0.050	1.63	5.23
Chemicals*	3.52%	9.28%	0.100	2.52	10.22
Plastics	1.23%	1.41%	0.038	1.10	3.72
Minerals*	1.27%	6.21%	0.081	4.68	1.71
Metals*	4.41%	15.80%	0.073	3.42	2.89
Electronics	2.43%	0.97%	0.012	0.38	4.69
Machinery	4.17%	1.93%	0.012	0.44	3.43
Transport Equipment	3.40%	1.36%	0.010	0.38	6.60
Other Manufacturing	1.49%	0.62%	0.010	0.40	3.30
Non-Tradable					
Construction	10.76%	4.32%	0.010	0.38	4.99
Wholesale and Retail	9.41%	5.04%	0.014	0.51	4.99
Transportation	4.28%	24.26%	0.146	5.41	4.99
Other Services	40.53%	15.86%	0.009	0.37	4.99

Notes: This table presents the characteristics of each non-energy sector across countries. The first two columns report each sector's share of global output value and CO_2 emissions, respectively. The third column reports the cost share of total energy inputs (coal, crude oil, natural gas, refined petroleum, electricity, and gas manufacture and distribution). The fourth column reports emission intensity, defined as carbon emissions per dollar of output, normalized by the level of the agriculture sector. The final column reports our estimated trade elasticities. For non-tradable sectors, the trade elasticity corresponds to the Fréchet shape parameter, which is assigned as the average of those for tradable sectors. Sectors marked with an asterisk are included in the EU's CBAM scope.

the highest emission intensities among tradable sectors, reflecting the carbon-intensive nature of their production technologies. These stylized provides a clear rationale for the EU's prioritization of the three sectors in the initial phase of CBAM.

Third, non-tradable sectors account for around half of the global carbon emissions despite their domestic orientation. In particular, the Transportation sector alone contributes 24.26% to total emissions, the highest among all sectors. Because these sectors are treated as non-tradable in our model, they are less responsive to trade-based instruments including CBAM, thereby limiting the effectiveness of such policies in reducing emissions from these industries.

5 Quantitative Exercises

In this section, we present our quantitative results on the economic, environmental and welfare impacts of the EU's CBAM. We begin by evaluating its unilateral implementation while other countries remain passive. We then examine non-cooperative Nash outcomes in which governments are allowed to adjust their domestic policies strategically in response to the CBAM. Next, we simulate global cooperation on carbon taxes, with and without CBAM, to highlight its role in promoting global climate policy alignment on emissions reduction. Lastly, we conduct several robustness checks and model extension to to validate the key insights behind our main results.

5.1 Evaluation of the EU's CBAM

To quantify the effects of the EU's CBAM policy, which is scheduled to be implemented from 2026, we simulate a counterfactual equilibrium in which the EU imposes carbon tariffs on its imports in the *baseline* sectors (Chemicals, Minerals, and Metals), based on carbon price differentials and embedded carbon content. At this stage, all other countries are assumed to remain passive. Table 3 reports the resulting percentage changes, relative to the status quo, in real consumption, CO_2 emissions, and consumption-equivalent welfare, along with the decomposition of real income and emission effects. Additionally, we illustrate the impact on trade flows in Figure1.

Trade Effects. Given that the EU has the highest carbon tax among regions, exports from all other countries in the targeted sectors are subject to carbon tariffs to equalize the price gap under the CBAM. Column (2) of Table B.2 presents the simple mean of CBAM-imposed carbon tariffs across the three baseline sectors for each country. On average, global carbon tariffs amount to 3.25%, with Russia and India facing the highest rates at 10.24% and 6.73%, respectively. In contrast, "cleaner" economies such as Japan and Korea register significantly lower CBAM burdens, at only 0.46% and 0.48%, respectively.

In addition to the EU's average tariff rate of 2.02%, the introduction of carbon tariffs alters global trade patterns. Figure 1 displays the corresponding impacts on non-EU countries. The blue and red boxes represent the percent change in each non-EU country's trade values with the EU and with non-EU trading partners, respectively, relative to the baseline with no policy intervention. As expected, the first column shows that total trade with the EU declines by 1.60% post-CBAM, as carbon tariffs make EU-bound exports more costly. In contrast, non-EU countries reallocate trade towards one another, resulting in a 0.08% increase in total trade among non-EU members. The last two columns of the figure compare

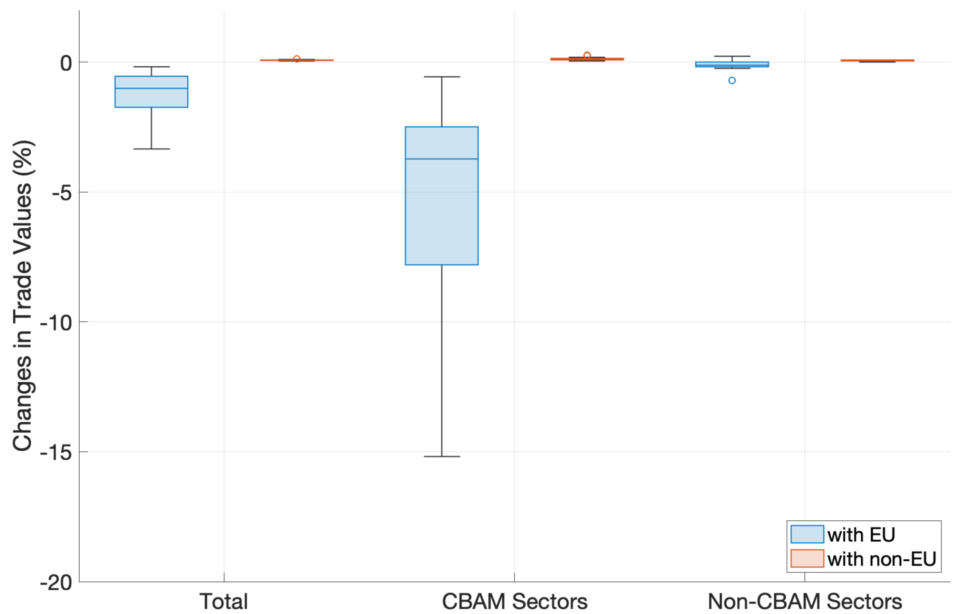

Figure 1: Trade Effects of the EU's CBAM Implementation

Note: The box plots display the percentage changes in trade values by different categories for each non-EU country, relative to the status quo, following the EU's implementation of CBAM targeting baseline sectors (Chemicals, Minerals, and Metals). The blue and red boxes represent the percentage change in trade values with the EU and with non-EU countries, respectively. Category "Total" covers trade across all tradable sectors. Categories "CBAM Sectors" and "Non-CBAM Sectors" refer to the CBAM-targeted baseline sectors and to the remaining tradable sectors, respectively.

the changes in trade values across sectoral categories. The trade diversion effect is particularly pronounced in CBAM-targeted sectors: on average, non-EU countries reduce their trade in these sectors by 6.56%, whereas trade in non-CBAM declines modestly by 0.11%.

Real Income Effects. Column (1) in Table 3 reports the percentage changes in real income for each country relative to the factual equilibrium. While the EU experiences a gain of 0.04%, most other countries incur real income losses, resulting in a global average decline of 0.002%. Russia is particularly affected, with real income falling by 0.068%.

Columns (2)–(4) decompose these real income effects into terms-of-trade (ToT), volume-of-trade (VoT), and volume-of-emission (VoEm) components, as specified in (21). For the EU, the real income gain is primarily driven by an improvement in ToT (0.046%), consistent with the trade literature showing that large economies can manipulate the terms of trade to their advantage through tariff policy. The ToT gain is partially offset by a small decline in VoT (–0.003%) due to reduced trade volumes. Meanwhile, the imposition of carbon tariffs

Table 3: The Impacts of the EU's CBAM Implementation

Country	$\Delta\frac{I}{P}$	Real Income Decomp.			ΔCO_2	Emission Decomp.			ΔW
		ToT	VoT	VoEm		Scale	Comp.	Tech	
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
ASEAN	-0.004	-0.003	-0.001	0.000	0.013	0.026	-0.025	0.011	-0.003
Australia	-0.012	-0.010	-0.002	0.000	0.014	-0.001	0.001	0.014	-0.009
Canada	-0.003	-0.003	0.000	0.000	0.038	0.033	0.013	-0.008	0.036
China	-0.008	-0.005	-0.003	0.000	-0.041	0.007	-0.061	0.012	-0.008
India	-0.015	-0.009	-0.004	-0.002	-0.153	-0.081	-0.123	0.052	-0.015
Japan	0.004	0.003	0.000	0.000	0.053	0.058	0.000	-0.005	0.009
Korea	0.005	0.003	0.001	0.000	0.060	0.053	-0.003	0.010	0.011
Mexico	-0.003	-0.004	0.001	0.000	-0.001	0.033	-0.036	0.002	-0.001
Russia	-0.068	-0.048	-0.012	-0.007	-0.812	-0.353	-0.673	0.214	-0.068
Turkey	-0.010	-0.012	0.003	0.000	-0.034	0.033	-0.096	0.029	-0.001
US	-0.003	-0.003	0.000	0.000	-0.003	0.018	-0.021	0.000	-0.002
EU	0.040	0.046	-0.003	0.002	0.294	0.204	0.146	-0.056	0.045
ROW	-0.030	-0.026	-0.003	0.000	-0.162	-0.087	-0.130	0.055	-0.029
Global	-0.002	0.000	-0.002	0.000	-0.071	-0.016	-0.082	0.026	0.000

Note: This table reports the percentage changes following the EU's implementation of CBAM targeting baseline sectors (Chemicals, Minerals, and Metals), relative to the factual equilibrium. The columns under $\Delta\frac{I}{P}$, ΔCO_2, and ΔW report each country's percentage change in real consumption, CO_2 emissions, and consumption-equivalent welfare, respectively. Global consumption-equivalent welfare and real consumption changes are calculated as output-weighted averages across countries. Columns (2)–(4) decompose real income changes into terms-of-trade, volume-of-trade, and volume-of-emission effects, respectively. Columns (6)–(8) decompose emission changes into scale, composition, and technique effects, respectively.

discourages imports and induces production reshuffling in targeted sectors back to the EU. Increased domestic production generates carbon tax revenue, which contributes positively to the VoEm component and supports the overall rise in real consumption.

In contrast, non-EU countries face significant ToT losses, especially those subject to higher carbon tariffs, such as Russia and India. These economies not only endure deteriorating trade terms but also experience reduced demand and production. On a global scale, CBAM results in a decline in total trade volumes, with an aggregate VoT effect of -0.002%.

Emission Effects. The impact of CBAM on aggregate carbon emissions is reported in Column (5) of Table 3. Emission reductions are most pronounced in countries with relatively high emission intensity and low environmental regulation, such as Russia, India, China, and the ROW, all of which face substantial carbon tariffs post-CBAM. In contrast, emissions increase in cleaner economies, including Canada, Japan, Korea, and the EU. Overall, CBAM implementation reduces global CO_2 emissions by 0.071%. These patterns underscore CBAM's effectiveness in directly addressing the "direct carbon leakage" problem: it redirects production away from high-intensity exporters toward low-intensity, strict-regulation producers such as the EU and Japan, thereby achieving net global emission reductions.

Following the decomposition in (23), Columns (6)–(8) disaggregate the emission changes into scale, composition, and technique channels. For the EU, the increase in emissions is primarily driven by the scale effect, as domestic production expands to replace CBAM-targeted imports. In addition, CBAM protects domestic producers in carbon-intensive sectors, leading to a reallocation of "dirty" production activities from foreign exporters to within the EU. Despite the EU's relatively cleaner production technologies, this sectoral shift causes a 0.146% increase in emissions through the composition effect.

Among non-EU countries, many regions experience modest increases in the scale effects due to the price effect of rising production costs and wages. However, Russia (–0.353%) and India (–0.081%) stand out with sharp declines in the scale component, reflecting significant contraction in exports to the EU. These declines contribute to an overall reduction in emissions of 0.016%. Meanwhile, the reduced demand for CBAM-targeted sectors reshapes the sectoral composition of production in exporting countries, resulting in a global composition-effect reduction of 0.082%.

While CBAM mitigates direct carbon leakage, it simultaneously induces an indirect leakage channel through global energy markets, as highlighted in recent literature (Fontagné and Schubert, 2023; Farrokhi and Lashkaripour, 2025). Since demand for energy inputs declines post-CBAM, global energy prices decrease. The resulting fall in energy costs lowers incentives for energy conservation in countries with lax environmental regulation, thereby raising carbon intensity.[18] Consequently, global CO_2 emissions increase via the technique effect by 0.026%, partially offsetting the reduction achieved by reversing direct leakage.[19]

Welfare Effects. The last column of Table 3 reports consumption-equivalent welfare changes following the implementation of CBAM. As discussed earlier, this consumption-equivalent metric captures the net welfare effect by accounting for both changes in real income and changes in disutility from global emissions, the latter of which is evaluated in units of real consumption in the factual baseline equilibrium.[20]

[18] Under constant energy input shares $\gamma_j^{s's}$ for $s' \in \mathbb{E}$, lower energy prices induce substitution toward greater energy use, increasing emission intensity χ_j^s per dollar of output.

[19] As shown in the final term of (23), the technique effect captures changes in aggregate emissions arising from changes in emission intensities. Because emission intensities $\chi_i^s \equiv \sum_{s' \in \mathbb{E}} v_i^{s's} \gamma_i^{s's} / \tilde{P}_i^{s's}$ are endogenously determined by after-tax energy prices, the technique effect represents indirect carbon leakage.

[20] Note that even with an identical reduction in global emissions and a common disutility parameter, the consumption-equivalent welfare change can differ across countries due to variation in baseline real consump-

Countries with higher perceived disutility from emissions, such as Canada, experience an increase in post-CBAM welfare, as the utility environmental gains from emission reductions overweight their real income losses. In contrast, more than half of the countries still experience a decrease in climate-adjusted welfare, suggesting the environmental benefits from reduced emissions, when evaluated relative to baseline consumption, are insufficient to to compensates for the associated economic losses. Nevertheless, the output-weighted global average welfare marginally improves with CBAM implementation.

The More, The Better? Given the modest reduction in global CO_2 emissions and the limited net welfare improvement associated with the EU's CBAM targeting only the three baseline sectors, a natural question arises: does expanding CBAM's coverage enhance its environmental performance? To address this, we conduct a counterfactual analysis in which *all* tradable sectors are covered by the EU's CBAM, while other countries still remain passive.

Table B.3 presents the corresponding simulation outcomes. As expected, broader sectoral coverage leads to a larger increase in the EU's real income. However, this comes at the cost of further deterioration in real income for all non-EU countries, primarily driven by worsening of ToT effects and greater VoT losses. Interestingly, the expansion of CBAM results in only a 0.065% reduction in global emission, which is less than the reduction achieved when coverage is limited to the three baseline sectors. Consequently, the associated global welfare change turns negative, declining by 0.001%.

The diminished environmental efficiency of expanded CBAM is partly due to a sharper contraction in energy demand, which amplifies CO_2 emissions via indirect leakage channels. At the same time, the composition effect, which played the dominant role in reducing emissions in the baseline scenario, exhibits a marked decline in strength.[21]

To explore the weakening of the composition effect, Table 4 reports regressions of changes in sectoral output shares post-CBAM on country-sector-level emission intensity. Column (1) shows that under the baseline CBAM scope, a one-unit increase in sectoral emission intensity is associated with a 19.5% decline in that sector's output share. In contrast, as shown in Column (2), when CBAM is extended to all tradable sectors, the responsiveness of output shares to emission intensity diminishes. This finding remains robust after controlling for

tion levels.

[21] Figure C.2 decomposes the contributions to global emission changes under different CBAM coverage scopes. As expected, expanding sectoral coverage increases aggregate abatement in non-EU countries through the scale effect, and even after accounting for the weakened composition effect. However, as the CBAM initiator, the EU registers a higher emission contribution due to greater expansion of domestic production when imports in all tradable sectors are subject to carbon tariffs. Therefore, even holding the technique effect constant, i.e., controlling for energy prices fluctuation, the expanded CBAM yields a modest global emission reduction of only 0.0014%.

Table 4: Composition Effects under Different CBAM Coverage Scopes

	Dependent Variable: Changes in Sectoral Output Share			
	(1) Baseline	(2) All	(3) Baseline	(4) All
Emission Intensity	-0.195***	-0.174**	-0.201***	-0.183***
	(0.070)	(0.067)	(0.050)	(0.047)
Country Fixed Effect	No	No	Yes	Yes
Observations	182	182	182	182
R-squared	0.282	0.315	0.385	0.419

Note: This table reports the regression of changes in sectoral output shares following the EU's implementation of CBAM on country-sector-level carbon emission intensity. Columns (1) and (3) correspond to the CBAM scope targeting baseline sectors (Chemicals, Minerals, and Metals). Columns (2) and (4) extend coverage to all tradable sectors. Robust standard errors are shown in parentheses. *p<0.1; **p<0.05; ***p<0.01.

country fixed effects in Columns (3) and (4). In addition, Figure C.1 visualizes changes in sectoral output shares against emission intensities under different CBAM scopes. Compared to the expanded CBAM coverage, high-emission sectors contract more sharply while cleaner sectors expand under the baseline scope. The underlying mechanism is that carbon tariffs on the three most carbon-intensive sectors reduce imports demand, prompting a shift in the industrial structure of exporting economies toward less carbon-intensive sectors. However, when all sectors are covered, the reduced variation in carbon tariff across sectors narrows the scope for reallocation, thereby diminishing the composition channel's contribution to global emission reductions.

5.2 Strategic Responses under CBAM

The previous analysis of the EU's implementation of CBAM assumes passive policy responses by other countries. In reality, however, governments may strategically adjust their domestic carbon taxes to mitigate the burden of carbon tariffs. In this subsection, we turn to examine how such strategic interactions affect CBAM's environmental effectiveness and shape global outcomes.

To illustrate the incentives for non-EU countries in response to the EU's CBAM, we first compute the change in each country's unilateral optimal carbon taxes post-CBAM. Figure 2 reveals a clear positive relationship: countries with larger export shares to the EU, particularly in the CBAM-regulated sectors, tend to raise their carbon taxes more sharply. The intuition is straightforward. Given that carbon tariffs are endogenously determined

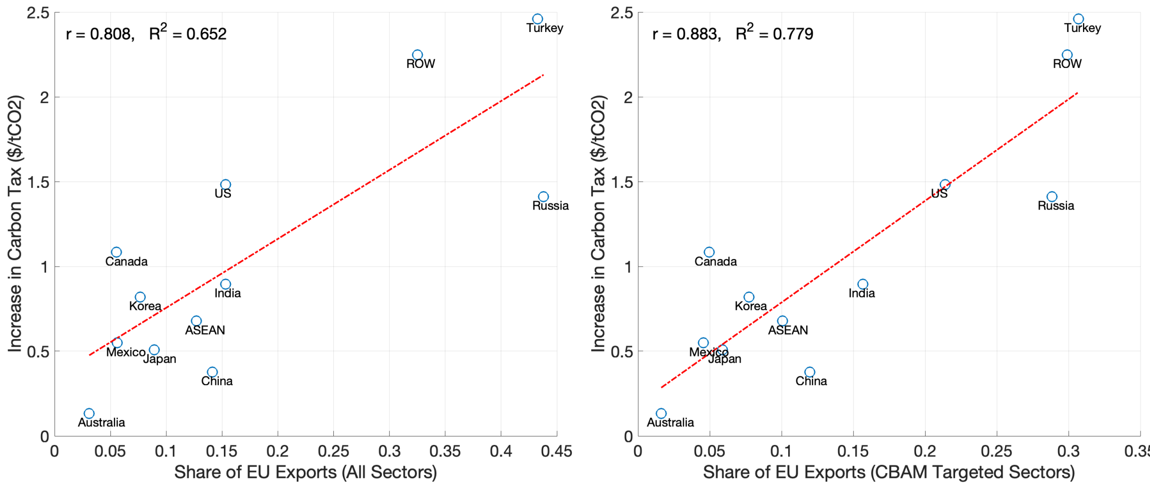

Figure 2: Strategic Incentives after the EU's CBAM Implementation

Note: The figure displays the increases in unilateral optimal carbon taxes following the EU's CBAM implementation against the factual share of exports to the EU across non-EU countries. "CBAM Targeted Sectors" refers to the baseline sectors (Chemicals, Minerals, and Metals). Each dot represents a non-EU country, and the red dashed line indicates the fitted regression line. The correlation coefficient (r) and coefficient of determination (R^2) are also reported.

by the gap between the EU's carbon price and that of exporters, greater export exposure increases the effective tariff burden under CBAM. In turn, raising domestic carbon taxes becomes a strategic tool to alleviate trade penalties and preserve market access to the EU.

Beyond the direct penalty channel, we also observe a broader interdependence in national carbon tax choices. Figure C.3 illustrates mutually reinforcing adjustment dynamics: when other countries raise their carbon taxes, the optimal response is to raise one's own tax as well. This complementarity stems from reduced competitiveness concerns in destination markets, as similar regulatory costs across producers globally lower the relative burden of domestic carbon pricing and incentivize further tax increases to pursue environmental objectives.

To fully investigate the strategic interactions among all countries, including the EU, we extend the analysis to a non-cooperative Nash equilibrium in carbon taxes. Specifically, each government chooses its optimal carbon tax level to maximize its climate-adjusted welfare, while taking others' optimal policies as given:

$$\begin{aligned} \max_{t_j^E} \quad & W_j(t_j^E), \quad \forall j \in \{1, \cdots, N\} \\ s.t. \quad & t_i^{E*} = \arg\max W_i(t_i^E), \quad \forall i \in \{1, \cdots, N\} \setminus j, \\ & \text{GE conditions: (1)–(13).} \end{aligned}$$

We follow the algorithmic approach in Ossa (2014) and solve for non-cooperative Nash carbon taxes by iterating over unilateral best responses across countries. In practice, for each iteration, we adopt the method of Mathematical Programming with Equilibrium Constraints (MPEC), as popularized by Su and Judd (2012).[22]

Columns (5) and (6) of Table B.2 report the adjustments in domestic carbon taxes and the resulting carbon tariffs under the Nash equilibrium. The EU raises its carbon tax by \$13.79/tCO_2, the largest increase among all economies. As the initiator of CBAM and the region with the highest disutility from global emissions, the EU strengthens its carbon price to intensify CBAM tariff pressure on foreign exporters, thereby incentivizing stricter environmental regulation abroad. This mechanism directly addresses the long-standing *free-riding* problem in global climate governance: under CBAM, countries can no longer benefit from others' abatement efforts while maintaining lax domestic policies. As a result, all non-EU countries respond by raising their carbon taxes, lifting the global average from \$24.94/tCO_2 to \$27.03/tCO_2. From a global perspective, the average carbon tariff increases from 3.25% to 4.15% in the non-cooperative scenario.

Columns (7)–(9) of Table 5 report the aggregate outcomes under Nash carbon taxes following the EU's CBAM implementation, with detailed decompositions provided in Table B.4. Compared to the baseline scenario in which non-EU countries remain passive, global average real income declines slightly further by 0.017%. This drop is driven by reductions in global trade volumes due to higher carbon tariffs and diminished carbon tax revenues as emissions fall in response to elevated tax rates across countries. Environmentally, the effectiveness of CBAM improves significantly: global emissions decrease by 1.44% relative to the status quo, surpassing the modest 0.07% reduction achieved under unilateral implementation.[23] This larger emission reduction is primarily driven by sharp declines in regions such as India, Russia, Turkey, the EU, and ROW. We also observe a further strengthening of the composition effect, reflecting a shift toward greener industrial structures induced by rising carbon tariffs and domestic carbon prices.

Importantly, indirect carbon leakage, which persists under unilateral implementation due to falling energy prices, is partially mitigated in the non-cooperative equilibrium. Although the decline in global energy demand depresses energy prices, the rise in carbon taxes across all countries offsets the cheaper sourcing and increases the after-tax cost of energy use, reducing

[22]We experimented with multiple initial values and found no differences in results, suggesting that the identified non-cooperative Nash equilibrium is unique in our quantitative exercise.

[23]Since our calibration of perceived disutility parameter involves matching observed and the model-predicted unilateral optimal carbon taxes, the factual equilibrium in our baseline corresponds to a non-cooperative Nash equilibrium in the absence of CBAM. The comparison thus isolates CBAM's impacts by evaluating two Nash equilibria, with and without CBAM.

emission intensity in production. Consequently, the technique effect contributes substantially to a global emissions reduction of 1.35%, highlighting the role of strategic policy responses in enhancing CBAM's environmental effectiveness.

5.3 Global Cooperation

To explore how CBAM contributes to global decarbonization alignment, we now analyze a scenario of international carbon tax cooperation, conditional on the EU's implementation of CBAM, and characterize the outcomes of efficient multilateral negotiations. Since the efficiency frontier spans a continuum of Pareto efficient outcomes, we adopt a Nash bargaining protocol in which countries jointly determine their domestic carbon tax to maximize the Nash product of their welfare gains. Formally, the problem of global cooperation on carbon taxation is specified as

$$\begin{aligned} \max_{\{t_j^E\}_{j=1}^N} \quad & \sum_{j=1}^{N} \vartheta_j \log\Big[W_j(\boldsymbol{t}^E) - W_j(\boldsymbol{t}^{E,0})\Big] \\ s.t. \quad & W_j(\boldsymbol{t}^E) \geq W_j(\boldsymbol{t}^{E,0}),\ \forall j \in \{1, \cdots, N\}, \\ & \text{GE conditions: (1)–(13).} \end{aligned}$$

Here, ϑ_j denotes the Pareto weight assigned to country j in the allocation of efficient gains, which we set equal to each country's GDP share in status quo, following Farrokhi and Lashkaripour (2025). The vector $\boldsymbol{t}^E$ represents the predicted cooperative carbon tax rates, while $\boldsymbol{t}^{E,0}$ denotes the carbon tax vector under the outside option. We assume that the disagreement point, in the event of failed multilateral negotiations, corresponds to the non-cooperative Nash equilibrium under the EU's CBAM implementation. The feasibility condition, $W_j(\boldsymbol{t}^E) \geq W_j(\boldsymbol{t}^{E,0})$, ensures that each country is at least as well off under cooperation as at the disagreement point.

Column (7) and (8) of Table B.2 report the model-predicted changes in cooperative carbon taxes and the resulting carbon tariffs across countries. Under global cooperation, most countries adopt substantially higher carbon taxes, raising the global average to \$36.07/tCO_2. Notably, the EU sets a lower carbon tax than in the non-cooperative scenario. Coordinated action internalizes global emission externalities, reducing the need for unilateral EU regulation to induce global compliance through strategic interactions. This harmonized alignment of carbon pricing narrows cross-country differentials, thereby mitigating trade distortions associated with border measures. Consequently, exports from nearly all sample countries become exempt from carbon tariffs, and the global average carbon tariff rate collapses from 4.15% in the non-cooperative equilibrium to approaching zero under cooperation.

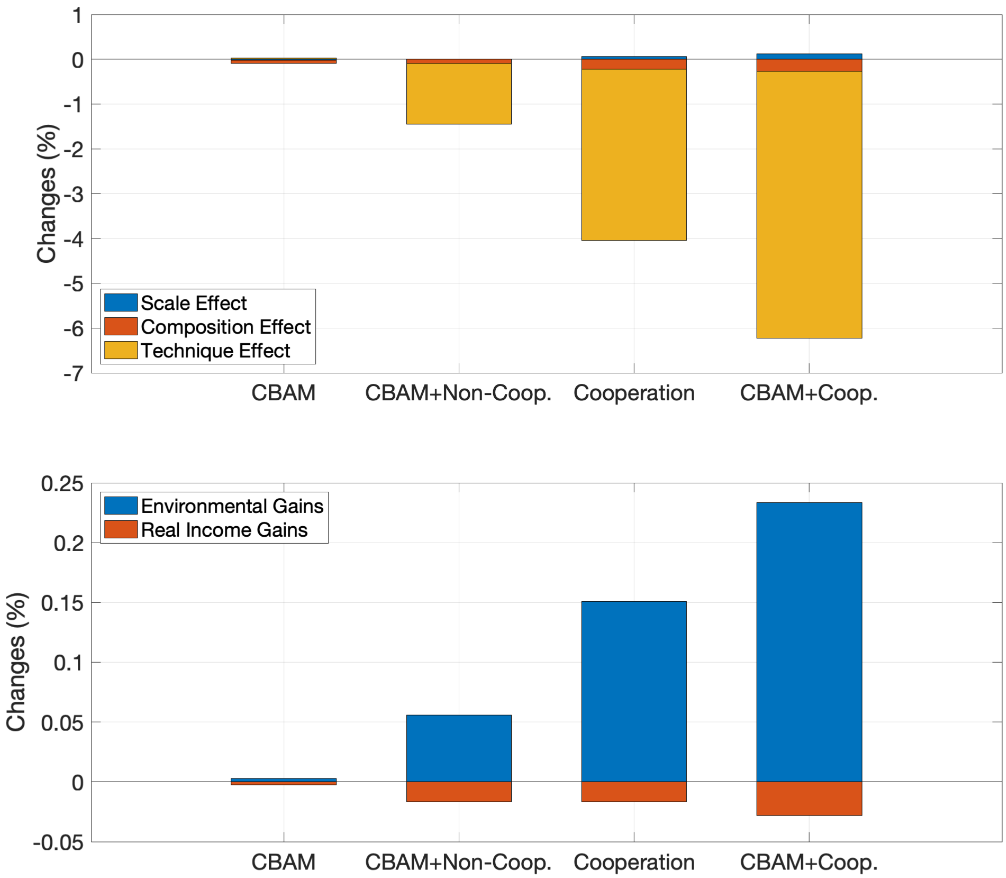

Figure 3: Decomposition of Global Emissions and Welfare Changes

Note: The figure displays the decomposition of percentage changes in global emissions (upper panel) and global welfare (lower panel). The different scenarios are I. the EU's implementation of CBAM targeting baseline sectors (Chemicals, Minerals, and Metals), II. non-cooperation on carbon taxes following the EU's implementation of CBAM targeting baseline sectors, III–IV. global cooperation on carbon taxes from the factual equilibrium and following the EU's implementation of CBAM targeting baseline sectors, respectively. Global consumption-equivalent welfare changes are computed as output-weighted averages across countries.

Columns (10)–(12) of Table 5 report the aggregate outcomes in the cooperative equilibrium, with detailed decompositions provided in Table B.5. While real income declines modestly in most countries, global CO_2 emissions fall sharply by 6.05%, a reduction exceeding the total emissions of the global Textile, Electronics, Machinery, and Transport Equipment sectors in the 2017 baseline. As a result, global climate-adjusted welfare rises by 0.17% on average, primarily driven by environmental gains. Decomposition reveals that cooperative carbon taxes reallocate industrial activity toward greener, less carbon-intensive sectors, contributing 0.27% to the overall emission reductions. Crucially, indirect carbon leakage is further mitigated, as shown in Figure 3. Carbon emission intensities decrease across most countries due to higher after-tax costs of energy use, accounting for 5.96% of the global emission reductions.[24]

To further investigate the implications of CBAM for multilateral negotiations, we simulate a global cooperation scenario starting from the factual equilibrium.[25] Column (5) of Table B.2 reports the resulting cooperative carbon taxes. The global average reaches \$32.13/tCO_2, notably below the \$36.07/tCO_2 achieved under cooperation with CBAM. The aggregate outcomes, shown in Columns (7)–(9) of Table 5, indicate that in the absence of CBAM, global cooperation reduces carbon emissions by 3.90%, achieving only 64.57% of the total reduction attainable with CBAM in place. This contrast underscores CBAM's catalytic role as an enforcement mechanism in the Nash bargaining framework. By credibly threatening foreign exporters with carbon tariffs, CBAM raises the cost of disagreement, especially for high-emission, carbon-intensive economies. Consequently, we observe substantial rise in cooperative carbon taxes in countries such as China, India, and Russia, which, in case of disagreement, face potentially severe trade penalties and welfare losses under CBAM. In this way, CBAM as a credible threatening point shifts the bargaining outcome toward stronger environmental commitments and facilitates deeper global cooperation.

5.4 Further Checks and Exercises

Fixed Trade Imbalances. Following the approach of Ossa (2014), our main analysis adopts the purged 2017 trade data without imbalances as the baseline equilibrium. As a robustness check, we simulate the EU's implementation of CBAM under an alternative setup in which country-level trade imbalances are held constant at their 2017 levels. As reported in Table B.6, the core findings remain robust under this alternative specification.

Alternative Estimates of Trade Elasticity. In the baseline calibration, we follow the gravity-based approach developed by Fontagné et al. (2022) to estimate trade elasticities. As an alternative parameterization, we incorporate sector-level elasticity estimates compiled by Farrokhi et al. (2025), which averages estimates from five recent studies employing different methodologies within models featuring a gravity structure comparable to ours. As shown in Table B.7, counterfactual simulations using this alternative set yield results that remain consistent with our main findings.

[24] Japan and Korea experience emission increases because their relatively cleaner, less emission-intensive production structures allow for lower carbon taxes to achieve Pareto improvement under cooperation relative to the non-cooperative equilibrium. This improves real income and symmetric welfare outcomes but results in higher emissions through positive composition and technique effects.

[25] We aim to compare cooperative outcomes with and without CBAM. As discussed earlier, the factual baseline corresponds to a Nash equilibrium absent CBAM, which serves as the disagreement point in this exercise.

Table 5: The Aggregate Outcomes under Different Scenarios

Country	I. CBAM			II. CBAM + Non-Coop.			III. Cooperation			IV. CBAM + Cooperation		
	$\Delta\frac{I}{P}$ (1)	ΔCO_2 (2)	ΔW (3)	$\Delta\frac{I}{P}$ (4)	ΔCO_2 (5)	ΔW (6)	$\Delta\frac{I}{P}$ (7)	ΔCO_2 (8)	ΔW (9)	$\Delta\frac{I}{P}$ (10)	ΔCO_2 (11)	ΔW (12)
ASEAN	-0.004	0.013	-0.003	-0.004	-0.507	0.015	-0.023	-9.062	0.029	-0.025	-9.092	0.055
Australia	-0.012	0.014	-0.009	-0.019	-0.028	0.037	0.007	-6.193	0.158	-0.014	-9.942	0.220
Canada	-0.003	0.038	0.036	-0.014	-0.665	0.769	-0.304	-26.516	1.820	-0.344	-28.333	2.946
China	-0.008	-0.041	-0.008	-0.009	-0.528	-0.003	-0.008	-5.913	0.010	-0.013	-7.247	0.015
India	-0.015	-0.153	-0.015	-0.013	-1.019	-0.010	-0.003	-3.693	0.006	-0.007	-6.952	0.007
Japan	0.004	0.053	0.009	0.007	-0.145	0.112	-0.016	23.641	0.268	0.010	17.494	0.449
Korea	0.005	0.060	0.011	0.011	-0.354	0.144	-0.030	22.568	0.331	0.031	6.235	0.591
Mexico	-0.003	-0.001	-0.001	-0.008	-0.355	0.029	-0.063	-15.569	0.038	-0.067	-15.048	0.089
Russia	-0.068	-0.812	-0.068	-0.095	-2.036	-0.084	-0.021	-8.295	0.011	-0.102	-14.768	-0.054
Turkey	-0.010	-0.034	-0.001	-0.016	-1.981	0.153	-0.334	-32.111	0.126	-0.248	-27.666	0.464
US	-0.003	-0.003	-0.002	-0.006	-1.258	0.010	-0.022	-6.857	0.023	-0.024	-7.511	0.045
EU	0.040	0.294	0.045	0.016	-5.284	0.121	0.054	28.138	0.340	0.066	23.858	0.509
ROW	-0.030	-0.162	-0.029	-0.075	-2.059	-0.054	-0.041	-11.478	0.015	-0.114	-12.714	-0.027
Global	-0.002	-0.071	0.000	-0.017	-1.440	0.039	-0.017	-3.903	0.134	-0.028	-6.045	0.205

Note: This table presents each country's percentage change in real consumption ($\Delta\frac{I}{P}$), CO_2 emissions (ΔCO_2), and consumption-equivalent welfare (ΔW) under different scenarios: I. the EU's implementation of CBAM targeting baseline sectors (Chemicals, Minerals, and Metals), II. non-cooperation on carbon taxes following the EU's implementation of CBAM targeting baseline sectors, III–IV. global cooperation on carbon taxes from the factual equilibrium and following the EU's implementation of CBAM targeting baseline sectors, respectively. Global consumption-equivalent welfare and real consumption changes are computed as output-weighted averages across countries.

Tariff Retaliation by Non-EU Countries. While our main analysis focuses on strategic carbon tax adjustments, CBAM's tariff-based structure naturally invites consideration of retaliatory trade responses. We extend the framework to simulate a counterfactual scenario in which non-EU countries impose import tariffs on EU goods alongside their domestic environmental policies. Specifically, we compute a non-cooperative Nash equilibrium in which all countries set optimal carbon taxes given others' choices and non-EU countries additionally use retaliatory tariffs to maximize their own welfare.

Columns (9) and (10) of Table B.2 report the resulting changes in carbon taxes and carbon tariffs, and Figure C.4 displays the trade-weighted average retaliatory tariffs. We find that all non-EU countries impose higher tariffs on EU exports, with an average increase of 7.90% relative to the status quo. In response, the EU moderates its carbon tax increase relative to the benchmark non-cooperative case without retaliation, thereby reducing the stringency of carbon tariffs applied to non-EU exports. The aggregate impacts are reported in Table B.8. Non-EU countries uniformly experience real income gains, primarily through improved terms of trade, while the EU incurs a 0.74% decline in real consumption due to worsened trade conditions and reduced export opportunities. Global carbon emissions fall by 1.64%, slightly exceeding the reduction achieved in the no-retaliation benchmark. This is driven by a 7.14% drop in EU emissions from lower production and trade diversion caused by retaliation. Additionally, non-EU countries substantially increase tariffs on EU energy exports, further helping to mitigate indirect leakage. Taken together, tariff retaliation redistributes both economic and environmental gains: it reduces EU welfare and dampens its incentive to pursue aggressive carbon pricing, while shifting income and abatement benefits toward non-EU countries and modestly improving global welfare.

Tariff and Carbon Tax Cooperation. Recognizing the joint influence of trade and climate policies on global outcomes, we extend the Nash bargaining framework to include multilateral negotiations over both carbon taxes and Most-Favored-Nation (MFN) tariffs. The disagreement point is defined as the non-cooperative equilibrium in carbon taxes with tariff retaliation by non-EU countries following the EU's CBAM implementation.

Figure C.5 displays the distribution of trade-weighted MFN tariffs across countries and sectors. Tariff rates rise across most sectors, with particularly sharp increases in energy industries. Electricity, Gas Manufacture and Distribution, and Coal sectors face the highest average tariff hikes, at 11.05%, 9.87% and 6.55%, respectively, reflecting governments' strategic use of trade policy as a complementary instrument to uniform national carbon taxation, consistent with the argument in Farrokhi and Lashkaripour (2025).

Table B.9 reports the aggregate outcomes under the extended cooperative equilibrium.

The global average carbon tax increases further from \$36.07/tCO_2 in the baseline cooperation scenario to \$39.00/tCO_2 with MFN tariffs included in the negotiations, further mitigating indirect carbon leakage and reducing global emissions by 8.24%. We also simulate a multilateral negotiation in both carbon taxes and MFN tariffs starting from the factual equilibrium. In this case, environmental effectiveness is weaker due to the absence of CBAM as credible enforcement mechanism. By linking trade and climate instruments, CBAM not only incentivizes higher carbon pricing but also facilitates tariff adjustments that promote fairer burden sharing and mitigate carbon leakage, thereby reinforcing the credibility and effectiveness of global cooperation.

6 Conclusion

We develop a multi-country, multi-sector general equilibrium model with input–output linkages, carbon supply chains, and global emission externalities, to investigate the environmental and economic consequences of the EU's Carbon Border Adjustment Mechanism.

Our quantitative analysis reveals nuanced effects of unilateral CBAM implementation. While CBAM curbs direct carbon leakage by shifting production away from high-emission economies, its overall effectiveness is constrained by indirect leakage through global energy markets. Global welfare improves marginally when environmental benefits are accounted for. Moreover, extending CBAM to all tradable sectors weakens its climate impact: broader coverage amplifies indirect leakage and diminishes the reallocation incentive that shifts demand toward less carbon-intensive sectors, ultimately resulting in negative global welfare effects.

We further highlight the strategic dimension of CBAM. Non-EU countries face a trade-off between avoiding tariff penalties through higher domestic carbon pricing and incurring the associated production costs. We show that in a non-cooperative equilibrium, CBAM incentivizes all non-EU partners to raise their carbon taxes, with the EU itself implementing the largest increase/ The strategic interaction mitigates both free-riding and indirect leakage, enhancing CBAM's environmental effectiveness at modest economic cost. When countries engage in global cooperation, average carbon prices rise substantially and global emissions fall sharply. Comparing cooperation scenarios with and without CBAM reveals that CBAM functions as an effective enforcement device that raises the cost of disagreement, especially for carbon-intensive countries, and fosters deeper international climate cooperation.

Future research could extend the analysis to dynamic settings that incorporate endogenous green technology innovation and investment responses, or apply the framework to evaluate complementary instruments, such as climate finance and industrial policy, in supporting global decarbonization.

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Appendix

A Derivations

A.1 Derivations of Real Income Effects

In this subsection, we present detailed derivations of the expressions for the changes in real income in equation (21). By assuming that exogenous trade deficits remain constant, $d\ln D_j = 0$, and holding iceberg shipping costs fixed, we take total differentiation of real income I_j/P_j and obtain

$$\begin{aligned} d\ln\frac{I_j}{P_j} &= \frac{w_jL_j}{I_j}d\ln w_j + \frac{1}{I_j}\sum_{s\in\mathbb{E}_1} r_j^sR_j^s d\ln r_j^s + \frac{1}{I_j}\sum_{s\in\$} t_j^E Z_j^s\left(d\ln t_j^E + d\ln Z_j^s\right) \\ &\quad + \frac{1}{I_j}\sum_{i=1}^N\sum_{s\in\$} t_{ij}^s M_{ij}^s\left(d\ln t_{ij}^s + d\ln M_{ij}^s\right) - d\ln P_j. \end{aligned} \tag{A.1}$$

For the change in wages, we take total differentiation of the definition of the cost of the input bundle (3) and get

$$d\ln w_j = \frac{1}{\beta_j^{s,L}}d\ln c_j^s - \frac{\beta_j^{s,R}}{\beta_j^{s,L}}d\ln r_j^s - \sum_{s'\in\$}\frac{\gamma_j^{s's}}{\beta_j^{s,L}}d\ln\tilde{P}_j^{s's}, \tag{A.2}$$

where $\beta_j^{s,R} = 0$ for $s\in\mathbb{E}_2\cup\mathbb{G}$ and $d\ln\tilde{P}_j^{s's} = d\ln P_j^{s'}$ for $s'\in\mathbb{G}$. The definition of sectoral prices (8) implies that

$$d\ln P_j^s = \sum_{i=1}^N \pi_{ij}^s\left(d\ln c_i^s + d\ln\tau_{ij}^s\right), \tag{A.3}$$

and by totally differentiating the definition of consumption price index (1), we obtain changes in consumption price index as

$$\begin{aligned} d\ln P_j &= \sum_{s\in\$}^S \alpha_j^s\sum_{i=1}^N \pi_{ij}^s\left(d\ln c_i^s + d\ln\tau_{ij}^s\right) \\ &= \frac{1}{I_j}\sum_{s\in\$}\left[(X_j^s - \sum_{s'\in\$}\gamma_j^{ss'}Y_j^{s'})\sum_{i=1}^N\pi_{ij}^s\left(d\ln c_i^s + d\ln\tau_{ij}^s\right)\right], \end{aligned} \tag{A.4}$$

where α_j^s is solved by the equation of country-sector total expenditure on final goods (10) to arrive at the second line. By totally differentiating the market clearing condition for natural resources (12), we obtain

$$d\ln r_j^s = d\ln Y_j^s. \tag{A.5}$$

Recall that the country-sector carbon emissions is given by $Z_j^s = \chi_j^s Y_j^s$. Hence, we can have

$$d\ln Z_j^s = d\ln Y_j^s + d\ln \chi_j^s. \tag{A.6}$$

The definition of the after-tax price of energy material inputs (2) implies that

$$d\ln \tilde{P}_j^{s's} = \frac{P_j^{s'}}{\tilde{P}_j^{s's}} d\ln P_j^{s'} + \frac{t_j^E v_j^{s's}}{\tilde{P}_j^{s's}} d\ln t_j^E, \tag{A.7}$$

where we have $\tilde{P}_j^{s's} = P_j^{s'}$ for $s' \in \mathbb{G}$.

Substituting (A.3) - (A.6) into (A.1) and rearranging, we get

$$\begin{aligned}
d\ln \frac{I_j}{P_j} = {} & \frac{w_j L_j}{I_j} d\ln w_j + \frac{1}{I_j}\sum_{s\in\$} t_j^E Z_j^s \left(d\ln t_j^E + d\ln Y_j^s + d\ln \chi_j^s\right) \\
& + \frac{1}{I_j}\sum_{i=1}^N \sum_{s\in\$} t_{ij}^s M_{ij}^s d\ln M_{ij}^s + \frac{1}{I_j}\sum_{s\in\$}\sum_{s'\in\$} \gamma_j^{ss'} Y_j^{s'} \sum_{i=1}^N \pi_{ij}^s \left(d\ln c_i^s + d\ln \tau_{ij}^s\right) \\
& + \frac{1}{I_j}\sum_{s\in\mathbb{E}_1} \beta_j^{s,R} Y_j^s d\ln Y_j^s - \frac{1}{I_j}\sum_{i=1}^N\sum_{s\in\$} \tau_{ij}^s M_{ij}^s d\ln c_i^s.
\end{aligned}$$

By adding and subtracting $\frac{1}{I_j}\sum_{i=1}^N \sum_{s\in\$} E_{ij}^s d\ln c_j^s$, we obtain

$$\begin{aligned}
d\ln \frac{I_j}{P_j} = {} & \frac{w_j L_j}{I_j} d\ln w_j + \frac{1}{I_j}\sum_{s\in\$} t_j^E Z_j^s \left(d\ln t_j^E + d\ln Y_j^s + d\ln \chi_j^s\right) \\
& + \frac{1}{I_j}\sum_{i=1}^N \sum_{s\in\$} t_{ij}^s M_{ij}^s \left(d\ln M_{ij}^s - d\ln c_i^s\right) + \frac{1}{I_j}\sum_{s\in\mathbb{E}_1} \beta_j^{s,R} Y_j^s d\ln Y_j^s \\
& + \frac{1}{I_j}\sum_{i=1}^N \sum_{s\in\$} \left(E_{ij}^s d\ln c_j^s - M_{ij}^s d\ln c_i^s\right) - \frac{1}{I_j}\sum_{i=1}^N \sum_{s\in\$} E_{ij}^s \left(d\ln c_j^s - \sum_{s'\in\$} \gamma_j^{s's} d\ln P_j^{s'}\right).
\end{aligned}$$

Finally, by substituting (A.2) and (A.7) into the equation above, we obtain the expression for the changes in real income as

$$\begin{aligned}
d\ln \frac{I_j}{P_j} = {} & \frac{1}{I_j}\sum_{i=1}^N \sum_{s\in\$} \left(E_{ij}^s d\ln c_j^s - M_{ij}^s d\ln c_i^s\right) + \frac{1}{I_j}\sum_{i=1}^N \sum_{s\in\$} t_{ij}^s M_{ij}^s \left(d\ln M_{ij}^s - d\ln c_i^s\right) \\
& + \frac{1}{I_j}\sum_{s\in\$} t_j^E Z_j^s \left(d\ln Y_j^s + d\ln \chi_j^s\right).
\end{aligned}$$

A.2 Derivations of Emission Effects

In this subsection, we present detailed derivations of the expressions for the changes in emissions, equation (23). Recall that global carbon emissions are the sum of carbon emissions in each country, $Z_w = \sum_{j=1}^{N} Z_j$. By taking total differentiation, we have the expression for the changes in global emissions as

$$d \ln Z_w = \frac{1}{Z_w} \sum_{j=1}^{N} Z_j d \ln Z_j .$$

National carbon emissions aggregate carbon emissions across sectors, $Z_j = \sum_{s=1}^{S} Z_j^s$. By using the definition of country-sector emission (4), we have

$$\begin{aligned} d \ln Z_j^s &= \frac{1}{Z_j} \sum_{s \in \$} \chi_j^s \frac{Y_j^s}{Y_j} Y_j \left(d \ln Y_j + d \ln \frac{Y_j^s}{Y_j} + d \ln \chi_j^s \right) \\ &= \frac{1}{Z_j} \sum_{s \in \$} \chi_j^s Y_j^s d \ln Y_j + \frac{1}{Z_j} \sum_{s \in \$} \chi_j^s Y_j^s d \ln \frac{Y_j^s}{Y_j} + \frac{1}{Z_j} \sum_{s \in \$} \chi_j^s Y_j^s d \ln \chi_j^s \\ &= \frac{1}{Z_j} \bar{\chi}_j Y_j d \ln Y_j + \frac{1}{Z_j} \sum_{s \in \$} \chi_j^s Y_j^s d \ln \frac{Y_j^s}{Y_j} + \frac{1}{Z_j} \sum_{s \in \$} \chi_j^s Y_j^s d \ln \chi_j^s , \end{aligned}$$

where $\bar{\chi}_j \equiv \sum_{s \in \$} \chi_j^s Y_j^s / Y_j$ stands for country j's average carbon emission intensity.

B Additional Tables

Table B.1: Estimates of Trade Elasticity Parameters

Sector	Trade Elasticity	Standard Error	Obs.
Agriculture	3.88	0.42	5,783,634
Other Mining	8.95	1.55	1,222,114
Food	4.15	0.11	10,838,303
Textile	3.25	0.12	21,645,435
Wood	7.90	0.42	2,241,999
Paper	5.23	0.32	4,037,226
Chemicals	10.22	0.26	19,035,739
Plastics	3.72	0.19	4,569,254
Minerals	1.71	0.22	4,512,081
Metals	2.89	0.19	15,958,945
Electronics	4.69	0.43	8,457,752
Machinery	3.43	0.16	19,324,279
Transport Equipment	6.60	0.38	3,892,596
Other Manufacturing	3.30	0.26	5,493,470

Note: This table presents the estimated trade elasticity parameters based on the specification in (25) by using Poisson Pseudo Maximum Likelihood (PPML) estimation. Robust standard errors are reported in the third column.

Table B.2: Carbon Tax Changes and Carbon Tariffs under Different Scenarios

Country	CBAM		CBAM + Non-Coop.		Cooperation		CBAM + Coop.		CBAM + Non-Coop. with Tariff Retaliation	
	$\hat{t}_j^E$ (1)	Carbon Tariffs (2)	$\hat{t}_j^E$ (3)	Carbon Tariffs (4)	$\hat{t}_j^E$ (5)	Carbon Tariffs (6)	$\hat{t}_j^E$ (7)	Carbon Tariffs (8)	$\hat{t}_j^E$ (9)	Carbon Tariffs (10)
ASEAN	1.00	3.02%	1.04	3.91%	1.66	0.00%	1.67	0.00%	1.04	3.52%
Australia	1.00	2.25%	1.01	3.02%	1.40	0.00%	1.66	0.00%	1.02	2.67%
Canada	1.00	0.46%	1.02	0.91%	2.17	0.00%	2.29	0.00%	1.02	0.72%
China	1.00	4.13%	1.03	5.24%	1.39	0.00%	1.50	0.00%	1.06	4.71%
India	1.00	6.73%	1.06	8.56%	1.26	0.00%	1.50	0.00%	1.06	7.73%
Japan	1.00	0.48%	1.02	0.73%	0.00	0.00%	0.23	0.24%	1.04	0.61%
Korea	1.00	0.72%	1.03	1.00%	0.00	0.00%	0.69	0.00%	1.04	0.87%
Mexico	1.00	3.85%	1.03	5.01%	2.34	0.00%	2.30	0.00%	1.04	4.49%
Russia	1.00	10.24%	1.10	12.74%	1.74	0.00%	2.42	0.00%	1.20	11.23%
Turkey	1.00	2.36%	1.11	2.98%	3.67	0.00%	3.17	0.00%	1.12	2.64%
US	1.00	1.33%	1.08	1.70%	1.44	0.00%	1.50	0.00%	1.09	1.50%
EU	1.00	0.00%	1.22	0.00%	0.20	0.00%	0.31	0.00%	1.14	0.00%
ROW	1.00	3.41%	1.45	3.99%	3.72	0.00%	4.20	0.00%	1.38	3.68%

Note: This table presents carbon tax changes, $\hat{t}_j^E$, and CBAM carbon tariff rates under different scenarios: I. the EU's implementation of CBAM targeting baseline sectors (Chemicals, Minerals, and Metals), II. non-cooperation on carbon taxes following the EU's implementation of CBAM targeting baseline sectors, III–IV. global cooperation on carbon taxes from the factual equilibrium and following the EU's implementation of CBAM targeting baseline sectors, respectively. V. non-cooperative equilibrium on carbon taxes with non-EU countries' tariff retaliation following the EU's implementation of CBAM targeting baseline sectors.

Table B.3: The Impacts of the EU's CBAM Implementation (All Tradable Sectors)

Country	$\Delta \frac{I}{P}$	Real Income Decomp.			ΔCO_2	Emission Decomp.			ΔW
		ToT	VoT	VoEm		Scale	Comp.	Tech	
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
ASEAN	-0.009	-0.007	-0.002	0.000	0.019	0.022	-0.024	0.020	-0.008
Australia	-0.019	-0.016	-0.003	0.000	0.017	-0.006	0.002	0.021	-0.016
Canada	-0.003	-0.004	0.000	0.001	0.050	0.056	0.013	-0.019	0.032
China	-0.013	-0.008	-0.005	0.000	-0.032	0.001	-0.052	0.019	-0.013
India	-0.026	-0.017	-0.006	-0.002	-0.174	-0.137	-0.129	0.092	-0.026
Japan	0.005	0.005	0.000	0.000	0.072	0.086	-0.004	-0.010	0.010
Korea	0.003	0.001	0.001	0.001	0.072	0.059	-0.002	0.015	0.009
Mexico	-0.005	-0.007	0.002	0.000	0.003	0.051	-0.044	-0.004	-0.004
Russia	-0.088	-0.063	-0.016	-0.007	-0.835	-0.413	-0.680	0.258	-0.087
Turkey	-0.026	-0.028	0.002	0.000	-0.027	0.004	-0.077	0.046	-0.018
US	-0.004	-0.004	0.000	0.000	0.009	0.037	-0.019	-0.009	-0.003
EU	0.064	0.072	-0.005	0.003	0.370	0.333	0.141	-0.104	0.068
ROW	-0.046	-0.041	-0.005	0.000	-0.175	-0.131	-0.125	0.081	-0.045
Global	-0.004	0.001	-0.003	0.000	-0.065	-0.020	-0.078	0.034	-0.001

Note: This table reports the percentage changes following the EU's implementation of CBAM targeting all tradable sectors, relative to the factual equilibrium. The columns under $\Delta \frac{I}{P}$, ΔCO_2, and ΔW report each country's percentage change in real consumption, CO_2 emissions, and consumption-equivalent welfare, respectively. Global consumption-equivalent welfare and real consumption changes are calculated as output-weighted averages across countries. Columns (2)–(4) decompose real income changes into terms-of-trade, volume-of-trade, and volume-of-emission effects, respectively. Columns (6)–(8) decompose emission changes into scale, composition, and technique effects, respectively.

Table B.4: Non-Cooperative Equilibrium under the EU's CBAM Implementation

Country	$\Delta\frac{I}{P}$	Real Income Decomp.			ΔCO_2	Emission Decomp.			ΔW
		ToT	VoT	VoEm		Scale	Comp.	Tech	
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
ASEAN	-0.004	0.000	-0.001	-0.004	-0.507	0.067	-0.017	-0.556	0.015
Australia	-0.019	-0.017	-0.003	0.000	-0.028	0.042	0.027	-0.098	0.037
Canada	-0.014	-0.008	0.000	-0.007	-0.665	0.064	0.003	-0.731	0.769
China	-0.009	-0.001	-0.004	-0.004	-0.528	0.047	-0.072	-0.503	-0.003
India	-0.013	0.002	-0.003	-0.012	-1.019	-0.106	-0.201	-0.716	-0.010
Japan	0.007	0.008	0.000	-0.001	-0.145	0.134	0.010	-0.289	0.112
Korea	0.011	0.011	0.002	-0.003	-0.354	0.112	0.002	-0.468	0.144
Mexico	-0.008	-0.008	0.001	-0.002	-0.355	0.088	-0.029	-0.414	0.029
Russia	-0.095	-0.061	-0.015	-0.017	-2.036	-0.488	-0.877	-0.685	-0.084
Turkey	-0.016	-0.004	0.005	-0.017	-1.981	0.014	-0.136	-1.862	0.153
US	-0.006	-0.001	0.000	-0.005	-1.258	0.060	-0.037	-1.281	0.010
EU	0.016	0.077	-0.003	-0.044	-5.284	0.146	0.123	-5.539	0.121
ROW	-0.075	-0.062	-0.009	-0.004	-2.059	-0.032	-0.093	-1.935	-0.054
Global	-0.017	0.001	-0.003	-0.012	-1.440	0.008	-0.095	-1.352	0.039

Note: This table reports the percentage changes under the non-cooperative equilibrium following the EU's implementation of CBAM targeting baseline sectors (Chemicals, Minerals, and Metals), relative to the factual equilibrium. The columns under $\Delta\frac{I}{P}$, ΔCO_2, and ΔW report each country's percentage change in real consumption, CO_2 emissions, and consumption-equivalent welfare, respectively. Global consumption-equivalent welfare and real consumption changes are calculated as output-weighted averages across countries. Columns (2)–(4) decompose real income changes into terms-of-trade, volume-of-trade, and volume-of-emission effects, respectively. Columns (6)–(8) decompose emission changes into scale, composition, and technique effects, respectively.

Table B.5: Cooperative Equilibrium under the EU's CBAM Implementation

Country	$\Delta\frac{I}{P}$	Real Income Decomp.			ΔCO_2	Emission Decomp.			ΔW
		ToT	VoT	VoEm		Scale	Comp.	Tech	
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
ASEAN	-0.025	0.055	0.006	-0.067	-9.092	0.086	-0.064	-9.112	0.055
Australia	-0.014	0.047	0.004	-0.050	-9.942	0.177	-0.351	-9.786	0.220
Canada	-0.344	0.120	-0.001	-0.295	-28.333	-1.217	-1.888	-26.076	2.946
China	-0.013	0.043	0.011	-0.055	-7.247	0.132	-0.206	-7.176	0.015
India	-0.007	0.079	0.009	-0.079	-6.952	-0.102	-0.441	-6.448	0.007
Japan	0.010	-0.049	-0.004	0.103	17.494	0.886	0.282	16.179	0.449
Korea	0.031	-0.016	0.005	0.046	6.235	0.769	0.248	5.176	0.591
Mexico	-0.067	0.062	-0.002	-0.079	-15.048	-0.264	-0.829	-14.132	0.089
Russia	-0.102	0.089	0.024	-0.124	-14.768	-1.238	-2.462	-11.472	-0.054
Turkey	-0.248	0.212	0.003	-0.236	-27.666	-1.035	-0.646	-26.436	0.464
US	-0.024	0.011	0.001	-0.030	-7.511	0.282	-0.085	-7.693	0.045
EU	0.066	-0.058	-0.004	0.199	23.858	0.978	0.375	22.241	0.509
ROW	-0.114	-0.039	-0.013	-0.026	-12.714	0.043	-0.178	-12.589	-0.027
Global	-0.028	0.002	0.000	0.004	-6.045	0.117	-0.268	-5.962	0.205

Note: This table reports the percentage changes under the cooperative equilibrium following the EU's implementation of CBAM targeting baseline sectors (Chemicals, Minerals, and Metals), relative to the factual equilibrium. The columns under $\Delta\frac{I}{P}$, ΔCO_2, and ΔW report each country's percentage change in real consumption, CO_2 emissions, and consumption-equivalent welfare, respectively. Global consumption-equivalent welfare and real consumption changes are calculated as output-weighted averages across countries. Columns (2)–(4) decompose real income changes into terms-of-trade, volume-of-trade, and volume-of-emission effects, respectively. Columns (6)–(8) decompose emission changes into scale, composition, and technique effects, respectively.

Table B.6: The Aggregate Outcomes under Different Scenarios (Fixed Trade Imbalances)

Country	I. CBAM			II. CBAM + Non-Coop.			III. Cooperation			IV. CBAM + Cooperation		
	$\Delta\frac{I}{P}$ (1)	ΔCO_2 (2)	ΔW (3)	$\Delta\frac{I}{P}$ (4)	ΔCO_2 (5)	ΔW (6)	$\Delta\frac{I}{P}$ (7)	ΔCO_2 (8)	ΔW (9)	$\Delta\frac{I}{P}$ (10)	ΔCO_2 (11)	ΔW (12)
ASEAN	-0.004	0.019	-0.003	-0.004	-0.662	0.015	-0.018	-8.989	0.033	-0.022	-9.121	0.060
Australia	-0.013	0.021	-0.010	-0.018	-0.589	0.041	-0.001	13.987	0.155	0.015	-3.797	0.265
Canada	-0.004	0.047	0.038	-0.013	-0.603	0.719	-0.021	-0.147	1.934	-0.086	-8.610	3.047
China	-0.008	-0.044	-0.008	-0.008	-1.074	-0.001	-0.008	-6.745	0.010	-0.010	-8.693	0.020
India	-0.010	-0.115	-0.009	-0.012	-0.386	-0.009	-0.006	-0.846	0.002	-0.016	-3.102	-0.003
Japan	0.005	0.062	0.011	0.009	-0.309	0.114	-0.013	22.739	0.265	0.027	7.842	0.473
Korea	0.014	0.064	0.023	0.031	-0.914	0.186	-0.017	23.344	0.396	0.076	13.095	0.739
Mexico	-0.002	0.018	0.001	-0.003	-1.094	0.034	-0.043	-13.518	0.055	-0.041	-13.573	0.116
Russia	-0.118	-1.195	-0.118	-0.153	-3.081	-0.139	-0.021	-5.689	0.015	-0.146	-16.347	-0.089
Turkey	-0.009	0.001	-0.001	-0.021	-1.357	0.126	-0.198	-26.283	0.194	-0.224	-26.628	0.405
US	-0.004	0.024	-0.003	-0.008	0.377	0.006	-0.022	-7.167	0.016	-0.029	-5.817	0.032
EU	0.043	0.302	0.049	0.019	-5.459	0.125	0.061	19.338	0.346	0.077	23.246	0.533
ROW	-0.030	-0.141	-0.028	-0.073	-1.908	-0.054	-0.041	-10.793	0.012	-0.113	-12.891	-0.028
Global	-0.003	-0.080	0.001	-0.016	-1.398	0.038	-0.008	-3.735	0.137	-0.020	-5.988	0.214

Note: We hold the international trade imbalances constant at the 2017 level and re-conduct the same quantitative exercises as in Table 5. This table presents each country's percentage change in real consumption ($\Delta\frac{I}{P}$), CO_2 emissions (ΔCO_2), and consumption-equivalent welfare (ΔW) under different scenarios.

Table B.7: The Aggregate Outcomes under Different Scenarios (Elasticities from Farrokhi et al. (2025))

Country	I. CBAM			II. CBAM + Non-Coop.			III. Cooperation			IV. CBAM + Cooperation		
	$\Delta\frac{I}{P}$ (1)	ΔCO_2 (2)	ΔW (3)	$\Delta\frac{I}{P}$ (4)	ΔCO_2 (5)	ΔW (6)	$\Delta\frac{I}{P}$ (7)	ΔCO_2 (8)	ΔW (9)	$\Delta\frac{I}{P}$ (10)	ΔCO_2 (11)	ΔW (12)
ASEAN	-0.003	0.002	-0.002	-0.005	-0.869	0.021	-0.024	-9.285	0.035	-0.027	-9.356	0.064
Australia	-0.012	0.006	-0.009	-0.021	3.236	0.056	-0.066	-19.458	0.105	-0.074	-19.343	0.187
Canada	-0.003	0.027	0.043	-0.039	-3.755	1.041	-0.179	-18.815	2.235	-0.315	-27.868	3.366
China	-0.008	-0.063	-0.008	-0.011	-0.160	-0.001	-0.007	-6.153	0.013	-0.012	-7.670	0.019
India	-0.018	-0.227	-0.018	-0.017	0.981	-0.012	-0.004	-2.220	0.007	-0.013	-5.957	0.004
Japan	0.003	0.042	0.009	0.002	-1.844	0.147	-0.024	23.582	0.299	0.006	16.406	0.498
Korea	0.004	0.053	0.012	0.007	-4.432	0.191	-0.066	22.131	0.345	-0.055	21.838	0.571
Mexico	-0.002	0.000	0.000	-0.011	-2.314	0.040	-0.066	-17.307	0.048	-0.072	-17.268	0.103
Russia	-0.074	-0.958	-0.073	-0.112	-1.947	-0.097	-0.022	-8.830	0.013	-0.118	-15.741	-0.063
Turkey	-0.013	-0.085	-0.003	-0.020	-0.835	0.214	-0.405	-34.317	0.117	-0.432	-35.110	0.365
US	-0.002	0.004	-0.001	-0.008	-3.656	0.015	-0.021	-8.855	0.030	-0.023	-9.206	0.053
EU	0.036	0.291	0.042	0.006	-6.623	0.152	0.031	31.252	0.356	0.051	23.500	0.547
ROW	-0.024	-0.131	-0.023	-0.090	-2.993	-0.061	-0.044	-13.187	0.020	-0.126	-14.336	-0.028
Global	-0.002	-0.084	0.001	-0.023	-1.986	0.053	-0.022	-4.436	0.149	-0.038	-6.763	0.223

Note: We adopt alternative set of trade elasticities from Farrokhi et al. (2025) and re-conduct the same quantitative exercises as in Table 5. This table presents each country's percentage change in real consumption ($\Delta\frac{I}{P}$), CO_2 emissions (ΔCO_2), and consumption-equivalent welfare (ΔW) under different scenarios.

Table B.8: Non-Cooperation with Tariff Retaliation under the EU's CBAM Implementation

Country	$\Delta\frac{I}{P}$	Real Income Decomp.			ΔCO_2	Emission Decomp.			ΔW
		ToT	VoT	VoEm		Scale	Comp.	Tech	
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
ASEAN	0.074	0.085	-0.001	-0.003	-0.426	0.333	0.107	-0.863	0.095
Australia	0.143	0.095	0.049	0.000	-0.066	0.552	0.158	-0.772	0.206
Canada	0.056	0.062	0.003	-0.005	-0.509	0.600	-0.085	-1.018	0.947
China	0.083	0.103	-0.002	-0.006	-0.733	0.503	0.077	-1.305	0.090
India	0.033	0.032	0.013	-0.010	-0.883	0.314	-0.145	-1.050	0.037
Japan	0.088	0.095	0.016	-0.002	-0.291	0.700	0.078	-1.062	0.207
Korea	0.189	0.255	0.009	-0.003	-0.350	0.771	-0.054	-1.059	0.340
Mexico	0.140	0.176	0.004	-0.001	-0.235	0.615	0.135	-0.978	0.183
Russia	0.163	0.213	-0.001	-0.023	-2.728	-0.170	-0.660	-1.917	0.176
Turkey	0.367	0.389	0.334	-0.019	-2.240	-0.334	0.300	-2.206	0.560
US	0.042	0.064	0.002	-0.006	-1.482	0.558	-0.107	-1.923	0.061
EU	-0.737	-0.636	-0.054	-0.061	-7.139	-5.359	-0.034	-1.845	-0.617
ROW	0.114	0.270	-0.013	-0.004	-1.754	0.519	-0.109	-2.152	0.138
Global	-0.062	-0.003	-0.006	-0.015	-1.636	0.004	-0.048	-1.594	0.001

Note: This table reports the percentage changes under the non-cooperative equilibrium on carbon taxes with non-EU countries' tariff retaliation following the EU's implementation of CBAM targeting baseline sectors (Chemicals, Minerals, and Metals), relative to the factual equilibrium. The columns under $\Delta\frac{I}{P}$, ΔCO_2, and ΔW report each country's percentage change in real consumption, CO_2 emissions, and consumption-equivalent welfare, respectively. Global consumption-equivalent welfare and real consumption changes are calculated as output-weighted averages across countries. Columns (2)–(4) decompose real income changes into terms-of-trade, volume-of-trade, and volume-of-emission effects, respectively. Columns (6)–(8) decompose emission changes into scale, composition, and technique effects, respectively.

Table B.9: Cooperative Equilibrium on Carbon Taxes and Tariffs

Country	Cooperation			Cooperation with CBAM		
	$\Delta\frac{I}{P}$ (1)	ΔCO_2 (2)	ΔW (3)	$\Delta\frac{I}{P}$ (4)	ΔCO_2 (5)	ΔW (6)
ASEAN	0.053	-10.788	0.129	0.029	-13.523	0.139
Australia	-0.141	-9.002	0.079	-0.056	-15.398	0.263
Canada	-0.722	-27.234	2.375	-0.916	-33.528	3.570
China	0.055	-8.144	0.082	0.063	-10.078	0.102
India	0.113	-6.310	0.126	0.024	-9.666	0.044
Japan	0.101	19.286	0.515	-0.070	13.082	0.529
Korea	-0.180	16.647	0.347	-0.336	1.538	0.427
Mexico	0.105	-19.832	0.252	0.045	-17.780	0.258
Russia	0.054	-6.540	0.100	0.185	-14.053	0.251
Turkey	0.240	-33.581	0.910	0.012	-34.729	0.983
US	-0.015	-8.376	0.050	-0.015	-11.698	0.079
EU	-0.275	23.768	0.143	-0.351	24.806	0.253
ROW	-0.019	-11.571	0.063	0.032	-12.724	0.151
Global	-0.049	-5.689	0.171	-0.072	-8.243	0.246

Note: This table reports the percentage changes under the cooperative equilibrium on carbon taxes and Most-Favored-Nation (MFN) tariffs, relative to the factual equilibrium. "Cooperation" refers to the global cooperation from the factual equilibrium, while "Cooperation with CBAM" refers to the cooperative scenario after the EU's implementation of CBAM targeting baseline sectors (Chemicals, Minerals, and Metals). The columns under $\Delta\frac{I}{P}$, ΔCO_2, and ΔW report each country's percentage change in real consumption, CO_2 emissions, and consumption-equivalent welfare, respectively. Global consumption-equivalent welfare and real consumption changes are calculated as output-weighted averages across countries.

C Additional Figures

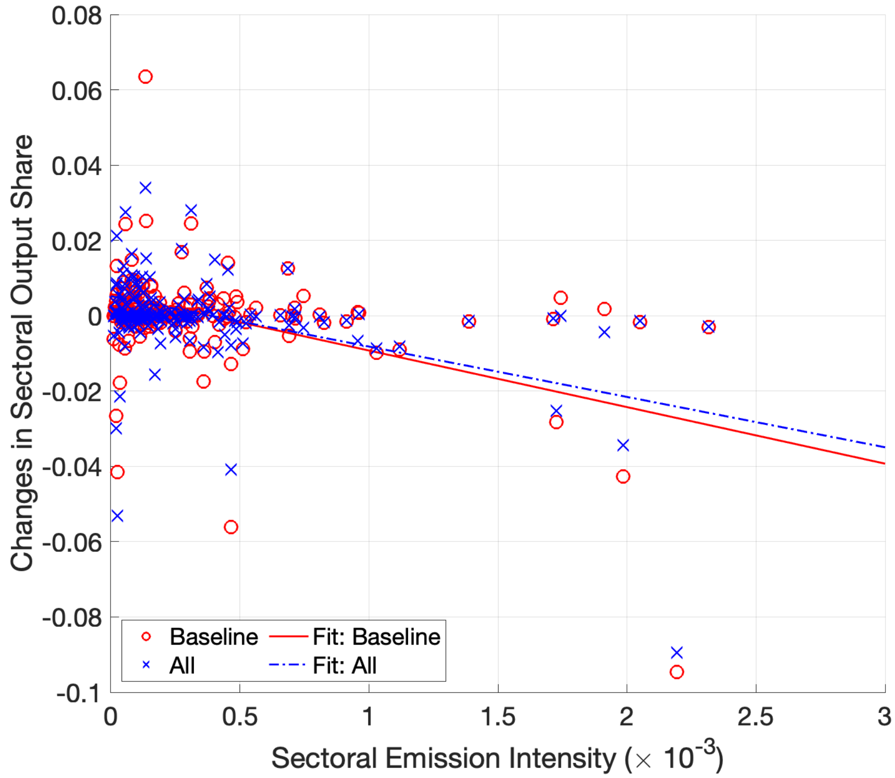

Figure C.1: Composition Effects under Different CBAM Scopes

Note: This figure displays changes in sectoral output shares across countries against country-sector emission intensities under different CBAM coverage scopes. Red circles represent changes in output shares under the CBAM scope targeting baseline sectors (Chemicals, Minerals, and Metals). Blue crosses represent changes in output shares under an extended CBAM scope covering all tradable sectors. Red solid and blue dashed lines are the fitted regression lines under baseline and extended CBAM scopes, respectively.

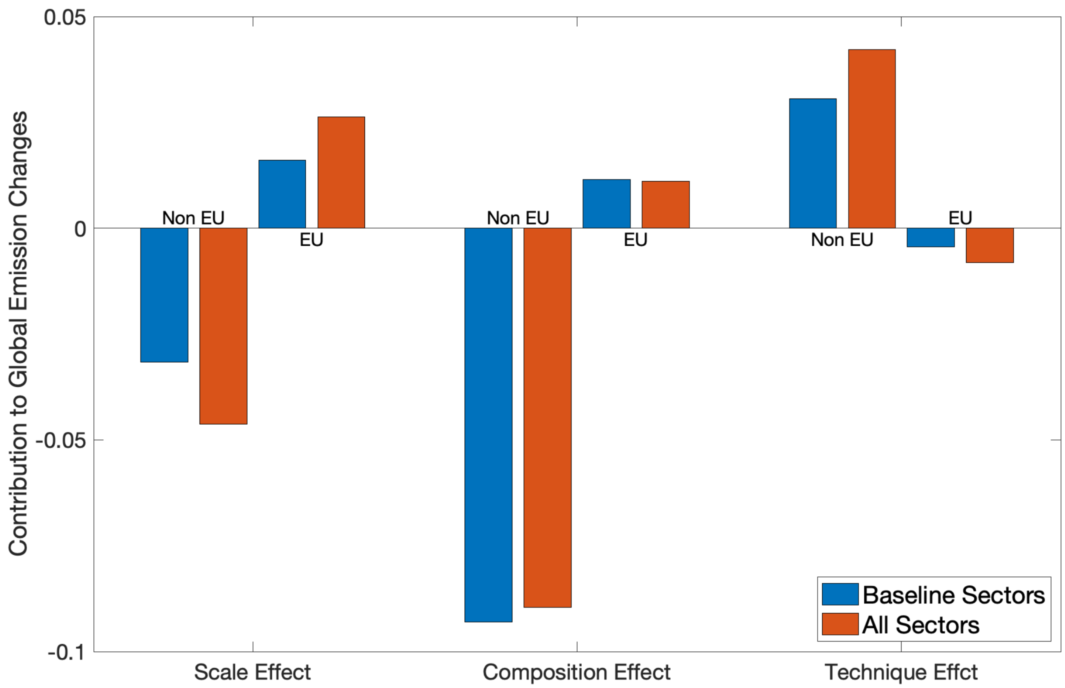

Figure C.2: Decomposition of Global Emission Changes under Different CBAM Scopes

Note: This figure displays the decomposition of contributions to global emission changes under different CBAM coverage scopes. Blue bars represent contributions under the CBAM scope targeting baseline sectors (Chemicals, Minerals, and Metals). Red bars represent contributions under an extended CBAM scope covering all tradable sectors.

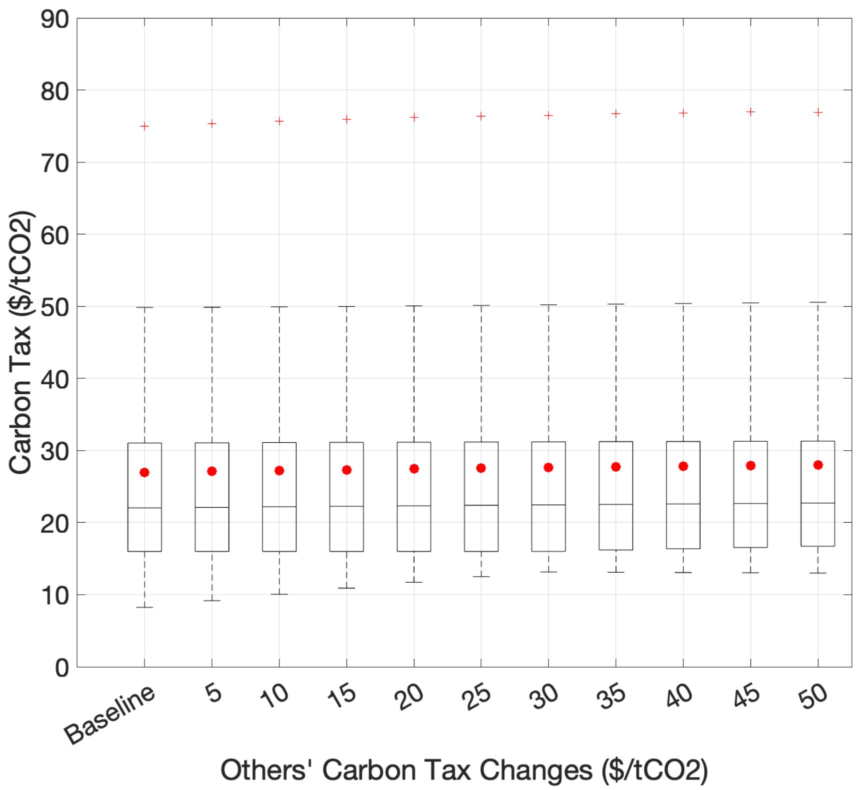

Figure C.3: Complementarity of Carbon Tax Choices across Countries

Note: The box plots display each country's unilateral optimal carbon tax choice under alternative scenarios where other countries raise their carbon taxes by different levels, following the EU's CBAM implementation in Chemicals, Minerals, and Metals. "Baseline" refers to the case in which all other countries keep their carbon taxes at the status quo. The red dot in each box indicates the cross-country average of counterfactual taxes, while the red cross outlier corresponds to the EU.

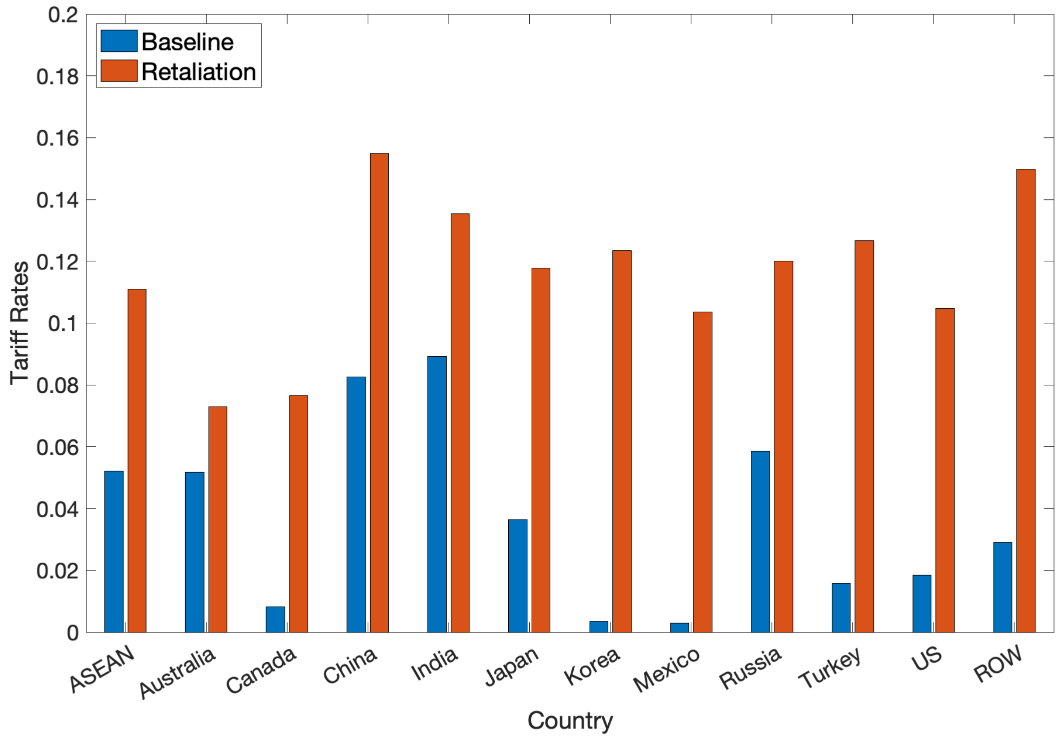

Figure C.4: Retaliatory Tariff Rates by Non-EU Countries

Note: This figure displays the trade-volume weighted average tariff rates by non-EU countries on the EU. "Baseline" refers to the factual baseline. "Retaliation" refers to the non-cooperative equilibrium on carbon taxes with non-EU countries' tariff retaliation after the EU's implementation of CBAM targeting baseline sectors (Chemicals, Minerals, and Metals).

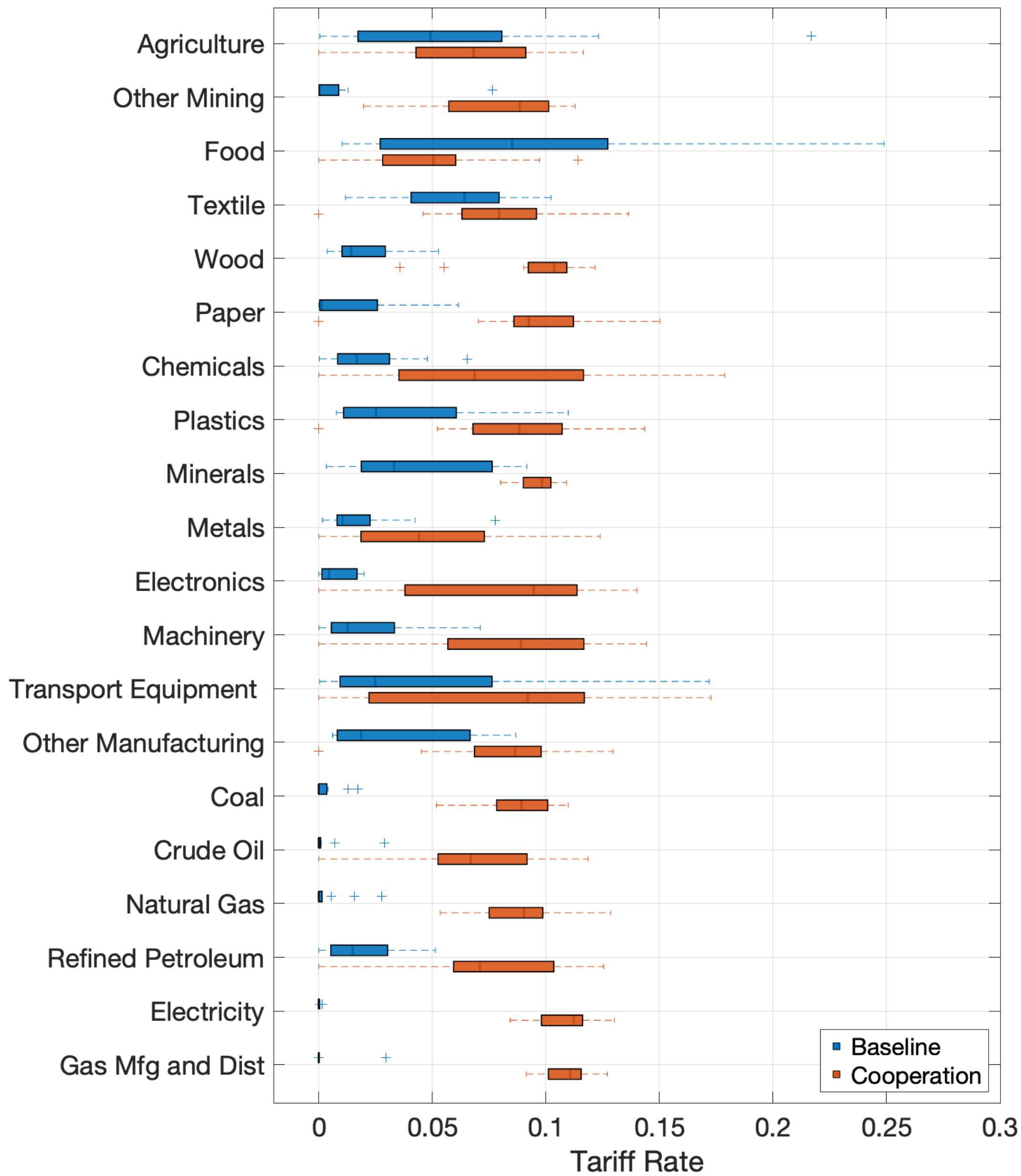

Figure C.5: Cooperative Tariff Rates across Sectors

Note: This box plot displays the trade-volume weighted tariff rates by each country across sectors. "Baseline" refers to the factual baseline. "Cooperation" refers to the cooperative equilibrium on carbon taxes and Most-Favored-Nation (MFN) tariffs after the EU's implementation of CBAM targeting baseline sectors (Chemicals, Minerals, and Metals).