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Abstract: Amid the escalating global climate crisis, the European Union (EU) has assumed a prominent role by introducing the Carbon Border Adjustment Mechanism (CBAM). This initiative aims to bolster climate action and mitigate carbon leakage. Nevertheless, considerable debate surrounds the practical efficacy of this measure and its conformity with World Trade Organization (WTO) regulations. This paper's objective is to quantitatively evaluate the welfare and carbon abatement effects of CBAM on the EU and other prominent economies. We develop a comprehensive multi-country, multi-sector general equilibrium model that incorporates EU carbon tariffs, global production networks, and carbon emissions to achieve this goal. The estimation of key parameters is conducted through a structural methodology that directly evaluates the impacts on welfare and carbon emissions resulting from unilateral or multilateral low-carbon policies. The analysis revealed that CBAM would enhance the welfare of the EU, Japan, South Korea, Norway, Switzerland, and the United States. Conversely, all other economies would experience a reduction in welfare, with Russia suffering the most significant loss and China the least. Furthermore, despite CBAM's effective global carbon emission reduction, its impact on the EU's domestic carbon reduction is limited. Counterfactual analyses indicate that global carbon emissions decrease in scenarios involving a globally standardized carbon pricing mechanism, China's elevation of carbon pricing alongside a carbon tariff, and the European Union's extension of taxation to all sectors. However, these scenarios result in substantial disparities in welfare levels among countries, with the most substantial reduction in global carbon emissions occurring exclusively with a globally harmonized carbon price, accompanied by the most minor overall welfare loss. In conclusion, this paper advocates for enhanced international collaboration and dialogue among nations to foster harmonizing carbon pricing policies and adopt a universally standardized carbon pricing mechanism.

Keywords：EU CBAM; Carbon leakage; Carbon abatement; Welfare analysis; Quantitative trade model

JEL Codes: F17; F64; Q56; Q58

[Word count: 9450]

1. Introduction

In recent years, the severity of the climate crisis has escalated, prompting widespread apprehension within the global community. Numerous studies have demonstrated a strong correlation between greenhouse gas emissions, global temperature increases, and heightened extreme weather events (Ledley et al., 1999; Meinshausen et al., 2011; Mora et al., 2018). In this context, low carbon is gradually becoming a global consensus, and establishing carbon markets has become one of the key initiatives to address climate change. Carbon markets aim to incentivize both businesses and individuals to curtail greenhouse gas emissions by assigning a price to carbon emissions, thereby fostering economic development in a low-carbon trajectory (Hammoudeh et al., 2015; Wen et al., 2020; Zheng et al., 2021). Nevertheless, while the carbon market is anticipated to be an efficacious instrument in addressing climate change, it has progressively revealed specific challenges during its evolution. One of the foremost challenges is the stark disparity in carbon pricing among nations. For instance, within the EU Emissions Trading System (ETS), the cost per ton of carbon emissions surpasses $50 (Ritz, 2022), while in carbon markets of other nations, a pronounced polarization exists, ranging from $1 to $127 per ton (Ramstein et al., 2019). This divergence deviates from the envisioned ideal of a globally optimized environmental governance system. This disparity in carbon pricing has also given rise to the issue of carbon leakage, where nations with stringent environmental regulations relocate portions of their high-carbon industry production to countries with laxer regulations, thus evading their emission reduction commitments. This poses a challenge to the efficacy of the carbon market and renders global emission reduction endeavors doubly ineffective (Aichele and Felbermayr, 2015; Böhringer et al., 2017a; Jakob, 2021).

Within the global carbon market, carbon pricing in the EU is notably elevated. To address the challenge of carbon leakage stemming from uneven carbon pricing and to prevent the EU from compromising its products' international competitiveness due to increased carbon pricing costs, the European Commission unveiled a proposal for a CBAM on July 14, 2021. The objective is to facilitate the decarbonization of industrial production within the EU by leveraging CBAM to bolster the competitive edge of the EU's energy-intensive sectors. The proposal will commence as a trial initiative on October 1, 2023, with a transitional phase from 2023 to 2025, followed by full implementation beginning in 2026. Initially, the chosen commodities are those characterized by high carbon intensity and the most significant susceptibility to carbon leakage. These commodities encompass cement, steel, aluminum, fertilizers, electricity, and hydrogen. The scope of coverage will progressively extend to include all commodities encompassed by the ETS. CBAM ensures that imported goods maintain carbon price parity with those within the EU by imposing tariffs on products with lower carbon pricing than EU countries. CBAM is an integral component of the EU's "Fit for 55" climate ambition package, aligning with the objectives of the 2030 Climate Targets program.

Ideally, achieving uniform global carbon pricing and reducing the risk of carbon leakage through implementing the Peguard Tax is the optimal strategy for addressing the global climate crisis. Nevertheless, CBAM, implemented unilaterally by the EU as a tariff measure, has raised concerns regarding its compliance, trade disputes, and policy alignment. Despite some research advancements regarding CBAM's compatibility with the WTO (Newman, 2022; Espa, 2022), numerous research areas remain unexplored and require further investigation. (1) CBAM's impact on carbon pricing varies among countries and regions (Wang et al., 2012; Zhong and Pei, 2022), raising questions about whether it constitutes beggar-thy-neighbor behavior. (2) Developing economies often encounter elevated carbon costs and trade limitations (Magacho et al., 2023), prompting consideration of whether they will bear the most significant welfare losses under CBAM. (3) Implementing CBAM significantly influences the carbon market's effectiveness and fairness (Bellora and Fontagné, 2023), and its capacity to eliminate carbon leakage remains to be evaluated. (4) CBAM is likely to be viewed as a trade impediment by other nations (Overland and Sabyrbekov, 2022), and major trading nations like China, the United States, and India may respond;

the resulting consequences must be explored. Therefore, it is imperative to address these issues within the framework of a coherent general equilibrium model and conduct a comprehensive evaluation of CBAM's policy implications, bearing both theoretical and practical significance.

To address the aforementioned research concerns, this study develops a comprehensive multiregional and multisectoral general equilibrium model. Considering that globalization is the primary trend of the current world development, and the economies of the world are closely linked through the global production network, in order to quantitatively study the economic, welfare, and carbon emission effects of CBAM on each country, it is necessary to take into account the input-output linkage of each country as well as the role of the international trade network, which requires that the model must incorporate the trade of products, input-output linkage, and carbon emissions. To achieve this objective, this study innovatively develops a quantitative trade model that integrates global production networks and pollution emissions. This model is calibrated using real-world data from the World Input-Output Database (WIOD) and industry-level tariff information for each country. Ventilation coefficients for each country serve as instrumental variables and pollution emission elasticities for each country are estimated using the two-stage least squares (2SLS) method. Lastly, a counterfactual analysis is employed to simulate changes in welfare and carbon emissions for each country under various scenarios: global carbon price harmonization, China's domestic carbon price increase with a carbon tariff, and the EU's extension of the tariff to the entire industry.

This paper's primary contributions are evident in three key areas: Firstly, this study introduces a novel quantitative trade model, which extends its scope to encompass EU carbon tariffs, global production networks, and carbon emissions within a multi-country, multi-sector general equilibrium framework, building upon the frameworks of Caliendo and Parro (2015) and Duan et al. (2021). The parameters of the model are calibrated using authentic data, providing a realistic depiction of global trade patterns and carbon emissions. This enhances the model's credibility and facilitates its direct application in assessing the effects of unilateral or multilateral low-carbon policies, thereby improving its relevance to real-world situations. Building upon the model above, this paper overcomes the constraint that parsimonious models typically cannot perform counterfactual analyses. This study simulates the welfare and carbon emission outcomes for countries across various scenarios through three counterfactual analyses. This approach aids countries in gaining a deeper understanding of the implications of the EU CBAM and make informed decisions regarding suitable response strategies. Lastly, by introducing the ventilation coefficient for each country as an instrumental variable, this paper effectively addresses the potential endogeneity issue in pollution elasticity estimation. This challenge has not been adequately resolved in cross-country-level studies. This approach ensures a robust identification of the crucial pollution elasticity parameter.

The subsequent sections of this paper are structured as follows: The second section conducts a comprehensive review of pertinent literature. The third section develops a multi-country, multi-sector general equilibrium model, presents the utilized data, and discusses parameter estimation and model calibration. The fourth section comprises a quantitative analysis. The fifth section encompasses a counterfactual analysis. The sixth section serves as the conclusion and provides policy recommendations.

2. Literature review

This paper is closely connected to articles that quantify the economic and environmental advantages of CBAM within the EU. Most existing articles evaluating the impact of CBAM adopt a dual approach. They either utilize computable general equilibrium (CGE) models to assess CBAM's effectiveness in mitigating carbon leakage resulting from unilateral climate policies or employ input-output (IO) models to calculate the implicit carbon content in trade.

Branger and Quirion (2014) employ a meta-analysis to review studies utilizing CGE models for assessing the impact of carbon tariffs from 2004 to 2012. They conclude that carbon tariffs have resulted in an average 8% reduction in carbon leakage. Dellink et al. (2014) use a global recursive-dynamic CGE model to evaluate the implications of linking national ETSs through direct or indirect channels. However, they do not directly investigate the effects of CBAM. Instead, they consider the EU ETS a crucial element of the global carbon market. Conversely, Clora et al. (2023) employ a CGE model to assess the effects of CBAM on both EU and non-EU nations. They argue that CBAM's effectiveness in mitigating carbon leakage hinges on the EU's consideration of the implied carbon content of imported goods rather than its average carbon emissions. Furthermore, they contend that retaliatory actions by non-member countries may partially counteract CBAM's carbon leakage prevention impact. Mattoo et al. (2013) also emphasize that a critical factor determining the role of border taxes is whether they are predicated on the carbon content of imports or domestic production. Antimiani et al. (2016) adopt a dynamic CGE approach to evaluate carbon leakage rates under various scenarios spanning from 2010 to 2050. The results indicate that the EU's unilateral climate policy adversely affects carbon leakage and competitiveness. Böhringer et al. (2017b) employ a multi-country, multisectoral CGE model to evaluate the consequences of border carbon adjustments under varying tariff structures. Their study reveals that a fixed-target tariff is more effective in reducing carbon leakage compared to an industry-level tariff. Böhringer et al. (2021) discover that carbon tariffs substantially reduce carbon leakage, ranging from 64% to 80% between 2000 and 2014. However, they also observe that the expansion of the power sector diminishes the efficacy of carbon tariffs by promoting increased fossil fuel usage. Fouré et al. (2016) determine that border carbon adjustments decrease output in energy-intensive sectors. However, they also note adverse effects on other industries. Importantly, they find that retaliatory actions by other countries do not significantly impact the EU or its real income.

Another subset of articles employing IO models to evaluate CBAM's impact shifts their focus towards calculating trade-implied carbon rather than welfare measurement. Magacho et al. (2023) utilize a multiregional input-output (MRIO) model, concentrating on the economic repercussions of CBAM on developing and emerging market nations. Their findings reveal that Russia, China, Turkey, and Ukraine face the most substantial risk shocks. Li et al. (2023) compute the effects of CBAM on China's steel exports, concluding that EU carbon tariffs will significantly increase the cost of exporting for China's steel industry, surpassing its average profitability level. Likewise, Ren et al. (2023) concentrate on CBAM's influence on economic carbon inequality in plastics exports. Their research identifies the Pacific region as bearing the heaviest cost burden, with Russia particularly affected. Zhong and Pei (2022) employ an enhanced MRIO model to quantify the shift in export prices between EU and non-EU countries following CBAM implementation. Their findings indicate that CBAM will initially boost production in the EU while reducing it in other nations, with the most significant production declines occurring in China, Russia, and India. Bellora and Fontagné (2023) conclude that CBAM effectively reduces carbon leakage. However, it also erodes the export advantage of EU downstream sectors not covered by CBAM and high-emission exporters. Beaufils et al. (2023) contend that CBAM currently encompasses fewer industries, potentially limiting its effectiveness.

After reviewing the literature above, it is evident that certain limitations persist in current research. Firstly, from a methodological perspective, CGE models employ the classical Armington assumption, enabling the quantification of trade or environmental policy effects on the macroeconomy and carbon emissions (Lin et al., 2019). Nevertheless, the CGE approach depends on numerous parameters, and its internal impact mechanisms lack intuitive transparency (Costinot and Rodríguez-Clare, 2014). Conversely, the IO approach mitigates certain CGE limitations but treats final demand as exogenous, hindering the estimation of demand or welfare changes (Wald et al., 2019). Quantitative trade modeling, a recent emergence, can depict key economic features with fewer parameters and transparently illustrate the impact channels of exogenous shocks. By structurally estimating model parameters for close integration with real data, this approach represents the forefront of research methodologies for studying the welfare and carbon emission impacts of trade or environmental policies. Nevertheless, it has seen limited application in the current literature on carbon emissions (Egger and Nigai, 2015; Larch and Wanner, 2017; Shapiro and Walker, 2018; Duan et al., 2021). Secondly, concerning research content, current studies have not comprehensively assessed the welfare and carbon emission implications of CBAM. In particular, they have not thoroughly examined the specific impact mechanisms of

CBAM and have overlooked the welfare and carbon emission effects of globally harmonized carbon pricing, China's carbon tariffs, and the European Union's expansion of carbon tariffs by industry.

3. A quantitative Trade-and-Environment model

This section sets up a multi-country, multi-sector trade model built on Caliendo and Parro (2015) and Duan et al. (2021) to capture the impact of the EU's CBAM on international trade and global carbon emissions. Specifically, we consider a world with N countries containing J industries. The labor force in each country, denoted as L, can freely move between industries within the country but not across borders. In line with Eaton and Kortum (2002), we assume a perfectly competitive market characterized by total employment in the labor market and the absence of product market markups. Furthermore, we introduce a two-product production framework, comprising composite goods and intermediate goods in this paper. Composite goods are produced using intermediate goods as inputs. These composite outputs are utilized partly for final consumption and as intermediate goods in further production processes. Notably, composite outputs are not involved in international trade.

In contrast, the production of intermediate goods requires labor inputs and intermediate goods from other industries, including the same industry. These intermediate goods can be traded internationally but face import and carbon tariffs imposed by importing countries. Additionally, the production of intermediates generates carbon emissions and is subject to exogenous environmental regulations in the home country. This setup forms the theoretical foundation for quantifying the carbon abatement effects of carbon tariffs imposed by the EU.

3.1 Households

In each country n there exists a population of representative consumers, each comprising L_n individuals who supply labor at a wage rate of w_n to obtain labor income. Additionally, they receive transfers from various sources, including import tariffs, carbon emission tax revenues, and trade deficits imposed by their respective country of residence. With this combined income, represented as I_n, each consumer maximizes their utility with the Cobb-Douglas utility function:

$$u(C_n) = \prod_{j=1}^{J} (C_n^j)^{\alpha_n^j} \tag{1}$$

where α_n^j is the consumption share of the representative consumer in country n for each industry, it holds that $\sum_j \alpha_n^j = 1$, signifying constant returns to scale within each country. C_n^j is the consumption of final goods by consumers in country n for industry j. The term I_n is consumer's income, comprising various components, including wages, transfers resulting from tariffs, and trade surpluses. Consequently, the representative consumer faces an income constraint, which is expressed as

$$I_n = w_n L_n + R_n + T_n + D_n \tag{2}$$

where R_n is tariff revenues, T_n is emissions tax revenues, and D_n is the trade surplus. We will also include carbon tariff revenues below. Considering the inherent characteristics of the Cobb-Douglas function, the portion of consumer expenditure on goods in sector j is denoted by α_n^j. Consequently, the total spending on industry j can be expressed as $P_n^j C_n^j = \alpha_n^j I_n$.

3.2 Production

3.2.1 Intermediate goods

A continuum of intermediate goods $\omega^j \in [0,1]$ is produced in each sector j. Firms require labor and intermediate goods as inputs, but this process also produces carbon emissions. Consequently, firms encounter additional costs associated with local exogenous environmental regulations, denoted as t_n. To establish our framework, we follow Copeland and Taylor (2004) and consider carbon emissions a production by-product. As a result, the production technology for intermediate goods follows this specific pattern:

$$q_n^j(\omega^j) = \left\{ z_n^j(\omega^j)[l_n^j(\omega^j)]^{\gamma_n^j} \prod_{k=1}^{J} [m_n^{k,j}(\omega^j)]^{\gamma_n^{k,j}} \right\}^{1-\beta_n^j} [e_n^j(\omega^j)]^{\beta_n^j} \tag{3}$$

where $q_n^j(\omega^j)$ is the output of intermediate good ω^j from sector j in country n, $l_n^j(\omega^j)$ is labor, and $m_n^{k,j}(\omega^j)$ are the composite goods from sector k in country n

that uses intermediate goods from sector j of ω^j. Assuming constant returns to scale, we can obtain the following equation $\gamma_n^j + \sum_{k=1}^{J} \gamma_n^{k,j} = 1$. Where γ_n^j is the share of sector j of country n that spends on the factor of labor, and $\gamma_n^{k,j}$ is the share of sector j's spending on intermediate goods from sector k in country n. Additionally, production leads to the generation of carbon emissions, denoted as $e_n^j(\omega^j)$, and the share of expenditures allocated to these emissions is β_n^j. Finally, $z_n^j(\omega^j)$ characterizes the production efficiency of the ω^jth product within sector j in country n.

Assume that the environmental cost of carbon emissions is t_n, and thus, the profit-maximizing decision of the intermediate goods producer is

$$\max_{\{l_n^j, m_n^{k,j}, e_n^j\}} \pi_n^j = p_n^j(\omega^j) q_n^j(\omega^j) - w_n l_n^j(\omega^j) - \sum_{k=1}^{J} P_n^k m_n^{k,j}(\omega^j) - t_n e_n^j(\omega^j) \tag{4}$$

$s.t.$ Eq. (3)

Given the context of a perfectly competitive market, we can express the marginal production cost of the input bundle, denoted as ψ_n^j, without taking into account the production efficiency $z_n^j(\omega^j)$:

$$\psi_n^j = \delta_{1,n}^j (t_n)^{\beta_n^j} (\xi_n^j)^{1-\beta_n^j} \tag{5}$$

$$\xi_n^j = \delta_{2,n}^j (w_n)^{\gamma_n^j} \prod_{k=1}^{J} (P_n^k)^{\gamma_n^{k,j}} \tag{6}$$

where $\delta_{1,n}^j = (\beta_n^j)^{-\beta_n^j} (1-\beta_n^j)^{-(1-\beta_n^j)}$, and $\delta_{2,n}^j = (\gamma_n^j)^{-\gamma_n^j} \prod \gamma_n^{k,j^{-\gamma_n^{k,j}}}$, both of which are constants. ξ_n^j is the input when there is no carbon emission input bundle's production cost.

Define the carbon emission intensity $\chi_n^j(\omega^j)$ for an intermediate goods manufacturer as the ratio of pollution emissions to total output, i.e., $\chi_n^j(\omega^j) = e_n^j(\omega^j)/p_n^j(\omega^j) q_n^j(\omega^j)$. Considering the characteristics of the Cobb-Douglas function, the proportion of firms' pollution expenditures to total output is represented by β_n^j.

Thus, $t_n e_n^j(\omega^j) = \beta_n^j p_n^j(\omega^j) q_n^j(\omega^j)$. Consequently, we can further express this relationship as:

$$\chi_n^j = \frac{\beta_n^j}{t_n} \tag{7}$$

Since the environmental regulation intensity t_n is exogenous, we can infer that the proportion of carbon emission expenditures to total output, represented as β_n^j, is smaller, resulting in a lower carbon emission intensity for industry j in country n.

3.2.2 Composite intermediate goods

Manufacturers of composite goods acquire intermediate goods from both domestic and foreign producers offering the lowest prices and aggregate these intermediate goods using a CES (Constant Elasticity of Substitution) function in the following manner:

$$Q_n^j = [\int r_n^j(\omega^j)^{1-1/\sigma^j} d\omega^j]^{\sigma^j/(\sigma^j-1)} \tag{8}$$

where Q_n^j is the output of composite goods in sector j within country n. Additionally, $r_n^j(\omega^j)$ is the demand for intermediate goods in this sector, and $\sigma^j > 0$ is the elasticity of substitution among intermediate goods in sector j. To further enhance our understanding, we define P_n^j as the price of composite goods within sector j in country n.

$$P_n^j = [\int p_n^j(\omega^j)^{1-1/\sigma^j} d\omega^j]^{1/(1-\sigma^j)} \tag{9}$$

The profit-maximizing choice $r_n^j(\omega^j)$ of the composite good manufacturer for ω^j is as follows:

$$r_n^j(\omega^j) = \left(\frac{p_n^j(\omega^j)}{P_n^j}\right)^{-\sigma^j} Q_n^j \tag{10}$$

3.2.3 International trade costs and prices

In international trade, two distinct forms of trade costs exist: iceberg trade costs d_{ni}^j, and ad valorem tariffs τ_{ni}^j. To successfully export 1 unit of an intermediate good to country n, sector j in country i must transport more than 1 unit of the good to compensate for losses in transit, hence, $d_{ni}^{j} \geq 1$. Importantly, this condition holds, with $d_{nn}^{j} = 1$. The CBAM primarily encourages cleaner production by increasing import tariffs on specific carbon-intensive goods at a higher risk of carbon leakage. Consequently, import tariffs τ_{ni}^{j} for these industries will be elevated within EU countries. Our analysis considers the combination of these two trade costs to provide a comprehensive understanding of their impact.

$$\kappa_{ni}^{j} = \tilde{\tau}_{ni}^{j} d_{ni}^{j} \tag{11}$$

Where $\tilde{\tau}_{ni}^{j} = (1 + \tau_{ni}^{j})$. After incorporating trade costs, the price of intermediate goods ω^{j} from sector j in country i exported to country n is $\psi_{i}^{j} \kappa_{ni}^{j} / z_{i}^{j}(\omega^{j})$. According to the Armington-type assumptions, the composite goods sector can always find the lowest-priced intermediate good from all countries, and thus, the price of intermediate good ω^{j} within country n is

$$p_{n}^{j}(\omega^{j}) = \min_{i} \left\{ \frac{\psi_{i}^{j} \kappa_{ni}^{j}}{z_{i}^{j}(\omega^{j})} \right\} \tag{12}$$

In line with Eaton and Kortum (2002), we make a similar assumption regarding the efficiency of intermediate goods production $\left[z_{n}^{j}(\omega^{j})\right]^{1-\beta_{n}^{j}}$ in Eq. (3). We posit that this efficiency follows a Fréchet distribution characterized by location and shape parameters, λ_{n}^{j} and θ^{j}, respectively. Notably, we enforce the condition $\lambda_{n}^{j} \geq 0$, leading us to determine the price within the composite goods sector in country n.

$$P_{n}^{j} = \delta_{3}^{j} [\sum_{i=1}^{N} \lambda_{i}^{j} (\kappa_{ni}^{j} \psi_{i}^{j})^{-\theta^{j}}]^{-\frac{1}{\theta^{j}}} \tag{13}$$

Where $\delta_{3}^{j} = \Gamma(\frac{\theta^{j}+1-\delta^{j}}{\theta^{j}})$ and $\Gamma(\cdot)$ is a gamma function. We provide detailed calculations about Eq. (13) in Appendix A.

Consumers in the country n acquire final goods at a price P_{n}^{j}. Considering the Cobb-Douglas form of preferences, the total consumer price index for country n is as follows:

$$P_n = \prod_{j=1}^{J} (P_n^j / \alpha_n^j)^{\alpha_n^j} \tag{14}$$

3.3 Equilibrium conditions

3.3.1 Import shares

Denote π_{ni}^j as the probability that the price of exports from country i to country n is the lowest among all countries, which can be formally expressed as $\pi_{ni}^j = \Pr[p_{ni}^j \leq \min\{p_{ns}^j; s \neq i\}]$. Upon substituting the Fréchet distribution, we can represent π_{ni}^j in the following manner:

$$\pi_{ni}^j = \frac{\lambda_i^j (\kappa_{ni}^j \psi_i^j)^{-\theta^j}}{\Phi_n^j} \tag{15}$$

where $\Phi_n^j = \sum_{i=1}^{N} \lambda_i^j \left(\kappa_{ni}^j \psi_i^j\right)^{-\theta j}$. We also provide detailed calculation about Eq. (15) in Appendix A. Eq. (15) represents the share of country n's imports of sector j products from country i relative to country n's total expenditure on sector j. This relationship can be expressed as $\pi_{ni}^j = X_{ni}^j / X_n^j$. Furthermore, Eq. (15) suggests that with all other parameters held constant, implementing the CBAM will result in a reduction in bilateral trade.

3.3.2 Product market clearing

In country n, expenditures within sector j encompass the consumption of final goods and the utilization of intermediate goods. This arrangement ensures equilibrium within the product market under the following conditions:

$$X_n^j = \sum_{k=1}^{J} (1-\beta_n^k) \gamma_n^{j,k} \sum_{i=1}^{N} X_i^k \frac{\pi_{ni}^k}{1+\tau_{ni}^k} + \alpha_n^j I_n \tag{16}$$

where I_n in Eq. (16) is given by Eq. (2). In particular, $R_n = \sum_{j=1}^{J} \sum_{i=1}^{N} \beta_n^j \pi_{in}^j X_i^j$ （这里应该是T_n，而非R_n） and $D_n = \sum_{j=1}^{J} D_n^j$.

3.3.3 Factor market clearing

In a perfectly competitive market where labor is unrestricted in its movement, wages across different sectors become uniform during labor market equilibrium. The wage w_n, is determined by the following equation when the labor market clears:

$$w_n L_n = \sum_{j=1}^{J} \gamma_n^j (1-\beta_n^j) \sum_{i=1}^{N} X_i^j \frac{\pi_{in}^j}{1+\tau_{in}^k} \tag{17}$$

3.3.4 Trade balance

On a global scale, the trade deficit collectively amounts to zero, which can be expressed as $\sum_{n=1}^{N} D_n = 0$. When merging this equation with Eq. (16), we obtain

$$\sum_{j=1}^{J} \sum_{i=1}^{N} X_n^j \frac{\pi_{ni}^j}{1+\tau_{ni}^j} - D_n = \sum_{j=1}^{J} \sum_{i=1}^{N} X_n^j \frac{\pi_{in}^j}{1+\tau_{in}^j} \tag{18}$$

From the above model, the exogenous parameters of this paper are $\{\gamma_n^{k,j}, \gamma_n^j, \alpha_n^j, \theta^j, \beta_n^j, \lambda_{ni}^j,\}$, exogenous variables are $\{t_n, \tau_{ni}^j, d_{ni}^j, z_{ni}^j\}$, and endogenous variables are $\{w_n, c_n^j, p_n^j, \pi_{ni}^j, X_n^j, e_n^j\}$. To solve for the equilibrium of all variables, we begin by assuming w_n is determined. Subsequently, the production cost ψ_n^j for the input bundle and the price P_n^j for sector j within country n can be determined by using Eqs. (5), (6), and (13). Following the determination of ψ_n^j and P_n^j, calculate π_{ni}^j using Eq. (15) and update the wage w_n using Eqs. (16) and (17). We present the detailed calculation process in Appendix A.

3.4 Equilibrium in relative changes

Within the framework of the general equilibrium modeling system outlined above, various exogenous parameters necessitate distinct treatments. These treatments extend beyond the adjustments in import tariffs for the high-carbon sector after implementing the CBAM. We adopt the Exact-hat Algebra method as suggested by Dekle et al. (2008) to circumvent the need for direct calibration of these high-dimensional parameters. This method allows us to eliminate select parameters from the general equilibrium equations. Denote w and P as the wages and prices prevailing in each EU country before the CBAM's enactment and w' and P' as the corresponding values post-enactment. Furthermore, it is worth noting that the EU import tariffs on the high-carbon sector assume the value τ' after the CBAM takes effect.

Additionally, we introduce the notation $\hat{x} = x'/x$ to represent the percentage change in x. This notation facilitates the representation of changes in the equilibrium conditions as follows

Cost of production:

$$\hat{\psi}_i^j = [\hat{w}_n^{\gamma_n^j} \prod_{k=1}^{J} \hat{P}_n^{k\,\gamma_n^{k,j}}]^{1-\beta_n^j} \tag{19}$$

Price index:

$$\hat{P}_n^j = \left[\sum_{i=1}^{N} \pi_{ni}^j (\hat{\kappa}_{ni}^j \hat{\psi}_i^j)^{-\theta^j}\right]^{-\frac{1}{\theta^j}} \tag{20}$$

Bilateral trade shares:

$$\hat{\pi}_{ni}^j = \left[\frac{\hat{\kappa}_{ni}^j \hat{\psi}_i^j}{\hat{P}_n^j}\right]^{-\theta^j} \tag{21}$$

Total expenditure in counterfactual:

$$X_n^{j'} = \sum_{k=1}^{J} (1-\beta_n^k)\gamma_n^{j,k} \sum_{i=1}^{N} X_i^{k'} \frac{\pi_{ni}^{k'}}{1+\tau_{in}^{k'}} + \alpha_n^j I_n' \tag{22}$$

Labor market clearing,

$$\hat{w}_n w_n L_n = \sum_{j=1}^{J} \gamma_n^j (1-\beta_n^j) \sum_{i=1}^{N} \pi_{in}^j \frac{X_i^{j'}}{1+\tau_{in}^{j'}} \tag{23}$$

Where $I_n' = \hat{w}_n w_n L_n + \sum_{j=1}^{J} \sum_{i=1}^{N} \beta_n^j \pi_{in}^j \frac{X_i^{j'}}{1+\tau_{in}^{j'}} + D_n'$.

3.5 Real wages and welfare effects

The change in real wages in country n can be expressed as follows, utilizing Eqs. (14), (19), and (21):

$$\ln \frac{\hat{w}_n}{\hat{P}_n} = -\sum_{j=1}^{J} \frac{\alpha_n^j}{\theta^j} \ln \hat{\pi}_{nn}^j - \sum_{j=1}^{J} \frac{\alpha_n^j}{\theta^j} \frac{1-\gamma_n^j}{\gamma_n^j} \ln \hat{\pi}_{nn}^j - \sum_{j=1}^{J} \frac{\alpha_n^j}{\gamma_n^j} \ln \prod_{k=1}^{J} (\hat{P}_n^k / \hat{P}_n^j)^{\gamma_n^{k,j}} \tag{24}$$

Following the approach of Caliendo and Parro (2015), the changes in real wages in Eq. (24) predominantly stem from alterations in trade involving final goods, intermediate goods, and sectoral linkages. Each component corresponds to one of the terms in the equation above. Consequently, the impact of CBAM on real wages across countries encompasses several facets. Firstly, it affects real wages by reducing the import share of higher-carbon products. Secondly, it facilitates substituting lower-priced and less carbon-intensive intermediate goods for relatively higher-priced and more carbon-emitting intermediates. Lastly, it influences the contribution of trade in goods to real wages through input-output linkages.

In the general equilibrium model presented in this paper, the representative consumer earns wage income through labor and receives full tariff revenue and revenue from domestic pollution emissions taxes. Consequently, the representative consumer's welfare is defined as price-adjusted income, represented as $W_n = I_n/P_n$. To estimate the welfare effect, this study isolates the influence of trade deficits and focuses on EU carbon tariff revenues and the welfare changes resulting from wage income. The equilibrium condition for welfare changes can be derived through a comprehensive differentiation of total income, W_n, as follows:

$$d\ln W_n = \frac{1}{I_n}\sum_{j=1}^{J}\sum_{i=1}^{N}(E_{ni}^j d\ln c_n^j - M_{ni}^j d\ln c_i^j) + \frac{1}{I_n}\sum_{j=1}^{J}\sum_{i=1}^{N}\tau_{ni}^j M_{ni}^j (d\ln M_{ni}^j - d\ln c_i^j) \quad (25)$$

In Eq. (25), the first term on the right-hand side of the middle value signifies the alteration in the overall terms of trade for country n, representing a shift in the relative price of trade. The second term illustrates the impact of trade liberalization on the volume of import trade, indicating changes in trade size. By disentangling the comprehensive welfare effects at both the price and quantity levels in the equation above, this study can analyze the transformations in consumer welfare within each country following the imposition of a carbon tax on high-carbon product imports by the EU CBAM. These products include cement, electricity, steel, and aluminum.

3.5 Decomposition of carbon emissions

Another question we are interested in is whether implementing the EU CBAM will achieve the policy's intended goal of effectively reducing the increase in global carbon emissions. In order to quantify the carbon reduction effect of CBAM implementation, we disaggregate carbon emissions concerning Duan et al. (2021):

$$d\ln e_n = d\ln Y_n + \frac{1}{e_n}\sum_{j=1}^{J}\beta_n^j\sum_{i=1}^{N}X_{in}^j d\ln \upsilon_n^j \quad (26)$$

Where $e_n = \sum_j^J e_n^j$ is the total carbon emissions of country n. Additionally, $Y_n^j = \sum_j^J X_{in}^j$ is the total output of industry j within country n, while $Y_n = \sum_j^J Y_n^j$ is the overall output of country n. Furthermore, $v_n^j = Y_n^j/Y_n$ is the share of industry j's output within country n relative to the total output of country n. Eq. (26) encompasses two distinct terms on the right-hand side. The first term quantifies the change in carbon emissions resulting from alterations in output, commonly known as the scale effect. The second term measures changes in emissions attributed to variations in an industry's share of total output, termed the composite effect. It is important to note that our assumption of constant environmental regulation intensity across countries, i.e., $\frac{t_n'}{t_n} = 1$, implies no emission reduction effect arising from technological changes, as indicated in Eq. (26). Furthermore, we proceed to decompose the impact of CBAM on global carbon emissions:

$$d\ln e_n = \frac{1}{e}\sum_{n=1}^{N}\left(\sum_{j=1}^{J}\frac{\beta_n^j}{t_n}\sum_{i=1}^{N}X_{in}^j d\ln Y_n\right) + \frac{1}{e}\sum_{n=1}^{N}\left(\sum_{j=1}^{J}\frac{\beta_n^j}{t_n}\sum_{i=1}^{N}X_{in}^j d\ln \upsilon_n^j\right) \quad (27)$$

4. Parameter estimation and data sources

4.1 model parameterization

4.1.1 Emission elasticity

The emission elasticity β_n^j delineates the portion of carbon emissions within the manufacturer's total output. We adopt the approach outlined in Duan et al. (2021) to estimate this elasticity. Our estimation proceeds in two steps: firstly, we determine the aggregate pollution elasticity β_n across countries, and secondly, we estimate β_n^j at the industry level, leveraging the relationship $\frac{\beta_n^i}{\beta_n^j} = \frac{\chi_n^i}{\chi_n^j}$. More specifically, our initial step involves running the following regression:

$$\ln Q_n = \eta_0 + \eta_1 \ln EPS_n + \eta_2 \ln \chi_n + \varepsilon_n \quad (28)$$

where Q_n is the portion of pollution tax revenues in country n relative to the country's GDP, while EPS_n is the intensity of environmental regulation in country n constants η_0 and error term ε_n are also integral components of the equation. Given that Eq. (28) may potentially encounter significant endogeneity challenges, we address this by calculating the ventilation coefficients for each country. These coefficients serve as instrumental variables for EPS_n in the 2SLS regression, mitigating potential endogeneity issues. Specifically, the instrumental variable computation process involves the following steps: firstly, we extract sub-datasets of wind speeds for each month of 2014, specific to each country, from the Climate Data Store[1]. Next, we utilize the raster calculator within ArcGIS Pro to compute the annual average decimeter wind speed and boundary layer height for each country. Subsequently, we employ the raster calculator once more to multiply the annual average decimeter wind speed and boundary layer height, yielding the annual average AFC raster data. These data are then further processed by applying a mask using the administrative division data of each country to extract the AFC raster data within each region. Upon obtaining estimates for η_1 and η_2, represented as $\hat{\eta}_1$ and $\hat{\eta}_2$, we proceed to calculate the pollution elasticities at the country level using Eq. (29). The estimation results for Eq. (29) are presented in Table B.1 in Appendix B.

$$\hat{\beta}_n = \hat{\beta}_{US} \cdot \left(\frac{EPS_n}{EPS_{US}} \right)^{\hat{\eta}_1} \left(\frac{\chi_n}{\chi_{US}} \right)^{\hat{\eta}_2} \tag{29}$$

Here, $\hat{\beta}_{US}$ represents the pollution elasticity for the United States, as estimated by Shapiro and Walker (2018) using firm-level data, with a specific value of $\hat{\beta}_{US} = 0.011$. Following the estimation of country-level pollution elasticity using Eq. (29), we leverage the property that $\frac{\beta_n^i}{\beta_n^j} = \frac{\chi_n^i}{\chi_n^j}$. This relationship, combined with the summation constraint $\sum_j \hat{\beta}_n^j = \hat{\beta}_n$, allows us to estimate the pollution elasticity at the industry level, denoted as β_n^j.

4.1.2 Trade elasticity

The trade elasticity θ^j is another critical variable in solving the model equilibrium. We refer to Caliendo and Parro (2015) to obtain industry-level trade elasticities by estimating Eq. (30). We report the values of θ^j in Table B.2 in Appendix B.

$$\ln\left(\frac{X_{ni}^j X_{ih}^j X_{hn}^j}{X_{in}^j X_{hi}^j X_{nh}^j} \right) = -\theta^j \ln\left(\frac{\tilde{\tau}_{ni}^j \tilde{\tau}_{ih}^j \tilde{\tau}_{hn}^j}{\tilde{\tau}_{in}^j \tilde{\tau}_{hi}^j \tilde{\tau}_{nh}^j} \right) + \tilde{\varepsilon}^j \tag{30}$$

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[1] Available at https://cds.climate.copernicus.eu/cdsapp#!/home.

4.1.3 Carbon tariffs

Following the EU carbon tariff collection rules, this paper adopts the model framework introduced by Larch and Wanner (2017). In this framework, the EU carbon tariff for each sector is determined by multiplying the difference in carbon prices between the EU and the exporting country with that sector's EU carbon emission intensity. Specifically, if the country n's carbon price s_n surpasses that of country i, then its imports from country i in sector j incur a carbon tariff rate denoted as $\phi_{ni}^{j} = (\frac{e_i^j}{Y_i^j})(s_n - s_i)$. In cases where s_n is not higher than s_i, the carbon tariff rate ϕ_{ni}^{j} is set to 0. At this stage, the trade cost that country n faces for sector j products imported from i can be expressed as $\kappa_{ni}^{j} = \tilde{\tau}_{ni}^{j}(1 + \phi_{ni}^{j})d_{ni}^{j}$.

4.2 Data sources

To more accurately assess the effects of EU CBAM implementation on individual economies worldwide, this study relies on the 2016 edition of the World Input-Output Database (WIOD) as its primary dataset. The WIOD 2016 dataset encompasses 28 EU member states and 15 other countries and territories. Notably, the Netherlands and Taiwan have been categorized as part of the "rest of the world" (ROW) due to these regions' unavailability of carbon emission data. Consequently, this paper investigates explicitly the influence of EU carbon tariffs on carbon emissions across 56 sectors within 42 countries. Each country's sector-specific carbon emissions data are sourced from the environmental account within the WIOD database, which aligns with the same set of countries and sectors found in the World Input-Output Table (WIOT). Leveraging the comprehensive WIOD dataset, this study performs calculations related to bilateral expenditures X_{ni}^{j}, gross output Y_n^j, value-added V_n^j, carbon emissions e_n^j, and the utilization of intermediate inputs.

To calculate the elasticity of pollution at the overall country level, we utilize data from the World Economic Forum's Executive Opinion Survey, a widely recognized source for assessing environmental regulations EPS (Milani, 2017). For the share of environmentally related tax revenue in GDP Q_n, we rely on data from the OECD database. Additionally, we acquire tariff data for each country at the International Standard Industrial Classification Revision 4 (ISIC Rev. 4) level from the World Bank's WITS database. It is important to note that all data calibration is set to the year 2014, which corresponds to the latest available year in WIOD 2016. In summary, our estimation methodology and data sources regarding exogenous parameters refer to Table 1.

Table 1 Calibration methods for exogenous parameters

Exogenous variables	Parameter Description	Data sources and estimation methods
X_{ni}^{j}	Bilateral expenditures	Acquired from WIOD
Y_{n}^{j}	Total output	Acquired from WIOD
V_{n}^{j}	Value added	Acquired from WIOD
e_{n}^{j}	Carbon emission	Acquired from WIOD environmental account
D_n	Trade deficit	Acquired from WIOD
γ_{n}^{j}	Value added share	Acquired from WIOD
$\gamma_{n}^{k,j}$	Input-output coefficient	Acquired from WIOD
α_{n}^{j}	Expenditure share	Acquired from WIOD
β_{n}^{j}	Emission elasticity	Referring to Duan et al. (2021)
τ_{ni}^{j}	Sectoral tariffs	Acquired from World Bank WITS dataset
ϕ_{ni}^{j}	Carbon tariffs	Referring to Larch and Wanner (2017)
θ_{n}^{j}	Sectoral trade elasticities	Referring to Caliendo and Parro (2015)
s_n	Carbon prices	Acquired from World Bank carbon pricing dashboard dataset

5. Quantitative Analysis

5.1 Economic and Welfare Effects of the EU CBAM

This section delves into the economic and welfare implications of the EU CBAM based on the model assumptions and parameter estimations discussed earlier. We assess the changes in consumer welfare and real wages in EU member states and other countries relative to 2014, following the formal implementation of the EU carbon tariff in 2026. The resulting data is presented in Table 2. Column (2) in Table 2 highlights that the introduction of the EU carbon tariff will boost total welfare for the EU, Japan, South Korea, Norway, Switzerland, and the United States by 1.338%, 0.048%, 0.573%, 0.711%, 0.259%, and 0.064%, respectively. Simultaneously, it will lead to decreased welfare for several other nations worldwide. Russia stands out with the most significant welfare reduction of 1.096%, while China experiences the slightest loss of 0.005%. Broadly, the EU carbon tariffs exert a more restrained impact on major developed nations, even managing to enhance the welfare of some of them. However, the welfare losses are notably more significant for developing countries like Russia, India, and Turkey. These nations, characterized by a higher volume of high-carbon product exports to the EU, bear the brunt of these consequences.

To understand the factors underlying changes in welfare across countries, this study further dissects the welfare effects in terms of trade and trade size effects. Table 2, specifically Column (3), outlines alterations in each country's trade terms. The results highlight that the primary driver behind the increased welfare gains in the EU, Japan, and South Korea stems from improvements in the terms of trade. When the EU levies carbon tariffs on non-member countries, particularly on high-carbon industries like cement, steel, and aluminum, it leads to a global reduction in the prices of high-carbon products. This, in turn, enhances the terms of trade for these countries. Consequently, there is a positive contribution from EU member countries to nations beyond the region concerning shifts in terms of trade, ultimately benefiting the EU's terms of trade. Switzerland and Norway, having secured CBAM exemptions, also experience substantial welfare boosts attributable to improved terms of trade. Overall, the alterations in terms of trade consistently align with changes in aggregate welfare, both in terms of direction and magnitude. These changes in terms of trade play a pivotal role in driving welfare transformations across countries.

Column (4) in Table 2 presents another factor influencing welfare changes: alterations in trade volume. Implementing the EU carbon tariff elevates the export costs from other countries to the EU, consequently reducing bilateral trade within the EU. This leads to a 0.015% decrease in the EU's trade volume. Notably, China's trade volume increased by 0.014% among developing nations, indicating a solid trade diversion effect resulting from the EU carbon tariff.

Regarding real wages, while the carbon tariff rebate boosts the incomes of EU residents, the rise in the prices of imported products ultimately leads to a 0.711% decrease in real wages within the EU. In contrast, China, Japan, Korea, Norway, Switzerland, and the United States of America experience increases in real wages by 0.008%, 0.046%, 0.425%, 0.258%, 0.004%, and 0.089%, respectively.

Table 2 Decomposition of Welfare Effects and Real Income Changes in Major Economies by the EU CBAM

Country	Welfare			Real wages
	Total	Terms of trade	Volume of Trade	
Australia	-0.182%	-0.182%	0.000%	-0.177%
Brazil	-0.109%	-0.083%	-0.026%	-0.106%
Canada	-0.180%	-0.170%	-0.010%	-0.159%
China	-0.005%	-0.019%	0.014%	0.008%
EU	1.338%	1.353%	-0.015%	-0.711%
India	-0.071%	-0.071%	0.000%	-0.067%
Indonesia	-0.151%	-0.151%	0.000%	-0.138%
Japan	0.048%	0.046%	0.003%	0.046%
Korea	0.573%	0.443%	0.130%	0.425%
Mexico	-0.275%	-0.244%	-0.031%	-0.253%
Norway	0.711%	0.741%	-0.030%	0.258%
Russia	-1.096%	-0.856%	-0.240%	-0.677%
Switzerland	0.259%	0.259%	0.000%	0.004%

Turkey	-0.626%	-0.626%	0.000%	-0.552%
United Kingdom	-0.032%	-0.022%	-0.010%	-0.509%
United States	0.064%	0.060%	0.004%	0.089%
ROW	-1.044%	-1.064%	0.020%	-1.529%

For a detailed breakdown of welfare changes within the EU member states, refer to Table 3. Notably, all member states witnessed increased total welfare, with Latvia, Luxembourg, and Belgium experiencing the most substantial gains. Additionally, Table B.3 in Appendix B provides insights into the percentage change in export shares across 22 tradable industries in the EU following the implementation of carbon tariffs. The results reveal a rising trend in the export shares of high-carbon industries such as cement, steel, and aluminum.

Table 3 Decomposition of welfare effects and real income changes in EU CBAM for member states

Country	Welfare			Real wage	Country	Welfare			Real wage
	Total	Terms of trade	Volume of trade			Total	Terms of trade	Volume of trade	
Austria	0.843%	0.850%	-0.006%	-0.321%	Ireland	2.236%	2.134%	0.102%	-1.761%
Belgium	2.813%	2.820%	-0.008%	-1.615%	Italy	0.911%	0.921%	-0.010%	-0.200%
Bulgaria	1.311%	1.349%	-0.037%	-0.924%	Latvia	1.208%	1.270%	-0.062%	-1.118%
Croatia	0.586%	0.605%	-0.019%	-0.996%	Lithuania	3.833%	3.878%	-0.044%	-1.357%
Cyprus	0.973%	1.038%	-0.065%	-1.734%	Luxembourg	2.908%	2.908%	0.000%	0.223%
Czech	1.943%	1.950%	-0.007%	0.041%	Malta	0.828%	0.88%	-0.052%	-1.086%
Denmark	0.807%	0.834%	-0.027%	-2.056%	Poland	1.677%	1.692%	-0.014%	-0.049%
Estonia	0.770%	0.812%	-0.042%	-1.225%	Portugal	0.450%	0.462%	-0.012%	-0.406%
Finland	0.703%	0.714%	-0.011%	-0.897%	Romania	0.875%	0.875%	0.000%	-0.362%
France	0.719%	0.726%	-0.007%	-0.236%	Slovakia	1.214%	1.227%	-0.013%	-0.513%
Germany	1.448%	1.455%	-0.007%	-0.428%	Slovenia	1.315%	1.351%	-0.036%	-0.826%
Greece	1.376%	1.382%	-0.006%	0.474%	Spain	0.894%	0.900%	-0.007%	-0.114%

Hungary	1.288%	1.294%	-0.006%	-0.536%	Sweden	0.850%	0.855%	-0.006%	-0.463%

5.2 Carbon Emission Abatement Effects of EU CBAM

Table 4 presents the decomposition results of changes in carbon emissions across economies resulting from implementing EU carbon tariffs. Column (2) displays the overall abatement effect across economies, while columns (3) and (4) reveal the scale and composition effects, respectively, following the methodology of Grossman and Krueger (1993) and Copeland and Taylor (2017). It is essential to note that the decomposition results in Table 3 exclude changes in technology effects, assuming a constant level of domestic environmental regulation in each country.

Implementing CBAM significantly reduces total global carbon emissions by 7.33%, though this effect varies across economies. Within the EU, the imposition of carbon tariffs results in a relatively minor reduction of 0.682% in total carbon emissions. The decomposition results in columns (3) and (4) further illustrate that, while the composite effect diminishes the EU's carbon emissions by 8.085%, the SCALE effect concurrently increases them by 7.402%. This phenomenon arises because carbon tariffs initially inflate the cost of importing high-carbon products, prompting the EU to decrease imports from countries with lower carbon prices. This enhances the trade structure of EU countries, thereby reducing carbon emissions through the composition effect. However, it also expands the production scale of high-carbon products within the EU, resulting in increased carbon emissions through the scale effect.

The different impacts of the EU carbon tariff on carbon emissions of other economies can be roughly categorized into the following three types. First, suppose the carbon price of the economy is lower than that of the EU. In that case, the EU will reduce its imports of high-carbon products from such countries, i.e., it will reduce the carbon emissions of exporting economies through composition effects and optimize the export structure of such countries. For example, CBAM will reduce the carbon emissions of low carbon price countries such as China, Brazil, and Australia by 0.485%, 0.170%, and 3.282%, respectively. Second, if the carbon price of that economy is higher than or similar to that of the EU, the EU will increase its imports of high-carbon products from such countries, e.g., Switzerland's carbon emissions will rise by 2.785%. Thirdly, if an economy has a lower carbon price than the EU but at the same time has less stringent domestic environmental regulations, other countries with relatively higher carbon prices will tend to move their production lines in high-carbon industries to that country, and then import intermediate goods from that country for production and re-export to the EU, where the carbon price is even higher, and this will lead to a rise in the economy's pollution emissions. For example, Indonesia's carbon emissions will rise by 0.621%.

Table 4 Decomposition of the carbon emission effects of the EU CBAM on major economies

Country	Emission effect	Scale effect	Composite effect
Australia	-3.282%	2.733%	-6.015%
Brazil	-0.170%	1.984%	-2.154%
Canada	-1.312%	3.086%	-4.398%
China	-0.485%	2.371%	-2.856%
EU	-0.682%	7.402%	-8.085%
India	0.197%	0.871%	-0.674%
Indonesia	0.621%	6.280%	-5.658%
Japan	-2.047%	3.774%	-5.821%
Korea	2.049%	5.460%	-3.411%
Mexico	0.515%	3.595%	-3.081%
Norway	-20.987%	14.926%	-35.912%
Russia	5.048%	8.358%	-3.311%
Switzerland	2.785%	4.805%	-2.020%
Turkey	0.057%	0.666%	-0.610%
United Kingdom	5.856%	5.368%	0.488%
United States	1.156%	1.678%	-0.522%

ROW	3.351%	3.121%	0.230%

Table 5 reveals varying effects of carbon tariffs within the EU, in which Denmark presents the most significant carbon abatement effects, while Croatia faces a rise in carbon emissions.

Table 5 Decomposition of Changes in Carbon Emissions in EU Member States via CBAM

Country	Emission effect	Scale effect	Composite effect	Country	Emission effect	Scale effect	Composite effect
Austria	-10.104%	6.569%	-16.673%	Ireland	0.553%	4.772%	-4.218%
Belgium	-4.281%	7.032%	-11.313%	Italy	0.424%	6.226%	-5.802%
Bulgaria	3.769%	5.427%	-1.658%	Latvia	-5.039%	6.379%	-11.419%
Croatia	14.871%	12.847%	2.023%	Lithuania	0.332%	9.104%	-8.772%
Cyprus	-0.462%	6.233%	-6.694%	Luxembourg	9.269%	7.982%	1.287%
Czech	-1.742%	5.330%	-7.072%	Malta	8.013%	13.050%	-5.038%
Denmark	-21.948%	3.497%	-25.444%	Poland	-1.272%	9.893%	-11.165%
Estonia	-2.735%	6.399%	-9.134%	Portugal	5.967%	7.575%	-1.608%
Finland	8.916%	10.560%	-1.644%	Romania	0.401%	6.068%	-5.667%
France	-10.646%	8.628%	-19.274%	Slovakia	2.998%	6.400%	-3.401%
Germany	-1.776%	7.126%	-8.903%	Slovenia	-0.584%	5.710%	-6.295%
Greece	5.841%	10.392%	-4.551%	Spain	-3.765%	7.065%	-10.830%
Hungary	3.268%	5.965%	-2.696%	Sweden	-18.011%	6.224%	-24.235%

6. Counterfactual analysis

6.1 Harmonized global carbon price

Differences in current carbon pricing levels across economies contribute significantly to carbon leakage. What would happen if a globally harmonized carbon price were implemented? This paper employs counterfactual analysis to simulate changes in welfare levels and carbon emissions worldwide when carbon pricing is harmonized globally—precisely when each country aligns its carbon price with the EU's.

To assess the welfare implications, Figure 1 illustrates the changes in welfare and their decomposition for major economies under a globally harmonized carbon price. In the case of the EU, total welfare increases by 0.254%, primarily driven by a 0.247% improvement in terms of trade and a 0.007% increase in trade volume. However, for Norway, which maintains a higher carbon price than the EU, global harmonization reduces Norway's domestic carbon price. While this lowers emissions costs in its high-carbon industries and decreases export prices, it worsens terms of trade and reduces trade volume, resulting in a 0.797% decline in Norway's welfare. Emerging market countries with lower carbon prices than the EU, such as China, India, and Brazil, experience a different outcome. A globally harmonized carbon price raises domestic production costs, consequently increasing export prices and improving terms of trade. Furthermore, it enables them to avoid carbon tariffs when trading with the EU, boosting their exports to the EU and leading to welfare increases of 0.143%, 0.085%, and 0.033%, respectively.

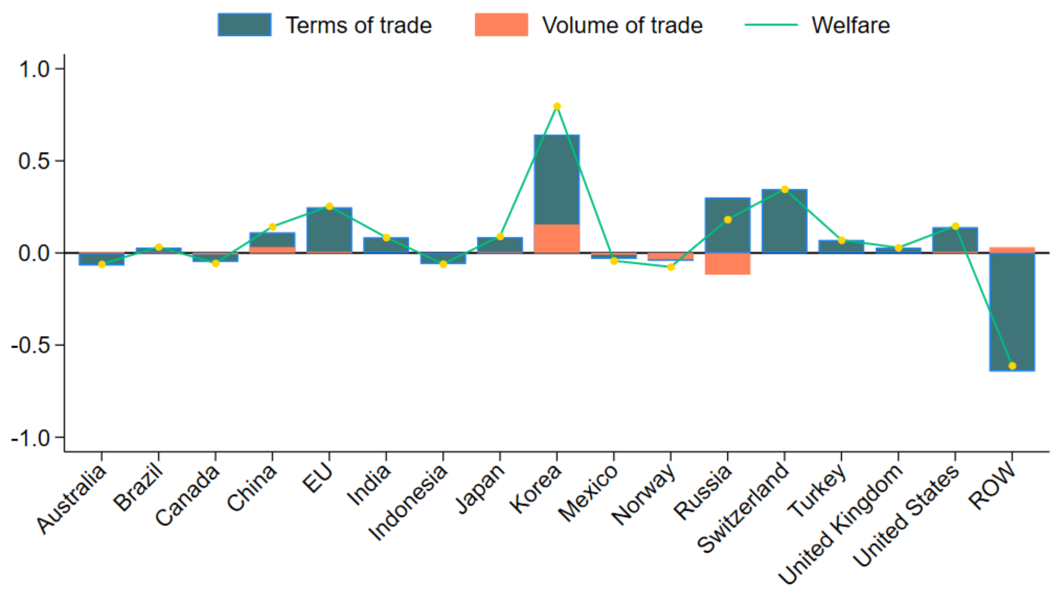

Figure 1 The impact of a globally harmonized carbon price on the welfare of major economies and its decomposition

Secondly, concerning the impact on carbon emissions, Figure 2 illustrates the changes and decomposition of carbon emissions for major economies under a globally harmonized carbon price. In total, introducing a unified carbon price substantially reduces global carbon emissions, amounting to a remarkable 43.135% decrease. Among the economies analyzed, the EU experiences a modest reduction of 0.96% in carbon emissions. However, this reduction pales compared to the decreases observed in emerging market countries. For instance, China, India, Brazil, and Turkey achieved reductions of 0.946%, 0.896%, 1.948%, and 4.577%, respectively. Notably, Norway stands out with the most significant reduction effect, recording a remarkable 25.991% decrease in carbon emissions. A substantial portion of this reduction, approximately 35.164%, can be attributed to structural adjustments. Norway's early establishment of a carbon market, complemented by effective carbon tax and emission quota mechanisms, has positioned it to adapt seamlessly to the global unified carbon price. Furthermore, Norway's economy heavily relies on high-tech, low-carbon sectors such as marine technology, electricity production, and clean technology, making its carbon emission reduction effect particularly pronounced. The results depicted in Figure 2 underscore the effectiveness of a globally harmonized carbon price in mitigating the risk of carbon leakage. This approach ensures that all countries bear the costs associated with carbon emissions and prevents a select few from benefiting disproportionately from carbon emissions.

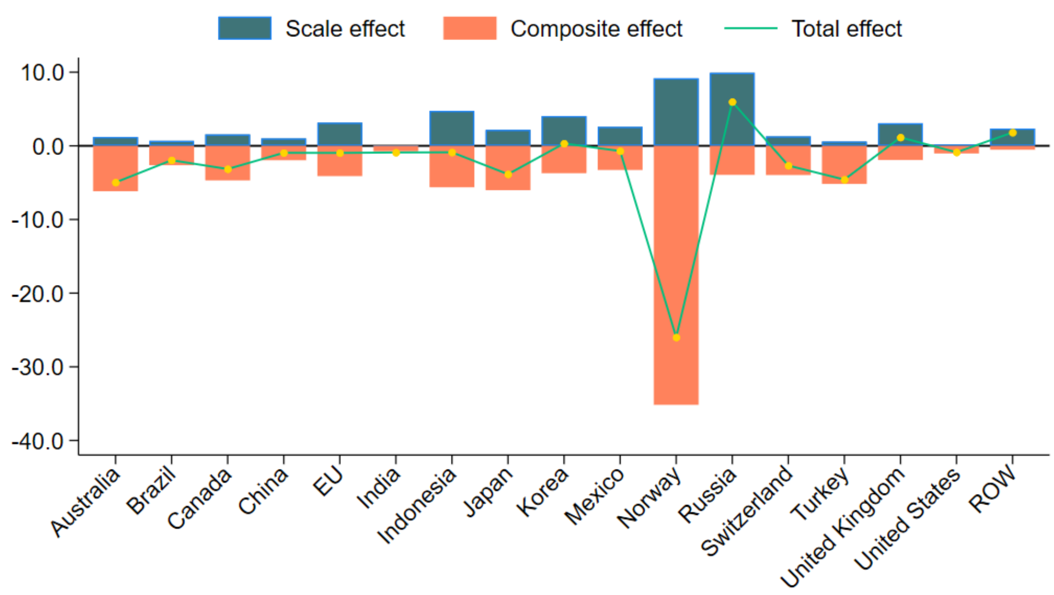

Figure 2 Impact of a globally harmonized carbon price on carbon emissions in

major economies and its decomposition

6.2 Implications of China's Carbon Tariffs

The trading price in China's carbon market 2022 stands at $10.19 per ton, starkly contrasting with the EU's rate of $88.06 per ton. In this section, we explore the consequences of elevating China's carbon price to match the EU's level, driven by the EU's carbon tariff policies. We investigate how this adjustment would impact major global economies' welfare and carbon emissions if China implemented a reciprocal carbon tariff.

As depicted in Figure 3, this change in China's carbon pricing and introduction of carbon tariffs resulted in a 0.122% increase in China's welfare. Notably, this improvement can be attributed to enhanced terms of trade (0.094%) and increased trade size (0.028%). The higher carbon price elevates the cost of China's exports relative to imports, favorably affecting its terms of trade. While this pricing shift may lead to increased production costs and reduced exports, it simultaneously encourages higher imports by substituting some domestic products. The interplay of these factors significantly amplifies China's trade size.

For other economies, a heightened carbon price in China has varying impacts. Norway, South Korea, and the EU witnessed the most substantial welfare gains, experiencing increases of 0.669%, 0.596%, and 0.552%, respectively. Conversely, Russia, Turkey, and Mexico incur the most considerable welfare losses, amounting to 1.049%, 0.615%, and 0.271%, respectively. These outcomes are predominantly shaped by each economy's domestic carbon pricing, energy trade structure, and economic and trade relations with China.

First, establishing a domestic carbon market in China, a major energy importer, has far-reaching consequences for global energy markets. One notable effect is the reduction in the world market price of energy, which, in turn, impacts the real incomes of net energy exporters and importers. Take Russia and Norway, for instance, where Russia is a significant energy exporter, while Norway is an energy importer. The lower energy market prices resulting from China's carbon market would exert substantial downward pressure on Russia's welfare, whereas Norway would experience an increase in its real income. This contrast underscores the significance of energy trade dynamics in shaping the outcomes of carbon market policies.

Second, China's decision to raise its carbon price has implications beyond its borders. This policy shift, aimed at curbing emissions, comes with a trade-off. While it does elevate China's production costs and subsequently lowers its output levels to some extent, these effects reverberate through the global production network. As a critical node within this network, China's increased production costs inevitably translate into higher costs for downstream economies. Consequently, these economies witnessed a reduction in their output and wage levels, deteriorating their terms of trade. For instance, India and Indonesia experienced declines in their terms of trade by 0.071% and 0.157%, respectively. In essence, the severity of the terms of trade deterioration in a given economy is directly related to its demand for Chinese imports of intermediate goods. Higher demand for such imports is strongly correlated with a more pronounced deterioration in the terms of trade.

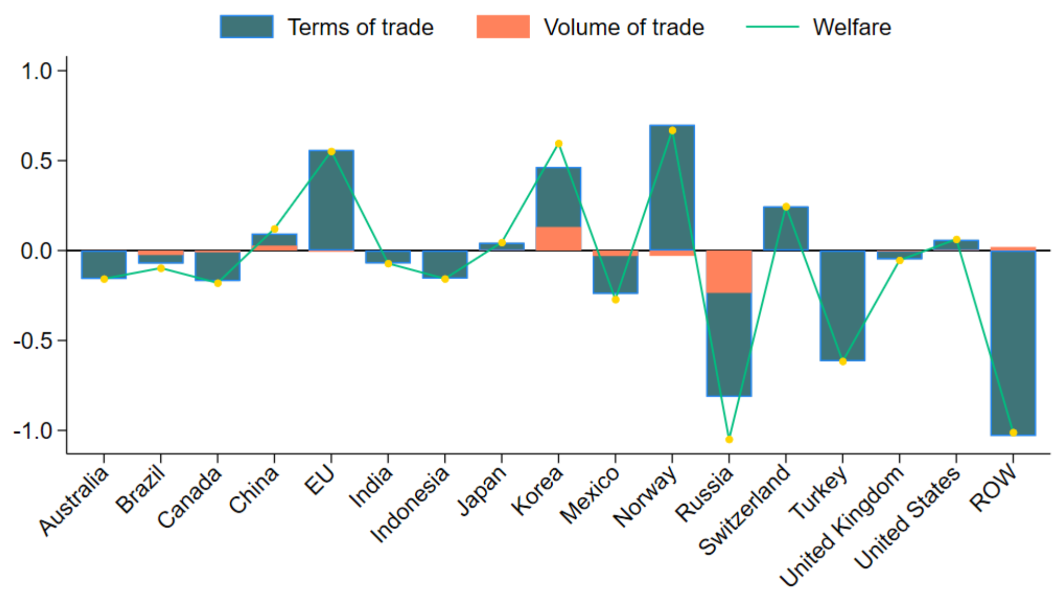

Figure 3 Welfare Implications of China's Carbon Price Increase and Carbon Tariff for Major Economies

Figure 4 illustrates the carbon emission effects of China's carbon price increase and carbon tariffs. These policies collectively contribute to a substantial global reduction in pollution emissions, amounting to 28.64%, highlighting their significant impact on emissions reduction. Remarkably, China experiences a relatively modest reduction in pollution emissions, at just 0.835%. This reduction can be dissected into two components: a 3.021% increase due to scale effects and a 3.856% decrease attributed to structural effects. Two key factors can explain this intricate outcome. Firstly, China's imposition of carbon tariffs leads to the relocation of foreign production to China, resulting in an expansion of domestic production and a subsequent rise in pollution emissions.

Secondly, China's higher domestic carbon price escalates the cost of domestic emissions, prompting China to reduce emissions by importing substitutes from abroad, thus reducing its carbon footprint. In contrast, other economies experience varying impacts. An increase in China's domestic carbon price spurs more significant imports from China, consequently elevating carbon emissions in economies closely linked to China's economic and trade networks. For example, Russia and South Korea witnessed increases in carbon emissions by 4.073% and 1.106%, respectively.

Furthermore, China's reduced demand for energy triggers lower energy prices globally. This increases the demand for fossil energy in select economies, resulting in heightened domestic carbon emissions. For instance, the United Kingdom and the United States see their carbon emissions rise by 4.83% and 0.08%, respectively.

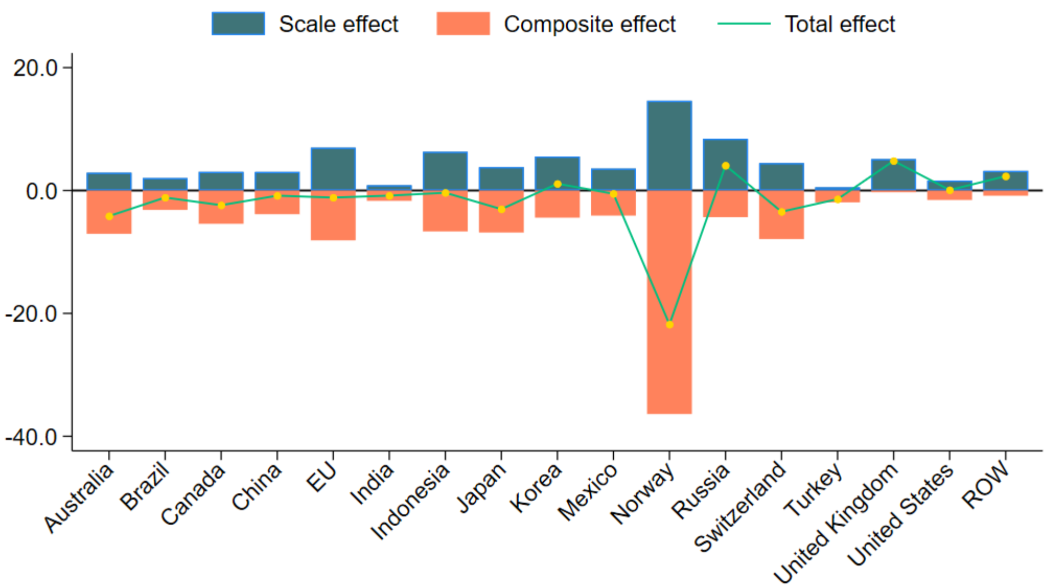

Figure 4 Impact of China's Carbon Price Increase and Carbon Tariff on Carbon Emissions in Major Economies

6.3 Expanding carbon tariffs to all sectors

The EU's existing carbon tariffs primarily target vital industries such as iron and steel, cement, and aluminum. This section examines the welfare implications and carbon emissions across economies when the EU extends these tariffs to encompass the entire spectrum of industries. The findings presented in Figure 5 reveal a noteworthy outcome: Should the EU implement an industry-wide carbon tariff, its welfare, as previously calculated at 1.338% (as shown in Table 2), would plummet to -0.032%. This policy shift resulted in a total welfare loss of 1.37%. The primary driver of this loss is the substantial deterioration in the terms of trade, reflecting a sharp 1.375% decline compared to the base case outlined in Table 2. This significant decline in the EU's terms of trade stems from the imposition of sector-wide carbon tariffs. It means that the EU would acquire the same volume of goods but at a higher cost of imports. The rapid escalation in import prices relative to export prices is the key driver behind the severe deterioration in the EU's terms of trade. For other economies, the picture varies. In the case of India and Indonesia, their welfare sees an increase of 0.119% and 0.08%, respectively, compared to the base case. This positive change is primarily attributed to the improved terms of trade. The extension of industry-wide carbon tariffs by the EU implies that countries like India would experience a rise in the prices of goods they export to the EU, ultimately enhancing their terms of trade in the European market.

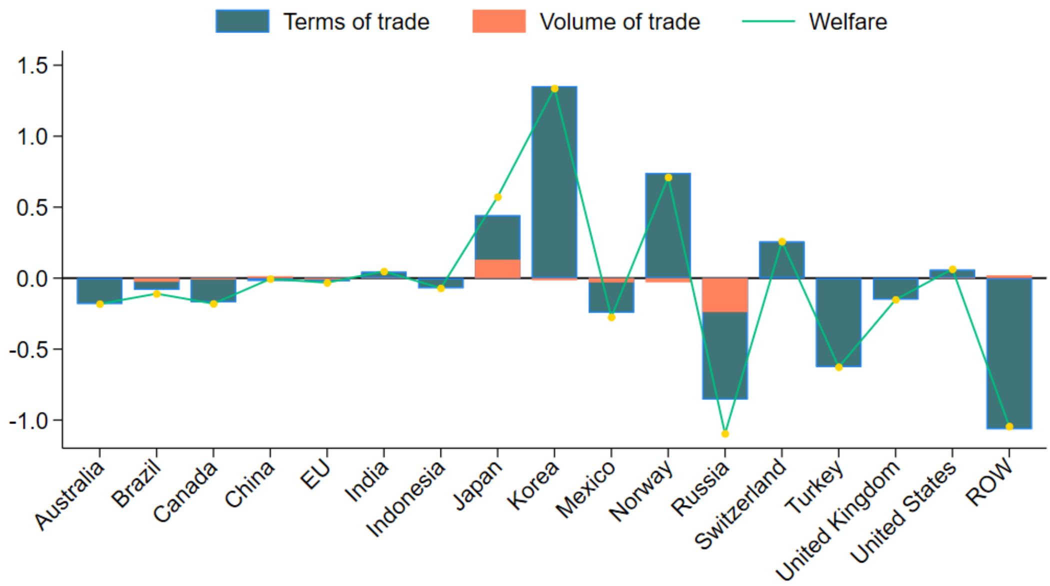

Figure 5 Welfare impacts of EU sectoral carbon tariffs on major economies

Figure 6 offers valuable insights into changes in carbon emissions across economies and provides a detailed decomposition of these results when the EU enforces an industry-wide carbon tariff. In the broader global context, there is a notable reduction in carbon emissions, with a remarkable 30.379% decrease observed. The EU exhibits a more complex pattern while experiencing a 2.299% reduction. Scale effects cause a 7.402% increase in carbon emissions, while structural effects lead to a 9.701% reduction. Turning our attention to other economies, a rapid decline in carbon emissions is evident in most countries. Notable exceptions include Switzerland, the UK, and the US. While these three nations experience an increase in carbon emissions, it is essential to highlight that their emissions still decline to a greater extent when compared to the changes in carbon emissions presented in Table 3.

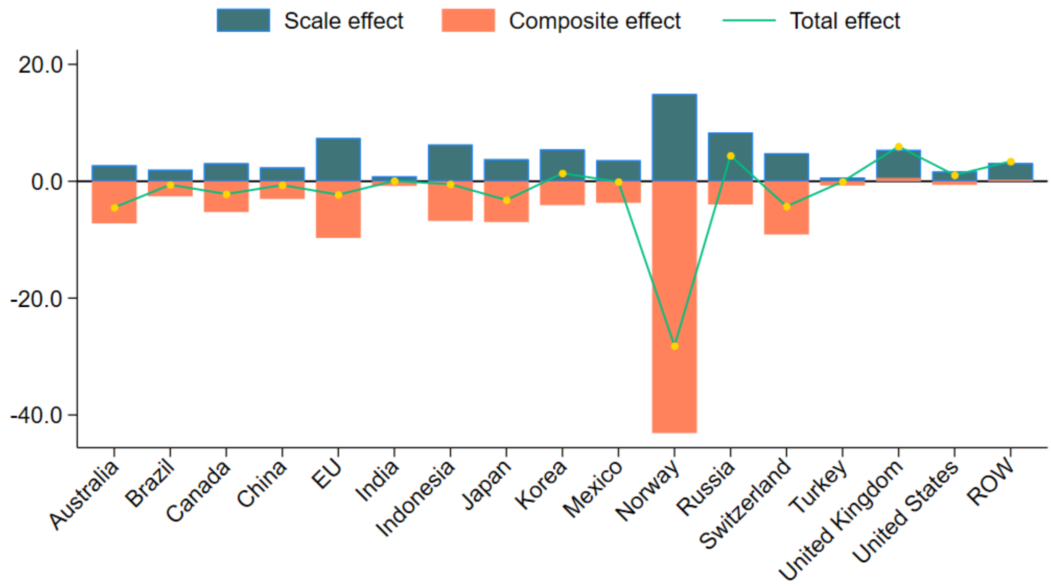

Figure 6 Impact of EU sectoral carbon tariffs on carbon emissions in major economies

7. Conclusion

This study quantifies the welfare and carbon emission implications of the EU Carbon Border Adjustment Mechanism (CBAM) for both the EU itself and other major global economies. Building upon the theoretical foundations outlined by Caliendo and Parro (2015) and Duan et al. (2021), we employ an instrumental variable approach to tackle the endogeneity challenge inherent in estimating pollution elasticities. Furthermore, we extend the model to incorporate carbon tariffs. These enhancements bolster the model's alignment with real-world dynamics and enhance our findings' credibility.

The outcomes of our analysis align closely with theoretical expectations and harmonize with previous research. Specifically, we observe that the implementation of CBAM yields a welfare increase for the EU, Japan, Korea, Norway, Switzerland, and the United States, amounting to 1.338%, 0.048%, 0.573%, 0.711%, 0.259%, and 0.064%, respectively. In contrast, the welfare of other countries worldwide experiences a decrease. Russia registers the most substantial welfare loss, 1.096%, while China faces the most minor loss at 0.005%. This shift in welfare predominantly arises from changes in the terms of trade among nations. Additionally, CBAM proves effective in reducing total global emissions, albeit with a limited impact on the EU. Furthermore, the effect varies among countries characterized by distinct carbon pricing strategies, with the structural effect playing a pivotal role in significantly curbing carbon emissions across nations.

The first counterfactual result of this paper reveals that global welfare experiences a decline in high carbon-priced countries while witnessing an increase in low carbon-priced countries. Furthermore, it substantially reduces global carbon emissions, surpassing the reduction achieved through the unilateral imposition of a carbon tariff by the EU. The second counterfactual result demonstrates that an increase in China's domestic carbon price coupled with implementing a carbon tariff benefits both China and the EU, albeit at the expense of certain energy-exporting nations, which experience a more adverse impact. Additionally, this counterfactual indicates a significant reduction in global carbon emissions, although the magnitude of this reduction is relatively smaller for China. The third counterfactual proposes that extending carbon tariffs to all sectors within the EU leads to a decline in overall welfare within the EU. However, it increases welfare in India and Indonesia. From the standpoint of carbon emissions, though expanding the tax's scope to all industries can effectively reduce global carbon emissions, this reduction effect remains less pronounced compared to the outcome when a globally harmonized carbon price is in place.

Based on the preceding findings, this paper posits that nations should contemplate establishing or fortifying international collaboration to advance the adoption of a globally harmonized carbon pricing mechanism. Such a strategy would curtail carbon emissions in high-carbon-priced nations while concurrently bolstering the well-being of low-carbon-priced nations and facilitating the attainment of global carbon emission reduction objectives. Recognizing that high-carbon-priced countries may experience a reduction in well-being, governments might contemplate implementing progressive carbon pricing policies. This would mitigate the welfare decline in high-carbon-priced countries and incentivize the adoption of more extensive carbon emission reduction measures. Furthermore, countries could establish a carbon trading market to curtail carbon emissions. High-carbon-priced countries would have the opportunity to procure carbon allowances from low-carbon-priced nations, thus mitigating the welfare disparity. Lastly, governments should institute effective monitoring and evaluation mechanisms to assess the efficacy of carbon pricing policies, ensuring their adequacy and facilitating adjustments and enhancements in light of real-world conditions.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

Aichele, R., Felbermayr, G., 2015. Kyoto and carbon leakage: An empirical analysis of the carbon content of bilateral trade. Rev. Econ. Stat. 97, 104-115.

Antimiani, A., Costantini, V., Kuik, O., Paglialunga, E., 2016. Mitigation of adverse effects on competitiveness and leakage of unilateral EU climate policy: An assessment of policy instruments. Ecol. Econ. 128, 246-259.

Beaufils, T., Ward, H., Jakob, M., Wenz, L., 2023. Assessing different European Carbon Border Adjustment Mechanism implementations and their impact on trade partners. Commun. Earth Environ. 4, 131.

Bellora, C., Fontagné, L., 2023. EU in search of a Carbon Border Adjustment Mechanism. Energy Econ. 123, 106673.

Böhringer, C., Bye, B., Fæhn, T., Rosendahl, K.E., 2017a. Targeted carbon tariffs: Export response, leakage and welfare. Resour. Energy Econ. 50, 51-73.

Böhringer, C., Rosendahl, K.E., Storrøsten, H.B., 2017b. Robust policies to mitigate carbon leakage. J. Public Econ. 149, 35-46.

Böhringer, C., Schneider, J., Asane-Otoo, E., 2021. Trade in carbon and carbon tariffs. Environmental and Resource Economics 78, 669-708.

Branger, F., Quirion, P., 2014. Would border carbon adjustments prevent carbon leakage and heavy industry competitiveness losses? Insights from a meta-analysis of recent economic studies. Ecol. Econ. 99, 29-39.

Caliendo, L., Parro, F., 2015. Estimates of the Trade and Welfare Effects of NAFTA. The Review of Economic Studies 82, 1-44.

Clora, F., Yu, W., Corong, E., 2023. Alternative carbon border adjustment mechanisms in the European Union and international responses: Aggregate and within-coalition results. Energy Policy 174, 113454.

Copeland, B.R., Taylor, M.S., 2004. Trade, growth, and the environment. J. Econ. Lit. 42, 7-71.

Copeland, B.R., Taylor, M.S., 2017. North-South trade and the environment. International Trade and the Environment, 205-238.

Costinot, A., Rodríguez-Clare, A., 2014. Trade theory with numbers: Quantifying the consequences of globalization. Handbook of international economics, 197-261.

Dekle, R., Eaton, J., Kortum, S., 2008. Global rebalancing with gravity: Measuring the burden of adjustment. IMF Staff Papers 55, 511-540.

Dellink, R., Jamet, S., Chateau, J., Duval, R., 2014. Towards global carbon pricing: Direct and indirect linking of carbon markets. OECD Journal: Economic Studies 2013, 209-234.

Duan, Y., Ji, T., Lu, Y., Wang, S., 2021. Environmental regulations and international trade: A quantitative economic analysis of world pollution emissions. J. Public Econ. 203, 104521.

Eaton, J., Kortum, S., 2002. Technology, geography, and trade. Econometrica 70, 1741-1779.

Egger, P.H., Nigai, S., 2015. Structural gravity with dummies only: Constrained ANOVA-type estimation of gravity models. J. Int. Econ. 97, 86-99.

Espa, I., 2022. Reconciling the climate/industrial interplay of CBAMs: what role for the WTO? Am. J. Int. Law 116, 208-212.

Fouré, J., Guimbard, H., Monjon, S., 2016. Border carbon adjustment and trade retaliation: What would be the cost for the European Union? Energy Econ. 54, 349-362.

Grossman, G.M., Krueger, A.B., 1991. Environmental impacts of a North American free trade agreement. NBER working paper, 3914.

Hammoudeh, S., Lahiani, A., Nguyen, D.K., Sousa, R.M., 2015. An empirical analysis of energy cost pass-through to CO2 emission prices. Energy Econ. 49, 149-156.

Jakob, M., 2021. Why carbon leakage matters and what can be done against it. One Earth 4, 609-614.

Larch, M., Wanner, J., 2017. Carbon tariffs: An analysis of the trade, welfare, and emission effects. J. Int. Econ. 109, 195-213.

Ledley, T.S., Sundquist, E.T., Schwartz, S.E., Hall, D.K., Fellows, J.D., Killeen, T.L., 1999. Climate change and greenhouse gases. Eos, Transactions American Geophysical Union 80, 453-458.

Li, W., Liu, X., Lu, C., 2023. Analysis of China's steel response ways to EU CBAM policy based on embodied carbon intensity prediction. Energy 128812.

Lin, J., Du, M., Chen, L., Feng, K., Liu, Y., V. Martin, R., Wang, J., Ni, R., Zhao, Y., Kong, H., 2019. Carbon and health implications of trade restrictions. Nat. Commun. 10, 4947.

Magacho, G., Espagne, E., Godin, A., 2023. Impacts of the CBAM on EU trade partners: consequences for developing countries. Clim. Policy 1-17.

Mattoo, A., Subramanian, A., van der Mensbrugghe, D., He, J., 2013. Trade effects of alternative carbon border-tax schemes. Rev. World Econ. 149, 587-609.

Meinshausen, M., Smith, S.J., Calvin, K., Daniel, J.S., Kainuma, M.L., Lamarque, J., Matsumoto, K., Montzka, S.A., Raper, S.C., Riahi, K., 2011. The RCP greenhouse gas concentrations and their extensions from 1765 to 2300. Clim. Change 109, 213-241.

Milani, S., 2017. The impact of environmental policy stringency on industrial R&D conditional on pollution intensity and relocation costs. Environmental and resource economics 68, 595-620.

Mora, C., Spirandelli, D., Franklin, E.C., Lynham, J., Kantar, M.B., Miles, W., Smith, C.Z., Freel, K., Moy, J., Louis, L.V., 2018. Broad threat to humanity from cumulative climate hazards intensified by greenhouse gas emissions. Nat. Clim. Chang. 8, 1062-1071.

Newman, N.S., 2022. The European Union's CBAM: Is It an Effective Economic Climate Policy? Pepperdine Policy Review 14, 3.

Overland, I., Sabyrbekov, R., 2022. Know your opponent: Which countries might fight the European carbon border adjustment mechanism? Energy Policy 169, 113175.

Ramstein, C., Dominioni, G., Ettehad, S., Lam, L., Quant, M., Zhang, J., Mark, L., Nierop, S., Berg, T., Leuschner, P., 2019. State and trends of carbon pricing.

Ren, Y., Liu, G., Shi, L., 2023. The EU Carbon Border Adjustment Mechanism will exacerbate the economic-carbon inequality in the plastic trade. J. Environ. Manage. 332, 117302.

Ritz, R.A., 2022. Global carbon price asymmetry. J. Environ. Econ. Manage. 114, 102687.

Shapiro, J.S., Walker, R., 2018. Why is pollution from US manufacturing declining? The roles of environmental regulation, productivity, and trade. Am. Econ. Rev. 108, 3814-3854.

Wang, L., Gu, M., Li, H., 2012. Influence path and effect of climate change on geopolitical pattern. J. Geogr. Sci. 22, 1117-1130.

Ward, H., Steckel, J.C., Jakob, M., 2019. How global climate policy could affect competitiveness. Energy Econ. 84, 104549.

Wen, F., Zhao, L., He, S., Yang, G., 2020. Asymmetric relationship between carbon emission trading market and stock market: evidences from China. Energy Econ. 91, 104850.

Zheng, Y., Zhou, M., Wen, F., 2021. Asymmetric effects of oil shocks on carbon allowance price: Evidence from China. Energy Econ. 97, 105183.

Zhong, J., Pei, J., 2022. Beggar thy neighbor? On the competitiveness and welfare impacts of the EU's proposed carbon border adjustment mechanism. Energy Policy 162, 112802.

Supplementary materials

Appendix A

1. The derivation of Eq. (12) is given by

Following Eaton and Kortum (2002), we assume that the efficiency of a producer is subject to Fréchet distribution. That is, $F_i(z) = \Pr[Z_i < z] = \exp(-\lambda_i^j z^{-\theta j})$。Accordingly, we have the distribution of prices as

$$\begin{aligned} G_{ni}^j(p) &= \Pr[p_{ni}^j < p] = \Pr\left[\frac{\psi_i^j \kappa_{ni}^j}{z_i^j(\omega^j)^{1-\beta_n^j}} < p\right] \\ &= \Pr\left[\frac{\psi_i^j \kappa_{ni}^j}{p} < z_i^j(\omega^j)^{1-\beta_n^j}\right] \\ &= 1-\exp(-\lambda_i^j(\kappa_{ni}^j\psi_i^j)^{-\theta^j} p^{\theta^j}) \end{aligned} \tag{A.1}$$

The actual prices in country n, denoted as P_n^j, conform to the subsequent distribution:

$$\begin{aligned} G_n^j(p) &= \Pr[p_n^j < p] = 1-\prod_{i=1}^N \Pr[p_{ni}^j \geq \mathrm{p}] \\ &= 1-\prod_{i=1}^N 1-G_{ni}^j(p) \\ &= 1-\mathrm{e}^{-p^{\theta^j}\Phi_n^j} \end{aligned} \tag{A.2}$$

where $\Phi_n^j = \sum_{i=1}^N \lambda_i^j \left(\kappa_{ni}^j \psi_i^j\right)^{-\theta j}$. According to Eq. (9), the price of the sectoral composite goods in sector j in country n is

$$\begin{aligned} P_n^j &= \left(\int_0^\infty p^{1-\sigma^j} dG_n^i(p)\right)^{\frac{1}{1-\sigma^j}} \\ &= \theta^j \Phi_n^j \int_0^\infty p^{\theta^j-\delta^j} e^{-p^{\theta^j}\Phi_n^j} dp \\ &= (\Phi_n^j)^{-\frac{1}{\theta^j}} \int_0^\infty (p^{\theta^j}\Phi_n^j)^{\frac{\theta^j+1-\delta^j}{\theta^j}} e^{-p^{\theta^j}\Phi_n^j} d(p^{\theta^j}\Phi_n^j) \\ &= \Gamma\left(\frac{\theta^j+1-\delta^j}{\theta^j}\right)(\Phi_n^j)^{-\frac{1}{\theta^j}} \end{aligned} \tag{A.3}$$

reorganizing Eq. (A.3), we can rewrite P_n^j as Eq. (13)

$$P_n^j = \delta_3^j \left[\sum_{i=1}^N \lambda_i^j (\kappa_{ni}^j \psi_i^j)^{-\theta^j}\right]^{-\frac{1}{\theta^j}} \tag{A.4}$$

2. The derivation of Eq. (15) is given by

$$
\begin{aligned}
\pi_{ni}^{j} &= \Pr[p_{ni}^{j} \le \min\{p_{ns}^{j}, s \ne i\}] \\
&= \int_0^{\infty} \Pr[\min\{p_{ns}^{j} \ge p, s \ne i\}] dG_{ni}^{j}(p) \\
&= \int_0^{\infty} \prod_{s \ne i} \Pr[\min\{p_{ns}^{j} \ge p\} dG_{ni}^{j}(p) \\
&= \int_0^{\infty} \prod_{s \ne i} 1 - G_{ns}^{j}(p) dG_{ni}^{j}(p)
\end{aligned} \tag{A.5}
$$

Combine equation (A.5) with Fréchet distribution. We can rearrange the above equation to reach

$$
\begin{aligned}
\pi_{ni}^{j} &= \int_0^{\infty} \prod_{s \ne i} e^{-[\lambda_s^j (\kappa_{ns}^j \psi_s^j)^{-\theta^j}] p^{\theta^j}} e^{-[\lambda_i^j (\kappa_{ni}^j \psi_i^j)^{-\theta^j}] p^{\theta^j}} \theta^j [\lambda_i^j (\kappa_{ni}^j \psi_i^j)^{-\theta^j}] p^{\theta^j - 1} dp \\
&= \lambda_i^j (\kappa_{ni}^j \psi_i^j)^{-\theta^j} \int_0^{\infty} e^{-p^{\theta^j} \Phi_n^j} dp^{\theta^j} \\
&= \frac{\lambda_i^j (\kappa_{ni}^j \psi_i^j)^{-\theta^j}}{\Phi_n^j}
\end{aligned} \tag{A.6}
$$

3. Model solving

The model-solving process employed in this paper primarily follows the stepwise solution approach proposed by Caliendo and Parro (2015), incorporating carbon tax revenues. Initially, we make an initial guess for the wage vector, denoted as $\hat{\boldsymbol{w}} = (\hat{w}_1, \dots, \hat{w}_N)$, and proceed to solve for $\hat{p}_n^j(\hat{w})$, $\hat{\psi}_n^j(\hat{w})$, and $\pi_{ni}^{j\prime}(\hat{w})$ at equilibrium using Eqs. (19), (20), and (21). Subsequently, these values are substituted into Eq. (A.7) to derive the total expenditure share $X_{ni}^{j\prime}(\hat{w})$ in the counterfactual scenario.

$$
\begin{aligned}
X_{\mathrm{n}}^{j'} = {} & \sum_{k=1}^{J} (1 - \beta_n^k) \gamma_n^{j,k} \sum_{i=1}^{N} \frac{\pi_{in}^{k'}(\hat{w})}{1 + \tau_{in}^{k'}} X_i^{k'} \\
& + \alpha_n^j (\hat{w}_n w_n L_n + (1 - \beta_n^k) \sum_{j=1}^{J} \sum_{i=1}^{N} \tau_{in}^{j'} M_{ni}^{j'}(\hat{w}) \\
& + \sum_{j=1}^{J} \beta_n^j \sum_{i=1}^{N} \frac{\pi_{in}^{j'}(\hat{w})}{1 + \tau_{in}^{k'}} X_i^{j'} + D_n^{'})
\end{aligned} \tag{A.7}
$$

Eq. (A.7) can be further written in its matrix form

$$
\Omega(\hat{w}) X = \Delta(\hat{w}) \tag{A.8}
$$

Where X is the vector of expenditures for each sector and country, and $\Delta(\hat{w})$ is the consumption matrix at the country-industry level

$$
\mathbf{X}' = \begin{pmatrix} X_1^{1'} \\ \vdots \\ X_1^{J'} \\ \vdots \\ X_n^{1'} \\ \vdots \\ X_n^{J'} \\ \vdots \\ X_N^{1'} \\ \vdots \\ X_N^{J'} \end{pmatrix}_{JN\times 1} ; \quad \Delta(\mathbf{w}) = \begin{pmatrix} \alpha_1^1\left(\hat{w}_1 w_1 L_1 + D_1^{'}\right) \\ \vdots \\ \alpha_1^J\left(\hat{w}_1 w_1 L_1 + D_1^{'}\right) \\ \vdots \\ \alpha_n^1\left(\hat{w}_n w_n L_n + D_n^{'}\right) \\ \vdots \\ \alpha_n^J\left(\hat{w}_n w_n L_n + D_n^{'}\right) \\ \vdots \\ \alpha_N^1\left(\hat{w}_N w_N L_N + D_N^{'}\right) \\ \vdots \\ \alpha_N^J\left(\hat{w}_N w_N L_N + D_N^{'}\right) \end{pmatrix}_{JN\times 1} \tag{A.9}
$$

$\Omega(\widehat{w})$ consists of four parts: I, $F(\widehat{w})$, $T(\widehat{w})$ and $\widetilde{H}(\widehat{w})$. First, I is an identity matrix. Second, the matrix $F(\widehat{w})$ is defined as:

$$
F(\mathbf{w}) = \begin{pmatrix} A_1 \otimes \tilde{F}_1^{'}(\mathbf{w}) & 0_{J\times J} & \cdots & 0_{J\times J} & 0_{J\times J} \\ 0_{J\times J} & A_2 \otimes \tilde{F}_2^{'}(\mathbf{w}) & \cdots & \vdots & \vdots \\ 0_{J\times J} & 0_{J\times J} & \ddots & 0_{J\times J} & 0_{J\times J} \\ \vdots & \vdots & \cdots & A_{N-1} \otimes \tilde{F}_{N-1}^{'}(\mathbf{w}) & 0_{J\times J} \\ 0_{J\times J} & 0_{J\times J} & \cdots & 0_{J\times J} & A_N \otimes \tilde{F}_N^{'}(\mathbf{w}) \end{pmatrix}_{JN\times JN} \tag{A.10}
$$

Where A_n is constructed by demand elasticities and pollution elasticities

$$
A_n = \begin{pmatrix} \alpha_n^1 \\ \vdots \\ \alpha_n^J \end{pmatrix}_{J\times 1}, \tilde{F}_n^{'}(\mathbf{w}) = \left(\left(1 - F_n^{1'}(\mathbf{w})\right)\cdots\left(1 - F_n^{J'}(\mathbf{w})\right)\right)_{1\times J'} \tag{A.11}
$$

Where $F_n^{j'}(\mathbf{w}) = \sum_{i=1}^{N} \frac{\pi_{ni}^{j'}(\mathbf{w})}{1+\tau_{ni}^{j}}$.

Second, the square matrix $\widetilde{H}(\widehat{w})$ is defined as

$$
\tilde{H}(\mathbf{w}) = \begin{pmatrix} (1-\beta_1^1)\gamma_1^{1,1}\tilde{\pi}_{1,1}^{1'}(\mathbf{w}) & \cdots & (1-\beta_1^J)\gamma_1^{1,J}\tilde{\pi}_{1,1}^{J'}(\mathbf{w}) & \cdots & (1-\beta_1^1)\gamma_1^{1,1}\tilde{\pi}_{N,1}^{1,}(\mathbf{w}) & \cdots & (1-\beta_1^J)\gamma_1^{1,J}\tilde{\pi}_{N,1}^{J'}(\mathbf{w}) \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ (1-\beta_1^1)\gamma_1^{J,1}\tilde{\pi}_{1,1}^{1'}(\mathbf{w}) & \cdots & (1-\beta_1^J)\gamma_1^{J,J}\tilde{\pi}_{1,1}^{J'}(\mathbf{w}) & \cdots & (1-\beta_1^1)\gamma_1^{J,1}\tilde{\pi}_{N,1}^{1'}(\mathbf{w}) & \cdots & (1-\beta_1^J)\gamma_1^{J,J}\tilde{\pi}_{N,1}^{J'}(\mathbf{w}) \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ (1-\beta_N^1)\gamma_N^{1,1}\tilde{\pi}_{1,N}^{1'}\widehat{(\mathbf{w})} & \cdots & (1-\beta_N^J)\gamma_N^{1,J}\tilde{\pi}_{1,N}^{J'}\widehat{(\mathbf{w})} & \cdots & (1-\beta_N^1)\gamma_N^{1,1}\tilde{\pi}_{N,N}^{1'}\widehat{(\mathbf{w})} & \cdots & (1-\beta_N^J)\gamma_N^{1,J}\tilde{\pi}_{N,N}^{J'}\widehat{(\mathbf{w})} \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ (1-\beta_N^1)\gamma_N^{J,1}\tilde{\pi}_{1,N}^{1'}\widehat{(\mathbf{w})} & \cdots & (1-\beta_N^J)\gamma_N^{J,J}\tilde{\pi}_{1,N}^{J'}\widehat{(\mathbf{w})} & \cdots & (1-\beta_N^1)\gamma_N^{J,1}\tilde{\pi}_{N,N}^{1'}\widehat{(\mathbf{w})} & \cdots & (1-\beta_N^J)\gamma_N^{J,J}\tilde{\pi}_{N,N}^{J'}\widehat{(\mathbf{w})} \end{pmatrix}_{JN\times JN}
$$

(A.12)

Third, the pollution tax revenue matrix is constructed as

$$T(\mathbf{w}) = \begin{pmatrix} \alpha_1^1\beta_1^1\pi_{1,1}^1 & \cdots & \alpha_1^1\beta_1^J\pi_{1,1}^J & \cdots & \alpha_1^1\beta_1^1\pi_{N,1}^1 & \cdots & \alpha_1^1\beta_1^J\pi_{N,1}^J \\ \vdots & \ddots & \vdots & \ddots & \vdots & \ddots & \vdots \\ \alpha_1^J\beta_1^1\pi_{1,1}^1 & \cdots & \alpha_1^J\beta_1^J\pi_{1,1}^J & \cdots & \alpha_1^J\beta_1^1\pi_{N,1}^1 & \cdots & \beta_1^J\beta_1^J\pi_{N,1}^J \\ \vdots & \ddots & \vdots & \ddots & \vdots & \ddots & \vdots \\ \alpha_n^1\beta_n^1\pi_{1,n}^1 & \cdots & \alpha_n^1\beta_n^J\pi_{1,n}^J & \cdots & \alpha_n^1\beta_n^1\pi_{N,n}^1 & \cdots & \alpha_n^1\beta_n^J\pi_{N,n}^J \\ \vdots & \ddots & \vdots & \ddots & \vdots & \ddots & \vdots \\ \alpha_n^J\beta_n^1\pi_{1,n}^1 & \cdots & \alpha_n^J\beta_n^J\pi_{1,n}^J & \cdots & \alpha_n^J\beta_n^1\pi_{N,n}^1 & \cdots & \alpha_n^J\beta_n^J\pi_{N,n}^J \\ \vdots & \ddots & \vdots & \ddots & \vdots & \ddots & \vdots \\ \alpha_N^1\beta_N^1\pi_{1,N}^1 & \cdots & \alpha_N^1\beta_N^J\pi_{1,N}^J & \cdots & \alpha_N^1\beta_N^1\pi_{N,N}^1 & \cdots & \alpha_N^1\beta_N^J\pi_{N,N}^J \\ \vdots & \ddots & \vdots & \ddots & \vdots & \ddots & \vdots \\ \alpha_N^J\beta_N^1\pi_{1,N}^1 & \cdots & \alpha_N^J\beta_N^J\pi_{1,N}^J & \cdots & \alpha_N^J\beta_N^1\pi_{N,N}^1 & \cdots & \alpha_N^J\beta_N^J\pi_{N,N}^J \end{pmatrix}_{JN\times JN} \tag{A.13}$$

Finally， we use $\Omega(\widehat{\boldsymbol{w}}) = I - \mathrm{F}(\widehat{\boldsymbol{w}}) - T(\widehat{\boldsymbol{w}}) - \widetilde{H}(\widehat{\boldsymbol{w}})$ to solve the counterfactual expenditure matrix X'

$$X' = \Omega(\hat{w})^{-1}\Delta(\hat{w}) \tag{A.14}$$

Appendix B

Table B.1 Calibrated pollution elasticities

Country	Pollution elasticities	Country	Pollution elasticities
Australia	0.0108	India	0.0141
Austria	0.0090	Ireland	0.0098
Belgium	0.0094	Italy	0.0105
Bulgaria	0.0141	Japan	0.0104
Brazil	0.0108	Korea	0.0123
Canada	0.0113	Lithuania	0.0116
Switzerland	0.0074	Luxembourg	0.0085
China	0.0135	Latvia	0.0109
Cyprus	0.0115	Mexico	0.0126
Czech	0.0115	Malta	0.0118
Germany	0.0100	Norway	0.0093
Denmark	0.0099	Poland	0.0124
Spain	0.0108	Portugal	0.0105
Estonia	0.0123	Romania	0.0126
Finland	0.0098	Russia	0.0143
France	0.0095	Slovakia	0.0112
United Kingdom	0.0099	Slovenia	0.0109
Greece	0.0125	Sweden	0.0088
Croatia	0.0117	Türkiye	0.0127
Hungary	0.0113	United States	0.0110
Indonesia	0.0132	ROW	0.0129

Table B.2 Trade elasticity

Name	WIOD code	Industry	Trade elasticity
Agriculture	A01	1	0.621
Forestry	A02	2	1.455
Fishing	A03	3	0.621
Mining	B	4	14.073
Food and Tobacco	C10-C12	5	0.313
Textile and Leather	C13-C15	6	3.299
Wood	C16	7	2.662
Paper	C17	8	15.286
Print	C18	9	5.367
Petroleum	C19	10	0.621
Chemical	C20	11	0.621
Pharmaceutical	C21	12	0.621
Rubber and Plastic	C22	13	5.367
Non-metallic mineral	C23	14	3.591
Basic metals	C24	15	6.622
Metal product	C25	16	3.854
Electronic and Optical	C26	17	0.288
Electrical	C27	18	0.621
Machinery n.e.c.	C28	19	0.621
Motor vehicle	C29	20	0.621
Other transport equipment	C30	21	3.666
Other manufacturing	C31_C32	22	0.985
Non-tradable industries	C33-U	23-56	2.458

Table B.3 Impact of Carbon Tariffs on the Share of EU Tradable Sector Exports

Industry	Share change	Industry	Share change
1	0.018%	12	-0.132%
2	0.011%	13	1.171%
3	0.007%	14	1.537%
4	1.441%	15	3.794%
5	-0.023%	16	-0.423%
6	-0.524%	17	-0.071%
7	-0.107%	18	-0.131%
8	-0.084%	19	-0.103%
9	-0.202%	20	-0.108%
10	0.234%	21	-0.651%
11	0.392%	22	0.6%