Evaluating Alternative Designs for Carbon Border Adjustment Mechanisms

Alireza Marahel*

Indiana University

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Abstract

This paper evaluates the Carbon Border Adjustment Mechanism (CBAM) as a potential tool to mitigate carbon leakage, with its design varying based on the inclusion of export subsidies and discrimination across trading partners. To this end, I adopt a quantitative multi-country, multi-industry trade model with climate externalities and abatement. I provide a novel theoretical decomposition of the welfare effects associated with carbon pricing in open economies, underscoring the incidence of the home country's carbon tax on foreign residents as a vital welfare channel. The welfare decomposition reveals ambiguous welfare effects when export subsidies are incorporated in the CBAM, as they mitigate leakage but reduce the incidence of home's carbon tax on foreign residents. I then map the model to data to evaluate these trade-offs quantitatively for the European Union. I find that non-discriminatory EU border adjustments lead to a Pareto improvement only if they exclude export subsidies, resulting in a 36 million tonnes reduction in carbon leakage. On the other hand, discriminatory EU border adjustments are Pareto improving if they feature export subsidies in addition to import tariffs, yielding a 130 million tonnes reduction in leakage. These results provide a possible justification for the current design of the EU CBAM.

*Department of Economics, Indiana University, Bloomington, IN, USA: amarahel@iu.edu.
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1 Introduction

Climate change poses an existential threat that demands urgent collective action among nations. However, international climate agreements, such as the 1997 Kyoto Protocol and the 2015 Paris Climate Accord, have thus far proved inadequate, with global greenhouse gas emissions continuing their upward trajectory. This failure has prompted some countries to turn to unilateral carbon policy measures as an alternative approach to emissions mitigation. As shown in Figure 1, carbon pricing, via carbon taxes, has already emerged as a prominent unilateral tool to internalize the environmental costs associated with carbon emissions[1]. However, unilateral carbon pricing measures also create unintended consequences. Notably, they risk causing "carbon leakage", which undermines the efficacy of unilateral climate policies by displacing rather than reducing emissions as production shifts to jurisdictions with lower carbon prices. Simultaneously, carbon pricing inadvertently disadvantages the domestic industries of implementing countries in international trade vis-à-vis competitors in nations without comparable climate regulations.

Recognizing these challenges, various remedies have been proposed, one of the most prominent being the Carbon Border Adjustment Mechanism (CBAM). This mechanism is not a mere theoretical construct; it has been implemented, most notably by the European Union (EU) in 2023. The primary goal of CBAM is to equalize the cost of carbon emissions across imports and domestically produced goods, thereby leveling the playing field and addressing leakage. Yet, even within the realm of CBAMs, the design choices and variations are manifold. The menu of options ranges from a non-discriminatory import tariff (as exemplified by the EU's CBAM) to more complex structures that employ either discriminatory or non-discriminatory import tariffs in conjunction with export subsidies[2]. Each of these variations offers distinct advantages and challenges, necessitating a deeper question central to both economic modeling and policy-making: which option is the most effective not just in mitigating carbon leakage but also in minimizing the associated economic costs for the implementing country?

To answer this question, I adopt an analytical framework to quantitatively assess the global welfare effects of alternative CBAM designs. To this end, I apply a special case of the Farrokhi and Lashkaripour (2021) model, combining a multi-sector Armington model with an extension of the Copeland and Taylor (2004) abatement model. Introducing carbon externalities and abatement choices into a quantitative general equilibrium model enables a comparative analysis of border tax trade-offs across different countries and industries, relative to the status quo in the absence of border adjustments.

To lay the groundwork for the quantitative analysis, I provide a novel theoretical decomposition of the welfare effects associated with carbon pricing in open economies[3]. The decomposition dissects the impacts of unilateral carbon taxes into four components: (1) domestic emission reduction, (2) carbon leakage, (3) tax incidence on foreign residents, and (4) factoral

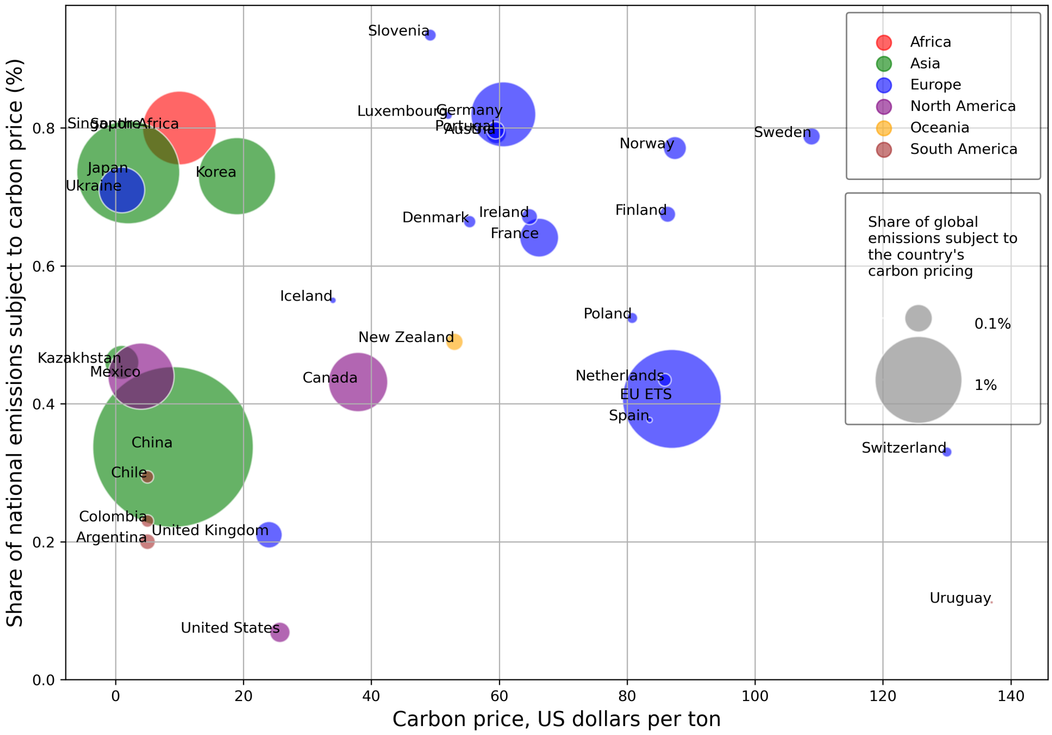
[1] This figure is constructed based on the publicly available data provided by Clausing and Wolfram (2023), which in turn utilized the World Bank Carbon Pricing Dashboard for its creation.

[2] Non-discriminatory policies apply uniformly to all trading partners, while discriminatory policies target specific countries or regions.

[3] The channels framework enables non-parametric analysis that holds even without the functional form assumptions used to quantify the model.

terms of trade. While the first two channels are well established in the literature, the latter two are less explored. In particular, the foreign tax incidence channel is quantitatively critical, representing a positive transfer to the domestic economy, as foreign consumers indirectly subsidize the home country's carbon tax by absorbing higher export prices.

Figure 1: *Global Overview of Carbon Pricing and Emission Coverage By Continent*



Source: Collected from Clausing and Wolfram (2023).
Notes: The figure illustrates greenhouse gas emissions priced per ton of CO2-equivalent. The size of each bubble represents the share of global emissions subject to the respective country's carbon pricing policy. Emissions under the EU Emissions Trading System (ETS) are allocated evenly among member countries, based on the assumption of uniform coverage of power and industrial emissions. The EU ETS is also represented collectively. It should be noted that this dataset does not account for factors like fossil fuel subsidies or specific fossil fuel taxes.

The decomposition proposed in this paper reveals that incorporating export subsidies in the CBAM leads to ambiguous welfare effects. On the one hand, a CBAM composed of both import tariffs and export subsidies can be more effective at mitigating carbon leakage and improving the terms of trade for the home country. On the other hand, leaning exclusively on import tariffs could be preferred, as the introduction of export subsidies reduces the incidence of the home country's carbon tax on foreign consumers. The question of whether to include export subsidies in the CBAM or not is ultimately an empirical one.

For the quantitative analysis, I map the model to data to evaluate the consequences of the European Union's (EU) unilateral carbon tax policy under four border adjustment configurations. Namely, non-discriminatory and discriminatory CBAMs, both with and without export subsidy rebates that neutralize the carbon tax burden on exporters. The model is calibrated using data on bilateral trade flows, sectoral carbon intensity, applied tariffs, and environmental taxes to characterize the baseline policy environment. The empirical findings suggest that the positive welfare effects arising from the incidence of the carbon tax on foreign consumers outweigh the welfare gained from further leakage mitigation and improved factoral terms of trade, which are associated with incorporating export subsidies.

Crucially, the model identifies two distinct Pareto-improving CBAM configurations for the EU–that is configurations that improve both the EU's and the rest of the world's welfare. This finding diverges from the conventional notion that carbon border adjustments necessarily impose harm abroad. Specifically, I find that non-discriminatory EU border adjustments lead to Pareto-improving outcomes only if they exclude export subsidies. The addition of import tariffs effectively reduces carbon leakage by 36 million tonnes, yielding a net global CO_2 emission reduction of 405 million tonnes. Moreover, these import tariffs, without eliminating the tax incidence on foreign residents, marginally improve the EU's factoral terms of trade, and consequently diminish the EU's consumption loss to 1.75 trillion US dollars. The net effect of the consumption loss and global emission reduction results in a marginal welfare improvement of 0.06% for the EU. Simultaneously, the welfare gain from global CO_2 emission reduction exceeds the consumption loss induced by the tax incidence on the rest of the world, thereby leading to a 0.33% welfare increase outside the EU. The welfare improvement, both within and beyond EU borders, results in 0.25% increase in global welfare. This choice of CBAM is particularly noteworthy, as it aligns with the design of the EU's CBAM, which, as of October 2023, has entered its transitional implementation phase.

The second Pareto-improving policy supplements the carbon tax with discriminatory import tariffs and export subsidies. This discriminatory approach allows the EU to impose higher import tariffs on carbon-intensive origins, thereby reducing carbon leakage more effectively compared to its non-discriminatory counterpart. Under this policy alternative, the leakage decreases by 130 million tonnes, leading to a global emission reduction of 490 million tonnes. Export rebates, while improving leakage mitigation, also offset the pass-through of carbon taxes to foreign consumers, leading to a less desirable welfare outcome for the EU. However, incorporating export subsidies into this CBAM framework is necessary to ensure a net welfare improvement for the rest of the world, thereby providing a more defensible justification for the policy's implementation. From both the EU's and the global perspective, the second Pareto-improving policy option emerges as the more favorable alternative, given that it yields a more substantial positive welfare effect compared to the first Pareto-improving policy. More specifically, the welfare gains under the second policy alternative are 1.18% for the EU and 0.16% for the rest of the world, resulting in a 0.44% global welfare improvement. The implementation of the second Pareto-improving policy, despite its unambiguous welfare benefits for both the EU and the global community, however, is likely to provoke political tensions and could be deemed incompatible with the existing WTO clauses on import tariffs and export subsidies. Such legal and diplomatic complexities provide support for the EU's decision to adopt a policy of non-discriminatory import tariffs as the CBAM to accompany its unilateral carbon tax policy.

Related Literature. The discourse on the application and efficacy of Carbon Border Adjustments Mechanisms (CBAMs) as a countermeasure to carbon leakage has been a recurrent theme in the field of climate policy and international trade[4]. Many studies have evaluated the CBAMs through the lens of optimal unilateral carbon tax policies (see Farrokhi and Lashkaripour (2021); Kortum and Weisbach (2021); Weisbach et al. (2023)). The pioneering work of Markusen (1975) posited that unilateral carbon pricing could indeed serve as an optimal strategy even in the presence of carbon leakage, employing a simplistic two-goods international trade model. Building upon this, Balistreri et al. (2018) incorporated CBAMs into the Markusen model to derive conditions for optimal carbon tariffs. Other seminal works (Copeland (1996); Hoel (1996)) unilaterally optimal import tariffs include a tax on the carbon content of importing goods. Farrokhi and Lashkaripour (2021) extend these studies to guide general equilibrium quantitative policy analysis and characterize the optimal border policy. This paper complements these analysis by exploring adjustments beyond import tariffs, like export subsidies, and empirically quantifying trade-offs, scrutinizing a spectrum of anti-leakage strategies, thereby offering a more comprehensive policy mix.

Some recent studies (Cosbey et al. (2019), Ambec (2022) and Böhringer et al. (2022)) have discussed that while carbon border adjustment mechanisms have been proposed as a theoretical solution to address carbon leakage, their practical implementation raises concerns and challenges. To address these issues, many studies have investigated the impact of unilateral carbon pricing, CBAM and other anti-leakage policies using numerical analysis with computable general equilibrium models (e.g. Branger and Quirion (2014), Balistreri, Böhringer, and Rutherford (2018), Balistreri, Kaffine, and Yonezawa (2019), Böhringer, Schneider, and Asane-Otoo (2021), Clora and Yu (2022), Magacho, Espagne, and Godin (2023)). They provide broad quantitative estimations but do not analytically characterize the economic outcomes and mitigation policies through different welfare channels the way this paper does.

Our research closely aligns with Ambec et al. (2023), which delves into the effects of CBAMs and the combination of CBAM with export subsidy policy instruments targeting carbon leakage mitigation. While they contend that the EU should adopt some form of export rebate to most effectively prevent leakage, our findings suggest that such a course is not optimal for the EU. Drawing from the methodology of Farrokhi and Lashkaripour (2021)–which integrates environmental externalities by intergrating Copeland and Taylor (2004) abatement design into advanced quantitative equilibrium models–we establish a framework to distinguish the various channels through which CBAMs and export subsidies impact both the welfare of the EU and the global welfare outside the EU. Our welfare analysis underscores the welfare improvements derived from the tax incidence that carbon tax policies place on foreign economies. Overlooking this dynamic can lead to obscure policy formulations and unforeseen welfare implications. Moreover, I explore the realm of discriminatory border adjustments, an area I believe has been largely uncharted in the existing literature.

The rest of the paper proceeds as follows: I first present the economic environment setup, including equilibrium model to investigate the welfare decomposition of carbon policies and economic effects of the CBAM policies in section 2. Section 3 describes the data and calibrations of parametric version of the model. In section 4, I characterize the policy counterfactuals for

[4]In some contexts, the mechanism is also referred to as Border Carbon Adjustments (BCA), which highlights the focus on cross-border carbon-related adjustments in trade models.

different policy scenarios. In section 5, I quantify the efficacy of of different CBAM structures. Section 6 concludes.

2 Economic Environment

This analysis adopts on a special case of the model proposed by Farrokhi and Lashkaripour (2021). I combine a multi-sector Armington model with an extension of the Copeland and Taylor (2004) abatement model. The global economy consists of multiple countries indexed by $i, j, n \in \mathbb{C}$. Each country i is endowed with labor L_i. Labor is freely mobile across industries within a country but cannot cross national borders. Workers supply one unit of labor inelastically. There are multiple industries indexed by $k, g \in \mathbb{K}$. Triplet (ji, k) indexes variable corresponding to *origin j—destination i–industry k*.

2.1 Demand

In this model, consumers in each country i consume a bundle of industry-level composite goods. Let $\mathbf{Q}_{ni} = \{Q_{ni,k}\}_{k\in\mathbb{K}}$ denote the quantities of these composite goods consumed by country i and originating from country n. The representative consumer in country i maximizes a non-parametric utility function, by choosing the vector of quantities, $\{\mathbf{Q}_{ni}\}_{n\in\mathbb{C}}$, subject to the budget constraint. In particular,

$$\max \; U_i\left(\mathbf{Q}_{1i}, ..., \mathbf{Q}_{Ni}\right) \qquad s.t \qquad Y_i = \sum_n \sum_k \tilde{P}_{ni,k} Q_{ni,k},$$

where Y_i denotes national expendable income, and $\tilde{P}_{ni,k}$ is the consumer price index of composite variety ni, k. For the purposes of quantification, we employ a Constant Elasticity of Substitution (CES) utility function, given by

$$U_i\left(\mathbf{Q}_{1i}, \ldots, \mathbf{Q}_{Ni}\right) = \prod_k \left[\sum_n Q_{ni,k}^{\frac{\sigma_k - 1}{\sigma_k}}\right]^{\frac{\sigma_k}{\sigma_k - 1}\beta_{i,k}},$$

which aggregates utility across different industries and origins. The parameter σ_k is the constant elasticity of substitution between national-level variaties in industry k, and $\beta_{i,k}$ dictates the constant share of expenditure on industry k goods. Intuitively, the within-industry elasticity of substitution σ_k indicates how easily goods from different origins within the same industry can be substituted for one another. A high value of σ_k implies that goods within the industry are close substitutes, while a low value indicates a high degree of product differentiation. The constant expenditure share $\beta_{i,k}$ implies that income and substitution effects cancel each other out in our model. The product differentiation by country of origin is often referred to as the Armington assumption, proposed by Armington (1969).

Under this parametrization, optimal demand quantities are given by

$$Q_{ni,k} = \left(\frac{\tilde{P}_{ni,k}}{\tilde{P}_{i,k}}\right)^{1-\sigma_k} \beta_{i,k} Y_i,$$

where $\tilde{P}_{i,k}$ is the CES consumer price index for industry k goods in country i, defined as

$$\tilde{P}_{n,k} = \left[\sum_{j=1}^{N} \left(\tilde{P}_{jn,k} \right)^{1-\sigma_k} \right]^{\frac{1}{1-\sigma_k}},$$

and $\lambda_{jn,k}$ denotes the within-industry expenditure share of country n on variety jn, k. Using the conumer's price index $\tilde{P}_{n,k}$, I formally define the within-industry expenditure share of origin j—destination n–industry k as

$$\lambda_{jn,k} = \frac{\tilde{P}_{jn,k} Q_{jn,k}}{\sum_i \tilde{P}_{ji,k} Q_{ji,k}},$$

where $Q_{jn,k}$ denotes the aggregate quantities of variety jn, k. Furthermore, the expenditure share of country n on industry k is denoted by

$$\beta_{n,k} = \frac{\tilde{P}_{jn,k} Q_{jn,k}}{\sum_k \sum_i \tilde{P}_{ji,k} Q_{ji,k}},$$

where the expression in the denominator represents the national income.

2.2 Supply

Within the supply-side framework of my model, since each unit of production (i.e., origin–industry pair) can be treated as one representative firm, I can simply focus on industry-level aggregates hereafter. This simplification allows us to focus on the macroeconomic dynamics of trade and production without the complexities that come from firm-level differences. These firms operate in a market characterized by perfect competition and free entry. The production functions for firms incorporate an environmental dimension, necessitating an optimal mix of labor and carbon inputs for production. More specifically, the function for the gross production quantity of variety ni, k is given by

$$Q_{ni,k} = \frac{\bar{\varphi}_{n,k}}{d_{ni,k}} \left[(1 - \kappa_{n,k})(l_{ni,k})^{\frac{\varsigma-1}{\varsigma}} + \kappa_{n,k}(z_{ni,k})^{\frac{\varsigma-1}{\varsigma}} \right]^{\frac{\varsigma}{\varsigma-1}}.$$

In this equation, $d_{ni,k}$ captures the iceberg trade costs, reducing the effective amount of goods that reach the destination country i from the origin n with $d_{ni,k} > 1 \ \ \forall n \neq i$ and $d_{nn,k} = 1$. $\bar{\varphi}_{n,k} > 0$ is the exogenously determined total factor productivity in origin n and industry k, affectubg the productive capacity of the firms. The terms $l_{ni,k}$ and $z_{ni,k}$ represent the labor and carbon inputs, respectively, used in production. The parameter $\kappa_{n,k}$ is the carbon intensity parameter, framed within $[0, 1]$, where higher values are indicative of a more carbon-intensive production mechanism. Lastly, ς is the elasticity of substitution between labor and carbon, influencing how easily firms can switch between these two inputs.

The functional form of the production function embodies a range of special cases. For $\varsigma \to 0$, the function degenerates into a Leontief function, implying rigid complementarity between labor and carbon. As $\varsigma \to 1$, the production function transforms into a Cobb-Douglas function, and for $\varsigma \to \infty$, it becomes linear, suggesting that labor and carbon are perfect substitutes.

Firms would then display gross substitutability between labor and carbon for $\varsigma \in (1, \infty)$, and gross complementarity for $\varsigma \in (0, 1)$.

The optimal input choices for labor $l_{ni,k}$ and carbon $z_{ni,k}$ in the model are shaped by their respective prices. For labor, the determining price is the national wage rate w_i in the country of origin. For carbon, the key price variable is the industry-specific carbon tax $\tau_{i,k}$. In the interest of elucidating how input prices inform the production function, we can make slight alterations to its representation. We assume that firms strategically allocate labor between actual production and abatement activities. Under this framework, the production function for a representative firm can be rewritten as

$$d_{ni,k} Q_{ni,k} = \bar{\varphi}_{n,k}(1 - a_{n,k}) l_{ni,k},$$

where $a_{n,k}$ represents the fraction of labor input devoted to abatement. Given a choice of abatement $a_{i,k}$, marginal cost of production can be expressed as

$$c_{ni,k} = d_{ni,k} \left[(1 - \kappa_{n,k})^{\varsigma} w_n + (\kappa_{n,k})^{\varsigma} \tau_{n,k}\right]^{\frac{1}{1-\varsigma}}$$

We can now clearly see the tradeoff that firms face in response to a higher carbon tax: A higher level of abatement means less carbon emission (and so less carbon taxes paid to the government) whereas it raises the marginal cost of production. It is immediate from these definitions that the carbon emission per unit of output corresponding to variety ni, k can be expressed as

$$\frac{z_{ni,k}}{d_{ni,k} q_{ni,k}} = \alpha_{n,k} \frac{c_{ni,k}}{\tau_{n,k}} = \left(\frac{\alpha_{n,k}}{\tau_{n,k}}\right)^{\frac{\varsigma}{\varsigma-1}}.$$

The literature often refers to $\alpha_{n,k} > 0$ as the "emission elasticity" which varies across industries $k \in \mathbb{K}$. But the simpler interpretation is that $\alpha_{i,k}$ is the input cost share of carbon which can be written as $\alpha_{n,k} = (\bar{\kappa}_{n,k})^{\varsigma} \left(\tau_{n,k}/c_{n,k}\right)^{1-\varsigma}$. Faced by the tradeoff between carbon tax and abatement level, the optimal choice of abatement is given by

$$(1 - a_{n,k}) = (1 - \kappa_{n,k})^{-\varsigma} \left[(1 - \kappa_{n,k})^{\varsigma} + (\kappa_{n,k})^{\varsigma} \left(\frac{\tau_{n,k}}{w_n}\right)^{1-\varsigma}\right]^{\frac{\varsigma}{\varsigma-1}}. \tag{1}$$

This equation provides a comprehensive understanding of how firms manage the trade-off between labor and carbon inputs in the face of varying input prices, thereby influencing their abatement strategies. The ratio of carbon tax-to-wage inversely influences the abatement choice. That means an increase in this ratio essentially elevates the relative cost of carbon emissions compared to labor and as a result, firms will naturally steer towards increasing their abatement activities to mitigate this cost. ς, which serves as the elasticity of substitution between carbon and labor inputs, can profoundly influences the effect of this ratio on firm's abatement choices. When $\varsigma < 1$, it suggests that labor and carbon are close substitutes in the production process. Under such conditions, even a modest increase in the carbon tax $\tau_{n,k}$ would lead firms to significantly reallocate labor from production to abatement activities, as the relative cost of emitting carbon rises. The model thus predicts a high responsiveness of abatement activities to changes in carbon taxation. Conversely, a high ς implies that labor and carbon are poor substitutes. In this scenario, the model predicts that firms are less responsive to changes in $\tau_{n,k}$. Even a substantial increase in carbon tax would result in only a marginal shift of labor from production to abatement, implying a lesser impact on the firm's carbon footprint.

The choice of abatement serves as a critical control variable through which firms mediate their labor and carbon inputs, given the external price variables like wages and carbon tax. Expressing other variables in terms of $a_{n,k}$ provides a more integral understanding of how firms react to changes in their operational environment. Consequently, we may rewrite firm-level marginal cost as

$$c_{ni,k} = \frac{d_{ni,k}}{\bar{\varphi}_{n,k}(1-\kappa_{n,k})}(1-a_{n,k})^{-\frac{1}{\varsigma}}w_n.$$

Following this, the input cost share of carbon $\alpha_{n,k}$ can also be reformulated to reflect its dependence on $a_{n,k}$ as follow

$$\alpha_{n,k} = 1-(1-\kappa_{n,k})(1-a_{n,k})^{-\frac{\varsigma-1}{\varsigma}}. \tag{2}$$

The aggregate producer's price index[5] and CO2 emissions associated with origin n–industry k can be specified as

$$P_{ni,k} = d_{ni,k}\bar{p}_{nn,k}w_n\,(1-a_{n,k})^{-\frac{1}{\varsigma}} \tag{3}$$

$$Z_{n,k} = \bar{z}_{n,k}\left(\frac{\alpha_{n,k}}{\kappa_{n,k}}\right)^{\frac{\varsigma}{\varsigma-1}}Q_{n,k} \tag{4}$$

where $\bar{p}_{nn,k}$ and $\bar{z}_{n,k}$ are constant exogenous multiplier of aggregate price index and carbon emission.[6] Note that $P_{ni,k} = d_{ni,k}P_{nn,k}$ by definition and $Q_{n,k} = \sum_i d_{ni,k}Q_{ni,k}$ denotes origin n–industry k's total gross output. It is immediate from these equations that higher abatement efforts lead to higher prices and lower emissions. For computational purposes, we further defined CO_2 emission per dollar of output as

$$v_{n,k} = \frac{Z_{n,k}}{P_{nn,k}Q_{n,k}} = \frac{\alpha_{n,k}}{\tau_{n,k}}.$$

This allow us to more directly observe the directional effects of carbon taxes on emission and compare the emissions intensities across countries.

2.3 Policy Instruments

The policy instruments $\mathbb{I}_n$ of country n's government consist of carbon taxes, import tariffs and export subsidies, defined as follow:

- Carbon taxes, $\tau_{n,k}$, applied to carbon content of varieties produced at origin n–industry k.
- Import tariffs $t_{ni,k}$, applied by country of destination i to products imported from origin n–industry k.

[5]We use tilde notation to differentiate between consumer prices and producer prices. The prices that have a tilde symbol above them are consumer prices.

[6]One may easily derive the constant multiplier and obtain $\bar{p}_{nn,k} = \frac{1}{\bar{\varphi}_{n,k}(1-\kappa_{n,k})}$ and $\bar{z}_{n,k} = \bar{\varphi}_{n,k}$.

- Export subsidies $x_{ni,k}$, applied by country of origin n–industry k to products exported to destination i.

From Equation (3), it is immediate to see how the government can use carbon taxes $\tau_{n,k}$ to alter the aggregate producer prices. Depending on the sensitivity of the choice of abatement in each industry with respect to the carbon taxes, determined by ς, governments can effectively reduce the usage of carbon-intensive inputs in the production process through higher taxes. On the other hand, the two border adjustment policy instruments, import tariffs $t_{ni,k}$ and export subsidies $x_{ni,k}$, influence the emission levels through consumer prices' channel. These border adjustment taxes create wedges between producer and consumer prices. More specifically, we may write consumer price index as a function of producer price index given in the form of

$$\tilde{P}_{ni,k} = \frac{(1 + t_{ni,k})}{(1 + x_{ni,k})} P_{ni,k}. \tag{5}$$

It is worth mentioning that the import tariff $t_{ni,k}$ is imposed by the destination country i, while the export subsidy is granted by the origin country n. The carbon tax $\tau_{n,k}$ is, however, uniformly applied to all product varieties manufactured within the jurisdiction of the country implementing the policy. The primary aim of such a tax is to internalize the external costs associated with carbon emissions, thereby providing an economic incentive for industries to reduce their carbon footprint. That said, the border adjustments can open up the road to transfer the tax burden resulting from policies implemented domestically to foreign consumers.

2.4 Tax Revenues and General Equilibrium

Utilizing the available policy instruments can generate a flow of tax revenues that is given by

$$T_n = \underbrace{\sum_k \sum_i \left[\left(\tilde{P}_{ni,k} - (1 - \alpha_{n,k}) P_{ni,k} \right) Q_{ni,k} \right]}_{\text{carbon tax + export subsidy}} + \underbrace{\sum_k \sum_{j \neq n} \left[\left(\tilde{P}_{jn,k} - P_{jn,k} \right) Q_{jn,k} \right]}_{\text{import tariff}} \tag{6}$$

The above tax revenue is decomposed into two principal elements, corresponding to the aforementioned policy instruments. The first term inside the summation for T_n effectively computes the net inflow due to carbon taxation and export subsidy. Intuitively, the greater the difference between $\tilde{P}_{ni,k}$ and $P_{ni,k}$, the higher the net tax revenue from these two source. This wedge essentially functions as the price markup due to the internalization of the carbon externality for industry k. The second term represents the transfers made via border adjustments. The net impact of the border adjustments can be either revenue-generating or revenue-draining and is determined by the balance struck between the two border taxes. Therefore, depending on the sets of policy decision made by the government, there could be an overall net inflow or outflow of revenues. In another word, T_n can take on any value, contingent upon the vector of policy decisions.

For a vector of policy $\tilde{\mathbb{P}}$, and parameters, $\{d, \alpha, \sigma, \varsigma, \kappa, L, \bar{p}, \bar{z}, \bar{\varphi}, \beta\}$, equilibrium is a vector of producer prices, P, quantities, Q, wages, w, and income, Y, such that goods' markets clear

(*i.e.*, national expenditure = national sales)

$$Y_n = w_n L_n + T_n, \tag{7}$$

and labor markets clear in each country (*i.e.*, labor supply = demand for labor)

$$w_n L_n = \sum_k \sum_i \left[(1 - \alpha_{n,k}) P_{ni,k} Q_{ni,k} \right]. \tag{8}$$

Note that the vector of equilibrium outcome need to additionally satisfy of all the Equations (1-8) to be considered as a feasible set of outcomes.

2.5 Carbon Accounting

To define environmentally adjusted national-level welfare, it is essential to develop a formal framework to measure the disutility arising from pollution emitted during the production process. This section provides such a framework, linking carbon emissions to changes in national welfare. In this framework, we consider that the perceived cost of CO_2 emissions for country n , denoted by δ_n, as an aggregate measure of disutilities associated with emitting $Z_{n,k}$ amount of CO_2 to the atmosphere[7]. Given this, the objective of the government in country n is to maximize the national-level welfare, W_n, which is defined as

$$W_n \equiv V_n \left(Y_n, \tilde{\mathbf{P}}_n \right) - \delta_n \sum_i \sum_k Z_{i,k},$$

where $V_n\left(.\right)$ is the indirect utility associated with utility maximization problem, i.e.,

$$\max_Q U \; s.t. \; P \cdot Q \leq Y.$$

In this expression, Y_n represents the national expendable income as given by Equation (7), and $\tilde{\mathbf{P}}_n$ is the vector of feasible consumer prices in country n. The second term in the welfare function captures the environmental disutility arising from pollution and carbon emissions.

In the context of an open economy, the impact of adjustments in carbon taxation on national welfare manifests through multiple channels. To isolate these individual channels and comprehensively decompose the welfare effects, we turn our analysis to a particular instantiation of our general model. Specifically, we set the elasticity of substitution between carbon (energy) and labor, denoted as ς, to be unity. Under this condition, the utility function of the representative consumer conforms to a Cobb-Douglas specification.

Assuming the absence of any other form of taxation–thereby isolating the effects of carbon taxes–we can straightforwardly express the equilibrium consumer prices and national income as follows:

$$\tilde{P}_{ni,k} = P_{ni,k} \quad \forall k \quad \implies \quad Y_n = w_n L_n + \sum_k \alpha_{n,k} P_{n,k} Q_{n,k}$$

In this special case of our general model, the consumer prices $\tilde{P}_{ni,k}$ align precisely with the producer prices $P_{ni,k}$ across all industries k. As a result, the national income Y_n of country n

[7]For a detailed explanation on how we define and estimate the perceived cost of carbon δ_n, see Appendix A.1.

can be expressed as the sum of its wage income $w_n L_n$ and the carbon tax revenues captured by the second term in the simplified national income expression. For the welfare analysis that follows, we need two key elasticities that capture the effect of a marginal change in the carbon tax rate $\tau_{i,k}$ on the producer prices $P_{ni,k}$ and CO_2 emissions $Z_{n,k}$, given by

$$\left(\frac{\partial \ln P_{in,k}}{\partial \ln \tau_{i,k}}\right)_{w_i} = \alpha_{i,k}; \qquad \left(\frac{\partial \ln Z_{i,k}}{\partial \ln \tau_{i,k}}\right)_{Q_{i,k}} = -\left(1-\alpha_{i,k}\right).$$

National wage w_n in the first derivation, and output $Q_{n,k}$ in the subsequent one are held constant.

To distinguish between the channels through which changes in carbon taxes impacts welfare, we may write the first order condition, given by

$$\frac{\mathrm{d}W_i}{\mathrm{d}\ln \tau_i} = \frac{\partial V_i\,(.)}{\partial Y_i}\frac{\mathrm{d}Y_i}{\mathrm{d}\ln \tau_i} + \sum_k \frac{\partial V_i\,(.)}{\partial \ln \tilde{P}_{ii,k}}\frac{\mathrm{d}\ln \tilde{P}_{ii,k}}{\mathrm{d}\ln \tau_i} - \delta_i \sum_n Z_n \frac{\mathrm{d}\ln Z_n}{\mathrm{d}\ln \tau_i}.$$

After some algebraic manipulation[8] and taking advantage of Roy's identity, *i.e.*, $\frac{\partial V_i}{\partial \ln \tilde{P}_{ii,k}} / \frac{\partial V_i}{\partial Y_i} = -P_{ii,k}Q_{ii,k}$, we arrive at the expression

$$\frac{\mathrm{d}W_i}{\mathrm{d}\ln \tau_i} = \frac{\partial V_i}{\partial Y_i}\left\{\underbrace{\left(\tau_i - \tilde{\delta}_i\right)\sum_k \left[Z_{i,k}\left(\frac{\mathrm{d}\ln Q_{i,k}}{\mathrm{d}\ln \tau_i} + \left(1-\alpha_{i,k}\right)\frac{\mathrm{d}\ln\left(w_i/\tau_i\right)}{\mathrm{d}\ln \tau_i}\right)\right]}_{\text{domestic emission reduction }(+)}\right. \tag{9}$$

$$\left. + \underbrace{\sum_k \left[\alpha_{i,k}P_{ii,k}\left(Q_{i,k} - Q_{ii,k}\right)\right]}_{\text{tax incidence on RoW}(+)} + \underbrace{\sum_k \left[\left(1-\alpha_{i,k}\right)P_{ii,k}\left(Q_{i,k} - Q_{ii,k}\right)\right]\frac{\mathrm{d}\ln w_i}{\mathrm{d}\ln \tau_i}}_{\text{factoral terms of trade}(-)} \underbrace{- \tilde{\delta}_i \sum_{n \neq i} Z_n \frac{\mathrm{d}\ln Q_n}{\mathrm{d}\ln \tau_i}}_{\text{leakage}(-)}\right\}.$$

The welfare decomposition in Equation (9) provides a comprehensive framework to understand how changes in carbon taxes impact national welfare through multiple channels. This equation outlines four key mechanisms that connect carbon tax adjustments to welfare outcomes:

i. *Domestic Emission Reduction*: The first term captures the welfare effects of domestic carbon emission and pollution reductions stemming from higher carbon taxes in country i. An increase in τ_i triggers a complex set of dynamics that affect both production and consumption behaviors. Specifically, a higher carbon tax induces firms to grapple with increased production costs, urging them to allocate a greater fraction of labor towards abatement activities. This labor reallocation results in a direct decrease in carbon emissions, $Z_{i,k}$. This adaptation, however, levies an opportunity cost: as labor is diverted away from production to abatement, it ensues a noticeable contraction in domestic output. This is accurately captured by the elasticity term $\frac{\mathrm{d}\ln Q_{i,k}}{\mathrm{d}\ln \tau_i} < 0$. Given that less labor is now available for production and demand for domestically produced goods are

[8] For a detailed derivation of the welfare decomposition, refer to Appendix A.2.

shifted to imports from other countries, demand for labor diminishes, thereby applying a downward pressure on the national wage rate, w_i. The elasticity of this wage decline in relation to the carbon tax is reflected by $\frac{\mathrm{d}\ln w_i}{\mathrm{d}\ln \tau_i} < 0$. Overall, the net effect of these two changes have the same net effect of decreasing total domestic carbon emissions. The overall welfare effect through domestic emission reduction is critically contingent upon two pivotal factors: the pre-policy emission level $Z_{i,k}$ and the societal valuation (disutility) of the carbon emissions and pollutions, $\tilde{\delta}_i$. A higher initial emission state magnifies the welfare gains originating from emission reductions. Concurrently, a higher $\tilde{\delta}_i$ means stronger societal incentives for emission reduction, thereby amplifying the welfare gains from any decrease in $Z_{i,k}$. An important nuance is present in the term $(\tau_i - \tilde{\delta}_i)$. When $\tau_i > \tilde{\delta}_i$, the real cost of carbon emissions exceeds its perceived disutility. However, this does not necessarily lead to welfare gains, given that this term is multiplied by a summation whose constituents, namely the decline in both output and wages with respect to the carbon tax, are negative. Importantly, the welfare-augmenting effects of this unilateral carbon tax policy hinge upon the initial carbon price being below the nation's unilateral optimal carbon tax, defined by the perceived disutility of emissions, $\tilde{\delta}_i$. If the governing body sets a policy rate that exceeds this optimal level, the welfare losses from diminished consumption could potentially outweigh the gains attributable to emission reduction, thereby turning the term negative.

ii. *Tax Incidence on Rest of World*: The second component for welfare impact sheds light on the complex welfare implications for country i due to its ability to partially shift its tax burden onto foreign consumers. This occurs when the unilateral carbon tax ($\mathrm{d}\ln \tau_i$) in country i raises production costs, which are then passed on to export prices in accordance with the cost share of carbon, denoted by $\alpha_{i,k}$. Essentially, this mechanism implies that foreign consumers are indirectly subsidizing country i's carbon tax policy by absorbing higher prices for goods imported from that country. The precise quantification of this transference of tax incidence onto foreign buyers is captured by the term $\alpha_{i,k} P_{i,k} \left(Q_{i,k} - Q_{ii,k}\right)$, which represents the fraction of the carbon tax revenue generated through exports in the originating country. The magnitude of this redistribution is strongly conditioned by the volume of production that is not domestically consumed but rather exported. The efficacy of this welfare channel is shaped by several key parameters. First, industries with higher carbon cost shares $\alpha_{i,k}$ contribute more significantly to this welfare effect, as they are more affected by the tax and are therefore more likely to pass it onto foreign consumers. Second, the extent to which the tax burden can be shifted is also governed by the volume of exported production, captured by the term $Q_{i,k} - Q_{ii,k}$. If country i is a dominant player in foreign markets, particularly in carbon-intensive industries, the scope for welfare gains could be substantial. Implicit in this analysis is the assumption is that the effectiveness of price pass-through–willingness of foreign consumers to accept higher prices due to elevated production cost–depends on the demand elasticity of substitution σ_k between varieties in industry k.

iii. *Factoral Terms of Trade*: The third element measures the adverse welfare impact from deterioration in country i's factoral terms of trade due to implementation of carbon taxes. In the wake of an increase in carbon prices τ, the marginal cost of production escalates due to the selection of higher abatement strategies. This rise translates into higher producer prices for domestic goods, as indicated by Equation (3). The inflation in these prices subsequently reduces the international competitiveness of country i's exports. Additionally, this inflationary pressure on producer prices is compounded by a potential decrease in overall production, as described by the first channel of the welfare decomposition. The negative repercussions of these shifts manifest as reduced demand for domestic labor, leading to a decline in national wages w_i. This decline is captured by the term $\frac{\mathrm{d}\ln w_i}{\mathrm{d}\ln \tau_i} < 0$, expected to be negative under the model's assumptions. The elasticity of this term captures how sensitive domestic wages are to changes in the carbon tax, effectively serving as a barometer for labor market volatility in the context of environmental policy shifts. Moreover, the welfare loss attributable to this channel is proportionally influenced by the degree of country i's exposure to the export market, which is quantified by the term $(1-\alpha_{i,k})\, P_{ii,k}\, (Q_{i,k} - Q_{ii,k})$. The larger this term, the more significant the welfare loss, especially in industries where $1-\alpha_{i,k}$ is high, indicating a greater labor share. Sizable volume of goods produced for export in each industry amplify the welfare implications of the factoral terms of trade channel. Labor mobility assumption between industries serves as a mitigative factor, enabling a smoother transition from carbon-intensive to greener industries. Additionally, the flexibility or rigidity of wages could either temper or exacerbate the welfare losses, underlining the need for empirical estimations of wage elasticities.

iv. *Carbon Leakage*: The final term in the welfare decomposition accounts for the phenomenon of carbon leakage, a critical negative externality that partly offsets the gains from domestic emission reductions in country i. The mechanism underlying this leakage effect can be categorized into economic interdependencies and policy responses. As the carbon tax τ_i escalates production costs for domestic industries within country i, firms may find it economically viable to relocate their production facilities to countries with lax or absent carbon taxation, engendering an increase in emissions in these nations. This geographical shift in production, and consequently, emissions, is captured by the elasticity term $\frac{\mathrm{d}\ln Q_n}{\mathrm{d}\ln \tau_i} > 0$, which quantifies the sensitivity of emissions in country n to changes in the carbon price in country i. The adverse welfare implications of the leakage phenomenon depends on the national perceived disutility for each unit of CO_2 emissions, denoted by $\tilde{\delta}_i$. In essence, any increase in emissions in other countries caused by country i's unilateral carbon policy would have detrimental impacts on its welfare and by extension, on the global welfare.

As previously indicated, the term $Q_{i,k} - Q_{ii,k}$ in the decomposition specified by Equation (9), which is non-negative by construction, represents the quantity of output exported to the rest of the world. In the context of a closed economy, exports are non-existent (implying $Q_{i,k} = Q_{ii,k}$), and there is no associated leakage term ($\frac{\mathrm{d}\ln Q_n}{\mathrm{d}\ln \tau_i} = 0,\ \forall n \neq i$). Consequently, our initial equation reduces to

$$\text{closed economy} \longrightarrow \quad \frac{\mathrm{d}W_i}{\mathrm{d}\ln\tau_i} = \frac{\partial V_i}{\partial Y_i}\left(\tau_i - \tilde{\delta}_i\right)\sum_k \left[Z_{i,k}\left(\frac{d\ln Q_{i,k}}{d\ln\tau_i} + \left(1-\alpha_{i,k}\right)\frac{d\ln\left(w_i/\tau_i\right)}{d\ln\tau_i}\right)\right],$$

which identifies Pigouvian carbon taxes as the optimal carbon tax rate, i.e. equating the carbon tax to social cost of carbon ($\tau_i^* = \tilde{\delta}_i$) maximizes the welfare. It's important to highlight that the welfare decomposition expressed in Equation (9), or its formulation for a closed economy, holds non-parametrically, i.e. it does not hinge on the specific CES-Cobb-Douglas functional forms chosen to parameterize the preference.

2.6 Carbon Border Adjustment Mechanism (CBAM)

As discussed earlier, the introduction of unilateral carbon taxes, though a viable solution to internalize the external costs of carbon emissions, presents challenges to the competitiveness of domestic industries and can inadvertently spur carbon leakage, where the production of goods shifts to countries with lower carbon prices. Such migration not only cancel out the environmental objectives of the carbon tax but also poses economic challenges to the policy-implementing country. A proposed remedy to counterbalance these potential ramifications is the Carbon Border Adjustment Mechanism (CBAM), in forms of import tariffs and export subsidies. The policy options range from a non-discriminatory import tariff (Policy A), as exemplified by the European Union's CBAM, to more complex combinations involving both non-discriminatory and discriminatory import tariffs coupled with export subsidies, as illustrated in Table 1. These mechanisms, denoted as Policies A through D in Table 1, offer different advantages and potential drawbacks. A pivotal question arises: Which option is more effective at minimizing leakage and lowering associated cost of policy for the local economy? The following discussion seeks to shed light on this pressing query. To facilitate this analysis, we establish a baseline scenario wherein the country enacting the policy refrains from implementing any border adjustments.

Table 1: *Matrix of Carbon Border Adjustment Policy Scenarios*

	Import Tariff	*Import Tariff & Export Subsidy*
Non-Discriminatory	Policy A	Policy B
Discriminatory	Policy C	Policy D

Note: Non-discriminatory policies apply uniformly to all trading partners, while discriminatory policies target specific countries or regions.

First, we analyze how incorporating a non-discriminatory import tariff influences the welfare outcomes of a unilateral carbon tax policy. Under Policy A, the country implementing this policy can address the unintended leakage stemming from its unilateral carbon tax. By introducing import taxes, there's a reduction in economic incentives to relocate production to countries without a carbon tax. As a result, production shifts outside the policy-implementing country, represented by $\frac{\mathrm{d}\ln Q_n}{\mathrm{d}\ln\tau_i}$, will be less positive compared to a baseline scenario without any border adjustments. Under certain conditions, this change might even be negative. Whether import-side border adjustments reduce carbon leakage and diminish the corresponding domestic welfare loss, or lead to emission reductions outside the implementing country and improvement in domestic welfare, remains an empirical question. Turning to other channels through which a carbon tax policy affect the welfare, it is important to note that the import tariff doesn't alter the prices of goods domestically produced within the policy-implementing country. Consequently, the changes total output of country i, $\frac{\mathrm{d}\ln Q_i}{\mathrm{d}\ln \tau_i}$, is expected to be largely unaffected and negative or at most, perhaps being marginally less negative. Similarly, domestic wage shifts, $\frac{\mathrm{d}\ln w_i}{\mathrm{d}\ln \tau_i}$ will either be minimal or slightly less negative. Simply put, the impact of unilateral carbon tax policy on domestic carbon emissions, tax incidence on the rest of the world, and factoral terms of trade largely remain unaffected by the introduction of non-discriminatory import tariffs.

Under Policy B, which combines an export subsidy with an import tax, the dual objectives are twofold: mitigating carbon leakage and enhancing the country's global competitiveness. The export subsidy is designed to offset the decline in export competitiveness resulting from elevated input costs. This could result in a less negative, or potentially positive, elasticity of domestic output with respect to the domestic carbon tax, denoted as $\frac{\mathrm{d}\ln Q_i}{\mathrm{d}\ln \tau_i}$. Simultaneously, the import tariffs continue to play their role in diminishing the economic incentives of shifting production to non-carbon-taxing countries, thereby reinforcing the mitigation of the leakage effect. The introduction of export subsidies can further accentuate this effect by making the policy-enacting country's goods more competitive in the global market. This dilutes the incentive for foreign producers to ramp up their output, thereby leading to a further decline in $\frac{\mathrm{d}\ln Q_n}{\mathrm{d}\ln \tau_i}$ for $n \neq i$, and while the direction is expectedly negative, the magnitude remains a puzzle that needs to be answered empirically. On the other hand, incorporating export subsidy eliminates the pass-through of carbon tax from the export prices. Consequently, the welfare gains that could be potentially accrued through the shifting of the tax incidence onto foreign consumers fade away. However, wage dynamics could experience an uplift under this dual-policy framework. Specifically, the rebound in demand for domestically produced goods could exert upward pressure on wages, compared to the baseline scenario without border adjustments. In formal terms, $\frac{\mathrm{d}\ln Q_n}{\mathrm{d}\ln \tau_i}$ becomes less negative, resulting in factoral terms of trade improvements for the policy-enacting country. Given that the reduction in total domestic production and wages are now less severe, as compared to a scenario without export subsidies, the welfare improvement through the domestic emission reduction will be less substantial. The net effect of introducing export-side adjustments to the policy framework remains an empirical question, as its ultimate impact is contingent upon the interplay among the various welfare channels previously discussed.

Under Policy C, which couples a discriminatory import tariff with a unilateral carbon tax, the overall welfare impact is qualitatively similar to that of the non-discriminatory case, albeit with potential variations in the magnitudes across different welfare channels. By implementing a discriminatory import tariff, the policy-enacting country can more effectively target carbon-intensive imports from other countries. A finely calibrated import tariff would reduce firms' incentives to shift production to high-emission countries more effectively than a uniform tariff. This targeted approach would serve as a more effective deterrent, reducing the negative impact of leakage, $\frac{\mathrm{d}\ln Q_n}{\mathrm{d}\ln \tau_i}$, but the exact magnitude would still need to be empirically validated.

To gain insights into the welfare effects via other channels, empirical analysis is indispensable. One can reasonably expect a marginal improvements in domestic production and national wage levels, signifying a more efficient resource allocation towards less carbon-intensive domestic sectors, accompanied by a reshuffling of import sourcing from trading partners.

Turning to Policy D, which augments Policy C with an export subsidy, the modifications in welfare outcomes across different channels are expected to echo the trends observed under Policy B. Specifically, the export subsidy would likely attenuate the negative welfare impacts previously experienced by foreign nations, as it nullifies the pass-through of the domestic carbon tax to international markets.

Regarding the welfare implications outside the policy-enacting country, the effects are expected to be heterogeneous. The baseline scenario generally enhances welfare in the rest of the world due to two main factors: first, a global emission reduction catalyzed by the policy-enacting country; and second, the carbon leakage effect, which stimulates higher production levels in those countries. The inclusion of import-side border policies generally tempers these welfare gains, with particularly adverse impacts on high-emission countries. Conversely, the integration of export subsidies is anticipated to moderate these negative welfare consequences on other regions by eliminating the pass-through effect of the carbon tax from export prices.

3 Data

To map the model framework to real-world data in our analysis, I primarily rely on the comprehensive dataset created by Farrokhi and Lashkaripour (2021). Their work provides a rich source of information, laying the groundwork for this study's empirical foundation. In this section, I provide a description of the datasets and the associated calibrations employed in this study. The comprehensive environmentally-extended dataset and tailored estimation of key elasticities enables a detailed quantification of the multi-faceted welfare impacts.

The sources for trade, production and CO2 emissions data are the World Input-Output Database (WIOD) Environmental Accounts for year 2009 (Timmer et al. (2012))[9]. This dataset, which reports annual international expenditure levels for 41 countries and 35 ISIC-level industries, is aggregated to 15 countries/regions and 19 broad industries. One of these regions is the the European Union (EU) since European nations often act as a single policymaking entity. This results in a $15 \times 15 \times 19$ matrix showing expenditure levels $\tilde{P}_{ni,k}Q_{ni,k}$ for each triplet ni, k (i.e. origin n— destination i– industry k). This is the key input needed to construct baseline trade shares, revenues and carbon intensities. The measure of carbon dioxide equivalent (CO_2e) emissions, $Z_{n,k}$, is constructed using the Global Warming Potential index (GWP-100) from the Pachauri et al. (2014) IPCC report, while accounting for the relative warming effect of different gases over a 100 year horizon[10].

Data on applied import tariffs is obtained from the United Nations Statistical Division, Trade Analysis and Information System (UNCTAD-TRAINS) database, which contains ad-

[9]The baseline year for our analysis is 2009, which represents the most current year with comprehensive data on trade, production, emissions, and environmentally related taxes documented in the WIOD Environmental Account. Additionally, 2009 marks the first year featuring extensive coverage of environmentally-related taxation data.

[10]The WGP-100 measures the absorption amount of one tonne of a specific gas in the atmosphere over a 100-year span, benchmarked against the emissions of one tonne of CO_2.

valorem tariff rates at the country-pair and industry level based on the ISIC classification system. A matrix of applied bilateral import tariff rates $t_{ni,k}$ for each triplet ni, k is constructed by aggregating the industries to match the 19 sectors in WIOD and taking an average of effectively applied most-favored nation tariffs. This data is used to initialize the baseline policy scenario prior to implementation of the carbon tax adjustment policies. As specified earlier in the baseline policy instruments, the export subsidies are assumed to be negligible, consistent with WTO clause on exports.

Environmentally-related tax records are obtained from Eurostat and OECD-PINE to infer countries' attitudes towards the social cost of emissions. Eurostat data provides the environmental taxes by economic activity, covering European countries and industries, while OECD data on environmentally-related taxes by country, as a share of GDP. These taxes are assumed to represent implicit carbon prices in the baseline. Specifically, the total value of environmental taxes paid is compared to the total emissions produced to back out the effective carbon tax rate $\tau_{i,k}$ faced by each country-industry.

The perceived emission disutility parameters $\tilde{\varphi}_i$ and $\tilde{\varphi}_{i,k}$, determining how governments value carbon reductions, are calibrated by assuming applied carbon tax rates equal the unilateral social cost. The global social cost of carbon (SCC) matches the literature consensus of around \$31 per tonne of CO_2-equivalent in 2010 USD terms, as estimated by U.S. Interagency Working Group. More specifically, the climate disutility $\tilde{\varphi}_i$ is calibrated to match the SCC, accounting for countries' GDP shares and relative emission tax rates. Then the local pollution disutility $\tilde{\varphi}_{i,k}$ is set to match applied taxes minus the inferred $\tilde{\varphi}_i$ in each country-industry. The trade elasticities σ_k, governing the sensitivity of trade flows to changes in trade costs like tariffs, are estimated using techniques from Caliendo and Parro (2015). The carbon input demand elasticity ς is estimated using instrumental variables regression. Using country-level energy reserves as an instrument, the estimation yields a carbon demand elasticity of around 0.6. This completes the data calibration and quantification of parameters necessary for counterfactual analysis[11]. With this mapping framework to data, we now turn to the Theoretical results from formulating the carbon tax policies and assessing their effectiveness for emissions reduction when combined with trade instruments.

4 Policy Counterfactuals

To quantify the potential impact of the proposed carbon border adjustment mechanisms (CBAMs) in reducing CO2 emissions, it's imperative to contrast changes in equilibrium conditions with a baseline scenario absent of such policies. The baseline taxes in our practice is given by

- $\{\tau_{i,k}\}$ represents the unilateral optimum taxes and is inferred from applied emission rates.
- $\{t_{ni,k}\}$ corresponds to observed applied tariffs.
- $\{x_{ij,k}\}$ is defaulted to zero.

[11] For more details on the description of data, see Appendix B.

As discussed in the preceding section, the carbon emission's perceived disutility within individual countries is caused by two distinct sources. The first source is the direct release of CO_2. Simultaneously, the second source pertains to local pollutants, such as nitrogen oxides (NOx), sulfur oxides (SOx), and carbon monoxide (CO), which are concurrently produced with CO_2 during various production processes. In our specification of the baseline, the carbon tax for country n can be articulated as $\tau_{n,k} = \tilde{\phi}_n + \tilde{\phi}_{n,k}$. This reflects the unilaterally optimal carbon tax for country n, a feature evident from our closed-economy model. Our proposed unilateral carbon tax policy raises the carbon taxes to the globally optimum level, consistent with the social cost of carbon, given by $\tau^*_{n,k} = \sum_i \tilde{\phi}_i + \tilde{\phi}_{n,k}$.

To assess the welfare implications of the channels detailed in Equation (9), we introduce two distinct carbon border adjustment policy sets. The first, termed the "non-discriminatory border adjustment", applies border adjustment taxes uniformly to all trading partners, independent of their specific carbon tax policies. Conversely, the second set, labeled "discriminatory border adjustment", modifies these taxes based on the carbon intensity inherent in each trading partner's production sectors. Governments have two instruments within each policy set: import tariffs and export subsidies. They can either impose import tariffs exclusively or couple them with export subsidies. This characterizes results in five distinct scenarios, four of which is outlined in Table 1 through Policy A - D, while the fifth scenario serves as a baseline in which no border adjustments are implemented.

These policy implementations, by definition, will affect the equilibrium outcomes specified by Equations (1-8). To quantify these shifts, we employ the hat algebra technique, denoting proportional changes in variables post-policy intervention. In what follows, we consider the existing equilibrium, determined by baseline data, parameters, and tax policies discussed previously, as our reference point. We operate under the assumption that other countries react passively and do not impose retaliatory taxes in response to policy-enacting country's initiatives.

To systematically capture the policy-induced deviations in equilibrium, let's designate z as the equilibrium value of a generic variable in the absence of any of the proposed policies. If a new policy alters this equilibrium value to z^*, the proportional deviation is expressed as $\hat{z} \equiv z^*/z$, where the hat notation $\hat{z}$ denotes the proportional deviation from the original equilibrium value z. According to our prior discussion on the unilateral carbon tax policy, the proportional deviation in carbon prices can be characterized as

$$\hat{\tau}_{n,k} = \frac{\sum_i \tilde{\phi}_i + \tilde{\phi}_{n,k}}{\tilde{\phi}_n + \tilde{\phi}_{n,k}}, \tag{10}$$

where $\tilde{\phi}_i$ and $\tilde{\phi}_{n,k}$ respectively represent the disutility stemming from CO_2 emissions and localized pollutants. Given the policy choices, the changes in border adjustment taxes for country n can be concisely represented as follows:

The term $(\widehat{1 - a_{n,k}})^{-1/\varsigma}$ represents the pass-through of the carbon tax to producer prices. Under the non-discriminatory policy framework, adopting this coefficient as the determinant for import tariff adjustments effectively neutralizes the price disparities between domestically produced and imported goods stemming from carbon taxes. Simultaneously, this adjustment

Table 2: Matrix of Policy Counterfactuals for Carbon Border Adjustments

	$\widehat{1+t_{in,k}}$	$\widehat{1+x_{ni,k}}$
a) No Adjustments	1	1
b) Non-Discriminatory	$(\widehat{1-a_{n,k}})^{-1/\varsigma}$	$(\widehat{1-a_{n,k}})^{-1/\varsigma}$
c) Discriminatory	$1+\frac{\tau_{n,k}(\hat{\tau}_{n,k}-1)\hat{v}_{i,k}v_{i,k}}{1+t_{in,k}}$	$(\widehat{1-a_{n,k}})^{-1/\varsigma}$

Notes: This table presents the shifts in border adjustment taxes for country n under three specific types of policy scenarios: no border adjustments, non-discriminatory, and discriminatory carbon border adjustment mechanisms. The first and second columns respectively describe the proportional changes in import tariffs and export subsidies arising from each policy frameworks. The non-discriminatory approach harmonizes domestic and foreign carbon production costs, while the discriminatory approach accounts for differences in carbon intensity across trading partners.

on the export-side takes place through rebating the carbon taxes as export subsidies. Simply put, the goal of these border adjustments is to align domestic and foreign carbon costs of production.

In the context of discriminatory import-side border adjustments, the underlying rationale is to charge the importers with the cost disparity per unit of CO_2 emission associated with the production of varieties destined for countries implementing unilateral carbon tax policies. The term $\tau_{n,k}(\hat{\tau}_{n,k}-1)$, or equivalently $\tau^*_{n,k}-\tau_{n,k}$, captures the effect of carbon tax policy and $v^*_{i,k}$ is the carbon emission per unit of output produced in the exporting country i– industry k, under the updated equilibrium conditions.

In what follows, we derive the changes in counterfactual outcomes as a function of changes in the vector of policies $\hat{\mathbb{P}} \equiv \{\hat{\tau}_{n,k}, \hat{t}_{in,k}, \hat{x}_{ni,k}\}$, and parameters $\{\sigma_k, \varsigma, \beta_{n,k}, \kappa_{n,k}, \varphi_{n,k}, d_{ni,k}, \phi_n, \phi_{n,k}, \bar{p}_{nn,k}, \bar{z}_{n,k}\}$. The changes in industry-level abatement is given by

$$\widehat{1-a_{n,k}} = \left[(1-\alpha_{n,k}) + (\alpha_{n,k})\left(\hat{\tau}_{n,k}/\hat{w}_n\right)^{1-\varsigma}\right]^{\varsigma/(\varsigma-1)}, \tag{11}$$

where equilibrium changes in national wages and carbon taxes jointly regulate the update in abatement choices. Subsequently, the change in industry-level carbon input cost share and carbon intensity is given by

$$\hat{\alpha}_{n,k} = \frac{1}{\alpha_{n,k}} - \frac{1-\alpha_{n,k}}{\alpha_{n,k}}(\widehat{1-a_{n,k}})^{(1-\varsigma)/\varsigma}, \qquad \hat{v}_{n,k} = \frac{\hat{\alpha}_{n,k}}{\hat{\tau}_{n,k}}. \tag{12}$$

The above expressions allow us to derive the changes in CO_2 emissions, which is given by

$$\hat{Z}_{n,k} = \hat{v}_{n,k}\sum_{i=1}^{N}\left[r_{in,k}\frac{(\widehat{1+x_{ni,k}})}{(\widehat{1+t_{ni,k}})}\hat{\lambda}_{in,l}\hat{Y}_i\right], \tag{13}$$

with $r_{ni,k} = P_{ni,k}Q_{ni,k}/\sum_j P_{nj,k}Q_{nj,k}$ defining the revenue share of variety ni,k in the total sales of origin n-industry k. Changes in consumer price index can be derived as

$$\begin{cases} \hat{P}_{ni,k} = \hat{w}_n \widehat{(1-a_{n,k})}^{-\frac{1}{\varsigma}} & \text{a) producer price } (ni,k) \\ \hat{\tilde{P}}_{ni,k} = \frac{\widehat{(1+t_{ni,k})}}{\widehat{(1+x_{ni,k})}} \hat{P}_{ni,k} & \text{b) consumer price } (ni,k) \\ \hat{\tilde{P}}_{i,k} = \left[\sum_{n=1}^{N} \lambda_{ni,k} (\hat{\tilde{P}}_{ni,k})^{1-\sigma_k} \right]^{\frac{1}{1-\sigma_k}} & \text{c) consumer price } (i,k) \\ \hat{\tilde{P}}_i = \prod_k (\hat{\tilde{P}}_{i,k})^{\beta_{i,k}} & \text{d) consumer price } (i) \end{cases} \tag{14}$$

Given these consumer price alterations, the changes in optimal demand quantities can be written as

$$\hat{Q}_{ni,k} = \left(\frac{\hat{\tilde{P}}_{ni,k}}{\hat{\tilde{P}}_{i,k}} \right)^{1-\sigma_k} \hat{Y}_i. \tag{15}$$

Labor market clearing condition, which regulates the changes in wages, is given by

$$\hat{w}_n w_n \bar{L}_n = \sum_j \sum_k \left[\frac{(1-\hat{\alpha}_{n,k}\alpha_{n,k})(1+x^{\star}_{nj,k})}{(1+t^{\star}_{nj,k})} \hat{\lambda}_{nj,k} \lambda_{nj,k} \beta_{j,k} \hat{Y}_j Y_j \right], \tag{16}$$

where the changes in within-industry expenditure and revenue shares can be calculate as

$$\begin{cases} \hat{\lambda}_{ni,k} = \left(\hat{\tilde{P}}_{ni,k} / \hat{\tilde{P}}_{i,k} \right)^{1-\sigma_k}, & \text{a) within-ind exp share } (ni,k) \\ \hat{r}_{ni,k} = \frac{\widehat{(1+t_{ni,k})}^{-1} \widehat{(1+x_{ni,k})} \hat{\lambda}_{ni,k} \hat{Y}_i}{\sum_\ell r_{j\ell,k} \widehat{(1+t_{n\ell,k})}^{-1} \widehat{(1+x_{n\ell,k})} \hat{\lambda}_{n\ell,k} \hat{Y}_\ell}. & \text{b) within-ind rev share } (ni,k) \end{cases} \tag{17}$$

Using the changes in labor income, we may write the overall changes in budget constraint as

$$\begin{aligned} \hat{Y}_n Y_n = \hat{w}_n w_n \bar{L}_n &+ \sum_k \sum_j \left[\frac{(\hat{\alpha}_{n,k}\alpha_{n,k})(1+x^{\star}_{nj,k})}{(1+t^{\star}_{nj,k})} \hat{\lambda}_{nj,k} \lambda_{nj,k} \beta_{j,k} \hat{Y}_j Y_j \right] \\ &+ \sum_k \sum_j \left[\frac{x^{\star}_{nj,k}}{(1+t^{\star}_{nj,k})} \hat{\lambda}_{nj,k} \lambda_{nj,k} \beta_{j,k} \hat{Y}_j Y_j + \frac{t^{\star}_{nj,k}}{1+t^{\star}_{jn,k}} \hat{\lambda}_{jn,k} \lambda_{jn,k} \beta_{n,k} \hat{Y}_n Y_n \right], \end{aligned} \tag{18}$$

where $t^{\star}_{nj,k}$ and $x^{\star}_{nj,k}$ represents the values of the import tariff and export subsidy under the proposed border policies, respectively. It is imperative to note that the effective border taxes are contingent on the specific scenario under evaluation. The equation above ensures that the changes in the budget constraint of the representative consumer is aligned with changes in the national income. The first term captures the changes in the labor revenue as specified in Equation (16). The second and third terms represent the adjustments in carbon tax revenue and cross-border revenue transfers, respectively.

With the help of Equations (11-18), one can solve for the new equilibrium outcome presented in the form of changes from the baseline scenario without the proposed policies. More specifically, we may find the set of changes in national wages $\hat{w}_n$, national incomes $\hat{Y}_i$, vector of prices $\hat{\tilde{P}}_{ni,k}$ and labor shares $\hat{l}_{ni,k}$ that satisfy the equilibrium conditions.

Finally, upon establishing the new equilibrium conditions, we can obtain the change to real consumption and welfare using

$$\hat{V}_n = \left(\frac{\hat{Y}_n}{\hat{\tilde{P}}_n}\right), \qquad \hat{W}_n = \underbrace{\frac{Y_i}{Y_n - \tilde{\delta}_n \sum_{i,k} Z_{i,k}} \hat{V}_n}_{\Delta \text{ consumption}} - \underbrace{\tilde{\delta}_n \sum_{i,k} \frac{Z_{i,k}}{Y_n - \tilde{\delta}_n \sum_{i,k} Z_{i,k}} \hat{Z}_{i,k}}_{\Delta \text{ disutility from } CO_2}. \tag{19}$$

The first component represents the consumption changes due to income and price shifts. The second component captures the change in the representative consumer's disutility arising from variations in CO_2 emissions. These formulations provide a comprehensive picture of the economic environment post-policy implementation. With this foundation in place, we're ready to transition to the next section, presenting the results and offering insights into their implications.

5 Results

This section unfolds the key findings from the quantitative analysis of equilibrium effects of unilateral carbon tax policies under the baseline with no border adjustments and four distinct border adjustment scenarios defined in Table 1, each of which offers unique insights into welfare effects of each channel indicated in Equation (9). In particular, we evaluate the welfare impacts of non-discriminatory and discriminatory carbon border adjustment mechanisms (CBAM) when a unilateral carbon tax policy is implemented by the European Union (EU). We investigate the local and global implications of EU's tax policies.

5.1 Non-Discriminatory Border Adjustment

This section presents the key findings from our quantitative analysis of non-discriminatory carbon border adjustment mechanisms (CBAM) consisting of uniform import tariffs and export subsidies.

Table 3 contrasts the welfare effects of unilateral carbon tax policies with and without border adjustments for the EU, the rest of the world (RoW), and at the global stage. In this section, we focus on non-discriminatory policy cases defined by Policy A and Policy B. The first row for each region denotes the scenario with a unilateral carbon tax policy without of any border adjustment, categorized under carbon tax. To evaluate the observed welfare effects, we will incorporate insights from Table 4, which respectively illustrate the changes in CO_2 emission and consumption under the different discriminatory and non-discriminatory tax policy scenarios.

The unilateral carbon tax policy leads to an increase in the carbon input costs for companies within the EU borders. As a result, industries devote higher share of their labor to adopt abatement measures, which in turn results in a significant reduction in CO_2 emissions within the EU, as depicted in Table 4. However, in the absence of border adjustment measures, a portion of the goods' production, which previously occurred within the EU border, is now being relocated outside of its borders. This shift has an unintended consequence of transferring emissions to countries with more lenient carbon pricing. This phenomenon, known as "leakage", undermines the global carbon emission reduction that the EU's unilateral tax policy intended to achieve. In the new equilibrium, the EU's overall carbon emissions decrease

Table 3: Changes in Welfare Outcomes Under Different Carbon Border Adjustment Policies

	ΔW_{EU}	ΔW_{RoW}	ΔW_{Global}
Carbon Tax	−1.12%	0.68%	0.18%
Carbon Tax & Policy A	0.06%	0.33%	0.25%
Carbon Tax & Policy B	−0.17%	0.55%	0.35%
Carbon Tax & Policy C	1.40%	−0.06%	0.34%
Carbon Tax & Policy D	1.18%	0.16%	0.44%

Notes: This table reports the changes in welfare, expressed as percentages, under various carbon tax and border adjustment policies. The columns represent welfare changes for the European Union, rest of the world, and global impact, respectively. Different rows designate distinct policy scenarios: a standalone carbon tax and carbon taxes paired with Policies A through D. Welfare changes are quantified based on consumption, emissions, and the subsequent climate-adjusted welfare implications of each policy scenario.

by approximately 427 million tonnes, while an extra 54 million tonnes of carbon gets released elsewhere globally. Nonetheless, there is a net reduction of 373 million tonnes in global carbon emissions, predominantly attributable to the substantial reductions within the EU.

The consumption level in the EU falls drastically due to several reasons. Firstly, the rise of carbon prices leads to higher production costs and favors higher choices of abatement, and consequently, the prices of domestic products will increase. This dynamic not only suppresses domestic production levels but also causes a shift of production to foreign countries, resulting in reduced domestic income within the EU. The combined effect of surging prices and diminishing income effectively decreases EU's consumption level.

In contrast, as certain goods, previously produced within the EU borders, now manufactured in other countries, global income–outside the EU–witnesses a rise, leading to increased consumption in these regions. Additionally, as some of foreign consumers continue to purchase goods imported from the EU, the unilateral carbon tax accidentally on purpose imposes a tax incidence on these non-EU consumers, driving up their overall prices and subsequently, shrinking their consumption levels. The ultimate impact on consumption depends on the interplay between these two forces. As denoted in Table 4, in the absence of EU border adjustments, the overall consumption level in the rest of the world increases by about 1.93 trillion US dollars[12]. Furthermore, the 373 million tonnes of global CO_2 emission reduction under EU's carbon tax policy results in an increase in the welfare of all the countries. Both the rise in consumption outside the EU and net global carbon emission reduction lead to 0.68% increase in climate-adjusted welfare for regions beyond the EU's borders.

Globally, welfare trends upward, primarily driven by improvements in the rest of the world which overshadow the decline in EU's welfare. Although there's a noticeable drop in global consumption, predominantly stemming from the EU, this is more than offset by the significant reduction in global emissions, resulting in an overall improvement of global welfare.

The second row of each region in Table 3 represents the implications of policy A. Under

[12] Determined using the expenditure-side real GDP at chained purchasing power parities (PPPs) in trillions of 2017 US dollars to provide a consistent metric for evaluating relative consumption values across different countries and regions.

this policy, the EU enforces non-discriminatory import tariffs on all products entering the region. The tariff rate is determined by the abatement choices made by industries within the EU borders. Consequently, the shifting of production for goods–originally driven abroad due to carbon taxes–becomes less viable. This is because the final product prices are now more aligned; goods produced outside the EU are subject to tariffs, effectively passing through the carbon taxes to the producer prices within the EU. As a result, leakage, or the movement of production overseas, is significantly reduced. The total leakage to the rest of the world is now estimated at about 19 million tonnes of CO_2. At the same time, the emission reduction within the EU borders remains largely unchanged by this border tax policy. This leads to further global carbon emission reduction, and as a result, the reduction in disutility associated with this channel will be higher.

Table 4: *Changes in Equilibrium Emission and Consumption Under Different Carbon Border Adjustment Policies*

	$\Delta CO_2^{(EU)}$	$\Delta CO_2^{(RoW)}$	ΔV_{EU}	ΔV_{RoW}
Carbon Tax	−426.82	53.64	−1.93	0.14
Carbon Tax & Policy A	−424.43	19.09	−1.75	−0.17
Carbon Tax & Policy B	−421.58	−6.82	−1.80	−0.06
Carbon Tax & Policy C	−416.36	−50.87	−1.56	−0.55
Carbon Tax & Policy D	−413.49	−76.76	−1.61	−0.44

Notes: This table presents the changes in CO_2 emissions and consumption values for the European Union (EU) and the rest of the world (RoW) under various carbon tax and adjustment policies. The first two columns denote the emission changes in million tonnes for the EU and RoW, respectively. The columns 3 and 4 represent the variations in consumption, measured in trillion 2017 US dollars, for the respective regions. The rows highlight five distinct policy scenarios: a carbon tax without border adjustments, and carbon taxes combined with four border adjustment policies introduced earlier. The cumulative global emission and consumption changes under each policy scenario can be calculated by summing the values corresponding to both the EU and RoW.

Under Policy A, the EU's imposition of import tariffs on products entering its borders generates additional revenue, primarily from tariffs paid by foreign producers, which subsequently boosts the income of domestic consumers. Furthermore, by preventing the relocation of production to countries outside the EU, the potential revenue losses from the unilateral carbon tax policy become less significant. Consequently, EU consumers see only 1.75 trillion USD drop in consumption–a less severe outcome than in scenarios without border adjustments. Nevertheless, this mitigation on production relocation also curtails potential revenue that might have been garnered for foreign consumers from such shifts. Moreover, the tax incidence that is paid by foreign consumers due to higher prices of goods produced within the EU borders still contributes to lower consumption level in the rest of the world. Tariffs collected at the EU border additionally erode income levels in other countries, leading to an overall decline of 0.17 trillion USD in global consumption outside the EU.

Overall, the two-fold mechanisms of reduced carbon leakage and minimized consumption loss translate into a marginal welfare improvement for the EU. Specifically, the simultaneous implementation of a carbon tax and import tariffs results in a 0.0.6% improvement in EU welfare. This represents a substantial improvement of 1.18% in EU's aggregate welfare, in contrast to the baseline scenario absent of border adjustments.

It is essential to recognize that the EU's carbon tax combined with a non-discriminatory import tariff yields positive welfare outcomes outside the EU, even though import tariffs typically induce negative welfare impacts for other nations. The reason is that the net global emission reduction is more pronounced than the baseline scenario due to leakage being mitigated. Under the implemented import tariff scenario, there is now a small consumption reduction in the rest of the world. However, the effect of the emission reduction dominates the negative welfare effect of consumption reduction, and as a result, the welfare of the rest of the world is increasing. It is worth noting that the introduction of import-side border adjustments generates heterogeneous effects across different countries, contingent upon their respective emission intensities. Countries with high carbon intensity, commonly referred to as "dirty" countries, experience lower welfare gains or, in certain instances, even welfare losses. Conversely, countries with lower carbon intensity witness more substantial welfare improvements. The net effect of these heterogeneous impacts is such that the welfare gains in less carbon-intensive countries outweigh the losses in their more carbon-intensive counterparts, thereby resulting in an overall increase in welfare among countries outside the EU.

It is evident that the European Union's policy A, which combines a unilateral carbon tax with non-discriminatory import tariffs, results in an improvement in welfare not only within the EU but also globally. Specifically, this policy structure yields a net increase in global welfare compared to a baseline scenario that lacks any unilateral carbon tax policies. The principal driver of this improvement is that the welfare gains accruing from additional global emission reductions outweigh the losses incurred due to reduced global consumption. In economic terms, the policy constitutes a Pareto-improving scenario. Under this framework, the welfare of all participating entities–both within and outside the EU–experiences an upward trajectory.

The policy structure represented by the third row in each region within Tables 3 and 4 corresponds to Policy B, which features the enactment of a unilateral carbon tax complemented by non-discriminatory import tariffs as well as an export subsidy. The introduction of the export subsidy diminishes the tax incidence of the EU's unilateral carbon tax policy on foreign consumers. By rebating the carbon tax levied on exported goods back to producers, foreign consumers are insulated from any direct price increase attributable to the EU's carbon tax. That leads to an overall milder consumption reduction in countries outside the EU. This arrangement, however, leads to diminished net border revenues and consequently a greater reduction in consumption levels in the EU, compared to the scenario with no export subsidies. Nevertheless, this consumption contraction is less severe than what is observed in the benchmark scenario without any border adjustments. The export subsidies also induces a market shift, enhancing the competitiveness of EU-produced goods in foreign markets. Given that domestic industries within the EU are generally more climate-conscious–owing to their abatement strategies–this shift results in a substantial global emissions reduction. Although the EU's own emissions reduction remains largely unaffected by the addition of export subsidies, not only is carbon leakage eliminated in the rest of the world, but also emissions in these regions begin to decline as well. However, it is important to note that the new equilibrium under this policy framework results in a 0.17% reduction in EU welfare. This decline is attributable to the increased tax incidence on domestic consumers, arising from the reduced net border revenues and the corresponding allocation of the tax burden.

The expansion of market share for domestic firms within the EU corresponds to a reduction of production activities in foreign countries, thereby leading to diminished income levels in these foreign economies. Although the tax burden on foreign consumers is alleviated due to EU's export subsidies, the decline in their income partially offsets this benefit and still culminates in a 60 billion US dollars reduction in consumption levels. However, this reduction is less severe compared to scenarios where import tariffs are imposed without any export subsidies. Given that the consumption decline is mitigated and the emissions reduction is higher under this policy framework, the net welfare effect for countries outside the EU is 0.55% in the new equilibrium. Notably, this welfare improvement is more pronounced than that observed in policy Policy A. It is imperative to note that, as evidenced by our empirical analysis, the alleviation of tax incidence on foreign consumers through the introduction of export subsidies more than compensates for the income loss incurred from reduced market share, irrespective of a country's carbon intensity ("dirtiness"). The addition of a lower disutility from emissions further solidifies this welfare-improving effect. Therefore, compared to scenarios without the incorporation of export subsidies, the welfare of all countries outside EU exhibits an improvement under this policy configuration.

In summary, when constraining the policy options to non-discriminatory border taxes, the most favorable course of action from the European Union's perspective is to complement a unilateral carbon tax with uniform import tariffs. Remarkably, this policy choice is Pareto-improving, yielding welfare gains of 0.0.06% for the European Union and 0.33% for the rest of the world (RoW). Collectively, this translates into a 0.25% net improvement in global welfare.

5.2 Discriminatory Border Adjustment

In this section, we present the key findings from our quantitative analysis of discriminatory CBAMs consisting of non-uniform import tariffs and export subsidies. We highlight the distinctions between these discriminatory mechanisms and their non-discriminatory counterparts.

In continuation of our prior analysis, the fourth row for each region in Tables 3 and 4 corresponds to policy scenario C wherein the EU enacts discriminatory import tariffs at its borders in conjunction with its unilateral tax policy. The introduction of discriminatory import tariffs yields effects on equilibrium outcomes that are qualitatively similar to those observed in non-discriminatory cases. However, the magnitudes of these effects differ, leading to distinct overall welfare implications, as illustrated by Table 3. Under discriminatory import-side border taxes, industries with greater carbon intensity face more substantial tax burdens compared to their less carbon-intensive counterparts. This stratified approach enables the EU to extract higher levels of tax revenue specifically from industries contributing significantly to global emissions. Consequently, these more carbon-intensive–or "dirty"–industries experience a contraction in both market share and production levels, thereby enabling the EU to more effectively mitigate cross-border leakage. As reported in Table 4, this policy framework not only eliminates leakage but also fosters emissions reductions in regions outside the EU. It is noteworthy that the EU's own emissions reductions remain largely unaffected by this import-side border adjustment policy, remaining steady at a level of 416 million tonnes of CO_2. Nevertheless, the policy results in a markedly more substantial global emissions reduction in the new equilibrium, quantified at 467 million tonnes of CO_2. Owing to higher border tax revenues, the EU experiences a more moderate consumption loss under this policy, amounting to approximately 1.56 trillion USD. This is more favorable than the outcome under non-discriminatory import tariffs. The combination of substantial emissions reductions and moderated consumption decline yields a net welfare gain of 1.4% for the EU, representing the EU's most favorable welfare outcome across all examined policy scenarios.

On the contrary, under this border adjustment scheme, the EU imposes more substantial taxes on dirty industries, which in turn results in a decrease in income for foreign consumers residing in countries where these high-emission industries are located. Empirical data reveals a dependency of industrial carbon intensity on country-level regulations, implying that industries in countries with lenient environmental oversight tend to be more carbon-intensive. Consequently, consumers in such dirty countries experience more severe reductions in consumption levels. It should be noted that all foreign consumers will experience a contraction in consumption levels. This contraction is attributable not only to the income reduction caused by the transfer of tax revenues at the EU border, but also to the direct tax incidence emerging from the EU's unilateral carbon tax policy. This dual effect leads to an overall 2.11 trillion US dollars decrease in global consumption outside the EU, as shown in Table 4.

As a consequence of the significant consumption declines experienced by countries with relatively high carbon emissions intensity, the aggregate welfare gains attributed to global emission reductions are largely offset by the welfare losses incurred due to diminished consumption in these nations. Accordingly, the aggregate welfare impact within these more carbon-intensive countries translates into a marginal net welfare loss of less than 0.1% for the rest of the world, as shown in Table 3. Despite this marginal decline in welfare for the rest of the world under this policy, global welfare still experience an overall increase of 0.34%, primarily driven by the substantial welfare gains realized within the EU.

The incorporation of the export subsidies under Policy D, denoted by the fifth rows in Tables 3 and 4), exhibits similar dynamics to those observed in the non-discriminatory case. Specifically, rebating the carbon tax to exporters effectively lowers the tax incidence on foreign consumers by mitigating any upward price adjustments originating from the EU's unilateral carbon tax measures. It is important to note, however, that these export subsidies also lead to a decline in the market share of foreign producers in global markets, which puts downward pressure on the incomes of foreign consumers. The net consumption loss of this border adjustment mechanism is anticipated to be more severe than its non-discriminatory version, due to the substantial tariffs on dirty industries, with an estimated magnitude of 0.44 trillion USD. This is further attributable to the fact that although foreign consumers are insulated from the direct price effects of the carbon tax (hence experiencing no tax incidence), they incur income losses due to declining market shares both within and outside the EU. Simultaneously, the increased market penetration of EU products leads to higher incomes for EU consumers. However, this benefit is partially offset by a decrease in border revenues previously collected from import tariffs. Therefore, depending on the net interplay of these competing factors, the EU may witness either a relative increase or decrease in consumption loss. In the resulting equilibrium, the EU incurs a consumption loss approximating 1.61 trillion USD.

In terms of emissions, the incorporation of export subsidies leads to a reconfiguration of industrial production: activity shifts from carbon-intensive country-industry pairs to less carbon-intensive ones. As illustrated in Table 4, this policy adjustment yields a higher overall reduction in global carbon emissions. Specifically, it results in a further decrease in emissions in the rest of the world, while the emission reductions within the EU remain relatively stable. The net reduction in global CO_2 emissions amounts to 490 million tonnes. In terms of welfare implications, the EU experiences a net welfare gain, as the benefits stemming from global emission reduction outweigh the negative impacts associated with consumption loss. Moreover, the welfare of the rest of the world also turns positive, driven by both more substantial emission reductions and mitigated consumption losses. This results in a global welfare improvement, establishing a second Pareto-improving policy option. Under this policy structure, which combines discriminatory import tariffs and export subsidies with unilateral carbon tax policy, the EU enjoys a 1.18% welfare gain, while the rest of the world experiences a 0.16% improvement. In aggregate, these effects yield a 0.44% increase in global welfare.

It is critical to underscore that, from the viewpoint of the European Union, the coupling of discriminatory import tariffs with unilateral carbon taxes yields the most favorable welfare outcomes for the EU. Nonetheless, this policy approach may attract scrutiny due to its marginally adverse impact on the welfare of the rest of the world. Such circumstances could prompt countries to lodge formal complaints with the World Trade Organization (WTO) regarding the effects of the EU's policies on their respective consumer bases. However, the incorporation of export subsidies into this policy framework ensures a net welfare improvement for the rest of the world, thereby providing a more defensible justification for the policy's implementation.

From both the EU's and the global perspective, the second Pareto-improving policy option –which incorporates both discriminatory import-side and export-side border adjustments– emerges as the more favorable option, given that it yields a more substantial positive welfare impact compared to the first Pareto-improving policy. However, it is imperative to consider the international legal framework, specifically the clauses outlined by the World Trade Organization (WTO). Article II of the General Agreement on Tariffs and Trade (GATT) 1994 establishes the principle of non-discriminatory tariff treatment, also known as the most-favored-nation (MFN) principle. Under this MFN principle, WTO members are obligated to accord equal treatment to all other WTO members with respect to tariff rates and other trade-related measures. Consequently, discriminatory taxes stand in contravention to the WTO's governing clauses on import tariffs. Furthermore, the WTO's Agreement on Subsidies and Countervailing Measures (SCM Agreement) explicitly prohibits export subsidies, deeming them detrimental to the integrity of international trade by providing exporters with an undue advantage and distorting competition. Therefore, the implementation of the second Pareto-improving policy, despite its unambiguous welfare benefits for both the EU and the global community, is likely to ignite political tensions and could be deemed incompatible with existing international trade laws. Such legal and diplomatic complexities substantiate the EU's decision to opt for a policy of non-discriminatory import tariffs as the carbon border adjustment mechanism accompanying its unilateral carbon tax initiatives. This choice is particularly remarkable given that, as of October 1, 2023, the Carbon Border Adjustment Mechanism (CBAM) has entered its transitional implementation phase.

6 Conclusion

As climate change persists as an existential threat to humanity, the need for urgent collective action has become increasingly dire. However, past international climate agreements have failed to deliver meaningful emissions reductions. This policy inertia at the global level has compelled some nations to spearhead unilateral carbon pricing initiatives as an alternative approach to driving decarbonization. While such unilateral measures can help internalize the costs of emissions, they also risk unintended consequences like carbon leakage and reduced domestic competitiveness. To countervail these challenges, Carbon Border Adjustment Mechanisms (CBAMs) have emerged as a prominent policy proposal. By levying variable taxes on imports and subsidizing exports based on their carbon footprints, CBAMs can help harmonize carbon costs across borders, thereby preserving the efficacy of unilateral climate policies.

This paper developed an analytical framework and empirical model to evaluate the efficacy and welfare impacts of alternative CBAM designs when implemented alongside a unilateral carbon tax. We focused specifically on the case of the European Union, quantifying outcomes under distinct policy scenarios involving import tariffs and export subsidies that were either discriminatory or non-discriminatory in their application across trade partners. The model framework allowed us to isolate four key mechanisms linking carbon border taxes to welfare outcomes: domestic emission reductions, tax incidence on the rest of the world, impacts on factoral terms of trade, and carbon leakage mitigation. This decomposition of channels enabled a comprehensive understanding of how each component of CBAMs influences economic outcomes and emissions abatement under different possible regimes.

The quantitative analysis yielded several pivotal insights that can inform the design of judicious climate policy. Non-discriminatory CBAMs with only import tariffs emerge as the most favorable unilateral policy structure from the EU's standpoint, yielding welfare gains for both the EU and its trade partners by mitigating leakage and representing a Pareto improvement over policy inaction. Incorporating export subsidies into CBAMs can exacerbate EU welfare losses, as the dissipation of tax incidence gains on foreign consumers outweighs factoral terms of trade benefits. Discriminatory CBAMs with both import tariffs and export subsidies maximize global emissions abatement but reduce EU's welfare relative to non-discriminatory import tariffs. All CBAM regimes substantially curb carbon leakage, but only discriminatory policies with export subsidies yield reverse leakage and net emission reductions abroad. The EU's current non-discriminatory import tariff CBAM design emerges as a judiciously balanced climate policy initiative given tradeoffs across economic and environmental objectives.

These findings carry valuable insights for both researchers and policymakers in navigating the complex terrain of unilateral climate policy. The methodology and conclusions can inform future trade and environmental modeling efforts by providing a blueprint for understanding incidence effects of border carbon taxes that transcends specific functional assumptions. On the policy front, the results highlight nuances in configuring carbon border taxes to align with domestic interests while still advancing collective climate action. The analysis suggests that even without export subsidies or discrimination, CBAMs can significantly mitigate competitiveness and leakage concerns that have hindered climate policy ambitions in open economies. But the study also reveals possibilities to judiciously design CBAM regimes that improve welfare globally, not just domestically, thereby garnering broader political support for unilateral carbon initiatives that are environmentally progressive yet economically pragmatic.

There remain fruitful avenues for further research to build upon this analysis, including endogenizing trading partners' strategic policy responses, expanding sectoral dimensions, utilizing finer-grained data, and dynamic modeling of year-to-year transitions. In closing, unilateral carbon pricing and border adjustments present a politically and analytically complex nexus with high stakes for both global cooperation and national interests. This study contributes to knowledge in an arena where research has fallen behind real world policy developments. With pragmatic design guided by rigorous analysis, unilateral initiatives can put meaningful carbon pricing into practice, serving as stepping stones towards a shared global vision of decarbonization.

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A Theoretical Framework Details

A.1 Carbon Accounting

To define environmentally adjusted national-level welfare, it is essential to develop a formal framework to measure the disutility arising from pollution emitted during the production process. This section provides such a framework, linking carbon emissions to changes in national welfare. In this framework, we consider that the perceived cost of CO_2 emissions has two fundamental components:

i. A climate-related cost component, denoted by ϕ_n, which quantifies the disutility of each unit of CO_2 emissions for the government in country n.

ii. A secondary pollutant-related cost component, denoted by ϕ_n^0, which represents the disutility inflicted by local pollutants, such as oxides of nitrogen or sulfur, that accompany CO_2 emissions during the production in sector k of country n.

Unlike the first term, the impact described by the second term is localized, affecting the immediate environment and human health within the emitting country. We assume that the rate of local pollution generated per unit of CO_2 emissions for a specific industry k within the country of origin n is quantitatively represented by the parameter $\zeta_{n,k}$. Accordingly, the total disutility of country n from the global CO_2 emissions and local pollutants will be given by $\phi_n \sum_i \sum_k Z_{i,k}$ and $\phi_n^0 \sum_k \zeta_{n,k} Z_{n,k}$, respectively. For the sake of simplicity of our notations, we introduce a new parameter $\delta_{in,k}$, which serves as an aggregate measure of both global and localized disutilities associated with emitting $Z_{n,k}$ amount of CO_2 to the atmosphere, to be given by

$$\delta_{in,k} = \phi_n + \phi_n^0 \zeta_{n,k} \cdot 1\{i = n\}.$$

Finally, the objective of the government in country n is to maximize the national-level welfare, W_n, which is defined as

$$W_n \equiv V_n\left(Y_n, \tilde{\mathbf{P}}_n\right) - \sum_i \sum_k \delta_{in,k} Z_{i,k},$$

To further reduce notational complexity, we introduce an average disutility term per unit of global emission, δ_n, expressed as

$$\delta_n \equiv \sum_i \sum_k \delta_{in,k} \frac{Z_{i,k}}{Z},$$

where $Z = \sum_i \sum_k Z_{i,k}$. Therefore, the national-level welfare can be reformulated as

$$W_n = V_n\left(Y_n, \tilde{\mathbf{P}}_n\right) - \delta_n \sum_i \sum_k Z_{i,k}.$$

In essence, the parameter δ_n acts as an integrated parameter that captures both the global and localized disutilities arising from CO_2 emissions in a given country. This parameter simplifies the welfare function, facilitating the subsequent empirical analyses and policy evaluations while retaining the core elements of environmental cost.

A.2 Welfare Decomposition

For the purpose of clarity, as we mentioned earlier, we consider a special case consumer utility that conforms to a Cobb-Douglas specification. Accordingly, the price index and CO2 emissions associated with origin n–industry k can be specified as

$$P_{ni,k} = d_{ni,k}\bar{p}_{nn,k}w_n \left(1 - a_{n,k}\right)^{-1},$$

$$Z_{n,k} = \left(1 - a_{n,k}\right)^{\frac{1}{\alpha_{i,k}}-1} Q_{n,k}.$$

In addition, the optimal choice of abatement under the Cobb-Douglas specification is given by

$$\left(1 - a_{i,k}\right) = \left(\frac{\alpha_{i,k}}{1-\alpha_{i,k}}\right)^{\alpha_{i,k}} \left(\frac{w_i/\bar{\varphi}_{i,k}}{\tau_{i,k}}\right)^{\alpha_{i,k}}.$$

Under the Cobb-Douglas assumption, the input cost share of carbon $\alpha_{i,k}$ is constant. Subsequently, we may expressed the first order difference of abatement with respect to changes in carbon prices by

$$\frac{\mathrm{d}\ln\left(1-a_{i,k}\right)}{\mathrm{d}\ln\tau_{i,k}} = \frac{\partial\ln\left(1-a_{i,k}\right)}{\partial\ln\tau_{i,k}} + \frac{\partial\ln\left(1-a_{i,k}\right)}{\partial\ln w_i}\frac{\mathrm{d}\ln w_i}{\mathrm{d}\ln\tau_{i,k}} = \alpha_{i,k}\left(\frac{\mathrm{d}\ln w_i}{\mathrm{d}\ln\tau_{i,k}} - 1\right).$$

As previously discussed, we may distinguish between the channels through which perturbing carbon taxes τ_n, k impacts welfare as may write the first order condition, given by

$$\frac{\mathrm{d}W_i}{\mathrm{d}\ln\tau_i} = \underbrace{\frac{\partial V_i\left(.\right)}{\partial Y_i}\frac{\mathrm{d}Y_i}{\mathrm{d}\ln\tau_i}}_{\text{income effects}} + \underbrace{\sum_k \frac{\partial V_i\left(.\right)}{\partial\ln\tilde{P}_{ii,k}}\frac{\mathrm{d}\ln\tilde{P}_{ii,k}}{\mathrm{d}\ln\tau_i}}_{\text{consumer price effects}} - \underbrace{\delta_i\sum_n Z_n\frac{\mathrm{d}\ln Z_n}{\mathrm{d}\ln\tau_i}}_{\text{carbon emissions}} \tag{20}$$

Using Equation (7) and the derivations for the Cobb-Douglas case, we may derive income effects, given by

$$\begin{aligned}
\frac{dY_i}{d\ln\tau_i} &= w_iL_i\frac{d\ln w_i}{d\ln\tau_{i,k}} + \sum_k \alpha_{i,k}P_{ii,k}Q_{i,k}\left(\frac{d\ln Q_{i,k}}{d\ln\tau_{i,k}} + \frac{\partial\ln P_{ii,k}}{\partial\ln\tau_{i,k}} + \frac{\partial\ln P_{ii,k}}{\partial\ln w_i}\frac{\mathrm{d}\ln w_i}{\mathrm{d}\ln\tau_{i,k}}\right) \\
&= \left(\sum_k\left(1+\alpha_{i,k}\right)\left(1-\alpha_{i,k}\right)P_{ii,k}Q_{ii,k}\right)\frac{\mathrm{d}\ln w_i}{\mathrm{d}\ln\tau_{i,k}} + \sum_k\left[\alpha_i P_{ii,k}Q_{i,k}\left(\frac{\mathrm{d}\ln Q_{i,k}}{\mathrm{d}\ln\tau_{i,k}} + \alpha_{i,k}\right)\right] \\
&= \left(\sum_k\left(1-\alpha_{i,k}\right)\left[P_{ii,k}Q_{ii,k} + \tau_{i,k}Z_{i,k}\right]\right)\frac{\mathrm{d}\ln w_i}{\mathrm{d}\ln\tau_{i,k}} + \sum_k\left[\tau_{i,k}Z_{i,k}\left(\frac{\mathrm{d}\ln Q_{i,k}}{\mathrm{d}\ln\tau_{i,k}} - \left(1-\alpha_{i,k}\right)\right) + \alpha_{i,k}P_{ii,k}Q_{i,k}\right]
\end{aligned} \tag{21}$$

where the second line uses $w_iL_i = \sum_k\left(1-\alpha_{i,k}\right)P_{ii,k}Q_{i,k}$ as well as invokes two relationships arising from cost minimization: (1) $\alpha_{i,k}P_{ii,k}Q_{i,k} = \tau_{i,k}Z_{i.k}$, and that (2) per Shephard's lemma

$$\frac{\partial\ln P_{i,k}}{\partial\ln\tau_{ii,k}} = \alpha_{i,k}, \qquad \frac{\partial\ln P_{ii,k}}{\partial\ln w_i} = 1 - \alpha_{i,k}$$

Supposing $d\ln w_n \approx 0$ if $n \neq i$, then the consumer price effects, which is the second term in the right hand side of Equation (21), can be written as

$$\sum_k \left[\frac{\partial V_i(.)}{\partial \ln \tilde{P}_{ii,k}} \frac{\mathrm{d}\ln P_{ii,k}}{\mathrm{d}\ln \tau_{i,k}}\right] = -\frac{\partial V_i(.)}{\partial Y_i} \sum_k \left(P_{ii,k} Q_{ii,k} \left[\frac{\partial \ln P_{ii,k}}{\partial \ln \tau_{i,k}} + \frac{d\ln P_{ii,k}}{d\ln w_i}\frac{d\ln w_i}{d\ln \tau_{i,k}}\right]\right)$$
$$= -\frac{\partial V_i(.)}{\partial Y_i} \sum_k \left(P_{ii,k} Q_{ii,k} \left[\alpha_{i,k} + (1-\alpha_{i,k})\frac{d\ln w_i}{d\ln \tau_{i,k}}\right]\right), \tag{22}$$

where the first line invokes Roy's identity, whereby $\frac{\partial V_i(Y_i,\tilde{\mathbf{P}}_i)}{\partial \tilde{P}_{ii,k}} = -\frac{\partial V_i(Y_i,\tilde{\mathbf{P}}_i)}{\partial Y_i} Q_{ii,k}$, and the fact that $\tilde{P}_{ii,k} = P_{ii,k}$ since the non-traded variety ii,k is not taxed.

With that, the final expression in the right hand side of first order condition of welfare, which represents the welfare effects of changes in carbon emission, can be written as

$$\delta_i \sum_n Z_n \frac{d\ln Z_n}{d\ln \tau_i} = \tilde{\delta}_i \frac{\partial V_i}{\partial Y_i}\left\{\sum_k Z_{i,k}\left(\frac{\partial \ln Z_{i,k}}{\partial \ln Q_{i,k}}\frac{d\ln Q_{i,k}}{\partial \ln \tau_{i,k}} + \frac{\partial \ln Z_{i,k}}{\partial \ln \tau_{i,k}} + \frac{\partial \ln Z_{i,k}}{\partial \ln w_i}\frac{d\ln w_i}{d\ln \tau_{i,k}}\right)\right.$$
$$\left. + \sum_{n\neq i} Z_n \frac{\partial \ln Z_n}{\partial \ln Q_n}\frac{\mathrm{d}\ln Q_n}{\mathrm{d}\ln \tau_i}\right\}.$$

It follows that

$$\delta_i \sum_n Z_n \frac{d\ln Z_n}{d\ln \tau_i} = \tilde{\delta}_i \frac{\partial V_i}{\partial Y_i}\left\{\sum_k Z_{i,k}\left(\frac{d\ln Q_{i,k}}{\partial \ln \tau_{i,k}} - (1-\alpha_{i,k}) + (1-\alpha_{i,k})\frac{d\ln w_i}{d\ln \tau_{i,k}}\right) + \sum_{n\neq i} Z_n \frac{\mathrm{d}\ln Q_n}{\mathrm{d}\ln \tau_i}\right\}, \tag{23}$$

where the expression it uses the following relationships:

$$\tilde{\delta}_i \equiv \delta_i \left(\frac{\partial V_i}{\partial Y_i}\right)^{-1}, \qquad \frac{\partial \ln Z_{i,k}}{\partial \ln Q_{i,k}} = \frac{\partial \ln Z_n}{\partial \ln Q_n} = 1, \qquad \frac{\partial \ln Z_{i,k}}{\partial \ln \tau_{i,k}} = -\frac{\partial \ln Z_{i,k}}{\partial \ln \tau_{i,k}} = 1 - \alpha_{i,k}.$$

Plugging Equations (21-23) back into Equation (20) and dropping the industry subscript for the carbon tax yields

$$\frac{\mathrm{d}W_i}{\mathrm{d}\ln \tau_i} = \frac{\partial V_i}{\partial Y_i}\left\{(\tau_i - \tilde{\delta}_i)\sum_k \left[Z_{i,k}\left(\frac{d\ln Q_{i,k}}{d\ln \tau_i} + (1-\alpha_{i,k})\frac{d\ln(w_i/\tau_i)}{d\ln \tau_i}\right)\right]\right.$$
$$\left. + \underbrace{\sum_k [\alpha_{i,k} P_{ii,k}(Q_{i,k} - Q_{ii,k})]}_{\text{carbon content of exports}} + \underbrace{\sum_k [(1-\alpha_{i,k}) P_{ii,k}(Q_{i,k} - Q_{ii,k})]}_{\text{labor content of exports}} \frac{d\ln w_i}{d\ln \tau_i} - \tilde{\delta}_i \sum_{n\neq i} Z_n \frac{\mathrm{d}\ln Q_n}{\mathrm{d}\ln \tau_i}\right\}.$$

Note that $\frac{d\ln(w_i/\tau_i)}{d\ln \tau_i} \sim \frac{d\ln(w_i)}{d\ln \tau_i} - 1$. With that, the welfare impact of carbon taxes under the closed economy can be rewritten as

$$\frac{\mathrm{d}W_i}{\mathrm{d}\ln \tau_i} = \frac{\partial V_i}{\partial Y_i}(\tau_i - \tilde{\delta}_i)\sum_k \left[Z_{i,k}\left(\frac{d\ln Q_{i,k}}{d\ln \tau_i} + (1-\alpha_{i,k})\frac{d\ln(w_i/\tau_i)}{d\ln \tau_i}\right)\right],$$

where it captures the change in welfare externalities from domestic emissions, as it equals zero if carbon is optimally taxed at $\tau_i = \tilde{\delta}_i$. And it is non-zero only if the carbon externality is not properly taxed.

B Data and Calibration

The WIOD Environmental Accounts contain data on emissions of several air pollutants, including CO_2, CH4, and N2O, broken down by country and industry of origin. We use these data to calculate CO_2 equivalent (CO_2e) emissions using the global warming potentials from the IPCC. More specifically, we write

$$Z_{i,k} = Z_{i,k}^{CO2} + 28 \times Z_{i,k}^{CH4} + 265 \times Z_{i,k}^{N2O}$$

for every pair of origin country and industry. This method is valid as emissions of CO_2, CH4, and N2O constitute 97% of global greenhouse gas emissions. This allows us to then calculate carbon intensity for origin i industry k using

$$v_{i,k} = \frac{Z_{i,k}}{P_{ii,k} Q_{i,k}}$$

where $Z_{i,k}$ is CO_2e emissions in tonnes, and the denominator is gross output measured in US dollars given by $\sum_n P_{in,k} Q_{in,k}$. We use carbon emissions or CO2 emissions as shorthand for CO_2e.

Table A.1 reports some key statistics at the industry level that will help interpret the quantitative results in Section 5. It is evident from these statistics that non-manufacturing industries such as Agriculture, Electricity, and Transportation account for a substantial portion of global CO_2 emissions. Conversely, all manufacturing industries combined (industries 3-14) are responsible for only one-fifth of total global emissions. Moreover, a negative relationship exists between an industry's tradeability and its contribution to global emissions. For instance, the most tradeable sectors, Machinery & Electronics and Textiles & Leather, jointly produce less than 1% of global emissions. In contrast, Electricity Generation, Gas & Water Supply, and Agriculture generate over half of total emissions yet are among the least tradeable sectors. More broadly, industries with a trade-to-GDP ratio exceeding 0.10 are responsible for just one-third of worldwide emissions. This suggests that the majority of global emissions originate from industries with relatively low tradeability.

The inverse association between trade intensity and emission contribution has important implications for the effectiveness of trade-based policies aimed at curbing carbon dioxide emissions globally. The quantitative analysis will further explore this relationship.

Table A.2 provides detailed information on countries/regions in the sample, and their principal characteristics. In the year 2009, which is the baseline year for this study, the European Union (EU) commanded the largest share of the global GDP, contributing 27.2%, while being responsible for a relatively smaller portion, 12.1%, of global CO2 emissions. This low ratio of Emission Share to GDP Share is further corroborated by a value of 0.45. Conversely, China emerges as the dominant contributor to global CO_2 emissions with a 23.1% share, despite ac-

Table A.1: Industry-Level Statistics and Elasticities

	Industry	CO2 Emissions (% of total)	$\frac{\text{Trade}}{\text{GDP}}$	Carbon Intensity (ν)	Carbon Input Share (α)	Trade Elasticity ($\sigma - 1$)
1	Agriculture	19.9%	6.8%	100.0	0.020	2.05
2	Mining	8.0%	27.6%	40.4	0.019	1.80
3	Food	1.1%	9.0%	4.2	0.004	1.36
4	Textiles and Leather	0.4%	27.1%	4.2	0.005	0.86
5	Wood	0.2%	8.4%	5.4	0.010	3.42
6	Pulp and Paper	0.6%	8.9%	6.8	0.004	3.21
7	Coke and Petroleum	2.7%	17.9%	23.2	0.006	3.31
8	Chemicals	3.4%	24.6%	19.5	0.017	0.89
9	Rubber and Plastics	1.0%	14.0%	15.2	0.006	1.55
10	Non-Metallic Mineral	9.6%	13.1%	31.5	0.006	1.95
11	Metals	0.3%	25.9%	2.1	0.001	3.97
12	Machinery and Electronics	0.4%	37.1%	1.8	0.004	1.90
13	Transport Equipment	0.3%	23.3%	1.6	0.002	0.59
14	Manufacturing, Nec	0.4%	32.8%	10.1	0.005	0.59
15	Electricity, Gas and Water	32.0%	1.0%	205.5	0.018	7.14
16	Construction	0.9%	0.3%	2.1	0.008	7.14
17	Retail and Wholesale	1.8%	3.7%	2.6	0.009	6.93
18	Transportation	8.1%	10.9%	30.2	0.033	7.14
19	Other Services	9.0%	2.6%	4.1	0.007	1.59

Note: This table shows for every one of the 19 industries share from world CO2 emission, world-level trade-to-GDP ratio, global average carbon intensity (tonnes of CO_2 per dollar of output) normalized by that of agriculture, calibrated carbon cost shares reported as unweighted mean across countries within every industry, estimated trade elasticities, and markups. All CO_2 measures are CO_2 equivalent.

counting for only 13.6% of the world's GDP, reflected by its elevated carbon intensity of 204.31 normalized by Australia's carbon intensity. Furthermore, the ratio of Emission Share to GDP Share is markedly disparate across nations. It attains its lowest values in Japan (0.34) and the EU (0.45) while peaking in India (2.90) and Russia (2.96), indicative of diverging carbon efficiencies and policy landscapes across these economies.

The data on trade tariffs for the year 2009 were collected from the UNCTAD-TRAINS database. It covers 31 sectors at the two-digit level per the ISIC Revision 3 categorization, which was aggregated into the 19 industries for which international expenditure and emission data were compiled. Amongst UNCTAD-TRAINS' multiple metrics for applied tariffs, a simple tariff line average of the effectively applied tariff is used in this paper. Unless the origin country is a member of the European Union (EU), the applied tariff rates are reported for each *origin–destination–industry* combination. For EU members, tariffs are assigned based on the fact that the EU imposes no taxes on trade within the EU, and all members apply a common external tariff on goods imported from outside the EU.

Additional data is compiled based on Environmental Taxes by Economic Activity from EUROSTAT and Environmentally-related Taxes from OECD-PINE. The EUROSTAT data cover European countries and document environmentally-related taxes by country-industry pairs

Table A.2: Countries and their Select Characteristics

Country	Share of World GDP	Share of World CO2	Carbon Intensity ($\bar{v}_i$)	Emission Tax Rate ($\bar{\tau}_i$)	CO2 Disutility ($\tilde{\phi}_i$)	Normalized $\tilde{\phi}_i$
AUS	1.7%	1.4%	100.00	32.51	0.49	40.43
EU	27.2%	12.1%	53.57	80.41	19.12	100.00
BRA	2.4%	2.4%	121.33	13.43	0.28	16.70
CAN	2.0%	1.7%	102.68	20.83	0.37	25.90
CHN	13.6%	23.1%	204.31	6.93	0.82	8.61
IDN	1.0%	1.8%	218.95	8.43	0.07	10.48
IND	2.2%	6.5%	359.48	5.25	0.10	6.53
JPN	8.4%	2.9%	40.99	69.13	5.08	85.97
KOR	1.9%	1.6%	99.68	26.80	0.44	33.33
MEX	1.2%	1.4%	137.31	3.76	0.04	4.67
RUS	2.0%	5.8%	344.11	3.69	0.07	4.59
TUR	1.0%	0.9%	116.09	48.45	0.41	60.25
TWN	0.7%	0.8%	139.84	13.69	0.09	17.03
USA	21.1%	15.3%	87.32	18.18	3.35	22.61
RoW	13.5%	22.1%	197.23	2.21	0.26	2.75

Notes: This table shows every one of the 15 regions (13 countries + the EU + the RoW), their share of world GDP, share of world CO2 emissions, carbon intensity (CO2 emissions per dollar of output) normalized by that of Australia, emission tax rate (dollar per tonne of CO2), calibrated CPI-adjusted disutility parameter from one tonne of CO2 emission ($\tilde{\phi}_i$), and the ratio of $\tilde{\phi}_i$ to country i's GDP normalized to 100 for the EU. All CO2 measures are CO2 equivalent.

based on the NACE Revision 2 categorization, which is then mapped into the 19 ISIC industries in the described sample. The OECD-PINE data report environmentally-related taxes in each country as a percentage of national GDP. the quantitative analysis treats these taxes as proxy "carbon taxes", adjusted to account for local pollution as modeled.

In section 2, I showed that carbon input shares, defined as CO_2 emission per dollar of output, can be inferred from statistics on carbon taxes, emission intensities, given by

$$v_{n,k} = \frac{Z_{n,k}}{P_{nn,k}Q_{n,k}} = \frac{\alpha_{n,k}}{\tau_{n,k}}.$$

This equation implies the carbon cost share can be calculated as

$$\alpha_{n,k} = \frac{\tau_{n,k}Z_{n,k}}{P_{nn,k}Q_{n,k}} = \tau_{n,k}\tau_{n,k}.$$

This gives $\alpha_{n,k}$ for each country n and industry k pairs. Table A.1 reports mean $\alpha_{n,k}$ across countries within each industry k.

Estimates of the trade elasticity, $(\sigma_k - 1)$, are generated by implementing Caliendo and Parro (2015) estimation methodology using 2009 data on trade values and applied import tariffs. This technique recovers $(\sigma_k - 1)$ under the identifying presumption that bilateral variations in trade costs are orthogonal to idiosyncratic changes in demand across origin-destination pairs. The approach exploits this orthogonality restriction to uncover the causal effect of trade costs on trade volumes. The resulting estimated elasticity values are documented in Table A.1.

Specifically, the estimation relies on a structural gravity model of trade that controls for origin and destination fixed effects. Identification stems from the fact that bilateral trade costs provide a source of exogenous variation in trade volumes across country pairs after controlling for multilateral resistance terms using fixed effects. The estimated coefficient on bilateral trade costs recovers the trade elasticity parameter. A key advantage of this strategy is that it requires minimal modeling assumptions while delivering consistent estimates by leveraging granular policy variation.

The carbon input demand elasticity is estimated using country and industry-level data on relative carbon prices and expenditure shares. Based on the production function I defined earlier, one can formulate the relative expenditure on carbon versus labor inputs as a function of relative input prices, given by

$$\ln\left(\frac{\alpha_{n,k}}{1-\alpha_{n,k}}\right) = (1-\varsigma)\ln\left(\frac{\tau_{n,k}}{w_n}\right) + \varsigma\left(\frac{\kappa_{n,k}}{1-\kappa_{n,k}}\right).$$

The second term can be considered as an exogenous demand residual specific to the origin n industry k pair. Accordingly, estimating the above equation provides us with an estimate for carbon input demand elasticity ς. Given that the industry-specific carbon intensity $\kappa_{j,k}$ is correlated with covariates in the above regression, we cannot use an OLS estimator, due to the endogeneity problem. Alternatively, an instrumental variable (IV) approach, using energy reserves in every country as an instrument for their relative carbon price $\tau_{n,k}/w_n$, can address this problem. This IV estimation approach results in an estimated value of $\varsigma = 0.58$, with high first-stage F-statistics.

The perceived disutility of carbon emissions is calibrated based on two assumptions:

i. A country's applied environment-related taxes correspond to its perceived disutility from emissions;

ii. Global disutility from CO2 equals the social cost of carbon.

As indicated in the section A.1, I assume the perceived carbon emission disutility has two fundamental components: A climate-related cost denoted by ϕ_n, and a pollutant-related cost component denoted by $\phi^0_{n,k}$. I defined the aggregate measure of both global and localized disutilities associated with emitting $Z_{n,k}$ amount of CO_2 to the atmosphere, to be given by

$$\delta_{in,k} = \phi_n + \phi_{n,k} \cdot 1\{i = n\}.$$

Then the CPI-adjusted perceived CO_2 disutility are given by $\tilde{\delta}_{in,k} = \tilde{P}_i \delta_{in,k}$. Accordingly, based on the first assumption, the total environmental taxes in country n is given by $T^E_n = \sum_k (\tilde{\phi}_n + \tilde{\phi}_{n,k}) Z_{n,k}$, which is compiled using IPCC global warming potential weights. The second assumption implies that the global disutility from CO_2 equals the social cost of carbon (SCC), i.e. SCC = $\sum_n \tilde{\phi}_n$. The values of $\tilde{\phi}_n$, however, are not directly observed and need to be recovered. To accomplish this task, two determinants are considered. If all individuals cared equally about climate change, disutility would be directly proportional to country size, implying $\tilde{\phi}_n / \tilde{\phi}_m \propto Y_n / Y_m$. In addition, a country's relative disutility was assumed proportional to its per unit carbon taxes, suggesting

$$\frac{\tilde{\phi}_n}{\tilde{\phi}_m} \propto \frac{(T_n^E/Z_n)}{(T_m^E/Z_m)}.$$

Combining these two determinants yielded the specification $\tilde{\phi}_n = \bar{h}y_i(T_n^E/Z_n)$. To calibrate $\bar{h}$, the global social cost of carbon (SCC) is matched with the literature consensus of around $31 per tonne of CO_2-equivalent in 2010 USD terms, as estimated by United States Government's Interagency Working Group. This approach provides the estimate for $\tilde{\phi}_n$ for all countries and accordingly, the values of $tilde\phi_{n,k}$ can be obtained from the expression given for T_n^E. Table A.1 reports these calibrated values for all the countries in the sample.

C Additional Tables

Table A.3: *Changes in Equilibrium Outcomes Under No Carbon Border Adjustment Policy*

	Carbon Tax		
Country	ΔCO_2	ΔV	ΔW
AUS	0.15%	0.37%	1.18%
EU	-8.80%	-10.64%	-1.12%
BRA	0.15%	0.20%	0.52%
CAN	0.17%	0.34%	0.83%
CHN	0.13%	0.05%	0.20%
IDN	0.14%	0.23%	0.40%
IND	0.13%	0.01%	0.09%
JPN	0.14%	0.13%	2.04%
KOR	0.17%	0.15%	0.80%
MEX	0.14%	0.25%	0.34%
RUS	0.18%	0.78%	0.81%
TUR	0.15%	0.91%	2.07%
TWN	0.21%	0.15%	0.44%
USA	0.16%	0.15%	0.60%
RoW	0.18%	0.34%	0.38%
Global	**-0.93%**	**-2.76%**	**0.18%**

Notes: This table presents the impacts of a unilateral carbon tax policy in the absence of any border adjustment policies on equilibrium outcomes for various countries and regions. The columns are labeled as ΔCO_2, signifying changes in carbon emissions; ΔV, representing changes in consumption levels; and ΔW, indicating shifts in welfare, which takes into account both consumption and environmental effects. Within the table, *RoW* stands for the Rest of the World, a notation that varies from the main text. The European Union, denoted as *EU*, is the entity implementing the policies in these scenarios. The row marked as *Global* provides the weighted average changes of all countries, offering a comprehensive view of the global effect. All changes are depicted in percentages, illustrating deviations from the baseline scenarios when the respective policies are applied. The values presented emerge from counterfactual analyses built upon the equilibrium, utilizing the hat algebra technique.

Table A.4: *Changes in Equilibrium Outcomes Under Non-Discriminatory Carbon Border Adjustment Policies*

	Carbon Tax & Policy A			*Carbon Tax & Policy B*		
Country	ΔCO_2	ΔV	ΔW	ΔCO_2	ΔV	ΔW
AUS	0.06%	-0.09%	0.88%	-0.02%	-0.07%	1.03%
EU	-8.75%	-9.64%	0.06%	-8.69%	-9.93%	-0.17%
BRA	0.03%	-0.21%	0.19%	-0.03%	-0.07%	0.38%
CAN	0.04%	-0.28%	0.35%	-0.02%	-0.12%	0.60%
CHN	0.05%	-0.09%	0.11%	-0.01%	-0.01%	0.23%
IDN	0.05%	-0.14%	0.09%	-0.02%	-0.05%	0.23%
IND	0.04%	-0.30%	-0.16%	-0.02%	-0.02%	0.17%
JPN	0.06%	0.00%	2.16%	-0.02%	-0.02%	2.34%
KOR	0.09%	-0.02%	0.75%	-0.02%	-0.01%	0.90%
MEX	0.04%	-0.36%	-0.25%	-0.02%	-0.07%	0.06%
RUS	0.04%	-0.61%	-0.52%	-0.03%	-0.32%	-0.19%
TUR	0.05%	-0.34%	1.09%	-0.02%	-0.14%	1.53%
TWN	0.07%	-0.29%	0.11%	-0.02%	-0.02%	0.46%
USA	0.05%	-0.14%	0.40%	-0.02%	-0.04%	0.57%
RoW	0.07%	-0.65%	-0.59%	-0.02%	-0.27%	-0.19%
Global	**-1.01%**	**-2.81%**	**0.25%**	**-1.07%**	**-2.77%**	**0.35%**

Notes: This table presents the impacts of a unilateral carbon tax policy supplemented with non-discriminatory carbon border adjustment policies, specifically Policies C and D, on equilibrium outcomes for various countries and regions. The columns are labeled as ΔCO_2, signifying changes in carbon emissions; ΔV, representing changes in consumption levels; and ΔW, indicating shifts in welfare, which takes into account both consumption and environmental effects. Within the table, *RoW* stands for the Rest of the World, a notation that varies from the main text. The European Union, denoted as *EU*, is the entity implementing the policies in these scenarios. The row marked as *Global* provides the weighted average changes of all countries, offering a comprehensive view of the global effect. All changes are depicted in percentages, illustrating deviations from the baseline scenarios when the respective policies are applied. Specifically, Policy C integrates a non-discriminatory import tariff, whereas Policy D combines a non-discriminatory import tariff with an export subsidy. The values presented emerge from counterfactual analyses built upon the equilibrium, utilizing the hat algebra technique.

***Table A.5:** Changes in Equilibrium Outcomes Under Discriminatory Carbon Border Adjustment Policies*

	Carbon Tax & Policy C			*Carbon Tax & Policy D*		
Country	ΔCO_2	ΔV	ΔW	ΔCO_2	ΔV	ΔW
AUS	-0.05%	-0.21%	1.01%	-0.13%	-0.19%	1.16%
EU	-8.58%	-8.61%	1.40%	-8.52%	-8.89%	1.18%
BRA	-0.33%	-0.66%	-0.13%	-0.38%	-0.52%	0.06%
CAN	-0.27%	-1.30%	-0.37%	-0.34%	-1.14%	-0.12%
CHN	-0.04%	-0.11%	0.16%	-0.11%	-0.02%	0.28%
IDN	-0.07%	-0.43%	-0.11%	-0.13%	-0.34%	0.04%
IND	-0.08%	-0.50%	-0.27%	-0.14%	-0.21%	0.06%
JPN	-0.03%	-0.01%	2.55%	-0.10%	-0.03%	2.72%
KOR	-0.01%	-0.06%	0.93%	-0.11%	-0.04%	1.08%
MEX	-0.06%	-0.22%	-0.08%	-0.11%	0.08%	0.24%
RUS	-0.42%	-4.76%	-4.54%	-0.50%	-4.47%	-4.22%
TUR	-0.12%	-0.43%	1.44%	-0.18%	-0.22%	1.88%
TWN	-0.27%	-1.61%	-0.97%	-0.37%	-1.34%	-0.62%
USA	-0.08%	-0.32%	0.36%	-0.14%	-0.22%	0.52%
RoW	-0.25%	-2.24%	-2.13%	-0.34%	-1.85%	-1.74%
Global	**-1.17%**	**-2.91%**	**0.34%**	**-1.22%**	**-2.88%**	**0.44%**

Notes: This table presents the impacts of a unilateral carbon tax policy supplemented with discriminatory carbon border adjustment policies, specifically Policies C and D, on equilibrium outcomes for various countries and regions. The columns are labeled as ΔCO_2, signifying changes in carbon emissions; ΔV, representing changes in consumption levels; and ΔW, indicating shifts in welfare, which takes into account both consumption and environmental effects. Within the table, *RoW* stands for the Rest of the World, a notation that varies from the main text. The European Union, denoted as *EU*, is the entity implementing the policies in these scenarios. The row marked as *Global* provides the weighted average changes of all countries, offering a comprehensive view of the global effect. All changes are depicted in percentages, illustrating deviations from the baseline scenarios when the respective policies are applied. Specifically, Policy C integrates a discriminatory import tariff, whereas Policy D combines a discriminatory import tariff with an export subsidy. The values presented emerge from counterfactual analyses built upon the equilibrium, utilizing the hat algebra technique.