Discussion Paper Series – CRC TR 224

Discussion Paper No. 495
Project B 06, B 07

Designing Effective Carbon Border Adjustment with Minimal Information Requirements: Theory and Evidence

Alessia Campolmi[1]
Harald Fadinger[2]
Chiara Forlati[3]
Sabine Stillger[4]
Ulrich J. Wagner[5]

July 2025
(First version: January 2024)
(Second version: February 2024)

[1]University of Verona
[2]University of Vienna & CEPR, Email: harald.fadinger@univie.ac.at
[3]University of Southampton
[4]University of Mannheim
[5]University of Mannheim & CEPR

Support by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) through CRC TR 224 is gratefully acknowledged.

Collaborative Research Center Transregio 224 - www.crctr224.de
Rheinische Friedrich-Wilhelms-Universität Bonn - Universität Mannheim

Designing Effective Carbon Border Adjustment with Minimal Information Requirements: Theory and Evidence*

Alessia Campolmi[†] Harald Fadinger[‡] Chiara Forlati[§]
Sabine Stillger[¶] Ulrich J. Wagner[‖]

July 31, 2025

Abstract

Carbon leakage undermines the effectiveness of unilateral carbon pricing. Taxes on import-embedded emissions, like the EU's CBAM, prevent leakage but their product coverage is limited due to strong information asymmetries. We propose an alternative policy (LBAM) that sterilizes carbon leakage without requiring information on foreign carbon intensities. In a quantitative trade model, LBAM tariffs significantly improve over the EU's CBAM in terms of global emissions and EU welfare. Importantly, LBAM avoids large welfare losses among EU trading partners that would result if CBAM were extended to all sectors. Combining LBAM tariffs with equivalent export subsidies reinforces these advantages.

Keywords: carbon leakage, carbon border adjustment, CO_2 tax, trade policy

JEL: F13, F64, Q54, Q56

*We thank Lorenzo Caliendo, Farid Farrokhi, Ralph Ossa, Mathieu Parenti, Philip Sauré, Joseph Shapiro, seminar participants at Arizona State University, Mainz University, Stanford, Verona University, the WTO and conference participants at the CREI @30 conference, the 2024 LSE Environment Week, the DIE Workshop, the CEPR-NBB Joint Research Workshop on Reaching Net Zero, the 2024 Villars Workshop, the 2024 EC Single-Market Conference, the 2024 EEA Annual Congress, the 2023 CITP conference, the CRC Workshop on Trade, Firms and Development and the 2023 CRC Retreat in Montabaur for helpful comments. Thanks to Martina Milcetic, Luca Mauritz, and Frederik Schmitz for capable research assistance. This work was supported by the Centre for Inclusive Trade Policy Innovation Fund, ESRC [grant number ES/W002434/1]. Funding by the German Federal Ministry of Education and Research (BMBF) through COMPLIANCE (grant 01LA1806C) and by the German Research Foundation (DFG) through CRC TR 224 (Projects B06 and B07), is gratefully acknowledged. Wagner received financial support from the European Research Council under the European Union's Horizon 2020 research and innovation programme (Grant Agreement No. 865181).

[†]University of Verona

[‡]University of Vienna and CEPR, corresponding author: harald.fadinger@univie.ac.at

[§]University of Southampton

[¶]University of Mannheim

[‖]University of Mannheim and CEPR

I Introduction

Only one quarter of greenhouse gas (GHG) emissions worldwide are subject to carbon taxes or cap-and-trade policies (World Bank, 2024). Differences in carbon prices across countries encourage carbon leakage by shifting comparative advantage in the production of carbon-intensive goods to countries with lax policies. Because leakage undermines global mitigation efforts, preventing it is a priority for countries pursuing ambitious climate policies.

The economically-preferred policy is to 'level the playing field' on domestic and export markets by taxing imports and subsidizing exports at the prevailing carbon price, based on the embedded emissions (Markusen, 1975; Hoel, 1996). Such border carbon adjustments have long been regarded as incompatible with the rules of the World Trade Organization (WTO). This paradigm has shifted with the recent launch of the EU's Carbon Border Adjustment Mechanism (CBAM), which was prompted by strong and persistent increases in carbon prices under the EU Emissions Trading System (EU-ETS). Starting in 2026, the EU will levy tariffs on imports based on embedded carbon emissions, at a rate pegged to the EU-ETS price. CBAM tariffs discourage the replacement of EU production with dirty imports (import leakage) and partially correct for the absence of carbon taxes abroad (Böhringer et al., 2022). Conceptually, CBAM improves over current policies granting overly generous subsidies to EU producers in trade-exposed sectors (Martin et al., 2014). In practice, however, CBAM is complicated by excessive information requirements for computing embedded emissions, a discriminatory tariff structure that prominent trade partners of the EU have repeatedly denounced as punitive, protectionist and incompatible with WTO rules,[1] as well as incomplete coverage that distorts global value chains (Draghi, 2024).

[1] For example, the ten BRICS nations recently declared: "We reject unilateral, punitive and discriminatory protectionist measures, that are not in line with international law, under the pretext of environmental concerns, such as unilateral and discriminatory carbon border adjustment mechanisms (CBAMs)" (BRICS, 2025, paragraph 88). Many countries have raised concerns about CBAM with the WTO's Committee on Market Access (WTO, 2024) and its Council for Trade in Goods (WTO, 2023) on multiple occasions.

Using a state-of-the-art quantitative economic model of international trade, we assess the impacts of CBAM on bilateral trade flows, global emissions, and welfare. A key insight is that border adjustments must be applied to *all* –not just a subset– of industries to effectively prevent carbon leakage. Universally applying CBAM tariffs would also substantially lower the EU welfare costs of carbon pricing, but it would do so by significantly restricting access to EU markets for the many trade partners where production is more carbon-intensive.

We propose a simple alternative to CBAM that is universally applicable due to its low information requirements and effectively prevents carbon leakage with minimal impacts on international trade: The Leakage Border Adjustment Mechanism (LBAM) implements product-specific import tariffs that exactly offset the changes in EU imports resulting from an increase in the carbon price differential between the EU and its trade partners. Knowledge of foreign carbon intensities is not needed to compute LBAM tariffs, making them easy to implement. Since LBAM tariffs do not discriminate across countries and minimize interference with international trade patterns, they are also easier to accept for Europe's trade partners than CBAM tariffs. Furthermore, our analysis shows that most carbon leakage arises from EU producers losing market share on export markets, an issue not addressed by CBAM. Extending the LBAM principle to export subsidies would prevent this type of leakage.

To characterize and quantify the trade, welfare and emission effects of unilateral carbon pricing in the EU under alternative border adjustment scenarios, we develop a tractable structural model of international trade in differentiated products with many sectors and countries. We regard the EU as the domestic economy that unilaterally implements a carbon price and a border adjustment mechanism. Consumers derive utility from bundles of differentiated product varieties offered by monopolistically-competitive firms. Firms have market-specific production functions with sector-specific returns to scale, so that production decisions can be separated across markets and export supply curves have sector-specific slopes. Given the short-run nature of our model, we assume that the number of firms is fixed. Carbon emissions are embodied in a composite energy input to production, along with physical factors. Emissions are thus a by-product of production which can be reduced with carbon taxes. Carbon emissions constitute a global public bad whose social marginal cost does not depend on the place of emission.

Our model allows deriving simple closed-form expressions for LBAM tariffs and export subsidies that undo changes in imports and exports resulting from any given change in the EU's carbon price (and the related energy price change) without interfering with fluctuations in EU trade driven by unrelated shocks. For any given sector, LBAM tariffs depend only on readily available information and structural parameters: the EU's absorption share falling on EU produced goods; the EU's import demand elasticity; the foreign export supply elasticity; and the output to energy elasticity. Similarly, LBAM export subsidies depend only on the latter two objects and undo fluctuations in EU export prices driven by changes in the EU carbon price.

For our quantitative analysis, we calibrate the model using comprehensive data on demand and supply in 131 4-digit manufacturing sectors for the year 2018. Sector-level price elasticities of import demand and export supply are estimated on bilateral trade flows between the EU27 and 56 other countries following Feenstra (1994); Broda and Weinstein (2006) and Soderbery (2015). Sectoral output elasticities of energy and physical production factors are obtained via the estimation of sector-specific production functions using detailed firm-level micro-data for Germany (Ackerberg et al., 2015; Wooldridge, 2009). We solve for an initial equilibrium with a low carbon price of 15 dollars per ton (the average EU ETS price in 2018) and one with a high carbon price of 105 dollars per ton (the approximate average price in 2023. Following Dekle et al. (2007), we replace equilibrium objects that depend on unknown parameters with bilateral trade flows and absorption data constructed by combining trade data with 4-digit production data. To compare LBAM with CBAM, and to evaluate the effect of EU policies on global emissions, we also require estimates of foreign emission intensities. We use our model in combination with newly compiled, comprehensive data on energy prices and the average fuel mix of manufacturing companies to construct emissions intensities in each country.

With this model in hand, we quantify the impacts of an increase in the EU's carbon price from $15 to $105 on EU welfare and global emissions. In the absence of border adjustments (no-BAM), this seven-fold increase in the carbon price reduces global emissions by just 0.85% while leading to significant welfare losses of $25 bn for the EU because the economic costs of around $ 57 bn outweigh the environmental benefits of $ 32 bn. Carbon leakage is manifest in sizable displacements of EU manufacturing production by dirty imports to the EU and by dirty exports of third countries to the rest of the world. For the average sector, EU imports increase by 11% and EU exports fall by 9.4%,

We analyze how different border adjustments affect welfare and emissions, relative to this reference case. An 'ideal' CBAM that covers all sectors and taxes all imports based on their (truthfully reported) carbon content would imply welfare gains for the EU and increase global abatement by 70%, to 1.43% of global emissions. A comprehensive CBAM where carbon tariffs are based on the EU emission intensity of the sector instead of the foreign one would fare almost as well. However, the current EU proposal limits CBAM tariffs to very few sectors which, in our simulations, improves only marginally upon the no-BAM case: global abatement rises from 0.85% to 0.87% and EU welfare losses remain similar to the reference scenario. In contrast, our proposed LBAM policies deliver much stronger emissions reductions because they directly target leakage. An LBAM tariff that adjusts for import leakage increases global abatement to 0.97% and almost halves EU welfare losses compared to the no-BAM case. Global abatement can be further raised to 1.28% and EU welfare losses reduced to $ 4 bn when LBAM additionally grants export subsidies to prevent leakage on export markets. This closes three quarters of the gap to the ideal CBAM while minimizing information requirements and political backlash from the EU's trading partners; the magnitudes of non-discriminatory LBAM tariffs and export subsidies are modest, averaging at 1.3 % and 3.7 %, respectively.

The literature on border adjustment mechanisms (BAMs) predominantly employs computable general equilibrium models (Böhringer et al., 2022)–a powerful tool that has limitations when it comes to including industry specific detail (Fowlie and Reguant, 2022) and to transparently connecting theory and data (Costinot and Rodríguez-Clare, 2014). Recent empirical studies of environmental regulation and emissions leakage showcase the benefits of using modern structural trade models in this context (Aichele and Felbermayr, 2015; Larch and Wanner, 2017; Shapiro and Walker, 2018; Sogalla, 2023; Stillger, 2025). Adopting this approach allows us to derive closed-form expressions of all border taxes and subsidies considered, based on highly granular data for 131 sectors and 83 countries. Related research has evaluated the effects of CBAM for a smaller set of industries (Ambec et al., 2024) or derived empirically-based *production* subsidies to mitigate leakage (Fowlie and Reguant, 2022). Our focus on implementation constraints sets this analysis apart from that of unilaterally *optimal* BAMs (Kortum and Weisbach, 2021; Farrokhi and Lashkaripour, 2025), and our LBAM proposal is an alternative to mitigating CBAM's information asymmetries using mechanism design (Cicala et al., 2023).

The main contributions of our paper can be summarized as follows. First, we quantify the economic and environmental consequences of various carbon border adjustments, with the key results that the limited application of CBAM tariffs to a handful of sectors is environmentally ineffective whereas a universal application of CBAM imposes large welfare costs on non-EU countries. Second, we propose an alternative border adjustment mechanism, LBAM, which effectively prevents carbon leakage and is better suited to overcome both legal and information constraints that plague other types of border carbon adjustments. Third, by explicitly considering export-driven carbon leakage within an LBAM framework, our analysis informs the political process of designing export subsidies which has just been initiated by the

European Commission (2025a).

The remainder of the paper is structured as follows. The next section summarizes the EU's CBAM policy and introduces the main idea behind LBAM, illustrated with simple graphical arguments. Section III develops a structural economic model and derives analytical results for how unilateral carbon pricing combined with different border adjustment mechanisms affect welfare and emissions. Section IV explains the model calibration and discusses the underlying data. In Section V, we present simulation results for studing the welfare, trade and emission effects of an EU carbon price increase under various border adjustment scenarios. Section VI examines the robustness of these results to alternative modeling assumptions. Section VII concludes.

II EU Carbon Pricing and Leakage Protection

In Europe, energy-intensive industries have been paying carbon prices since the launch of the EU-ETS in 2005. The EU-ETS permit price has been below €20 for many years (Ellerman et al., 2016; Hintermann et al., 2016), but it climbed to over €100 between October 2020 and February 2023, and has rarely fallen below €60 since then. Against this background, and in view of the European Green Deal's increasingly ambitious climate policies, the EU Commission proposed the introduction of CBAM in July 2021.

A The Carbon Border Adjustment Mechanism (CBAM)

CBAM applies to EU imports in a handful of very carbon-intensive industries considered at high risk of carbon leakage (iron and steel, cement, fertilizers, aluminum, hydrogen, and electricity). Starting in 2026, EU importers must buy a 'CBAM certificate' for each ton of CO_2 emissions embedded in those goods.[2] The certificate price is

[2]Current draft legislation defers the start of actual payments to Feburary 1, 2027 and introduces a new exemption threshold which further limits CBAM obligations to those companies importing more 50 tons of CBAM goods per year (European Commission, 2025b).

pegged to the weekly EU-ETS price, and can be deducted by pertinent carbon prices already paid in the origin country. This design establishes a level playing field between imports and domestic production, providing non-EU countries with an incentive to green their production processes.

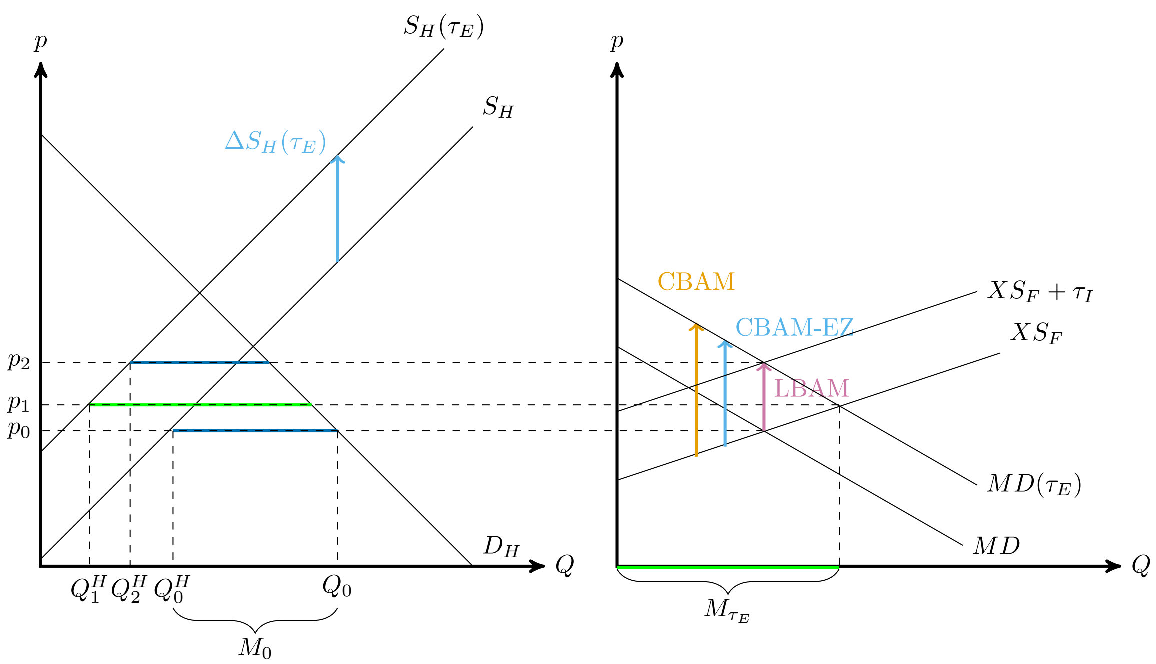
A CBAM reporting system was launched in October 2023 to close immense information gaps before financial adjustments can be implemented. EU importers must calculate the actual, plant-specific CO_2 emissions in the origin country. Given the lack of such data (Fowlie and Reguant, 2018) and obvious incentives for under-reporting, the regulation stipulates that effective monitoring and verification processes be established. This creates a dilemma. On one hand, extending CBAM to all leakage-relevant sectors requires a large bureaucracy that is expensive to maintain for the EU and acts like a trade barrier towards its trade partners (Cosbey et al., 2019; Draghi, 2024). On the other hand, allowing importers to fall back on average carbon intensities in the exporting country or in the EU fails to level the playing field with respect to carbon costs and leads to other evasion problems (e.g., re-routing imports via 'clean' third countries).

There is an urgent need to fix these problems because CBAM's incomplete coverage misses embedded emissions of many unregulated products and threatens the competitiveness of downstream industries in the EU (Draghi, 2024). For example, CBAM tariffs are levied on imported steel but not on imported cars. As a solution, we propose a border adjustment mechanism focused on leakage prevention which keeps bureaucracy, compliance costs, and trade impacts to a minimum.

B The Leakage Border Adjustment Mechanism (LBAM)

Figure 1 illustrates the workings of different border adjustment mechanisms in partial equilibrium with two countries, Home and Foreign. Home is a net importer of a good that it can produce at increasing marginal cost. The difference between Home's demand (D_H) and supply (S_H) curves for any given price p gives Home's import demand curve (MD). Foreign is characterized by an upward-sloping export supply curve XS_f. Under free trade, equilibrium obtains at the world price p_0 where domestic demand Q_0 is met by domestic supply Q_0^H and imports M_0 from Foreign. A carbon tax τ_E raised unilaterally in Home increases marginal production cost for any given quantity ($S_H(\tau_E)$). The equilibrium price rises to p_1 and imports increase to M_{τ_E} as they become cheaper relative to domestic production. This goes along with emissions 'leaking' from Home to Foreign.

Figure 1: Trade Effects of a Carbon Tax and Border Adjustment Mechanisms



Home can exactly offset carbon leakage by imposing a tariff τ_I ("LBAM") that cancels out the cost disadvantage of domestic producers generated by the domestic carbon tax. The tariff shifts out Foreign export supply ($XS_F + \tau_I$) and raises the consumer price in Home such that domestic production increases and import demand falls until imports are back at their initial level M_0. Global emissions fall with imports because, by assumption, production in Home is less carbon intensive than in Foreign.

CBAM targets embedded emissions rather than leakage. A CBAM tariff based on Home's carbon intensity ("CBAM-EZ") shifts out Foreign's export supply curve by

$\Delta S_H(\tau_E)$, the increment in Home's marginal cost due to the carbon tax. When based on Foreign's actual carbon intensity, the tariff would further increase ("CBAM"). Both CBAM tariffs reduce imports beyond what is needed to prevent carbon leakage because they tax all emissions embedded in domestic consumption. This foreshadows our quantitative result that CBAM tariffs reduce welfare of non-EU countries. In contrast, LBAM does not hurt foreign exporters; it merely re-establishes the *status quo* before the unilateral carbon price increase.

III Economic Model

To rigorously analyze these policies, we build a quantitative trade model that satisfies structural gravity (Costinot and Rodríguez-Clare, 2014). While LBAM eliminates carbon leakage, imports are also affected by demand and supply shocks that are unrelated to carbon pricing and hence should not be neutralized. Computing LBAM tariffs thus requires us to simulate changes in imports at different levels of the EU-ETS price while holding fixed the effects of other shocks. Our model transparently solves for LBAM instruments as closed-form functions of observable data and econometrically estimable parameters.

A Model Setup

We solve a multi-country model with countries denoted by $i, j = 1, ..., I$. The first subindex denotes the location of consumption and the second one the location of production. In each country there is a continuum of tradable sectors indexed by s.

Consumers We assume quasi-linear utility between a tradable outside sector and a Cobb-Douglas aggregate of a continuum of differentiated tradable sectors with weights η_{is}. Carbon emissions constitute a public bad with constant marginal social costs (SCC) θ_i. Utility of the representative consumer in country i is given by

$$U_i = C_{i0} + \int_s \eta_{is} \log C_{is} ds - \theta_i \int_s e_s ds, \tag{1}$$

where C_{i0} is the numéraire and

$$C_{is} = \left[\sum_{j=1}^{J} \int_0^{N_{ijs}} c_{ijs}(\omega)^{\frac{\varepsilon_s - 1}{\varepsilon_s}} d\omega \right]^{\frac{\varepsilon_s}{\varepsilon_s - 1}}$$

is a CES aggregator for sector-specific varieties ω. $c_{ijs}(\omega)$ denotes consumption of an individual variety ω produced in j. N_{ijs} is the (exogenous) measure of varieties produced by j available in i. The elasticity of substitution across varieties, $\varepsilon_s > 1$, is sector-specific. e_s denotes worldwide emissions of sector s. Standard calculations yield i's demand for sector-s varieties sourced from j

$$c_{ijs}(\omega) = \left(\frac{p_{ijs}(\omega)}{P_{ijs}} \right)^{-\varepsilon_s} C_{ijs}, \tag{2}$$

demand for the aggregate consumption bundle sourced from j

$$C_{ijs} = \left(\frac{P_{ijs}}{P_{is}} \right)^{-\varepsilon_s} C_{is} \tag{3}$$

and demand for the aggregate sector s bundle

$$C_{is} = \eta_{is} P_{is}^{-1}, \tag{4}$$

where

$$P_{ijs} = \left[\int_0^{N_{ijs}} p_{ijs}(\omega)^{1-\varepsilon_s} d\omega \right]^{\frac{1}{1-\varepsilon_s}}, \quad P_{is} = \left[\sum_{j=1}^{J} P_{ijs}^{1-\varepsilon_s} \right]^{\frac{1}{1-\varepsilon_s}}. \tag{5}$$

Firms In each sector, a fixed number of firms operate under monopolistic competition. Production decisions are taken separately across markets.[3] Production y_{ijs} of a

[3] Separability of production decisions is realistic since most exporters are multi-plant firms that can operate plant-specific technologies with a different energy mix. Chen et al. (2025) show that Chinese multi-plant firms shift emissions between plants.

firm located in j for location i in sector s is given by

$$y_{ijs} = \phi_{ijs} \left(\frac{z_{ijs}}{\beta_s} \right)^{\beta_s} \left(\frac{l_{ijs}}{\alpha_s} \right)^{\alpha_s},$$

where z_{ijs} is the energy use associated with the production, l_{ijs} is a composite physical input (factors other than energy), ϕ_{ijs} is a productivity shifter and α_s, β_s denote the output elasticities of physical inputs and energy. Sectors with decreasing returns-to-scale (DRS; $\alpha_s + \beta_s < 1$) exhibit an upward-sloping supply curve whereas that curve is horizontal for sectors with constant returns (CRS; $\alpha_s + \beta_s = 1$).[4] The associated marginal cost function is given by

$$MC_{ijs} = \left(\frac{y_{ijs}}{\phi_{ijs}} \right)^{\gamma_s} p_{Zj}^{\beta_s(\gamma_s+1)} \phi_{ijs}^{-1},$$

where $\gamma_s \equiv \frac{1}{\alpha_s+\beta_s} - 1$ ($\gamma_s = 0$ implies CRS and $\gamma_s > 0$ implies DRS). p_{Zj} is the (exogenous) price of energy in country j.[5] The price of the composite physical input has been normalized to unity due to the presence of a freely traded outside good with a linear production function which uses the physical factor as the only input.

Energy use generates emissions in proportion to the prevailing share of fossil fuels in a country's energy mix. Emissions embedded in goods produced by j for i can be computed as

$$e_{ijs} = d_j z_{ijs},$$

where d_j denotes the rate of carbon emissions per unit of energy in country j.[6] Emis-

[4] Allowing for increasing returns ($\alpha_s + \beta_s > 1$) would be straightforward but our empirical estimates do not support this case.

[5] Exogenous energy prices rule out energy price leakage, i.e., additional demand for fossil fuels in non-EU countries which results from prices falling due to carbon taxation in the EU. This assumption is made in much of the CBAM literature (Böhringer et al., 2022) and relaxed in Sogalla (2023).

[6] Consistent with our focus on short-run analysis, we assume that d_j is fixed and does not respond to carbon pricing. In the longer run, the energy sector might adjust to higher prices of ETS allowances and CBAM certificates by investing in renewable electricity generation and other technologies that reduce d_j.

sion intensity of exports from j to i in sector s is given by:

$$\frac{e_{ijs}(p_{Zj}, y_{ijs})}{y_{ijs}} = d_j \beta_s y_{ijs}^{\gamma_s} p_{Zj}^{-\alpha_s(1+\gamma_s)} \phi_{ijs}^{-(1+\gamma_s)}, \tag{6}$$

which is decreasing in p_{Zj} and increasing in y_{ijs} for $\gamma_s > 0$. Thus, emission intensity of production may vary across countries due to variation in output, energy prices, or productivity.

To specify the relationship between energy prices and carbon taxes, denote by $\tilde{p}_{Zj}$ the energy price in j net of carbon taxes. Assuming a per-unit tax of τ_{Ej} Dollars per ton of CO_2 emissions,[7] we write the price of a unit of energy gross of the carbon tax as $p_{Zj} = \tilde{p}_{Zj} + d_j \tau_{Ej}$. Thus, the carbon tax increases the price of energy by more in countries with higher carbon emission intensity d_j.

We assume iceberg trade costs τ_{ijs} for shipping a variety from j to i. Tariffs on imports by i on origin j in sector s are denoted by τ_{Iijs}, taxes on exports levied by j on exports to i in sector s are denoted as τ_{Xijs}. We abstract from trade taxes and transport costs within the same country ($\tau_{iis} = \tau_{Iiis} = \tau_{Xiis} = 1 \; \forall i$).

Since firms are monopolists for their variety, they set a markup over their marginal cost. The consumer price of a sector-s variety produced in i and consumed in j is then

$$p_{jis} = \tau_{jis} \tau_{Ijis} \tau_{Xjis} \mu_s \left(\frac{y_{jis}}{\phi_{jis}} \right)^{\gamma_s} p_{Zi}^{\beta_s(\gamma_s+1)} {\phi_{jis}}^{-1}, \tag{7}$$

where $\mu_s = \frac{\varepsilon_s}{\varepsilon_s - 1}$ denotes the sectoral markup.

Total profits of sector s in i are given by

$$\Pi_{is} = \sum_{j=1}^{J} \Pi_{jis} \tag{8}$$

where

$$\Pi_{jis} = N_{jis} \left[\mu_s - \frac{1}{1+\gamma_s} \right] \left(\frac{y_{jis}}{\phi_{jis}} \right)^{\gamma_s+1} p_{Zi}^{\beta_s(\gamma_s+1)} \tag{9}$$

[7] All nominal variables in the model are in US Dollars.

are the profits that firms earn in each market j.

Equilibrium in Levels Imposing market clearing in each sector, i.e., $y_{ijs} = \tau_{ijs} c_{ijs}$ and using (2), (3), (4) and (7), we can find an expression for the equilibrium levels of y_{ijs} and p_{ijs}.

$$y_{ijs} = \left(\eta_{is}\tau_{ijs}^{1-\varepsilon_s}\right)^{\frac{1}{\gamma_s\varepsilon_s+1}} \left(\phi_{ijs} p_{Zj}^{-\beta_s}\right)^{\frac{(\gamma_s+1)\varepsilon_s}{\gamma_s\varepsilon_s+1}} \left(\mu_s \tau_{Iijs}\tau_{Xijs}\right)^{\frac{-\varepsilon_s}{\gamma_s\varepsilon_s+1}} P_{is}^{\frac{\varepsilon_s-1}{\gamma_s\varepsilon_s+1}} \tag{10}$$

$$p_{ijs} = \eta_{is}^{\frac{\gamma_s}{\gamma_s\varepsilon_s+1}} \left(\tau_{ijs}\phi_{ijs}^{-1} p_{Zj}^{\beta_s}\right)^{\frac{\gamma_s+1}{\gamma_s\varepsilon_s+1}} \left(\mu_s \tau_{Iijs}\tau_{Xijs}\right)^{\frac{1}{\gamma_s\varepsilon_s+1}} P_{is}^{\frac{\gamma_s(\varepsilon_s-1)}{\gamma_s\varepsilon_s+1}} \tag{11}$$

$$P_{is}^{\frac{(\gamma_s+1)(1-\varepsilon_s)}{\gamma_s\varepsilon_s+1}} = \sum_{j=1}^{J} N_{ijs} \left(\eta_{is}^{\frac{\gamma_s}{\gamma_s\varepsilon_s+1}} \left(\tau_{ijs}\phi_{ijs}^{-1} p_{Zj}^{\beta_s}\right)^{\frac{\gamma_s+1}{\gamma_s\varepsilon_s+1}} \left(\mu_s \tau_{Iijs}\tau_{Xijs}\right)^{\frac{1}{\gamma_s\varepsilon_s+1}}\right)^{1-\varepsilon_s} \tag{12}$$

Equilibrium in Changes We can then rewrite the equilibrium conditions in terms of gross changes in variables $\hat{X} = \frac{X'}{X}$ from the initial equilibrium value X to the new equilibrium value X'. This allows us to express changes in equilibrium outcomes as:

$$\hat{y}_{ijs} = \left(\hat{\phi}_{ijs}\hat{p}_{Zj}^{-\beta_s}\right)^{\frac{(\gamma_s+1)\varepsilon_s}{\gamma_s\varepsilon_s+1}} \left(\hat{\tau}_{Iijs}\hat{\tau}_{Xijs}\right)^{\frac{-\varepsilon_s}{\gamma_s\varepsilon_s+1}} \hat{P}_{is}^{\frac{\varepsilon_s-1}{\gamma_s\varepsilon_s+1}}, \tag{13}$$

$$\hat{p}_{ijs} = \left(\hat{\phi}_{ijs}^{-1}\hat{p}_{Zj}^{\beta_s}\right)^{\frac{\gamma_s+1}{\gamma_s\varepsilon_s+1}} \left(\hat{\tau}_{Iijs}\hat{\tau}_{Xijs}\right)^{\frac{1}{\gamma_s\varepsilon_s+1}} \hat{P}_{is}^{\frac{\gamma_s(\varepsilon_s-1)}{\gamma_s\varepsilon_s+1}}. \tag{14}$$

where $\hat{p}_{Zj} = \frac{\tilde{p}_{Zj}+d_j\hat{\tau}_{Ej}\tau_{Ej}}{\tilde{p}_{Zj}+d_j\tau_{Ej}}$.

Moreover, given that by (3) and (4) $P_{ijs}C_{ijs} = P_{ijs}^{1-\varepsilon_s} P_{is}^{1-\varepsilon_s}$ and $P_{is}C_{is} = \eta_{is}$, we rewrite condition (5) in changes as:

$$\hat{P}_{is}^{1-\varepsilon_s} = \sum_{j=1}^{J} \delta_{ijs}\hat{p}_{ijs}^{1-\varepsilon_s}, \tag{15}$$

where $\delta_{ijs} \equiv \frac{P_{ijs}C_{ijs}}{P_{is}C_{is}}$ is the expenditure share of i on goods imported from j. Substituting (14) into (15) we obtain:

$$\hat{P}_{is}^{\frac{(1+\gamma_s)(1-\varepsilon_s)}{\gamma_s\varepsilon_s+1}} = \sum_{j=1}^{J} \delta_{ijs} \left(\hat{\phi}_{ijs}^{-1}\hat{p}_{Zj}^{\beta_s}\right)^{\frac{(\gamma_s+1)(1-\varepsilon_s)}{\gamma_s\varepsilon_s+1}} \left(\hat{\tau}_{Iijs}\hat{\tau}_{Xijs}\right)^{\frac{1-\varepsilon_s}{\gamma_s\varepsilon_s+1}}. \tag{16}$$

This expression gives an explicit solution for the change in the price index. By combining (16) with (13) and (14) we can recover equilibrium changes in $\hat{y}_{ijs}$, $\hat{p}_{ijs}$, $\hat{c}_{ijs}$ and $\hat{C}_{ijs}$ as a function of changes in policy instruments, productivity shocks, parameters (β_s, γ_s, ε_s) and observable trade shares only. Finally, from (6) changes in emissions are given by

$$\hat{e}_{ijs} = \left(\frac{\hat{y}_{ijs}}{\hat{p}_{Zj}^{\alpha_s}}\right)^{1+\gamma_s} \hat{\phi}_{ijs}^{-(1+\gamma_s)} = \hat{y}_{ijs}^{1+\gamma_s} \hat{p}_{Zj}^{\beta_s(1+\gamma_s)-1} \hat{\phi}_{ijs}^{-(1+\gamma_s)}. \tag{17}$$

Welfare Welfare is given by

$$\begin{aligned} W_i &= C_{i0} + \int_s \eta_{is} \log C_{is} d_s - \theta_i \int_s e_s ds \\ &= I_i + \int_s \eta_{is} \log C_{is} d_s - \int_s P_{is} C_{is} ds - \theta_i \int_s e_s ds, \end{aligned}$$

where income $I_i = w_i L_i + \int_s \Pi_{is} ds + \int_s T_{is} d_s$ is derived from labor, profits and transfers. Worldwide emissions are given by $e_s \equiv \sum_{i=1}^{J} \sum_{j=1}^{J} N_{ijs} e_{ijs}$. Thus, welfare corresponds to consumer surplus, producer surplus, labor income, tax income and the disutility from global emissions.

We compute the absolute difference in welfare before and after the policy change,

$$\begin{aligned} & W_i' - W_i \\ &= \int_s (\hat{\Pi}_{is} - 1)\Pi_{is} ds + \int_s (\hat{T}_{is} - 1) T_{is} ds + \int_s \eta_{is} \log \hat{C}_{is} ds - \theta_i \int_s (\hat{e}_s - 1) e_s ds, \end{aligned}$$

where we have used the fact that $\widehat{P_{is} C_{is}} = 1$ from (4). We substitute $\hat{C}_{is} = \hat{P}_{is}^{-1}$ from the previous section and express $\hat{\Pi}_{is}$, Π_{is}, $\hat{T}_{is}$, and T_{is} in terms of observables (see Appendix A.2). With quasi-linear utility, the marginal utility of income is unity. Thus, taking the outside good as the numéraire and defining it as money, changes in indirect utility correspond to the amount of money consumers need to receive/pay in order to stay indifferent to a policy change.

Changes in global emissions can be written as

$$\hat{e}_s = \sum_{i=1}^{J} \sum_{j=1}^{J} \hat{e}_{jis} \frac{N_{jis} e_{jis}}{\sum_{i=1}^{J} \sum_{j=1}^{J} N_{jis} e_{jis}}. \tag{18}$$

Using (6), (7), and (17), we obtain

$$e_s = \beta_s \mu_s^{-1} \sum_{i=1}^{J} p_{Zi}^{-1} d_i \sum_{j=1}^{J} \tau_{Ijis}^{-1} \tau_{Xjis}^{-1} \eta_{js} \delta_{jis},$$

and

$$\hat{e}_s = \sum_{i=1}^{J} \hat{p}_{Zi}^{\beta_s(1+\gamma_s)-1} \sum_{j=1}^{J} \tilde{\sigma}_{jis} \left(\frac{\hat{y}_{jis}}{\hat{\phi}_{jis}} \right)^{(1+\gamma_s)}, \tag{19}$$

where $\tilde{\sigma}_{jis} = \frac{p_{Zi}^{-1} d_i \tau_{Ijis}^{-1} \tau_{Xjis}^{-1} \eta_{js} \delta_{jis}}{\sum_{i=1}^{J} p_{Zi}^{-1} d_i \sum_{j=1}^{J} \tau_{Ijis}^{-1} \tau_{Xjis}^{-1} \eta_{js} \delta_{jis}}$ are the global sales shares in each market, measured before trade and carbon taxes are applied.

B Border Adjustment Mechanisms

This section characterizes the workings of various BAMs using the equilibrium-in-changes notation introduced above. All scenarios assume that country i unilaterally raises its domestic carbon tax ($\hat{\tau}_{Ei} > 1$) and that climate and trade policies remain unchanged in all other countries ($\hat{\tau}_{Ej} = \hat{\tau}_{Ijis} = \hat{\tau}_{Xijs} = 1$ for all $j \neq i$). Since we focus on the impact of policy changes, for simplicity, we assume that productivity shocks are absent ($\hat{\phi}_{ijs} = 1$ for all i, j, s). We comment on the effect of such shocks where appropriate.

No-BAM The unilateral carbon tax increase raises energy prices in the domestic market ($\hat{p}_{Zi} > 1$) while leaving foreign energy prices unchanged ($\hat{p}_{Zj} = 1$ for all $j \neq i$). In the absence of a BAM ($\hat{\tau}_{Iijs} = \hat{\tau}_{Xijs} = 1$ for all s and j), this puts domestic producers at competitive disadvantage on the domestic and export markets. By combining (13) with (16), we obtain the equilibrium response in sales of domestic producers in their home market

$$\hat{y}_{iis} = \hat{p}_{Zi}^{\frac{-\beta_s\ (\gamma_s+1)\varepsilon_s}{1+\varepsilon_s\gamma_s}} \hat{P}_{is}^{\frac{\varepsilon_s-1}{1+\varepsilon_s\gamma_s}} = \hat{p}_{Zi}^{\frac{-\beta_s\ (1+\gamma_s)\varepsilon_s}{1+\varepsilon_s\gamma_s}} \left[\delta_{iis}\hat{p}_{Zi}^{\frac{\beta_s(1+\gamma_s)(1-\varepsilon_s)}{1+\varepsilon_s\gamma_s}} + 1 - \delta_{iis}\right]^{\frac{-1}{1+\gamma_s}} < 1$$

and imports from foreign producers in that market

$$\hat{y}_{ijs} = \hat{P}_{is}^{\frac{\varepsilon_s-1}{1+\varepsilon_s\gamma_s}} = \left[\delta_{iis}\hat{p}_{Zi}^{\frac{\beta_s(1+\gamma_s)(1-\varepsilon_s)}{1+\varepsilon_s\gamma_s}} + 1 - \delta_{iis}\right]^{\frac{-1}{1+\gamma_s}} > 1. \tag{20}$$

Intuitively, raising the domestic carbon tax raises the price of domestic relative to foreign varieties and leads to substitution of domestic consumption towards imported varieties. To the extent that domestic production is cleaner than abroad, this process increases global emissions as domestic output is replaced by more polluting foreign production (*import leakage*).

From (13) and (15) we obtain that the carbon-tax increase reduces exports:

$$\hat{y}_{jis} = \hat{p}_{Zi}^{\frac{-\beta_s\ (\gamma_s+1)\varepsilon_s}{1+\varepsilon_s\gamma_s}} \hat{P}_{js}^{\frac{\varepsilon_s-1}{1+\varepsilon_s\gamma_s}} = \hat{p}_{Zi}^{\frac{-\beta_s\ (\gamma_s+1)\varepsilon_s}{1+\varepsilon_s\gamma_s}} \left[\delta_{jis}\hat{p}_{Zi}^{\frac{\beta_s(1+\gamma_s)(1-\varepsilon_s)}{1+\varepsilon_s\gamma_s}} + 1 - \delta_{jis}\right]^{\frac{-1}{1+\gamma_s}} < 1.$$

The reduction in domestic exports increases global emissions as long as domestic production is cleaner than abroad (*export leakage*).

CBAM To level the playing field w.r.t carbon pricing, country i levies a tariff $\hat{\tau}_{Iijs}$ on imports from j in sector s such that import-embedded emissions are taxed at the same rate as domestic carbon emissions. CBAM thus requires knowledge of the carbon intensity of foreign production. We assume that this can be perfectly observed (having duly noted the importance of asymmetric information above).

CBAM raises the effective energy price for goods produced in j and exported to i, p_{Zij}, by an amount consistent with the domestic carbon tax, $\hat{p}_{Zij} = 1 + \frac{d_j\hat{\tau}_{Ei}\tau_{Ei}}{p_{Zj}} > 1$, assuming zero initial carbon prices in foreign countries ($\tau_{Ej} = 0$). For sectors s not affected by CBAM, energy costs remain unchanged ($\hat{p}_{Zij} = 1$).

In our model, the carbon tariff can be implemented by setting bilateral discriminatory tariffs equal to the cost pass-through of a carbon tax on imports, i.e., $\hat{\tau}_{Iijs} = \hat{p}_{Zij}^{\beta_s(\gamma_s+1)}$ in CBAM sectors and $\hat{\tau}_{Iijs} = 1$ elsewhere. Other trade instruments are not used ($\hat{\tau}_{Xijs} = 1$ for all $\forall s, j$). Using these assumptions in (13), (14), and (16), we obtain the following equilibrium responses to raising the domestic carbon tax in combination with CBAM tariffs:

$$
\begin{aligned}
\hat{y}_{ijs} &= \hat{p}_{Zij}^{\frac{-\beta_s(\gamma_s+1)\varepsilon_s}{\gamma_s\varepsilon_s+1}} \hat{P}_{is}^{\frac{\varepsilon_s-1}{\gamma_s\varepsilon_s+1}} \\
\hat{p}_{ijs} &= \hat{p}_{Zij}^{\frac{\beta_s(\gamma_s+1)}{\gamma_s\varepsilon_s+1}} \hat{P}_{is}^{\frac{\gamma_s(\varepsilon_s-1)}{\gamma_s\varepsilon_s+1}} \\
\hat{P}_{is} &= \left[\sum_{j=1}^{J} \delta_{ijs}\hat{p}_{Zij}^{-\beta_s\frac{(\gamma_s+1)(\varepsilon_s-1)}{\gamma_s\varepsilon_s+1}}\right]^{-\frac{\gamma_s\varepsilon_s+1}{(1+\gamma_s)(\varepsilon_s-1)}} > 1.
\end{aligned}
$$

Prices of all varieties rise, inducing $\hat{P}_{is} > 1$, and so do energy prices p_{Zij}, especially for varieties produced in locations with a carbon-intensive energy mix. However, in most cases this effect dominates and $\hat{y}_{ijs} < 1$. Since CBAM only applies to imports, there is export leakage as in No-BAM.

LBAM To prevent import leakage, country i introduces a tariff that stabilizes bilateral imports within each sector at the level before the carbon-tax increase. Consistent with this objective, domestic tariff changes $\hat{\tau}_{Iijs} > 1$ neutralize the effects on demand of imported varieties induced by $\hat{\tau}_{Ei} > 1$, in the sense that $\hat{C}_{ijs} = \hat{c}_{ijs} = \hat{y}_{ijs} = 1$ for all j and s. Imposing this condition on (13) and (16) yields[8]

$$
\hat{\tau}_{Iis}^{\frac{-\varepsilon_s(1+\gamma_s)}{\gamma_s\varepsilon_s+1}} = \delta_{iis}\hat{p}_{Zi}^{\frac{\beta_s(\gamma_s+1)(1-\varepsilon_s)}{\gamma_s\varepsilon_s+1}} + (1-\delta_{iis})\hat{\tau}_{Iis}^{\frac{1-\varepsilon_s}{\gamma_s\varepsilon_s+1}} \tag{21}
$$

with $\hat{\tau}_{Iijs} = \hat{\tau}_{Iis}\ \forall j$, i.e., LBAM tariffs are independent of the trade partner and hence non-discriminatory. Condition (21) implicitly defines a tariff that stabilizes bilateral

[8]In the online appendix, we prove that any tariff that (i) prevents import leakage by keeping *aggregate* imports constant and (ii) does not discriminate between partner countries must hold *bilateral* imports from each origin country constant.

imports for a change in the carbon tax $\hat{\tau}_{Ei}$ and the energy price $\hat{p}_{Zi}$. The tariff depends on (i) the effect of the carbon tax on the price of domestically produced varieties and (ii) on the effect of the tariff on the price of imported varieties from other countries, weighted by the respective expenditure shares. Computing the LBAM tariff only requires information on the elasticities of import demand ε_s and export supply γ_s, the output elasticity of emissions β_s, and the share of domestic absorption that falls on domestically produced varieties *before* the carbon tax increase δ_{ii}. Since the tariff holds the level of bilateral imports constant, the foreign carbon intensity does not change, and hence import-embedded emissions also remain constant: LBAM prevents import leakage.

Observe that the formula for LBAM tariffs is independent of productivity shocks as long as such shocks are sector-specific, i.e. when $\phi_{ijs} = \phi_{is}$. In the more general case where productivity shocks are sector-country-specific, LBAM tariffs remain independent of these shocks up to a first-order approximation.[9] Thus, policy makers can disregard the effect of domestic or foreign productivity shocks when sterilizing the effect of domestic carbon price changes on imports. Instead, imports will fluctuate in response to domestic or foreign productivity shocks.

Combining (13) and (16) and imposing LBAM yields

$$\hat{y}_{iis} = \hat{p}_{Zi}^{\frac{-\beta_s \varepsilon_s (1+\gamma_s)}{1+\varepsilon_s \gamma_s}} \hat{\tau}_{Iis}^{\frac{\varepsilon_s}{1+\varepsilon_s \gamma_s}} < 1 \qquad (22)$$

Thus, domestic sales to the home market fall, but by less than under the No-BAM scenario. Given that $\hat{\tau}_{Xjis} = 1$ for all $\forall j, s$ export leakage is the same as in the No-BAM scenario.

LBAM-X To prevent export leakage, country i introduces an export subsidy that keeps its bilateral exports within each sector constant at the level before the carbon-

[9]See Appendix A.3.

tax increase.[10] Formally, the export subsidy $\hat{\tau}_{Xjis} < 1$ is chosen such that $\hat{C}_{jis} = \hat{c}_{jis} = \hat{y}_{jis} = 1$ for all j, s, in response to $\hat{\tau}_{Ei} > 1$. Combining the last condition with (13) and (16) yields:

$$\hat{\tau}_{Xjis}^{\frac{-\varepsilon_s(1+\gamma_s)}{\gamma_s\varepsilon_s+1}} = \delta_{jis}\hat{p}_{Zi}^{\beta_s(\gamma_s+1)}\hat{\tau}_{Xjis}^{\frac{1-\varepsilon_s}{\gamma_s\varepsilon_s+1}} + (1-\delta_{jis})\hat{p}_{Zi}^{\frac{\beta_s(\gamma_s+1)^2\varepsilon_s}{\gamma_s\varepsilon_s+1}}. \tag{23}$$

A straightforward solution to this equation is a non-discriminatory export subsidy

$$\hat{\tau}_{Xi} = \frac{1}{\hat{p}_{Zi}^{\beta_s(\gamma_s+1)}}.$$

This subsidy exactly offsets the pass-through of higher energy prices (in the denominator) and thus prevents export prices from increasing, irrespective of the destination. Since the price index does not change ($\hat{P}_{js} = 1$), domestic producers do not change their exports ($\hat{y}_{jis} = 1$). The only information required to compute the LBAM-X export subsidy is the output elasticity of carbon β_s and the export supply elasticity γ_s. Finally, note that LBAM-X export subsidies are independent of domestic or foreign productivity shocks and do not interfere with them: exports will fluctuate freely in the presence of such shocks.[11]

[10] There is no connection between export and import decisions in the model, so the export border adjustment can be analyzed independently from import border adjustment.

[11] See Appendix A.3.

C Decomposition of Emissions Cha†nges

To clarify how global emissions and carbon leakage are affected by climate and trade policies, we decompose equation (19) as follows:

$$\hat{e}_s = \underbrace{\hat{p}_{Zi}^{\beta_s(1+\gamma_s)-1}\tilde{\sigma}_{iis}\hat{y}_{iis}^{1+\gamma_s}}_{\substack{\textbf{(i)}\ \textit{Emission changes due to}\\ \textit{a change in production of domestically}\\ \textit{consumed and produced goods}}} + \underbrace{\hat{p}_{Zi}^{\beta_s(1+\gamma_s)-1}\sum_{j\neq i}^{J}\tilde{\sigma}_{jis}\hat{y}_{jis}^{1+\gamma_s}}_{\substack{\textbf{(ii)}\ \textit{Emission changes due to}\\ \textit{changes in domestic exports}}} \tag{24}$$

$$+ \underbrace{\sum_{j\neq i}^{J}\tilde{\sigma}_{ijs}\hat{p}_{Zj}^{\beta_s(1+\gamma_s)-1}\hat{y}_{ijs}^{1+\gamma_s}}_{\substack{\textbf{(iii)}\ \textit{Emission changes due to}\\ \textit{changes in domestic imports}}} + \underbrace{\sum_{k\neq i}^{J}\sum_{j\neq i}^{J}\tilde{\sigma}_{jks}\hat{y}_{jks}^{1+\gamma_s}}_{\substack{\textbf{(iv)}\ \textit{Emission changes due to}\\ \textit{changes in production of goods consumed}\\ \textit{and produced in the rest of the world}}}$$

The four components disentangle equilibrium changes in domestic emissions from those in foreign emissions.

Emissions embedded in domestic production By increasing the cost of energy inputs, a rise in the domestic carbon tax directly reduces the emissions embedded in each unit of domestic production. Moreover, since production for the home market falls in response to a domestic carbon-tax increase ($\hat{y}_{iis} < 1$), so do emissions (i). The same mechanism reduces domestic emissions from exports ($\hat{y}_{jis} < 1$) unless an LBAM-X export subsidy is granted (ii).

Import leakage In the absence of import-related BAMs, emissions embedded in imports increase in response to a carbon-tax increase (iii). LBAM tariffs completely sterilize such import leakage by ensuring $\hat{y}_{ijs} = 1$. In contrast, the effect of CBAM on leakage depends very much on how it is implemented, as we will show below.

Export leakage Since prices of domestic exports increase with the carbon tax, foreign consumers substitute towards varieties produced in third countries. This increases output in those countries and thus leads to higher emissions in the rest of the world rise (iv). LBAM-X export subsidies can prevent export leakage.

IV Calibration

We calibrate the model for the EU-27 and 56 other countries, using data on 131 4-digit manufacturing industries from the year 2018. Sector-level price elasticities of import demand and export supply are estimated on bilateral trade flows for these countries using state-of-the-art methods (Feenstra, 1994; Broda and Weinstein, 2006; Soderbery, 2015). Sectoral output elasticities of energy and physical production factors are obtained by estimating sector-specific production functions on firm-level data from the German manufacturing census (Ackerberg et al., 2015; Wooldridge, 2009). We analytically solve for an initial equilibrium with a low carbon price of $15 (the average EU-ETS price in 2018) and one with a high carbon price of $105 per ton (the approximate average price in 2023). We assume an SCC of $178 per ton of CO_2 equivalent, based on the central estimate in Rennert et al. (2022), discounted back to 2018. Equilibrium objects that depend on unknown parameters are replaced with data on bilateral trade flows and absorption (Dekle et al., 2007; Ossa, 2014). To estimate foreign emissions intensities, we use our model in combination with newly compiled data on industrial energy prices and fuel mixes across countries. The remainder of this section describes the data and parameter estimation in more detail.

A Data

A realistic calibration of the model calls for detailed data that we compile from a host of sources. First, we need sectoral production and trade data for all countries in the sample for the year 2018 to construct the sectoral expenditure η_{is} and bilateral expenditure shares δ_{ijs}. We obtain 4-digit production (gross output) data for each country from UNIDO INDSTAT 2022 at the ISIC Rev. 4. level. For EU-27 and other European countries we compile these data from Eurostat's COMEXT database and convert it from NACE Rev. 2 to ISIC Rev. 4 classification.

Second, we source bilateral product-level import and export values at the 4-digit

ISIC Rev. 3 level from the World Integrated Trade Solution (WITS) and convert them to the ISIC Rev. 4 classification. Sectoral expenditure η_{is} is defined as absorption (i.e., production minus total exports plus total imports) and expenditure shares are computed as the share of bilateral sectoral imports in total sectoral expenditure.

Third, we need bilateral sectoral tariff data for 2018 to compute the initial tariffs τ_{Iijs}. We source bilateral applied tariff rates at the 4-digit ISIC Rev. 3 level from WITS and convert them to ISIC Rev. 4.[12] We set the initial levels of gross export taxes τ_{Xij} to unity because there is no systematic data on export taxes, and because export subsidies are forbidden under WTO rules.

Fourth, we need data for the carbon emission intensity of energy d_i by country. We source information on energy use in manufacturing by fuel type (coal, oil, natural gas, electricity) for the year 2018 from the International Energy Agency (IEA World Energy Statistics-World Energy Balances).[13] The country-specific emission intensity parameter d_i is computed as a weighted average of energy use by fuel type using emission factors from the Intergovernmental Panel on Climate Change (IPCC 2006 emission factor database for manufacturing industries). To gauge the carbon intensity of the electricity sector in each country, we use data on total CO_2 emissions and total generation of the electricity sector from IEA (IEA World CO_2 Emissions from Fuel Combustion). More details are provided in the Online Appendix.

Fifth, given the prominent role of energy prices in the model, we go to great lengths compiling data on energy prices p_{Zi} in US$/ton or US$/MWh for 2018 from a host of sources, including the IEA World Energy Prices, World Energy Prices Yearly, Enerdata and GlobalPetrolPrices.com. Whenever information is missing in these data sources, we complement it with information from other sources such as national statistics. As a last resort, when no such information is available for a given country, we impute values based on predictions from an OLS regression of (log) energy prices on region

[12]The original data source in WITS is TRAINS at HS6 level.

[13]Where information is missing, we impute fuel consumption with a regression on country-level correlates of energy use (GDP per capita, population, capital intensity, obtained from Penn World Tables 9.0) and region dummies.

dummies, producer dummies, GDP per capita, population, and capital stock, which we obtain from Penn World Tables 9.0 and BP Statistical Review of World Energy. Oil and coal prices are converted from US$/ton to US$/TJ using conversion factors from the UN Statistics Division, 2004 Energy Balances and Electricity Profiles.

The result is a comprehensive dataset of the energy mix among industrial firms and the fuel prices they pay across countries. With this in hand, we compute the country-specific energy price index p_{Zi} as the average energy price weighted by the fuel shares. More details are provided in the Online Appendix.

B Demand Elasticities and Returns to Scale

Demand elasticities ϵ_s and returns to scale γ_s play a key role in our model. To estimate these parameters, we follow the methodology developed by Feenstra (1994), Broda and Weinstein (2006) and, in particular, Soderbery (2015). Rewriting the demand equation (3) in terms of market shares $\delta_{ijs} \equiv \frac{P_{ijs}C_{ijs}}{P_{is}C_{is}}$ yields

$$\log \delta_{ijst} = (1 - \varepsilon_s) \log P_{ijst} + (\varepsilon_s - 1) \log P_{ist}.$$

To facilitate consistent estimation, we first eliminate origin-sector-specific unobservables by taking time differences of log prices and log market shares (denote first differences by Δ). Second, to eliminate sector-importer-time specific unobservables, such as the price index in the importing country, P_{ist}, we difference again by a reference country k (denote reference differences by superscript k). Write the double-differenced demand equation as

$$\Delta^k \ln \delta_{ijst} = \Delta \log \delta_{ijst} - \Delta \log \delta_{ikst} = (1 - \varepsilon_s)\Delta^k \log p_{ijst} + \epsilon^k_{ijst} \tag{25}$$

where ϵ^k_{ijst} are unobservable demand shocks.[14]

[14]Note that the term $1/(\varepsilon_s - 1) \log N_{ijs}$ does not vary over time and thus drops from the equation when taking time differences.

To derive the empirical analog of the supply equation (7), we write the price of a country-j, sector-s firm in market i as a function of the market share

$$p_{ijst}^{1+\gamma_s} = \left(\mu_s \tau_{ijs} \tau_{Iijs} \tau_{Xijs} p_{Zj}^{\beta_s(\gamma_s+1)} \phi_{ijst}^{-(1+\gamma_s)}\right) (\delta_{ijst} \eta_{ist})^{\gamma_s}$$

Taking logs and assuming that the tax instruments are constant over time, the double-differenced supply equation can be written as:

$$\Delta^k \log P_{ijst} = \Delta \log P_{ijst} - \Delta \log P_{ikst} = \frac{\gamma_s}{1+\gamma_s} \Delta^k \log \delta_{ijst} + \omega_{ijst}^k \quad (26)$$

where $\omega_{ijst}^k = -\Delta^k \log(\phi_{ijst})$ are unobservable supply shocks.

The estimator relies on a variance identification and, in particular, the assumption that supply and demand shocks are orthogonal, i.e. $\mathbb{E}(\epsilon_{ijst}^k \omega_{ijst}^k) = 0$. The sample analog of this condition leads to an estimation equation for σ_s and γ_s (Feenstra, 1994) which we estimate using the hybrid limited information maximum likelihood estimator developed by Soderbery (2015).

We estimate demand and supply elasticities at the 4-digit level from EU import data.[15] Table 1 reports summary statistics for our estimates of demand and supply elasticities, which are similar to those reported by Soderbery (2015). Our mean demand elasticity is 4.6 and the median is 2.4. Our median estimate for γ_s is 0.5, implying that the typical sector exhibits decreasing returns to scale ($\alpha_s + \beta_s = 0.67$). In Section VI, we show that our results are qualitatively robust to setting $\gamma_s = 0$ (CRS) and $\epsilon_s = 6$ for all sectors, which have been suggested as standard values in the literature (Costinot and Rodríguez-Clare, 2014).

[15] We use data on the EU's bilateral import values and quantities from EUROSTAT for the sample period 2005-2018 at the 8-digit NACE level (Extrastat) and 4-digit NACE production data, which we convert both to the ISIC Rev.2 4-digit sector level. We construct import prices by dividing unit values by import quantities and market shares by dividing bilateral import values by the EU's total imports.

C Output Elasticities

Production of gross output in 4-digit industries resorts to labor, capital, materials, and energy inputs. In the absence of a European-wide dataset on firm-level energy use (Wagner et al., 2020), we use restricted-access data from the annual census of German manufacturing industries (AFiD- *Amtliche Firmendaten in Deutschland*). German AFiD data combine broad industry coverage with high representativeness. As demonstrated by earlier work, AFiD data are highly suitable for analyzing how energy inputs and CO_2 emissions interact with other input factors in the production process (Petrick et al., 2011; Gerster and Lamp, 2024).

AFiD covers the universe of German manufacturing plants with more than 20 employees, corresponding to approximately 50,000 plants per year. We construct a representative panel of firms for the years from 1998 until 2018 with information on electricity consumption and primary energy use by fuel type, gross output, employment, allowance for depreciation, and materials (drawn from AFiD modules *Energieverbrauch, Industriebetriebe* and *Industrieunternehmen*). We back out firm-level capital stocks by combining firm-level depreciation of fixed assets with sector-level averages of the lifetime of fixed assets, following Wagner (2010).

For each 4-digit NACE industry, we estimate a gross-output production function which is Cobb-Douglas in the factors capital, number of workers, materials and energy. To address well-known endogeneity issues, we adopt the estimator by Wooldridge (2009), using either materials or energy as proxy variables and instrumenting for endogenous inputs with their first and/or second lags. The estimator employs the moment conditions proposed by Olley and Pakes (1996) and Levinsohn and Petrin (2003) in a joint GMM framework that addresses the critique by Ackerberg et al. (2015) by placing additional restrictions on the underlying data generating process. This is slightly less general than their solution but offers computational benefits which are essential in the remote-server environment that governs our data access at the German Federal Research Data Centre.

Table 1: Summary Statistics of Production Function Parameters and Demand Elasticities

	No. Obs.	Mean	Median	Min	Max	SD
α_s	131	0.541	0.530	0.061	0.993	0.306
β_s	131	0.086	0.063	0.001	0.393	0.085
γ_s	131	2.020	0.563	0.000	10.045	3.171
ε_s	131	4.613	2.415	1.317	18.078	5.124

Notes: Summary statistics of GMM estimates for sector-level estimates of demand and supply parameters. Source: Research Data Centres of the Federal Statistical Office and the Statistical Offices of the Federal States of Germany, AFiD-Modul Energieverwendung (1998–2018), AFiD-Panel Industriebetriebe (1998–2018), AFiD-Panel Industrieunternehmen (1998–2018), project-specific preparations, own calculations.

Following the estimation, we retain the output elasticity of energy, β_s, and aggregate all non-energy elasticities to obtain the elasticity of the composite physical input, α_s. Finally, we convert the estimates to the ISIC Rev.4 classification.[16] We rescale output elasticities to make them compatible with the returns to scale estimate obtained from the trade data above. Table 1 reports summary statistics of the production function coefficients. The median output to energy elasticity is 0.06, while the median output elasticity to the composite physical input equals 0.53. We provide robustness checks for these estimates in section VI.

V Policy Scenarios and Results

We quantify the impact of an increase in the EU carbon price from \$15 to \$105 on global emissions, bilateral trade flows between the EU and third countries, EU money-metric welfare, the distribution of abatement across sectors, and the economic costs

[16] To obtain a single output elasticity per ISIC industry, we take an unweighted average of all elasticities with non-negative coefficients after removing obvious outliers. To implement this, we construct a crosswalk between NACE Rev. 2 and ISIC Rev. 4. For those 4-digit industries for which we are not able to obtain a meaningful output elasticity estimate in this way, we use two-digit industry output elasticities.

Table 2: Impact of EU Carbon Price Increase on EU Trade

Leakage Policy	**Mean**	**Median**	**SD**	**Min**	**Max**
A. Imports (% change)					
No-BAM	11	0	35	0	305
CBAM-EU	10	0	35	-51	305
CBAM-ID	-8	-3	21	-100	482
CBAM-EZ	-8	-3	17	-100	253
LBAM, LBAM-X	0	0	0	0	0
B. Import tariffs (% change)					
No-BAM	0	0	0	0	0
CBAM-EU	0.3	0	1.7	0	39.2
CBAM-ID	8.3	5.7	8.8	0	105.6
CBAM-EZ	7.5	5.3	7.8	0.1	94.8
LBAM, LBAM-X	1.3	0.6	1.8	0	8.6
C. Exports (% change)					
No-BAM, CBAM-**, LBAM	-9.4	-2.9	15.4	-79.5	-0.0
LBAM-X	0	0	0	0	0
D. Export subsidies (% change)					
No-BAM, CBAM-**, LBAM	0	0	0	0	0
LBAM-X	3.7	3.0	2.6	0.2	10.5

Notes: Summary statistics of changes in EU trade and trade policy relative to 2018, following an EU carbon price increase from \$15 to \$105 per ton. Statistics are reported for: imports (Panel A), import tariffs (Panel B), exports (Panel C), and export subsidies (Panel D).

imposed on non-EU countries. Non-EU countries are assumed to keep their tax instruments unchanged. We consider the case of No-BAM, three CBAM variants, and two LBAM scenarios: CBAM-EU denotes the current implementation that applies only to aluminum, iron and steel, fertilizers, and cement. All other policies apply to all sectors. Specifically, CBAM-ID is the *ideal* variant that would tax import-embedded emissions across *all* sectors. CBAM-EZ is a simpler variant where embedded emissions are computed using EU (rather than foreign) carbon intensities. The LBAM scenario implements tariffs that eliminate import-related leakage in all sectors. LBAM-X additionally assumes that the EU grants export subsidies that sterilize export leakage.

EU trade Table 2 summarizes the changes in EU trade across policy scenarios. Without border adjustments, bilateral imports increase by 11% on average, and by up to 305% in some sectors (Panel A). This is because unilateral carbon pricing increases energy costs for EU producers and thereby shifts comparative advantage to dirty producers, inducing substantial import leakage. In contrast, CBAM-ID *reduces* imports compared to no carbon pricing by 8% on average, and virtually shuts down trade in some very carbon-intensive sector-country pairs.[17] CBAM-EU gives rise to both these phenomena; average imports increase by almost 10% whereas imports for some sector-country-pairs drop by up to one half. As explained in Section 2, this is because the objective of CBAM tariffs is to tax emissions embedded in domestic consumption. This implies that, in most cases, tariffs reduce imports beyond what is needed to prevent carbon leakage, and provides a rationale for strong opposition by non-EU countries against CBAM as a policy that limits access to EU markets (WTO, 2024). LBAM avoids this by raising tariffs just enough to eliminate import leakage. Given high average trade elasticities, modest LBAM tariffs of 1.3% on average would suffice (median 0.6%, maximum 8.6%; Panel B). In contrast, implementing CBAM across all sectors would raise bilateral tariffs by 8.3% on average (7.5% in the EZ variant), and double tariff rates in some industries. While CBAM-EU leaves most imports untaxed, affected sectors will see tariff increases as high as 39.2%.

Unilateral carbon pricing weakens the competitiveness of EU exporters on world markets, reducing bilateral EU exports by 9.4% on average and almost 80% in the most impacted sector-country pairs (Panel C). Border adjustments on imports leave this export leakage intact. However, it can be neutralized with a modest export subsidy under the LBAM-X scenario, which averages at 3.7% across sector-country pairs and never exceeds 10.5%. In Appendix Tables C.1 and C.2, we report changes in EU imports and exports aggregated by 2-digit sector for readability.[18]Imports surge in

[17]Conversely, EU imports of cleaner goods increase in a small number of country-sector pairs.

[18]Remember that the model simulations are disaggregated into 131 4-digit sectors. Aluminum, iron and steel fall into the sector Metals, while fertilizers are part of Chemicals and cement is part of Minerals.

virtually all sectors due to the EU carbon price increase, while exports fall across the board. The magnitudes of these adjustments are very heterogeneous across sectors, as they are governed by a complex combination of factors including trade elasticities, energy intensity, returns to scale, and size.

EU welfare and global emissions Table 3 compares the policy scenarios in terms of two outcomes: EU welfare effects, comprised of economic costs and environmental benefits, and impact on global emissions. Column (iv) shows that unilaterally increasing its carbon price has significant economic costs for the EU, but the incidence varies substantially across policies, as shown in columns (i)-(iii): No-BAM and CBAM-EU are practically indistinguishable in terms of economic costs and load the bulk of them on consumers, while profits fall moderately and government revenue surges. Compared to those scenarios, CBAM-ID and CBAM-EZ *halve* the economic costs as the boost in government revenue induced by taxing all import-embedded carbon emissions (and, to a lesser extent, a smaller contraction in domestic profits) compensates for the (even larger) drop in consumer surplus.

After netting out environmental benefits, only the comprehensive CBAMs lead to welfare gains for the EU in the amount of $29 bn (CBAM-ID) and $22 bn (CBAM-EZ), reported in column (vi). In contrast, welfare losses are largest for No-BAM and for CBAM-EU ($25 bn and $23 bn, respectively).[19] LBAM policies outperform both CBAM-EU and No-BAM in terms of welfare because they generate significantly larger environmental benefits. Compared to the comprehensive CBAMs, they impose a smaller burden on EU consumers but also generate much less tariff revenue. LBAM gives rise to a welfare loss of $15.1 bn, a reduction by one third compared to CBAM-

[19] Our calculations attribute the global environmental benefit entirely to the EU while setting $\theta_i = 0$ for non-EU countries. This parameterization closely aligns with the intention behind CBAM to support globally optimal emissions abatement by the EU when other countries do not value such abatement; it provides an upper-bound estimate of the welfare the EU can get taking this unilateral approach. As an alternative, we assign a share of the global SCC to each country following the approach in Farrokhi and Lashkaripour (2025). This renders welfare changes more negative but leaves the ranking of policy instruments unchanged. This and other robustness checks are discussed in Section VI below.

Table 3: Impact of EU Carbon Price Increase on EU Welfare and Global Emissions

	(i) Government Revenue	(ii) Consumer Surplus	(iii) Profits	(iv) Economic Costs = (i)+(ii)+(iii)	(v) Environmental Benefit	(vi) Welfare = (iv) + (v)	(vii) Global Abatement [%]
No-BAM	68.6	-101.7	-23.6	-56.7	31.9	-24.9	0.85
CBAM-EU	70.4	-103.6	-22.7	-55.9	32.9	-23.0	0.87
CBAM-ID	135.5	-151.8	-8.8	-25.1	53.8	28.7	1.43
CBAM-EZ	129.2	-146.4	-10.1	-27.2	49.4	22.2	1.31
LBAM	79.1	-112.1	-18.7	-51.6	36.6	-15.1	0.97
LBAM-X	32.6	-112.1	27.3	-52.2	48.1	-4.1	1.28

Notes: Change in EU welfare (vi) and its components (i-iii, v) following an EU carbon price increase from $15 to $105, in billions of 2018 US$. The percentage reduction in global emissions (vii) is relative to 2018 levels and valued at a SCC of $178 per ton to compute the global environmental benefit (v, in billions of 2018 US$).

EU. Additionally subsidizing EU exports to prevent export leakage (LBAM-X) brings the welfare loss down to \$4 bn as environmental benefits rise to a level comparable to the comprehensive CBAMs. LBAM-X also boosts profits by shifting government revenue to exporting firms in the EU.

Higher carbon taxes generate global environmental benefits in proportion to EU emissions reductions, net of carbon leakage arising from the trade impacts documented above. Comparing global abatement across scenarios, reported in column (vii) of Table 3, reveals the extent of carbon leakage. Since LBAM-X holds foreign production fixed at the level before the carbon price increase, global abatement in this scenario (1.28%) is entirely determined by how EU emitters respond to the increase in the EU-ETS price. Without any border adjustments, global abatement drops to 0.85%, implying that one out of three tons of CO_2 abated in the EU 'leaks' to the rest of the world. LBAM import tariffs prevent only 30% of such carbon leakage. The remaining 70% occur due to the substitution of EU exports with production from the rest of the world. Such export leakage is not mitigated by any policy except LBAM-X, as shown in Figure 2. Universal applications of CBAM achieve comparable reductions in world emissions but require larger reductions in domestic production and imports. This is because CBAM implements (CBAM-ID) or approximates (CBAM-EZ) a consumption-based carbon tax for the EU which discourages carbon-intensive production in the foreign export sectors. Due to its limited sector coverage, however, CBAM-EU reduces carbon leakage only minimally.

The result that comprehensive CBAMs impose the smallest economic cost on the EU is due to CBAM's extraterritorial effects and comes at the expense of the EU's trade partners whose exports contract in response to high EU carbon prices. On environmental grounds, shifting abatement towards non-EU countries is not strictly necessary; by shutting down import *and* export leakage, LBAM-X yields almost the same emissions reductions as the feasible consumption-based carbon tax CBAM-EZ.

Cross-sectoral abatement To shed light on the distribution of abatement across sectors, Appendix Table C.3 reports the percentage change in global emissions attributed to each 2-digit sector measured relative to global sectoral emission levels in 2018. Only in the metals sector does CBAM-EU increase environmental effectiveness of EU carbon pricing compared to No-BAM. In contrast, the more comprehensive border adjustment mechanisms lead to greater emissions reductions in virtually all sectors.

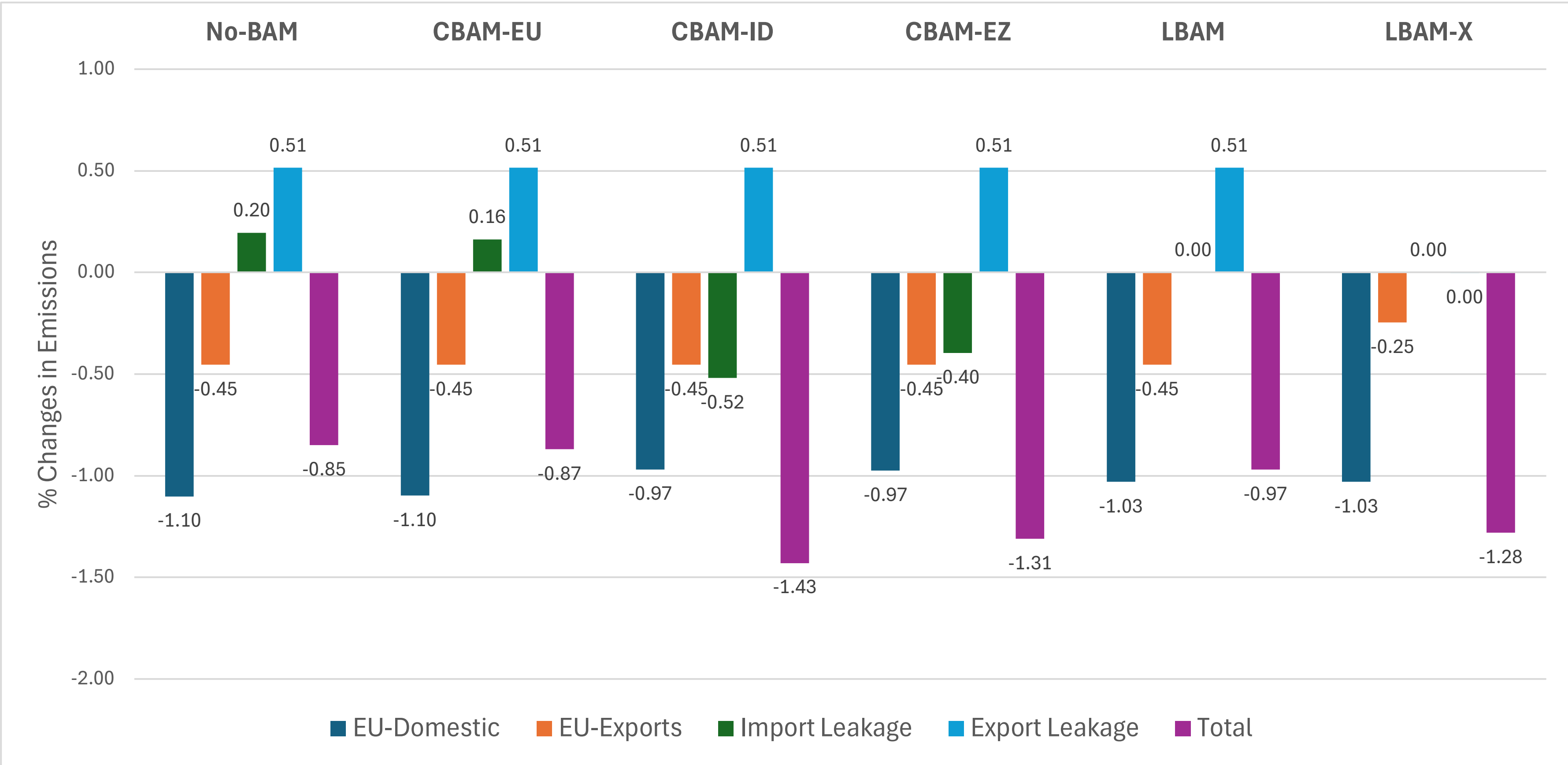
Third-country economic costs Figure 3 illustrates the economic costs of EU policies imposed on other countries in terms of their distribution across countries (3a) and their composition for the average country (3b).[20] In non-EU countries, higher export prices from the EU induce substitution to otherwise less competitive suppliers. Without BAM, or with CBAM-EU, this negative effect dominates the positive effect of increased competitiveness in most countries, imposing small costs. By contrast, the comprehensive CBAMs induce large additional economic costs on many non-EU countries as they significantly reduce exports to the EU (up to $20 bn. for China). Therefore, broadening CBAM's sector coverage in the future, as envisaged by the EU, will likely amplify the already strong political opposition from BRICS states and other countries towards this policy. This conclusion is robust to attributing a share of global environmental benefits to each country because the economic costs would still outweigh the environmental benefits in most countries (see Section VI below).

Since LBAM neutralizes the (positive) effect on EU imports, many countries are left with economic costs that are a bit larger than under no-BAM. LBAM-X additionally restores EU exports to their initial levels, thus eliminating all economic impacts on foreign countries. Hence, LBAM-X avoids negative extraterritorial effects of EU climate policies while providing large global environmental benefits—a combination that would render it politically acceptable for all countries. The export subsidies we

[20] Notice that, under the baseline calibration, economic costs and welfare imposed on non-EU countries coincide.

propose thus provide a valuable reference as the EU Commission is beginning the process of designing support measures that mitigate the risk of carbon leakage for EU-exporters of CBAM goods (European Commission, 2025a).

Figure 2: Impact of EU Carbon Price Increase on Carbon Emissions



Notes: The figure shows the percentage change in emissions following a unilateral increase in the EU carbon price from \$15 to \$105 per ton. Emissions changes (in % of baseline emissions) are computed for six scenarios: No-BAM, CBAM-EU, CBAM-ID, CBAM-EZ, LBAM and LBAM-X. Following the decomposition in eq. (24), total emissions change due to changes in (i) EU production for the home market (EU-Domestic), (ii) EU production for the export market (EU-Exports), (iii) foreign production for the EU market (Import leakage), and (iv) foreign production for other foreign markets (Export leakage).

VI Robustness

This section assesses the robustness of our results to using alternative values for some key parameters. We start by showing welfare results for the EU and Non-EU countries when assuming country-specific values for the social cost of carbon instead of attributing the global welfare benefit of abatement to the EU. We then discuss welfare and emission results obtained for alternative choices of the trade and output elasticicities.

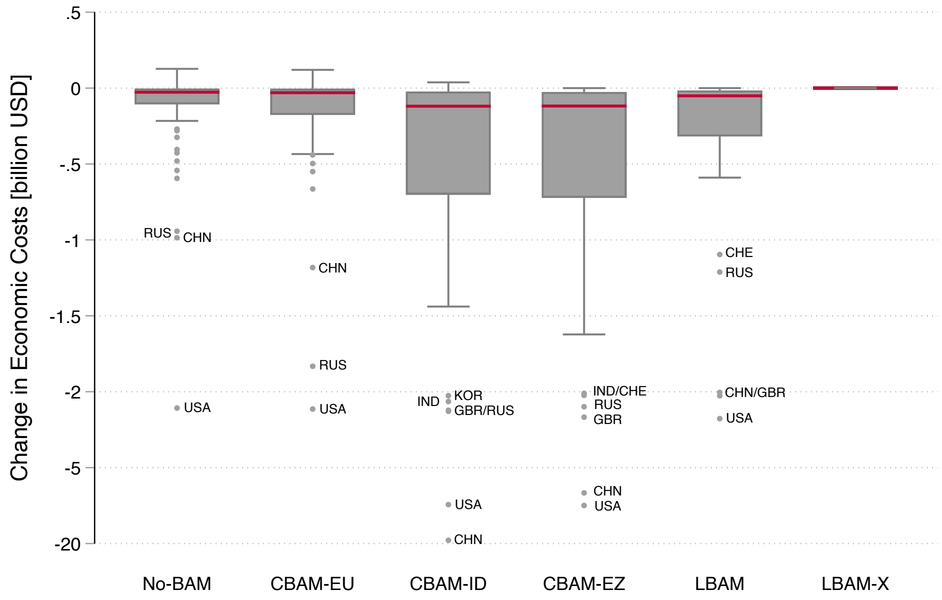
Country-level SCC Dis-aggregating global estimates of SCC down to the level of the individual country is methodologically challenging and subject to ongoing research. Here we adopt the approach proposed by Farrokhi and Lashkaripour (2025) who recover country-specific estimates of the disutility from emissions via a revealed preference approach, based on implemented environmental taxes scaled by population and energy use. The sum of these country-level disutilities is assumed to equal the global SCC.[21] Figure D.1 in the Appendix shows the SCC for selected countries.

Table 4 reports the EU welfare effects when adopting country-specific SCC estimates. The EU's SCC is reduced from \$178 to \$71, which lowers the estimated environmental benefits by approximately 60%. As a result, the net welfare effect for the EU turns negative across all policy scenarios, including those that delivered a net welfare gain with our preferred parameterization (CBAM-ID and CBAM-EZ). The relative welfare ranking of scenarios is not affected, however: LBAM and LBAM-X still provide larger welfare than No-BAM or CBAM-EU.

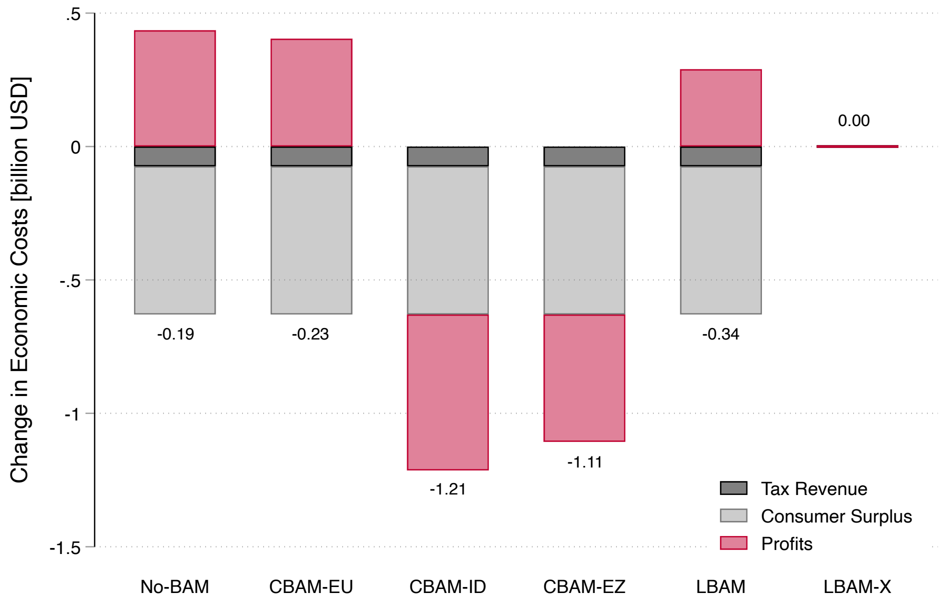
In contrast to the EU, non-EU countries benefit from assigning country-specific SCC estimates to them. Except under CBAM-ID and CBAM-EZ, welfare increases across these countries (see Figure 4b). However, CBAM-ID and CBAM-EZ, which

[21] To apply their estimates to our data, we first allocate the SCC to the countries in our sample, as our country coverage differs from theirs. Countries included in Farrokhi and Lashkaripour (2025)'s sample but not in ours, specifically Turkey and Japan, are excluded. We assign countries that are included in our sample but absent from theirs to the appropriate 'Rest-of-the-World' regions defined in their study and distribute the SCC according to population shares within each region. We also apply this approach to recover the SCC of the United Kingdom, initially part of the EU aggregate, but treated as a separate country following Brexit. Finally, we rescale the values so that the sum matches our preferred global SCC estimate of \$178.

Figure 3: Impact of EU Carbon Price Increase on Economic Costs for Non-EU Countries



(a) Distribution of the changes in economic costs



(b) Decomposition of the change in economic costs

Notes: The figure shows changes in economic costs following a unilateral increase in the EU carbon price from $15 to $105 per ton. Subfigure (a) shows the distribution of the change in economic costs, subfigure (b) shows the average contribution of its different components. Economic costs are defined as the sum of consumer surplus, profits, and government revenue after taxes, subsidies, and tariffs, expressed in 2018 US$. Economic costs changes are computed for six different scenarios: No-BAM, CBAM-EU, CBAM-ID, CBAM-EZ, LBAM, and LBAM-X.

Table 4: Impact of EU Carbon Price Increase on EU Welfare and Global Emissions for alternative choice of SCC

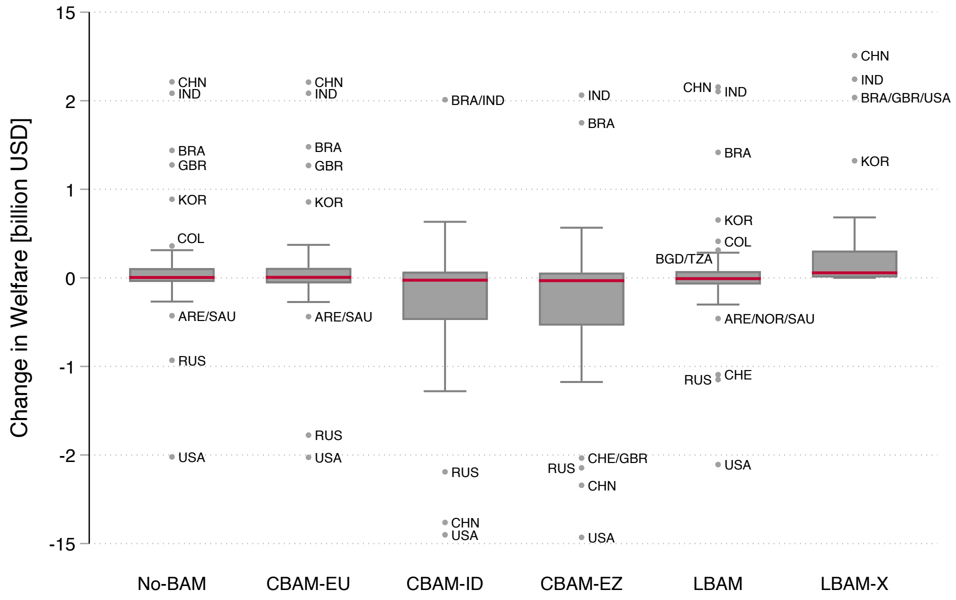
	(i) Government Revenue	(ii) Consumer Surplus	(iii) Profits	(iv) Economic Costs = (i)+(ii)+(iii)	(v) Environmental Benefit	(vi) Welfare = (iv) + (v)	(vii) Global Abatement [%]
No-BAM	68.6	-101.7	-23.6	-56.7	12.7	-44.0	0.85
CBAM-EU	70.4	-103.6	-22.7	-55.9	13.1	-42.8	0.87
CBAM-ID	135.5	-151.8	-8.8	-25.1	21.4	-3.7	1.43
CBAM-EZ	129.2	-146.4	-10.1	-27.2	19.7	-7.5	1.31
LBAM	79.1	-112.1	-18.7	-51.6	14.6	-37.1	0.97
LBAM-X	32.6	-112.1	27.3	-52.2	19.2	-33.0	1.28

Notes: Change in EU welfare (vi) and its components (i-iii, v) following an EU carbon price increase from $15 to $105, in billions of 2018 US$. The percentage reduction in global emissions (vii) is relative to 2018 levels and valued at a SCC of $178 per ton to compute the global environmental benefit. Column (v) reports the EU's share in global environmental benefits (in billions of 2018 US$) computed following Farrokhi and Lashkaripour (2025).

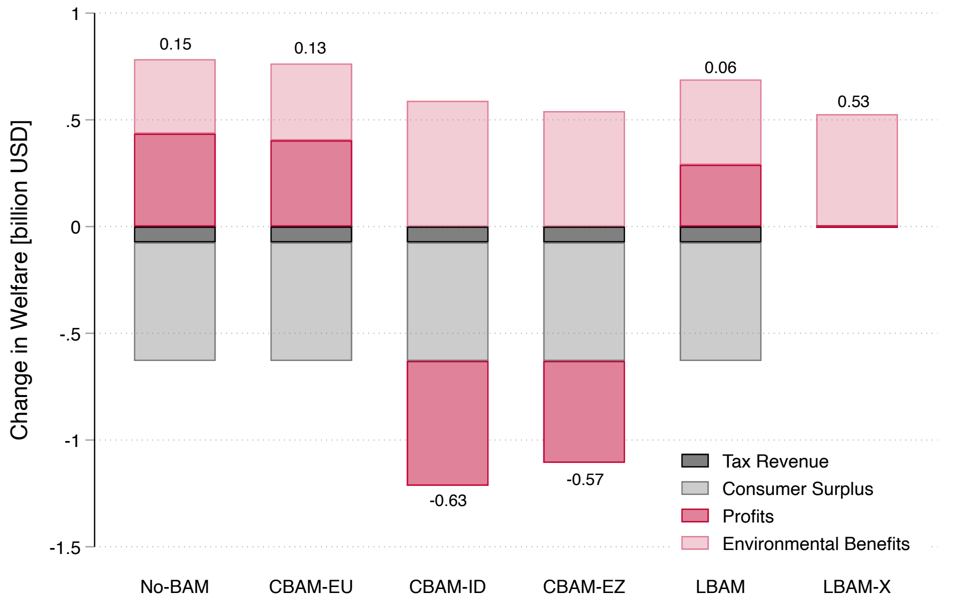
achieve the largest emissions reductions relative to the benchmark still imply large welfare losses for many countries, in particular for the US and China (see Figure 4a). Under No-BAM, CBAM-EU or LBAM, countries either experience small welfare losses or small gains. LBAM-X makes all foreign countries better off as they now value global emission reductions while still facing zero economic costs.

Alternative trade and output elasticities We now turn to the robustness checks on the other structural model parameters. In our first robustness check, we exclude outliers from the data when computing trade and output elasticities. Rather than winsorizing, we impose a sensible upper bound on the output elasticity of energy to limit the influence of extreme values. Missing elasticity estimates are imputed using available 4-digit industry values within the same 2-digit classification. The same procedure is applied to trade elasticities. In the second robustness check, we compute capital stocks using the perpetual inventory method instead of using the method proposed by Wagner (2010). In the third robustness check, instead of using estimated values for the returns to scale and the trade elasticity for each sector, we set them to standard values in the literature. Specifically, we set $\gamma = 0$ (implying CRS) and $\varepsilon = 6$ (Costinot and Rodríguez-Clare, 2014) for all sectors. Appendix Table C.4 reports summary statistics of these alternative parameters. We report the EU welfare and global emission effects for these robustness check in Table 5. In addition, Appendix Figures D.2- D.4b show box plots of the distribution of the foreign economic costs, as well as a decomposition of average foreign economic costs, respectively. Compared to the baseline calibration, the numbers change somewhat across the different robustness checks. However, the ranking of scenarios in terms of welfare and emissions reductions remains unchanged. Moreover, the distribution of economic costs also remains heterogeneous across countries with the most impacted countries experiencing costs of EU policies of up to $ 15-20 bn.

Figure 4: Impact of EU Carbon Price Increase on Welfare for Non-EU Countries for alternative choice of SCC



(a) Distribution of the changes in welfare



(b) Decomposition of the change in welfare

Notes: The figure shows changes in welfare following a unilateral increase in the EU carbon price from \$15 to \$105 per ton. Subfigure (a) shows the distribution of the change in economic costs, and subfigure (b) shows the average contribution of its different components. Welfare is defined as the sum of consumer surplus, profits, government revenue after taxes, subsidies, and tariffs, and environmental benefits expressed in 2018 \$US. Welfare changes are computed for six different scenarios: No-BAM, CBAM-EU, CBAM-ID, CBAM-EZ, LBAM, and LBAM-X. Country-specific values of SCC are computed following Farrokhi and Lashkaripour (2025).

Table 5: Impact of EU Carbon Price Increase on EU Welfare and Global Emissions for Alternative Parameter Estimates

	(i) Government Revenue	(ii) Consumer Surplus	(iii) Profits	(iv) Economic Costs = (i)+(ii)+(iii)	(v) Environmental Benefit	(vi) Welfare = (iv) + (v)	(vii) Global Abatement [%]
A. Excluding Outliers in Elasticities							
No-BAM	64.5	-96.9	-22.4	-54.8	36.3	-18.5	1.02
CBAM-EU	66.2	-98.8	-21.5	-54.0	37.4	-16.6	1.05
CBAM-ID	122.8	-144.2	-8.6	-30.1	49.3	19.2	1.39
CBAM-EZ	116.9	-138.8	-9.8	-31.7	46.8	15.1	1.32
LBAM	73.1	-105.3	-18.2	-50.4	38.6	-11.8	1.09
LBAM-X	31.5	-105.3	22.0	-51.8	44.2	-7.6	1.25
B. Capital Stock via Perpetual Inventory Method (PIM)							
No-BAM	37.8	-54.6	-15.0	-31.8	19.3	-12.5	0.75
CBAM-EU	39.3	-56.5	-14.0	-31.2	21.4	-9.7	0.83
CBAM-ID	78.6	-93.8	-2.7	-17.8	34.9	17.1	1.35
CBAM-EZ	73.1	-87.3	-4.6	-18.8	31.5	12.8	1.22
LBAM	45.7	-62.5	-11.6	-28.4	22.3	-6.1	0.86
LBAM-X	24.0	-62.5	9.6	-29.0	26.5	-2.5	1.02
C. Constant returns to scale and demand elasticity for all sectors							
No-BAM	62.7	-72.4	-24.3	-34.0	26.5	-7.5	0.64
CBAM-EU	64.5	-74.5	-23.1	-33.1	27.8	-5.3	0.67
CBAM-ID	100.0	-118.3	-5.3	-23.6	58.2	34.6	1.40
CBAM-EZ	96.8	-111.8	-8.1	-23.1	51.2	28.1	1.23
LBAM	76.8	-87.1	-17.3	-27.6	34.9	7.3	0.84
LBAM-X	56.9	-87.1	1.6	-28.6	45.0	16.4	1.08

Notes: This table reports the change in EU welfare (vi) and its components (i-iii, v) following an EU carbon price increase from $15 to $105, in billions of 2018 US$ for alternative parameter estimates. The percentage reduction in global emissions (vii) is relative to 2018 levels and valued at a SCC of $178 per ton to compute the global environmental benefit (v, in billions of 2018 US$). Panel A excludes a broader set of outliers from the output and trade elasticity estimates, Panel B estimates the capital stock using the perpetual inventory method (PIM), while Panel C assumes constant returns to scale ($\gamma = 0$) and a demand elasticity $\varepsilon = 6$ for all industries.

VII Conclusion

With the adoption of CBAM, the EU has overcome a long-standing hesitation to restrict free trade in pursuit of environmental goals. As our analysis has shown, however, CBAM covers too few sectors to effectively prevent import leakage, and does not address substantial export leakage. Expanding CBAM's sector coverage is subject to formidable information requirements and would restrict market access more than needed to prevent leakage, imposing heavy welfare losses on some non-EU countries.

The alternative developed in this paper, LBAM, mitigates carbon leakage with minimal information requirements and trade impacts. LBAM neither discriminates between trade partners, nor does it make them worse off as the EU-ETS price increases. These features are aligned with the WTO's core principles of national treatment and non-discrimination (Staiger, 2022). For CBAM, however, the EU invokes environmentally-based exceptions from those principles. As several prominent WTO member states firmly reject this view (WTO, 2023, 2024; BRICS, 2025), CBAM is at risk of becoming a political non-starter. In that case, a "climate club" of countries with high carbon price would lack a credible instrument to persuade non-members to adopt carbon pricing on their own (Nordhaus, 2015; G7, 2022).

LBAM is a more consensual alternative as it only sterilizes the trade impacts of increasing EU-ETS prices. If other countries implement carbon prices different from the EU's, LBAM tariffs would become partner-country specific. They would still satisfy non-discrimination, as they would guarantee the previous level of market access. Finally, as the EU decarbonizes its own production over time, LBAM tariffs would converge to zero, thus re-establishing free trade.

References

Ackerberg, D. A., Caves, K., and Frazer, G. (2015). Identification properties of recent production function estimators. Econometrica, 83(6):2411–2451.

Aichele, R. and Felbermayr, G. (2015). Kyoto and Carbon Leakage: An Empirical Analysis of the Carbon Content of Bilateral Trade. Review of Economics and Statistics, 97(1):104–115.

Ambec, S., Esposito, F., and Pacelli, A. (2024). The economics of carbon leakage mitigation policies. Journal of Environmental Economics and Management, 125:102973.

Black, M. S., Liu, A. A., Parry, I. W., and Vernon, N. (2023). IMF fossil fuel subsidies data: 2023 update. WP/23/169, International Monetary Fund.

BRICS (2025). Rio de Janeiro Declaration - Strengthening Global South Cooperation for a More Inclusive and Sustainable Governance. `https://brics.br/en/documents/presidency-documents/250705-brics-leaders-declaration-en.pdf/`. Accessed 14 July 2025.

Broda, C. and Weinstein, D. E. (2006). Globalization and the Gains From Variety. Quarterly Journal of Economics, 121(2):541–585.

Böhringer, C., Fischer, C., Rosendahl, K. E., and Rutherford, T. F. (2022). Potential impacts and challenges of border carbon adjustments. Nature Climate Change, 12(1):22–29.

Chen, Q., Chen, Z., Liu, Z., Suárez Serrato, J. C., and Xu, D. Y. (2025). Regulating conglomerates: Evidence from an energy conservation program in China. American Economic Review, 115(2):408–47.

Cicala, S., Hemous, D., and Olsen, M. (2023). Adverse selection as a policy instrument: Unraveling climate change. Technical report, Tufts University.

Cosbey, A., Droege, S., Fischer, C., and Munnings, C. (2019). Developing guidance for implementing border carbon adjustments: Lessons, cautions, and research needs from the literature. Review of Environmental Economics and Policy, 13(1):3–22.

Costinot, A. and Rodríguez-Clare, A. (2014). Chapter 4 - Trade Theory with Numbers: Quantifying the Consequences of Globalization. In Gopinath, G., Helpman, E., and Rogoff, K., editors, Handbook of International Economics, volume 4 of Handbook of International Economics, pages 197–261. Elsevier.

Dekle, R., Eaton, J., and Kortum, S. (2007). Unbalanced trade. American Economic Review, 97(2):351–355.

Draghi, M. (2024). The Future of European Competitiveness - Part B. Technical report, European Commission.

Ellerman, D., Marcantonini, C., and Zaklan, A. (2016). The European Union Emissions Trading System: Ten years and counting. Review of Environmental Economics and Policy, 10(1):89–107.

European Commission (2025a). Cbam: Commission announces plan to mitigate carbon leakage risk for exporters. `https://taxation-customs.ec.europa.eu/news/cbam-commission-announces-plan-mitigate-carbon-leakage-risk-exporters-2025-07-03_en`. Published 3 July 2025, accessed 15 July 2025).

European Commission (2025b). Proposal for a Regulation of the European Parliament and of the Council amending Regulation (EU) 2023/956 as regards simplifying and strengthening the Carbon Border Adjustment Mechanism. COM(2025) 87 final, Brussels, 26 February 2025. ECLI: CELEX 52025PC0087.

Farrokhi, F. and Lashkaripour, A. (2025). Can trade policy mitigate climate change? Econometrica, forthcoming.

Feenstra, R. C. (1994). New product varieties and the measurement of international prices. American Economic Review, pages 157–177.

Fowlie, M. and Reguant, M. (2018). Challenges in the measurement of leakage risk. AEA Papers and Proceedings, 108:124–29.

Fowlie, M. L. and Reguant, M. (2022). Mitigating emissions leakage in incomplete carbon markets. Journal of the Association of Environmental and Resource Economists, 9(2):307–343.

G7 (2022). Terms of Reference for the Climate Club. Available online at www.g7germany.de. Accessed February 6, 2024.

Gerster, A. and Lamp, S. (2024). Energy Tax Exemptions and Industrial Production. Economic Journal, 134(663):2803–2834.

Hintermann, B., Peterson, S., and Rickels, W. (2016). Price and Market Behavior in Phase II of the EU ETS: A Review of the Literature. Review of Environmental Economics and Policy, 10(1):108–128.

Hoel, M. (1996). Should a carbon tax be differentiated across sectors? Journal of Public Economics, 59(1):17–32.

Kortum, S. and Weisbach, D. A. (2021). Optimal unilateral carbon policy. Cowles Foundation Discussion Paper 2311, Yale University.

Larch, M. and Wanner, J. (2017). Carbon tariffs: An analysis of the trade, welfare, and emission effects. Journal of International Economics, 109:195–213.

Levinsohn, J. and Petrin, A. (2003). Estimating Production Functions Using Inputs to Control for Unobservables. Review of Economic Studies, 70(2):317–341.

Markusen, J. R. (1975). International externalities and optimal tax structures. Journal of International Economics, 5(1):15–29.

Martin, R., Muûls, M., de Preux, L. B., and Wagner, U. J. (2014). Industry compensation under relocation risk: A firm-level analysis of the EU Emissions Trading Scheme. American Economic Review, 104(8):2482–2508.

Nordhaus, W. (2015). Climate clubs: Overcoming free-riding in international climate policy. American Economic Review, 105(4):1339–70.

Olley, S. and Pakes, A. (1996). The dynamics of productivity in the telecommunications equipment industry. Econometrica, 64(6):1263–1298.

Ossa, R. (2014). Trade wars and trade talks with data. American Economic Review, 104(12):4104–46.

Petrick, S., Rehdanz, K., and Wagner, U. J. (2011). Energy use patterns in German industry: Evidence from plant-level data. Journal of Economics and Statistics, 231(3):379–414.

Rennert, K., Errickson, F., Prest, B., and et al. (2022). Comprehensive evidence implies a higher social cost of CO_2. Nature, 610:687–692.

Research Data Centres of the Federal Statistical Office and Statistical Offices of the Federal States of Germany. AFiD-Modul Energieverwendung (1998–2018). doi: 10.21242/43531.2021.00.03.1.1.0.

Research Data Centres of the Federal Statistical Office and Statistical Offices of the Federal States of Germany. AFiD-Panel Industriebetriebe (1998–2018). doi: 10.21242/42111.2021.00.01.1.1.0.

Research Data Centres of the Federal Statistical Office and Statistical Offices of the Federal States of Germany. AFiD-Panel Industrieunternehmen (1998–2018). doi: 10.21242/42221.2021.00.01.1.1.0.

Shapiro, J. S. and Walker, R. (2018). Why is pollution from us manufacturing declining? the roles of environmental regulation, productivity, and trade. American Economic Review, 108(12):3814–54.

Soderbery, A. (2015). Estimating import supply and demand elasticities: Analysis and implications. Journal of International Economics, 96(1):1–17.

Sogalla, R. (2023). Unilateral carbon pricing and heterogeneous firms. DIW Discussion Paper 2060, Deutsches Institut für Wirtschaftsforschung (DIW), Berlin.

Staiger, R. (2022). A World Trading System for the Twenty-First Century. The MIT Press.

Stillger, S. (2025). The role of firm heterogeneity and intermediate inputs in carbon leakage. CRC TR 224 Discussion Paper No. 670.

Wagner, J. (2010). Estimated capital stock values for German manufacturing enterprises covered by the cost structure surveys. Journal of Contextual Economics – Schmöllers Jahrbuch, 130(3):403–408.

Wagner, U. J., Kassem, D., Gerster, A., Jaraite, J., Klemetsen, M. E., Laukkanen, M., Leisner, J., Martin, R., Muûls, M., Munch, J. R., de Preux, L., Rosendahl, K. E., Schusser, S., and Nielsen, A. E. (2020). Carbon footprints of European manufacturing jobs: Stylized facts and implications for climate policy. CRC TR 224 Discussion Paper No. 250.

Wooldridge, J. M. (2009). On estimating firm-level production functions using proxy variables to control for unobservables. Economics Letters, 104(3):112–114.

World Bank (2024). Carbon Pricing Dashboard. `https://carbonpricingdashboard.worldbank.org/compliance/coverage`. Accessed 18 September 2024.

WTO (2023). European union - carbon border adjustment mechanism (id 148). Trade

Concerns Raised in the Council for Trade in Goods G/C/M/147, World Trade Organisation.

WTO (2024). European Union - Carbon border adjustment mechanism (ID 69). Trade Concerns Raised in the Committee on Market Access G/MA/M/80, World Trade Organisation.

Appendix (for online publication)

A Theory Appendix

A.1 LBAM

By virtue of holding bilateral imports constant, the tariff changes in condition (21) hold fixed the aggregate import quantity. However, in principle, other tariff changes could also hold aggregate imports constant, while leaving bilateral imports free to adjust. To establish uniqueness, we show that there exist no other non-discriminatory tariffs that hold aggregate imports constant.

Consider a scenario where tariffs on imports are set in order to keep changes in aggregate imports equal to zero, i.e. $\hat{C}_{iI} = 1$. First, we need to define total imports, both in levels and in changes:

$$C_{iIs}^{\frac{\varepsilon_s - 1}{\varepsilon_s}} \equiv \sum_{j \neq i} C_{ijs}^{\frac{\varepsilon_s - 1}{\varepsilon_s}} \tag{A.1}$$

$$\hat{C}_{iIs}^{\frac{\varepsilon_s - 1}{\varepsilon_s}} = \sum_{j \neq i} \delta_{ijs}^I \hat{c}_{ijs}^{\frac{\varepsilon_s - 1}{\varepsilon_s}} = \sum_{j \neq i} \delta_{ijs}^I \left[\hat{p}_{Zj}^{-\beta_s \frac{(\gamma_s + 1)\varepsilon_s}{\gamma_s \varepsilon_s + 1}} \left(\hat{\tau}_{Iijs} \hat{\tau}_{Xijs} \right)^{\frac{-\varepsilon_s}{\gamma_s \varepsilon_s + 1}} \hat{P}_{is}^{\frac{\varepsilon_s - 1}{\gamma_s \varepsilon_s + 1}} \right]^{\frac{\varepsilon_s - 1}{\varepsilon_s}} \tag{A.2}$$

where $\delta_{ijs}^I \equiv \frac{P_{ijs} C_{ijs}}{P_{iIs} C_{iIs}}$ represents the share of imports of country i from country j. Then given condition (A.2)

$$1 = \sum_{j \neq i}^{J} \delta_{ijs}^I \left[\hat{\tau}_{Iijs}^{\frac{-\varepsilon_s}{\gamma_s \varepsilon_s + 1}} \hat{P}_{is}^{\frac{\varepsilon_s - 1}{\gamma_s \varepsilon_s + 1}} \right]^{\frac{\varepsilon_s - 1}{\varepsilon_s}} \Rightarrow \hat{P}_{is}^{-\frac{(\varepsilon_s - 1)^2}{(\gamma_s \varepsilon_s + 1)\varepsilon_s}} = \sum_{j \neq i}^{J} \delta_{ijs}^I \hat{\tau}_{Iijs}^{\frac{1 - \varepsilon_s}{\gamma_s \varepsilon_s + 1}} \tag{A.3}$$

At the same time from condition (16) it follows:

$$\hat{P}_{is}^{\frac{(1+\gamma_s)(1-\varepsilon_s)}{\gamma_s \varepsilon_s + 1}} = \delta_{iis} \hat{p}_{Zi}^{\frac{\beta_s (\gamma_s + 1)(1 - \varepsilon_s)}{\gamma_s \varepsilon_s + 1}} + \sum_{j \neq i}^{J} \delta_{ijs} \hat{\tau}_{Iijs}^{\frac{1 - \varepsilon_s}{\gamma_s \varepsilon_s + 1}} \tag{A.4}$$

Combining the last two conditions we have that keeping aggregate imports constant implies the following condition:

$$\left[\sum_{j\neq i}^{J}\delta_{ijs}^{I}\hat{\tau}_{Iijs}^{\frac{1-\varepsilon_s}{\gamma_s\varepsilon_s+1}}\right]^{\frac{\varepsilon_s(1+\gamma_s)}{(\varepsilon_s-1)}} = \delta_{iis}\hat{p}_{Zi}^{\frac{\beta_s(\gamma_s+1)(1-\varepsilon_s)}{\gamma_s\varepsilon_s+1}} + \sum_{j\neq i}^{J}\delta_{ijs}\hat{\tau}_{Iijs}^{\frac{1-\varepsilon_s}{\gamma_s\varepsilon_s+1}} \tag{A.5}$$

There is no unique solution to this problem and thus there exist multiple tariff schemes that ensure constant aggregate imports. However, when imposing the additional condition that tariffs must be non-discriminatory between partner countries (Most-favored-nation principle), condition (A.5) can be rewritten as condition (21). Consequently, holding aggregate imports constant without discriminating between origin countries is equivalent to choosing a tariff change that holds bilateral imports constant.

A.2 Welfare

To write profits and tax income in terms of observables note that from (4) and the definition of δ_{jis} we have $p_{jis}c_{jis} = \delta_{jis}\eta_{js}$.

From (9):

$$\hat{\Pi}_{jis} = \left(\frac{\hat{y}_{jis}}{\hat{\phi}_{jis}}\right)^{1+\gamma_s}\hat{p}_{Zi}^{\beta_s(\gamma_s+1)} \tag{A.6}$$

Using (7) and (9) we can write $\Pi_{jis} = N_{jis}\tau_{Ijis}^{-1}\tau_{Xjis}^{-1}[1-\mu_s^{-1}(1+\gamma_s)^{-1}]\eta_{js}\delta_{jis}$. Thus,

$$\hat{\Pi}_{is} = \sum_{j=1}^{J}\hat{\Pi}_{jis}\frac{\Pi_{jis}}{\sum_{j=1}^{J}\Pi_{jis}} = \sum_{j=1}^{J}\hat{\Pi}_{jis}\sigma_{jis} \tag{A.7}$$

where

$$\sigma_{jis} \equiv \frac{\Pi_{jis}}{\sum_{j=1}^{J}\Pi_{jis}} = \frac{\tau_{Ijis}^{-1}\tau_{Xjis}^{-1}\eta_{js}\delta_{jis}}{\sum_{j=1}^{J}\tau_{Ijis}^{-1}\tau_{Xjis}^{-1}\eta_{js}\delta_{jis}} \tag{A.8}$$

Hence,

$$\hat{\Pi}_{is} = \hat{p}_{Zi}^{\beta_s(\gamma_s+1)}\sum_{j=1}^{J}\sigma_{jis}\hat{y}_{jis}^{\gamma_s+1} \qquad \Pi_{is} = \left[1-\frac{1}{\mu_s(1+\gamma_s)}\right]\sum_{j=1}^{J}\tau_{Ijis}^{-1}\tau_{Xjis}^{-1}\eta_{js}\delta_{jis},$$

To handle zero initial tax revenues, we write the expression for welfare changes as:

$$\int_s (\hat{T}_{is} - 1) T_{is} ds = \int_s (\hat{T}_{Eis} - 1) T_{Eis} ds + \int_s (T'_{Iis} - T_{Iis}) ds + \int_s (T'_{Xis} - T_{Xis}) ds, \quad \text{(A.9)}$$

where

$$\begin{aligned} T_{Eis} &\equiv \tau_{Ei} \sum_{j=1}^{J} N_{jis} e_{jis} \\ T_{Iis} &\equiv \sum_{j \neq i}^{J} (\tau_{Iijs} - 1) N_{ijs} \tau_{Iijs}^{-1} p_{ijs} c_{ijs} \\ T_{Xis} &\equiv \sum_{j \neq i}^{J} (\tau_{Xjis} - 1) N_{jis} \tau_{Ijis}^{-1} \tau_{Xjis}^{-1} p_{ji} c_{jis} \end{aligned}$$

By (4), (6), (7), (A.8), and the definition of δ_{jis} we have:

$$\begin{aligned} \hat{T}_{Eis} &= \hat{\tau}_{Ei} \hat{p}_{Zi}^{\beta_s(1+\gamma_s)-1} \sum_{j=1}^{J} \sigma_{jis} \left(\frac{\hat{y}_{jis}}{\hat{\phi}_{jis}} \right)^{(1+\gamma_s)} & T_{Eis} &= \beta_s \mu_s^{-1} d_i \tau_{Eis} p_{Zi}^{-1} \sum_{j=1}^{J} \tau_{Ijis}^{-1} \tau_{Xjis}^{-1} \eta_{js} \delta_{jis} \\ T'_{Iis} &= \eta_{is} \sum_{j \neq i}^{J} (\tau'_{Iijs} - 1) \tau'^{-1}_{Iijs} \delta'_{ijs} & T_{Iis} &= \eta_{is} \sum_{j \neq i}^{J} (\tau_{Iijs} - 1) \tau_{Iijs}^{-1} \delta_{ijs} \\ T'_{Xis} &= \sum_{j \neq i}^{J} \eta_{js} (\tau'_{Xjis} - 1) \tau'^{-1}_{Ijis} \tau'^{-1}_{Xjis} \delta'_{jis} & T_{Xis} &= \sum_{j \neq i}^{J} \eta_{js} (\tau_{Xjis} - 1) \tau_{Iji}^{-1} \tau_{Xji}^{-1} \delta_{jis}, \end{aligned}$$

where $\delta'_{ijs} = \delta_{ijs} \hat{\delta}_{ijs} = \delta_{ijs} \hat{p}_{ijs} \hat{y}_{ijs}$.

A.3 LBAM and LBAM-X in the Presence of Productivity Shocks

In this section we derive LBAM and LBAM-X policies for the case when $\hat{\phi}_{ijs} \neq 1$. Specifically, we show that LBAM-X export subsidies are always independent of productivity shocks. Thus, LBAM-X export subsidies exactly sterilize the effect of carbon price shocks in the origin country on export prices, while productivity shocks in the origin country are completely passed through to consumers in the destination market. For LBAM tariffs, we show that they are independent of productivity shocks as long as these are sector-specific, i.e., $\hat{\phi}_{ijs} = \hat{\phi}_{is} \quad \forall j$. For the most general case in which productivity shocks vary at the importer-exporter-sector level ($\hat{\phi}_{ijs}$), non-discriminatory LBAM tariffs still remain independent of productivity shocks up to a first order-approximation.

As a first step, it is useful to substitute (16) into (13) to obtain $\hat{y}_{ijs}$ as a function of productivity shocks and policy instruments:

$$\hat{y}_{ijs} = (\hat{\phi}_{ijs}\hat{p}_{Zj}^{-\beta_s})^{\frac{(\gamma_s+1)\varepsilon_s}{\gamma_s\varepsilon_s+1}} (\hat{\tau}_{Iijs}\hat{\tau}_{Xijs})^{\frac{-\varepsilon_s}{\gamma_s\varepsilon_s+1}} \left(\sum_{k=1}^{K} \delta_{iks} (\hat{\phi}_{iks}\hat{p}_{Zk}^{-\beta_s})^{\frac{(\gamma_s+1)(\varepsilon_s-1)}{\gamma_s\varepsilon_s+1}} (\hat{\tau}_{Iiks}\hat{\tau}_{Xiks})^{\frac{1-\varepsilon_s}{\gamma_s\varepsilon_s+1}} \right)^{\frac{-1}{\gamma_s+1}} \tag{A.10}$$

Next, we compute the change in country i's imports and exports induced exclusively by productivity shocks by imposing $\hat{p}_{Zi} = 1$ and $\hat{\tau}_{Iijs} = \hat{\tau}_{Xjis} = 1$ in (A.10):

$$\hat{y}_{ijs} = \hat{\phi}_{ijs}^{\frac{(\gamma_s+1)\varepsilon_s}{\gamma_s\varepsilon_s+1}} \left(\sum_{k=1}^{K} \delta_{iks} \hat{\phi}_{iks}^{\frac{(\gamma_s+1)(\varepsilon_s-1)}{\gamma_s\varepsilon_s+1}} \right)^{\frac{-1}{1+\gamma_s}} \tag{A.11}$$

$$\hat{y}_{jis} = \hat{\phi}_{jis}^{\frac{(\gamma_s+1)\varepsilon_s}{\gamma_s\varepsilon_s+1}} \left(\sum_{k=1}^{K} \delta_{jks} \hat{\phi}_{jks}^{\frac{(\gamma_s+1)(\varepsilon_s-1)}{\gamma_s\varepsilon_s+1}} \right)^{\frac{-1}{1+\gamma_s}} \tag{A.12}$$

A.3.1 LBAM

If we consider LBAM tariffs in country i only (i.e., $\hat{p}_{Zi} > 1$ and $\hat{\tau}_{Iijs} \neq 1$ for country i, $\hat{p}_{Zj} = 1$ for $j \neq i$, $\hat{\tau}_{Ikjs} = 1$ for $k \neq i$, and $\hat{\tau}_{Xijs} = 1$ for all for i, j), condition (A.10) simplifies to:

$$\hat{y}_{ijs} = \hat{\phi}_{ijs}^{\frac{(\gamma_s+1)\varepsilon_s}{\gamma_s\varepsilon_s+1}} \hat{\tau}_{Iijs}^{\frac{-\varepsilon_s}{\gamma_s\varepsilon_s+1}} \left(\delta_{iis}(\hat{\phi}_{iis}\hat{p}_{Zi}^{-\beta_s})^{\frac{(\gamma_s+1)(\varepsilon_s-1)}{\gamma_s\varepsilon_s+1}} + \sum_{k\neq i}^{K} \delta_{iks}\hat{\phi}_{iks}^{\frac{(\gamma_s+1)(\varepsilon_s-1)}{\gamma_s\varepsilon_s+1}} \hat{\tau}_{Iiks}^{\frac{1-\varepsilon_s}{\gamma_s\varepsilon_s+1}} \right)^{\frac{-1}{1+\gamma_s}} \tag{A.13}$$

In the main text we computed LBAM tariffs for the case $\hat{\phi}_{ijs} = 1 \forall i, j, s$ by imposing $\hat{y}_{ijs} = 1$, and we showed that they are non-discriminatory and implicitly defined by:

$$\hat{\tau}_{Iis}^{\frac{-\varepsilon_s}{\gamma_s\varepsilon_s+1}} \left(\delta_{iis}\hat{p}_{Zi}^{\beta_s \frac{(\gamma_s+1)(1-\varepsilon_s)}{\gamma_s\varepsilon_s+1}} + \hat{\tau}_{Iis}^{\frac{1-\varepsilon_s}{\gamma_s\varepsilon_s+1}} \sum_{k\neq i}^{K} \delta_{iks} \right)^{\frac{-1}{1+\gamma_s}} = 1 \tag{A.14}$$

When $\hat{\phi}_{ijs} \neq 1$, we need to verify that LBAM tariffs exclusively sterilize the effect of a change in the domestic carbon price on imports, without interfering with the adjustment of imports to productivity shocks, i.e., imports should change according to (A.11). By combining (A.13) with (A.11) we obtain the necessary and sufficient conditions that LBAM tariffs need to satisfy to exlusively sterilize the impact of changes in the domestic carbon price:

$$\begin{aligned} &\delta_{iis}\hat{\phi}_{iis}^{\frac{(\gamma_s+1)(\varepsilon_s-1)}{\gamma_s\varepsilon_s+1}} + \sum_{k\neq i}^{K} \delta_{iks}\hat{\phi}_{iks}^{\frac{(\gamma_s+1)(\varepsilon_s-1)}{\gamma_s\varepsilon_s+1}} = \\ &\hat{\tau}_{Iijs}^{\frac{\varepsilon_s(\gamma_s+1)}{\gamma_s\varepsilon_s+1}} \left(\delta_{iis}(\hat{\phi}_{iis}\hat{p}_{Zi}^{-\beta_s})^{\frac{(\gamma_s+1)(\varepsilon_s-1)}{\gamma_s\varepsilon_s+1}} + \sum_{k\neq i}^{K} \delta_{iks}\hat{\phi}_{iks}^{\frac{(\gamma_s+1)(\varepsilon_s-1)}{\gamma_s\varepsilon_s+1}} \hat{\tau}_{Iiks}^{\frac{1-\varepsilon_s}{\gamma_s\varepsilon_s+1}} \right) \end{aligned} \tag{A.15}$$

If productivity shocks are sector-specific but not origin-country-specific, i.e. $\hat{\phi}_{ijs} = \hat{\phi}_{is} \forall j$, then (A.15) simplifies to:

$$\hat{\tau}_{Iis}^{\frac{\varepsilon_s(\gamma_s+1)}{\gamma_s\varepsilon_s+1}} \left(\delta_{iis}\hat{p}_{Zi}^{-\beta_s \frac{(\gamma_s+1)(\varepsilon_s-1)}{\gamma_s\varepsilon_s+1}} + \sum_{k\neq i}^{K} \delta_{iks}\hat{\tau}_{Iiks}^{\frac{1-\varepsilon_s}{\gamma_s\varepsilon_s+1}} \right) = 1 \tag{A.16}$$

Note that (A.16) is identical for all origin countries j, implying that the tariff is non-discriminatory. Once we impose $\hat{\tau}_{Iijs} = \hat{\tau}_{Iis} \quad \forall j$ then (A.16) coincides with (A.14). Hence, non-discriminatory LBAM tariffs exactly sterilize the change in the carbon price while passing through sector-specific changes in productivity. Specifically, imposing $\hat{\phi}_{ijs} = \hat{\phi}_{is}$ and $\hat{\tau}_{Iijs} = \hat{\tau}_{Iis}$ in (A.13) and using (A.14) we obtain $\hat{y}_{ijs} = \hat{\phi}_{is}$ which coincides with (A.11) when productivity shocks are sector-specific.

If productivity shocks are, instead, sector-country-specific, LBAM tariffs that satisfy (A.15) cannot be non-discriminatory. Indeed, if we assume $\hat{\tau}_{Iijs} = \hat{\tau}_{Iis}\forall j$, (A.15) simplifies to:

$$\delta_{ii}\hat{\phi}_{iis}^{\frac{(\gamma_s+1)(\varepsilon_s-1)}{\gamma_s\varepsilon_s+1}}\left(\hat{p}_{Zi}^{\beta_s\frac{(\gamma_s+1)(1-\varepsilon_s)}{\gamma_s\varepsilon_s+1}} - \hat{\tau}_{Iis}^{\frac{-\varepsilon_s(1+\gamma_s)}{\gamma_s\varepsilon_s+1}}\right) = \hat{\tau}_{Iis}^{\frac{-\varepsilon_s(1+\gamma_s)}{\gamma_s\varepsilon_s+1}}(1-\hat{\tau}_{Iis})\sum_{k\neq i}^{K}\delta_{iks}(\hat{\phi}_{iks})^{\frac{(\gamma_s+1)(\varepsilon_s-1)}{\gamma_s\varepsilon_s+1}} \tag{A.17}$$

Notice that δ_{iks} and $\hat{\phi}_{iks}^{-1}$ are exogenously given. Hence, for (A.17) to be satisfied for any possible realization of $\hat{\phi}_{iks}$, we would need both $\hat{\tau}_{Iis} = \hat{p}_{Zi}^{\frac{\varepsilon-1}{\varepsilon}}$ and τ_{Iis}=1.This is possible only when $\hat{p}_{Zi} = 1$. Thus, in this case, LBAM tariffs that exclusively sterilize carbon price shocks cannot be non-discriminatory.

However, even if non-discriminatory LBAM tariffs as implied by condition (A.14) do not exclusively sterilize the effect of carbon price shocks when productivity shocks are country-sector-specific, they do it up to a first-order approximation.

To show this, we take a log-linear approximation of (A.15) and use it to derive the LBAM tariffs that solve the approximated equation. Then, we check whether these tariffs coincide, up to the first order, with our original solution in (A.14). In what follows, we use the fact that $\hat{x} = e^{\log\hat{x}}$, and we indicate with $\log\hat{x}^*$ the value of the variable at the approximation point. As a first step, we take the first-order approximation of condition (A.15) around an equilibrium where shocks are sector-specific, i.e. $\hat{\phi}_{ijs}^* = \hat{\phi}_{is}^* \quad \forall j$. Then, by condition (A.16), LBAM tariffs are non-discriminatory, i.e. $\hat{\tau}_{ijs}^* = \hat{\tau}_{is}^*$. Thus, by linearizing condition (A.15) w.r.t. $\log\hat{x}$ we obtain:

$$
\begin{aligned}
&\delta_{iis}\frac{(\gamma_s+1)(\varepsilon_s-1)}{\gamma_s\varepsilon_s+1}\left(\log\hat{\phi}_{iis}-\log\hat{\phi}^*_{is}\right)\\
&+\frac{(\gamma_s+1)(\varepsilon_s-1)}{\gamma_s\varepsilon_s+1}\sum_{k\neq i}^{K}\delta_{iks}(\log\hat{\phi}_{iks}-\log\hat{\phi}^*_{is})=\\
&\frac{\varepsilon_s(\gamma_s+1)}{\gamma_s\varepsilon_s+1}(\hat{\tau}^*_{Iis})^{\frac{\varepsilon_s(\gamma_s+1)}{\gamma_s\varepsilon_s+1}}\delta_{iis}(\hat{p}^*_{Zi})^{-\beta_s\frac{(\gamma_s+1)(\varepsilon_s-1)}{\gamma_s\varepsilon_s+1}}(\log\hat{\tau}_{Iijs}-\log\hat{\tau}^*_{Iis})\\
&+\frac{(\gamma_s+1)(\varepsilon_s-1)}{\gamma_s\varepsilon_s+1}(\hat{\tau}^*_{Iis})^{\frac{\varepsilon_s(\gamma_s+1)}{\gamma_s\varepsilon_s+1}}\delta_{iis}(\hat{p}^*_{Zi})^{-\beta_s\frac{(\gamma_s+1)(\varepsilon_s-1)}{\gamma_s\varepsilon_s+1}}\left((\log\hat{\phi}_{iis}-\log\hat{\phi}^*_{is})-\beta_s(\log\hat{p}_{Zi}-\log\hat{p}^*_{Zi})\right)\\
&+\frac{\varepsilon_s(\gamma_s+1)}{\gamma_s\varepsilon_s+1}\hat{\tau}^*_{Iis}(1-\delta_{iis})(\log\hat{\tau}_{Iijs}-\log\hat{\tau}^*_{Iis})\\
&+\hat{\tau}^*_{Iis}\sum_{k\neq i}^{K}\delta_{iks}\left(\frac{(\gamma_s+1)(\varepsilon_s-1)}{\gamma_s\varepsilon_s+1}(\log\hat{\phi}_{iks}-\log\hat{\phi}^*_{is})-\frac{\varepsilon_s-1}{\gamma_s\varepsilon_s+1}(\log\hat{\tau}_{Iiks}-\log\hat{\tau}^*_{Iis})\right)
\end{aligned} \tag{A.18}
$$

Next, we impose that at the point of approximation there are no policies in place, i.e., $\hat{\tau}^*_{Iis}=\hat{p}^*_{zi}=1$ to obtain:

$$
\varepsilon_s(\gamma_s+1)\log\hat{\tau}_{Iijs}=\beta_s(\gamma_s+1)(\varepsilon_s-1)\delta_{iis}\log\hat{p}_{Zi}+(\varepsilon_s-1)\sum_{k\neq i}^{K}\delta_{iks}\log\hat{\tau}_{Iiks} \tag{A.19}
$$

Condition (A.19) implies that, up to a first order approximation, LBAM tariffs for the general case where $\hat{\phi}_{ijs}\neq 1$ do not need to be discriminatory across origin countries. We can thus assume that $\log\hat{\tau}_{Iijs}=\log\hat{\tau}_{Iis}\forall j$ to rewrite (A.19) as follows:

$$
\varepsilon_s(\gamma_s+1)\log\hat{\tau}_{Iis}=\beta_s(\gamma_s+1)(\varepsilon_s-1)\delta_{iis}\log\hat{p}_{Zi}+(\varepsilon_s-1)(1-\delta_{iis})\log\hat{\tau}_{Iis} \tag{A.20}
$$

As a final step we need to take a first-order approximation of (A.14) around the same equilibrium and show that it coincides with (A.20). First, note that we can rewrite this condition as follows:

$$
\hat{\tau}_{Iis}^{\frac{-\varepsilon_s(1+\gamma_s)}{\gamma_s\varepsilon_s+1}}=\delta_{iis}\hat{p}_{Zi}^{-\beta_s\frac{(\gamma_s+1)(\varepsilon_s-1)}{\gamma_s\varepsilon_s+1}}+\hat{\tau}_{Iis}^{-\frac{\varepsilon_s-1}{\gamma_s\varepsilon_s+1}}(1-\delta_{iis}) \tag{A.21}
$$

Taking a log-linear approximation of (A.21) we obtain exactly (A.20). This proves our conjecture.

A.3.2 LBAM-X

If we consider LBAM-X export subsidies in country i only (i.e., $\hat{p}_{Zi} > 1$ and $\hat{\tau}_{Xjis} \neq 1$ for country i, $\hat{p}_{Zj} = 1$ for $j \neq i$, $\hat{\tau}_{Iijs} = 1$ for all for i, j, and $\hat{\tau}_{Xjks} = 1$ for $k \neq i$) then condition (A.10) simplifies to:

$$\hat{y}_{jis} = (\hat{\phi}_{jis}\hat{p}_{Zi}^{-\beta_s})^{\frac{(\gamma_s+1)\varepsilon_s}{\gamma_s\varepsilon_s+1}} \hat{\tau}_{Xjis}^{\frac{-\varepsilon_s}{\gamma_s\varepsilon_s+1}} \left(\delta_{jis}(\hat{\phi}_{jis}\hat{p}_{Zi}^{-\beta_s})^{\frac{(\gamma_s+1)(\varepsilon_s-1)}{\gamma_s\varepsilon_s+1}} \hat{\tau}_{Xjis}^{\frac{1-\varepsilon_s}{\gamma_s\varepsilon_s+1}} + \sum_{k\neq i} \delta_{jks}\hat{\phi}_{jks}^{\frac{(\gamma_s+1)(\varepsilon_s-1)}{\gamma_s\varepsilon_s+1}}\right)^{-\frac{1}{1+\gamma_s}} \tag{A.22}$$

In the main text we showed that when $\hat{\phi}_{jis} = 1$, the non-discriminatory export subsidy for which $\hat{y}_{jis} = 1 \forall j \neq i$ is given by $\hat{\tau}_{Xjis} = \hat{p}_{Zi}^{-\beta_s(\gamma_s+1)}$. If we substitute this LBAM-X subsidy into (A.22) we get:

$$\begin{aligned}\hat{y}_{jis} =& (\hat{\phi}_{jis}\hat{p}_{Zi}^{-\beta_s})^{\frac{(\gamma_s+1)\varepsilon_s}{\gamma_s\varepsilon_s+1}} \hat{p}_{Zi}^{\beta_s\frac{\varepsilon_s(\gamma_s+1)}{\gamma_s\varepsilon_s+1}} \left(\delta_{jis}(\hat{\phi}_{jis}\hat{p}_{Zi}^{-\beta_s})^{\frac{(\gamma_s+1)(\varepsilon_s-1)}{\gamma_s\varepsilon_s+1}} \hat{p}_{Zi}^{\beta_s\frac{(\gamma_s+1)(\varepsilon_s-1)}{\gamma_s\varepsilon_s+1}} + \sum_{k\neq i} \delta_{jks}\hat{\phi}_{jks}^{\frac{(\gamma_s+1)(\varepsilon_s-1)}{\gamma_s\varepsilon_s+1}}\right)^{-\frac{1}{1+\gamma_s}} \\ =& \hat{\phi}_{jis}^{\frac{(\gamma_s+1)\varepsilon_s}{\gamma_s\varepsilon_s+1}} \left(\delta_{jis}\hat{\phi}_{jis}^{\frac{(\gamma_s+1)(\varepsilon_s-1)}{\gamma_s\varepsilon_s+1}} + \sum_{k\neq i} \delta_{jks}\hat{\phi}_{jks}^{\frac{(\gamma_s+1)(\varepsilon_s-1)}{\gamma_s\varepsilon_s+1}}\right)^{-\frac{1}{1+\gamma_s}}\end{aligned} \tag{A.23}$$

which coincides with (A.12). This result implies that the LBAM-X export subsidy is independent of productivity shocks: while it sterilizes the effect of a change in the domestic carbon price on exports, it does not interfere with fluctuations in exports due to domestic or foreign productivity shocks.

B Data Appendix

B.1 Imputation of Fuel Consumption

Table B.1 reports the outcome and goodness of fit for the imputation of fuel consumption by energy type. With our preferred regression specification, we achieve an R^2 above 0.7 for all four fuel types. Table B.3 presents summary statistics of imputed and non-imputed fuel shares. Electricity followed by natural gas are the most used fuel types in our sample. The share of imputed observations ranges between 8 and 26%.

B.2 Imputation of Fuel Prices

Table B.2 reports the outcome and goodness of fit for the imputation of fuel prices by energy type. We run our preferred regression specification on a dataset that includes both official IEA and our hand-collected prices to increase the number of observations. We achieve an R^2 between 0.09 for electricity and 0.48 for coal. The low goodness of fit is driven by considerable heterogeneity across countries in fuel prices (see Table B.4). While we have industry electricity prices for nearly all countries, with a share of imputed observations of 6%, we have to impute prices for roughly 50% or more observations for the other fuel types. For the ten largest countries in terms of fuel consumption, we hand-collected fuel prices and do not rely on imputed prices.

Table B.1: Imputation of Fuel Consumption

	Log Fuel consumption			
	Electricity (1)	Oil (2)	Natural Gas (3)	Coal (4)
Log GDP per capita	0.436	1.022*	1.374*	1.302
	(0.312)	(0.394)	(0.661)	(0.738)
Log Population	0.593	0.708*	1.007	2.229***
	(0.302)	(0.306)	(0.690)	(0.625)
Log Capital stock	0.382	0.136	-0.132	-0.624
	(0.275)	(0.278)	(0.574)	(0.505)
Dummy oil		0.234		
		(0.271)		
Dummy natural gas			1.473*	
			(0.580)	
Dummy coal				1.243
				(0.664)
Region FE	Yes	Yes	Yes	Yes
Sub-region FE	Yes	Yes	Yes	Yes
N	67	67	53	57
Within R2	0.789	0.771	0.707	0.735

Notes: This table presents estimates from OLS regressions used to impute missing fuel consumption values. The dependent variable in each column is the log of fuel consumption: electricity (Column 1), oil (Column 2), natural gas (Column 3), and coal (Column 4). Independent variables include log GDP per capita, log population, log capital stock, and a dummy variable indicating the production of each respective fuel type. All regressions include region and sub-region fixed effects. Standard errors are reported in parentheses. Significance levels are indicated as * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

Table B.2: Imputation of Fuel Prices

	Log Fuel price			
	Electricity (1)	Oil (2)	Natural Gas (3)	Coal (4)
Log GDP per capita	-0.660	-0.0801	-0.395	-2.006***
	(0.380)	(0.126)	(0.505)	(0.413)
Log Population	-0.541	-0.0525	-0.108	-1.512**
	(0.394)	(0.120)	(0.353)	(0.333)
Log Capital stock	0.495	0.00645	0.0750	1.107**
	(0.381)	(0.117)	(0.343)	(0.307)
Dummy oil		-0.0840		
		(0.0863)		
Dummy natural gas			-0.0449	
			(0.0285)	
Dummy coal				0.500
				(0.224)
Region FE	Yes	Yes	Yes	Yes
Sub-region FE	Yes	Yes	Yes	Yes
N	105	59	38	21
Within R2	0.0849	0.139	0.215	0.478

Notes: This table presents estimates from OLS regressions used to impute missing fuel prices. The dependent variable in each column is the log of fuel consumption: electricity (Column 1), oil (Column 2), natural gas (Column 3), and coal (Column 4). Independent variables include log GDP per capita, log population, log capital stock, and a dummy variable indicating the production of each respective fuel type. All regressions include region and sub-region fixed effects. Standard errors are reported in parentheses. Significance levels are indicated as * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

Table B.3: Summary Statistics Fuel Shares

	N (1)	Mean (2)	Median (3)	Min (4)	Max (5)	SD (6)	% imputed (7)
Fuel share coal	74	0.175	0.114	0.000	0.605	0.164	0.216
Fuel share electricity	74	0.327	0.327	0.048	0.970	0.147	0.081
Fuel share natural gas	74	0.275	0.234	0.005	0.804	0.213	0.257
Fuel share oil	74	0.223	0.165	0.018	0.766	0.178	0.081

Notes: Column 1 reports the number of observations for each fuel share variable. Columns 2 and 3 report the mean and standard deviation of each fuel share variable across all observations. Columns 4 to 6 present the median, minimum, and maximum values for each fuel share. Column 7 shows the percentage of imputed data for each fuel share variable.

Table B.4: Summary Statistics Fuel Prices

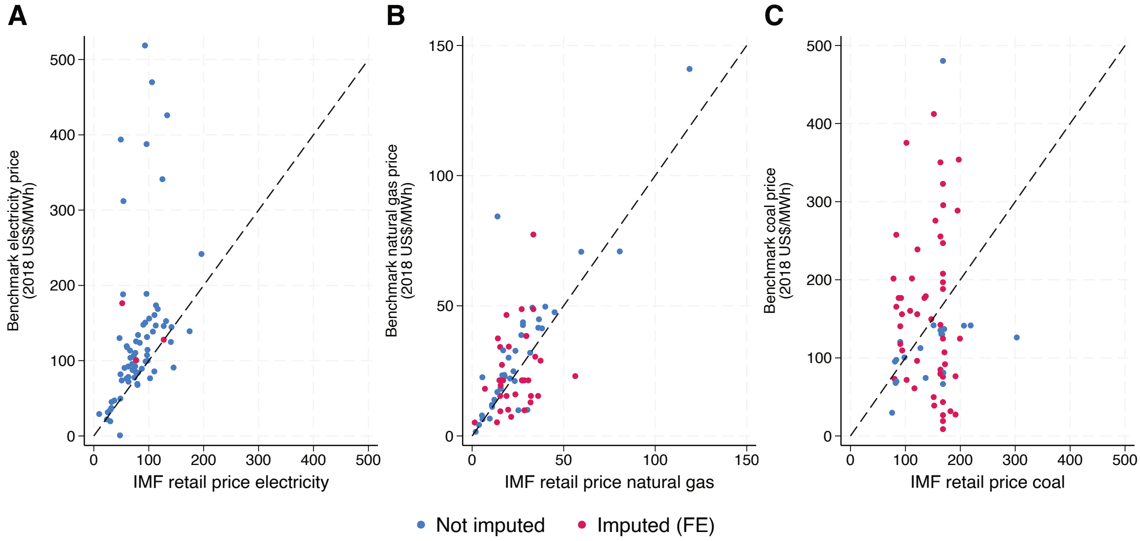
	N (1)	Mean (2)	Median (3)	Min (4)	Max (5)	SD (6)	% imputed (7)
Price coal	74	146.564	127.837	8.736	480.300	97.224	0.716
Price electricity	74	133.405	107.044	0.777	518.742	101.327	0.055
Price oil	74	569.616	549.311	134.010	1026.786	155.381	0.486
Price natural gas	74	21.646	11.556	0.210	140.970	26.774	0.473

Notes: Column 1 reports the number of observations for each fuel price variable. Columns 2 and 3 report the mean and standard deviation of the fuel prices across all observations. Columns 4 to 6 present the median, minimum, and maximum values for each fuel price variable. Column 7 shows the percentage of imputed data for each fuel price variable.

B.3 Comparison with IMF Energy Prices

Getting the energy prices right is crucial for the validity of our results. To assess our approach of collecting data from different sources and imputing missing data using OLS regressions, we compare our data with Black et al. (2023), a readily available dataset. Figure B.1 plots our benchmark price data against IMF data for electricity, natural gas and coal. Overall, our benchmark data show a wider dispersion than the IMF data and suggest higher energy prices on average. This is most pronounced for electricity and coal. Natural gas prices are the most similar. In general, given a sufficient number of data points, our imputation method predicts prices that are no more different from the IMF data than from the prices we collect. In the case of coal, the lack of data points leads to a wider dispersion of coal prices than observed in the

Figure B.1: Comparison of IMF prices and collected prices for different fuel types



Notes: This figure depicts scatter plots of (**A**) collected electricity prices as the dependent variable and IMF electricity retail prices as independent variable, (**B**) collected natural gas as dependent variable and IMF natural gas prices as independent variable, and (**C**) collected coal prices as dependent variable and IMF coal prices as independent variable. IMF prices are deflated and converted into Euro using the FRED Global price of Energy Index and U.S. Dollars to Euro Spot Exchange Rate.

IMF data. The differences between our benchmark and the IMF prices can mainly be explained by two factors. First, the IMF primarily uses IMF and World Bank country desk data, while we rely on IEA data. Second, when industry prices are missing, even after using reliable third-party sources such as the IEA and Eurostat, the IMF uses prices from the electricity sector or import prices to impute these observations. Overall, we prefer to use our, on average, higher benchmark energy prices as they give us more conservative results for welfare, emissions, and trade effects. As a result, the negative economic impact on foreign countries is smaller than when using the IMF data.

C Additional Tables

Table C.1: Policy-Induced Changes in EU Imports by 2-digit Sector

Description	ISIC	No-BAM	CBAM-EU	CBAM-ID	CBAM-EZ	LBAM	LBAM-X
Food	10	22.5	22.5	-9.3	-10.8	0.0	0.0
Beverages	11	52.6	52.6	-10.6	-15.7	0.0	0.0
Tobacco	12	6.7	6.7	-15.0	-14.5	0.0	0.0
Textiles	13	0.9	0.9	-7.0	-5.2	0.0	0.0
Apparel	14	2.3	2.3	-9.6	-6.6	0.0	0.0
Leather	15	2.6	2.6	-10.2	-6.7	0.0	0.0
Wood	16	0.5	0.5	-4.9	-3.9	0.0	0.0
Paper	17	0.6	0.6	-4.2	-4.3	0.0	0.0
Printing	18	2.3	2.3	-4.8	-4.2	0.0	0.0
Petroleum	19	0.0	0.0	-4.6	-4.1	0.0	0.0
Chemicals	20	2.4	2.2	-7.3	-6.6	-0.0	-0.0
Pharma	21	6.4	6.4	-9.3	-10.4	0.0	0.0
Plastics	22	0.6	0.6	-8.3	-6.4	0.0	0.0
Minerals	23	17.5	17.4	-20.7	-16.9	0.0	0.0
Metals	24	4.7	-6.2	-6.6	-6.4	0.0	0.0
Metalwork	25	3.0	3.0	-8.2	-6.1	0.0	0.0
Electronics	26	5.8	5.8	-13.0	-9.5	0.0	0.0
Electrical	27	2.3	2.3	-6.4	-4.8	0.0	0.0
Machinery	28	3.4	3.4	-3.1	-2.7	0.0	0.0
Vehicles	29	11.5	11.5	-7.9	-7.1	0.0	0.0
Transport	30	1.1	1.1	-3.6	-2.7	0.0	0.0
Furniture	31	0.0	0.0	-1.3	-1.0	0.0	0.0
Misc	32	0.2	0.2	-0.8	-1.9	0.0	0.0
Repair	33	0.1	0.1	-7.6	-6.2	0.0	0.0

Notes: The table reports the change in EU imports for 2-digit ISIC sectors following an EU carbon price increase from $15 to $105, in billions of 2018 US$. The percentage change in EU imports is relative to 2018 levels.

Table C.2: Policy-Induced Changes in EU Exports by 2-digit Sector

Description	ISIC Code	No-BAM, CBAM-EU, CBAM-ID, CBAM-EZ, and LBAM	LBAM-X
Food	10	-24.0	0.0
Beverages	11	-31.6	0.0
Tobacco	12	-11.2	0.0
Textiles	13	-3.9	0.0
Apparel	14	-5.1	0.0
Leather	15	-7.5	0.0
Wood	16	-2.4	0.0
Paper	17	-3.1	0.0
Printing	18	-3.4	0.0
Petroleum	19	-2.8	0.0
Chemicals	20	-6.4	0.0
Pharma	21	-11.1	0.0
Plastics	22	-4.0	0.0
Minerals	23	-11.3	0.0
Metals	24	-6.8	0.0
Metalwork	25	-3.8	0.0
Electronics	26	-29.2	0.0
Electrical	27	-4.0	0.0
Machinery	28	-3.4	0.0
Vehicles	29	-11.5	0.0
Transport	30	-2.2	0.0
Furniture	31	-0.5	0.0
Misc	32	-7.6	0.0
Repair	33	-5.0	0.0

Notes: The table reports the change in EU exports for 2-digit ISIC sectors following an EU carbon price increase from \$15 to \$105, in billions of 2018 US\$. The percentage change in EU exports is relative to 2018 levels.

Table C.3: Policy-Induced Changes in Emissions by 2-digit Sector

Description	ISIC	No-BAM	CBAM-EU	CBAM-ID	CBAM-EZ	LBAM	LBAM-X
Food	10	-1.4	-1.4	-1.7	-1.6	-1.5	-1.8
Beverages	11	-1.2	-1.2	-1.4	-1.4	-1.3	-2.3
Tobacco	12	-0.3	-0.3	-0.3	-0.3	-0.3	-0.3
Textiles	13	-0.3	-0.3	-0.9	-0.7	-0.4	-0.5
Apparel	14	-0.6	-0.6	-1.3	-1.1	-0.7	-0.7
Leather	15	-0.7	-0.7	-1.4	-1.2	-0.8	-1.1
Wood	16	-1.0	-1.0	-1.4	-1.3	-1.0	-1.0
Paper	17	-2.1	-2.1	-2.3	-2.2	-2.1	-2.0
Printing	18	-2.0	-2.0	-2.1	-2.1	-2.0	-2.0
Petroleum	19	-0.3	-0.3	-0.4	-0.3	-0.3	-0.3
Chemicals	20	-0.8	-0.8	-1.1	-1.1	-0.8	-0.9
Pharma	21	-1.8	-1.8	-2.4	-2.4	-1.9	-2.2
Plastics	22	-1.8	-1.8	-2.2	-2.1	-1.9	-1.8
Minerals	23	-0.4	-0.4	-0.6	-0.6	-0.5	-0.5
Metals	24	-0.6	-1.3	-1.3	-1.1	-0.7	-0.8
Metalwork	25	-1.3	-1.3	-1.6	-1.5	-1.4	-1.4
Electronics	26	0.9	0.9	-0.7	-0.3	0.6	-0.4
Electrical	27	-0.6	-0.6	-1.8	-1.5	-0.9	-1.0
Machinery	28	-1.3	-1.3	-2.1	-2.0	-1.7	-2.3
Vehicles	29	-2.1	-2.1	-2.3	-2.3	-2.2	-2.6
Transport	30	-0.9	-0.9	-1.3	-1.2	-1.0	-1.0
Furniture	31	-1.9	-1.9	-1.9	-1.9	-1.9	-1.9
Misc	32	0.9	0.9	-0.9	-0.4	0.8	-0.8
Repair	33	-0.9	-0.9	-2.4	-2.1	-0.9	-0.9

Notes: The table reports the change in global emissions for 2-digit ISIC sectors following an EU carbon price increase from $15 to $105. The percentage change in global sectoral emissions is relative to 2018 levels.

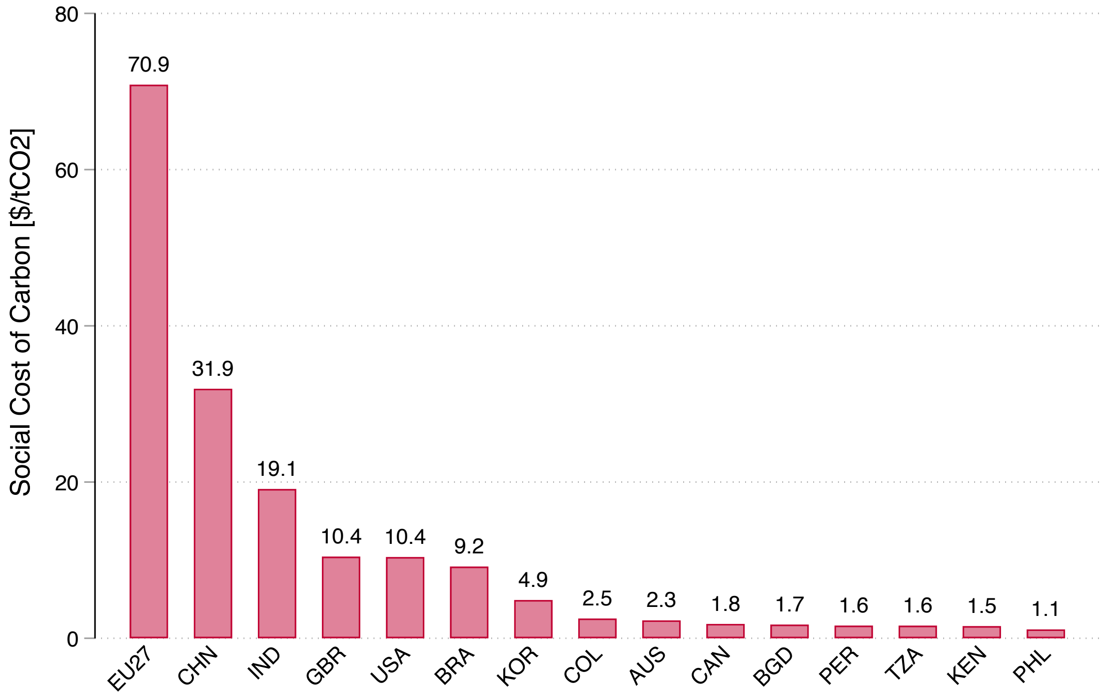
Table C.4: Summary Statistics of Production Function Parameters and Demand Elasticities or Alternative Parameter Estimates

	N	Mean	Median	SD	Min	Max
A. Excluding Outliers in Elasticities						
α_s	131	0.614	0.664	0.282	0.073	0.993
β_s	131	0.097	0.075	0.088	0.003	0.393
γ_s	131	1.117	0.290	1.971	0.000	11.545
ϵ_s	131	3.296	2.368	2.769	1.317	18.078
B. Capital Stock via PIM						
α_s	131	0.656	0.735	0.290	0.078	0.996
β_s	131	0.055	0.024	0.072	0.001	0.315
γ_s	131	1.117	0.290	1.971	0.000	11.545
ϵ_s	131	3.296	2.368	2.769	1.317	18.078
C. Setting $\gamma = 0$ and $\varepsilon = 6$ for all Industries						
α_s	131	0.930	0.965	0.073	0.685	0.998
β_s	131	0.070	0.035	0.073	0.002	0.315
γ_s	131	0.000	0.000	0.000	0.000	0.000
ϵ_s	131	6.000	6.000	0.000	6.000	6.000

Notes: Column 1 reports the number of observations for each parameter. Columns 2 and 3 show the mean and standard deviation for each parameter across all observations. Columns 4 to 6 present the median, minimum, and maximum values for each parameter. Panel A excludes a broader set of outliers from the output and trade elasticity estimates, Panel B estimates the capital stock using the perpetual inventory method (PIM), while Panel C assumes constant returns to scale ($\gamma = 0$) and a demand elasticity $\varepsilon = 6$ for all industries. Source: Research Data Centres of the Federal Statistical Office and the Statistical Offices of the Federal States of Germany, AFiD-Modul Energieverwendung (1998–2018), AFiD-Panel Industriebetriebe (1998–2018), AFiD-Panel Industrieunternehmen (1998–2018), project-specific preparations, own calculations.

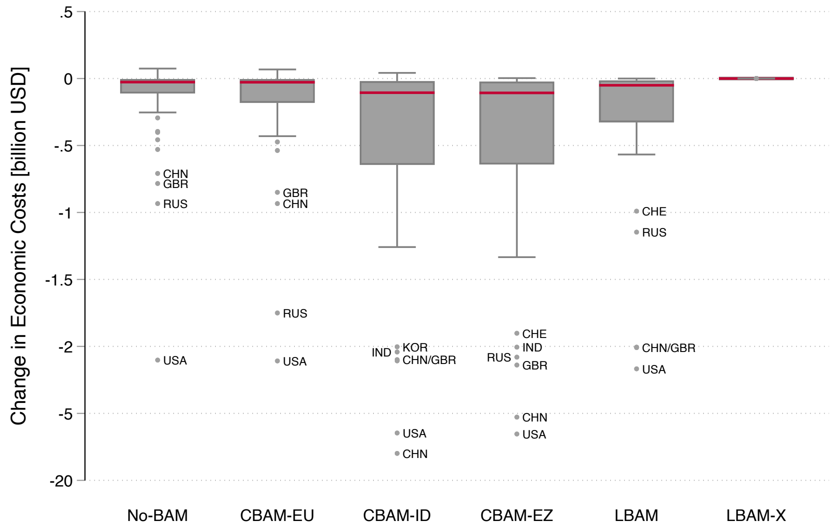
D Additional Figures

Figure D.1: Country-specific Social Cost of Carbon

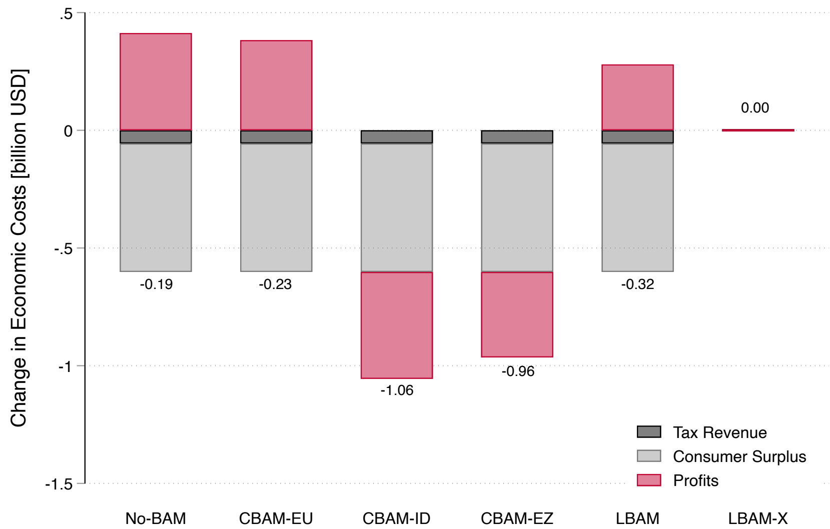


Notes: The figure displays the 15 highest country-specific social cost of carbon (SCC) estimates when allocating the global SCC estimate of $178 by Rennert et al. (2022) across countries using the method proposed by Farrokhi and Lashkaripour (2025).

Figure D.2: Impact of EU Carbon Price Increase on Economic Costs for Non-EU Countries for Alternative Trade and Output Elasticity Estimates



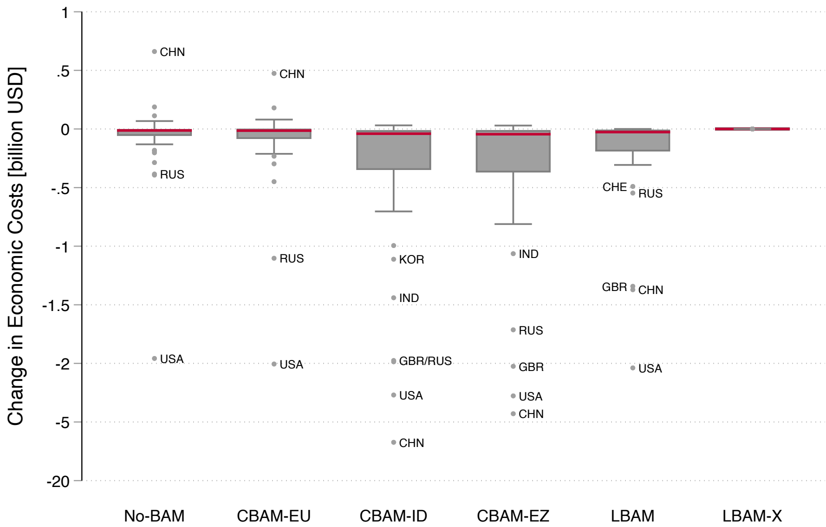
(a) Distribution of the changes in economic costs



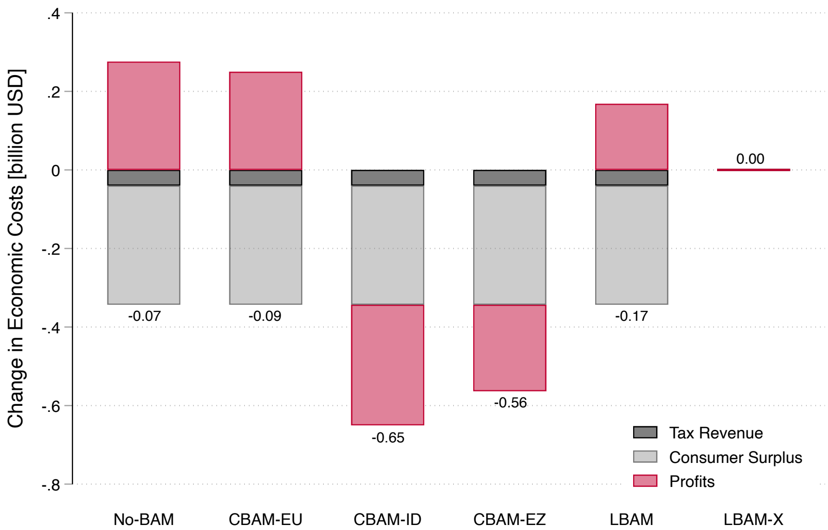
(b) Decomposition of the change in economic costs

Notes: The figure shows changes in economic costs following a unilateral increase in the EU carbon price from \$15 to \$105 per ton, under an alternative specification that excludes a broader set of outliers from the output and trade elasticity estimates. Subfigure (a) shows the distribution of the change in economic costs, subfigure (b) shows the average contribution of its different components. Economic costs are defined as the sum of consumer surplus, profits, and government revenue after taxes, subsidies, and tariffs, expressed in 2018 US\$. Economic costs changes are computed for six different scenarios: No-BAM, CBAM-EU, CBAM-ID, CBAM-EZ, LBAM, and LBAM-X.

Figure D.3: Impact of EU Carbon Price Increase on Economic Costs for Non-EU Countries for Alternative Capital Stock



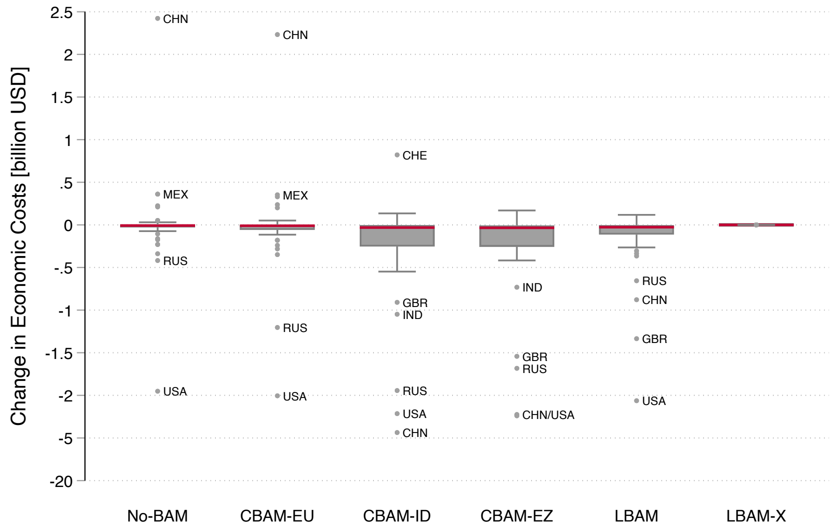
(a) Distribution of the changes in economic costs



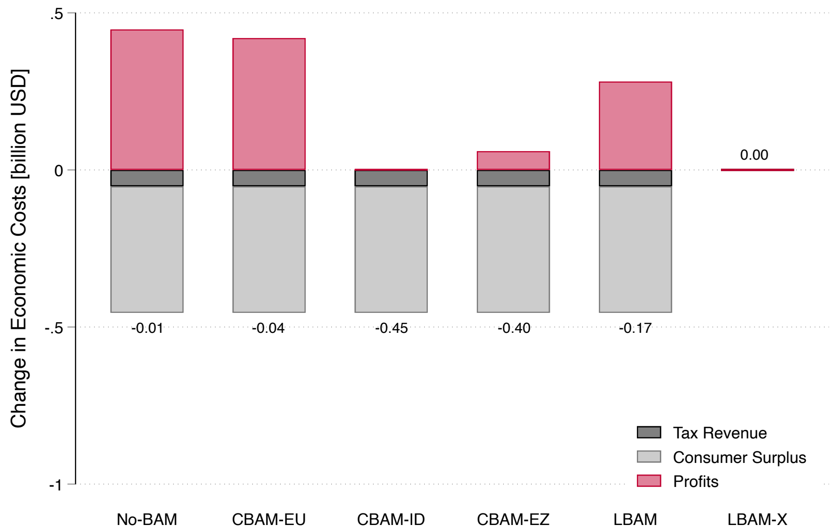
(b) Decomposition of the change in economic costs

Notes: The figure shows changes in economic costs following a unilateral increase in the EU carbon price from \$15 to \$105 per ton, under an alternative specification that excludes a broader set of outliers from the output and trade elasticity estimates and estimates the capital stock using the perpetual inventory method (PIM). Subfigure (a) shows the distribution of the change in economic costs, subfigure (b) shows the average contribution of its different components. Economic costs are defined as the sum of consumer surplus, profits, and government revenue after taxes, subsidies, and tariffs, expressed in 2018 US\$. Economic costs changes are computed for six different scenarios: No-BAM, CBAM-EU, CBAM-ID, CBAM-EZ, LBAM, and LBAM-X.

Figure D.4: Impact of EU Carbon Price Increase on Economic Costs for Non-EU Countries for CRS ($\gamma = 0$) and Standard Choice of Trade Elasticity ($\varepsilon = 6$)



(a) Distribution of the changes in economic costs



(b) Decomposition of the change in economic costs

Notes: The figure shows changes in economic costs following a unilateral increase in the EU carbon price from \$15 to \$105 per ton, under an alternative specification that excludes a broader set of outliers from the output elasticity estimates and assumes constant returns to scale ($\gamma = 0$) and a demand elasticity $\varepsilon = 6$ for all industries. Subfigure (a) shows the distribution of the change in economic costs, subfigure (b) shows the average contribution of its different components. Economic costs are defined as the sum of consumer surplus, profits, and government revenue after taxes, subsidies, and tariffs, expressed in 2018 US\$. Economic costs changes are computed for six different scenarios: No-BAM, CBAM-EU, CBAM-ID, CBAM-EZ, LBAM, and LBAM-X.