European Commission

ISSN 2529-332X

Designing Effective Carbon Border Adjustment with Minimal Information Requirements. Theory and Empirics.

SINGLE MARKET ECONOMICS PAPERS

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Working Paper 19

This paper has been presented at the

Research Conference on the Single Market

organised by

European Commission, Directorate General for Internal Market, Industry, Entrepreneurship and SMEs

Brussels, 7 February 2024

EUROPEAN COMMISSION

Directorate-General for Internal Market, Industry, Entrepreneurship and SMEs
Directorate A – Strategy & Economic Analysis
Unit A1 – Chief Economist Unit

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B-1049 Brussels

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EN PDF	ISBN 978-92-68-12942-5	ISSN 2529-332X	DOI: 10.2873/336612	ET-AF-24-003-EN-N

Manuscript completed in February 2024

1st edition

Luxembourg: Publications Office of the European Union, 2024

Designing Effective Carbon Border Adjustment with Minimal Information Requirements. Theory and Empirics*

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February 8, 2024

Abstract

High carbon prices in the EU might drive emission-intensive industrial processes towards countries with relatively lower carbon prices. To prevent such carbon leakage, the EU's Carbon Border Adjustment Mechanism (CBAM) taxes emissions embedded in imports for the difference between carbon prices in the EU and the origin country. Because embedded emissions are very difficult to measure, CBAM applies to only five industries and accepts benchmarks instead of actual embedded emissions. These simplifications make CBAM tractable but compromise its effect on carbon leakage. We propose an alternative policy that requires no knowledge of embedded emissions and can be applied to all tradable sectors: the Leakage Border Adjustment Mechanism (LBAM). LBAM implements import tariffs (and, possibly, export subsidies) that sterilize the changes in imports (and exports) induced by a higher EU carbon price. LBAM requires information only about domestic output-to-emissions elasticities as well as elasticities of import demand and export supply, which we estimate using publicly available data. We calibrate a granular structural trade model with 57 countries and 131 sectors to quantify the welfare and emission impacts of LBAM. We find that LBAM improves over CBAM in terms of global emissions and EU welfare. We assess how 'climate clubs' of countries that adopt common carbon prices and border adjustments mechanisms perform on these outcomes.

*We thank participants at the 2023 CITP conference and at the CRC Workshop on Trade, Firms and Development and the 2023 CRC Retreat in Montabaur for helpful comments. Thanks to Martina Milcetic 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 Foundati

on (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).

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1 Introduction

While progress on international negotiations over globally coordinated climate policies remains slow, some countries do tax harmful carbon emissions[1] (or subsidize for low-carbon technologies) at significant rates. Unilateral climate policies can have positive global spillovers,[2] but they reduce global emissions only if carbon leakage – i.e. emissions displacement to other parts of the world – is effectively prevented. International trade is an important channel for carbon leakage because levying a carbon tax unilaterally lowers a country's comparative advantage in the production of carbon intensive goods and intermediate inputs. Border carbon adjustments, which tax imports and subsidize exports according to the embedded carbon emissions, have long been proposed as the appropriate policy response to this type of leakage (Markusen, 1975; Hoel, 1996). Yet this instrument has not been implemented until recently, when the EU launched its Carbon Border Adjustment Mechanism (CBAM). CBAM seeks to preserve the international competitiveness of European industrial and electricity firms as rapid increases in carbon prices under the EU Emissions Trading System (EU ETS) have not been matched by similar regulation in Europe's trading partners. The policy stipulates that EU imports from such countries be taxed on the basis of the embedded carbon emissions, at a rate given by the prevailing ETS price. In this way, CBAM discourages the replacement of EU production with dirty imports (import leakage), while also correcting for the absence of a foreign carbon tax (Böhringer et al., 2022). CBAM marks an ambitious improvement over the EU's prevailing anti-leakage policy of granting overly generous subsidies to large polluters in trade exposed sectors, which runs counter to the polluter-pays principle (Martin et al., 2014b).

Implementing CBAM is complicated because data on carbon emissions at foreign production sites are exceedingly difficult to obtain (Fowlie & Reguant, 2018). Therefore, the EU will initially charge CBAM tariffs in only a handful of energy-intensive sectors.[3] When importers cannot adequately determine embedded emissions, they may use default values based on the average emission intensity of each exporting country for each good. These simplifications make CBAM tractable, but they come with major drawbacks. Incomplete sector coverage provides incentives for offshoring the production of unregulated final products that contain CBAM-regulated intermediates. Emission intensity defaults weaken foreign producers' incentive to abate carbon emissions while encouraging re-routing of exports via third countries with a lower default. Such simplifications aside, the reporting requirement creates a distortive non-tariff barrier to trade by shifting the burden of col-

[1] In addition to carbon dioxide (CO_2), which is the most important driver of climate change, the IPCC regulates several other gases that also contribute to global warming. For brevity, we subsume emissions of all those gases under the term 'carbon emissions'.

[2] For example, unilateral policies can lead to abatement cost reductions that benefit all countries, or even promote technological breakthroughs that transform the strategic environment from a 'tragedy of the commons' (Hardin, 1968) into a coordination game (Barrett, 2006).

[3] Aluminum, iron & steel, cement, fertilizers, electricity, and hydrogen.

lecting data on carbon content to foreign firms. Since those firms have obvious incentives to under-report the true carbon content of their production, the EU plans to engage in extensive monitoring and verification. The bureaucracy required for is guaranteed to significantly increase the costs of CBAM, but it cannot avoid all forms of underreporting. For example, multi-plant firms might simply reshuffle emissions without truly cutting them by shipping output from their cleanest plants to the EU and output from dirtier plants to the rest of the world.

This paper develops an alternative policy instrument that prevents leakage without requiring any knowledge about foreign carbon intensities of production. The basic idea is to implement product-specific import tariffs (and, possibly, export subsidies) that exactly offset the changes in EU imports (and exports) that would otherwise result from an increase in the carbon price differential between the EU and its trading partners. To distinguish this from emissions-based border adjustments, we call this the Leakage Border Adjustment Mechanism (LBAM).

While LBAM eliminates carbon leakage, shocks to demand and supply that are unrelated to carbon price changes will also affect imports and exports, and such changes should not be neutralized. Using a structural trade model allows us to simulate counterfactual changes in imports and exports in response to rising EU carbon prices and to then compute LBAM tariffs and export subsidies that undo those changes while holding fixed other shocks to demand and supply. Given the model, the information requirements for this calculation boil down to (i) how domestic production costs change with the carbon price and (ii) how those cost changes affect substitution between domestic and foreign products among domestic consumers. These requirements can be easily met using readily available data and well-established econometric methods, as explained below. LBAM thus overcomes the information constraints that plague CBAM, minimizing the reporting burden on foreign firms as well as the monitoring burden on EU authorities. Because of this, LBAM can be applied to all tradable sectors which minimizes distortions between sectors and along the value chain. Furthermore, since LBAM does not discriminate between firms or origin countries, foreign exporters have little to gain from re-shuffling output across plants or re-routing exports via third countries (i.e., arbitrage opportunities created by CBAM). Apart from economic advantages, LBAM also offers a political one: CBAM taxes and reduces imports from countries that are typically poorer than the EU and, historically, have contributed less to cumulative emissions. This fuels political opposition against EU border adjustments. In contrast, LBAM does not hurt foreign exporters; it just re-establishes the *status quo ante* before the unilateral carbon price increase.

We derive closed-form expressions for LBAM tariffs and export subsidies in 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 create a global public bad whose social marginal cost does not depend on the place of emission.

For our quantitative analysis, we calibrate the model using comprehensive data on demand and supply in 131 four-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 & 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, this seven-fold increase in the carbon price reduces global emissions by just 0.85%. 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. 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 reduce EU welfare costs by 85% and increase global abatement by 70%, to 1.43% of global emissions. However, the current EU proposal limits CBAM tariffs to very few sectors which, in our simulations, improves only marginally upon the reference case, increasing global abatement from 0.85% to 0.87%. In contrast, our proposed LBAM policies deliver stronger emissions reductions because they directly target leakage. An LBAM tariff that adjusts for import leakage increases global abatement to 0.97%. This figure can be raised to 1.28% 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 3.6 %, respectively.

We extend our analysis of these scenarios to the case where the EU coordinates its carbon pricing and border adjustment policies with other countries, akin to the climate club proposed by Nordhaus (2015). In the political sphere, such a club has been advocated by Germany (Bundesministerium für Finanzen, 2021), the G7 countries, and the EU (G7, 2022). The members of the climate club share a common internal price of carbon and, potentially, a border adjustment vis-à-vis non-members. When Canada and the UK coordinate their carbon tax with the EU, LBAM with import and export leakage border adjustment increases the effectiveness of the club in reducing global emissions by around 60% compared to a club without border adjustment. If the US joins too, global emission reductions are magnified by a factor of six without border adjustment and by a factor of seven with LBAM compared to the baseline case of unilateral EU policies without border adjustment. This justifies the introduction of an LBAM even when more countries join the climate club. Finally, when the US joins the club, EU welfare increases, while this is neither the case if the EU pursues policies unilaterally nor for the smaller carbon club.

Relation to the literature By proposing a new policy instrument for preventing carbon leakage, our paper adds to a rich literature on the environmental, competitive and welfare effects of unilateral climate policy. Much of this literature has analyzed this topic through the lens of computable general equilibrium (CGE) models of the world economy, which lend themselves to extensive *ex-ante* simulation of different policy instruments. This strand of literature highlights the economic advantages of border carbon adjustments over other anti-leakage policies such as subsidies on domestic output (see Böhringer et al., 2022, for a recent review). However, it also recognizes practical difficulties associated with computing the approriate tariff rates and respecting the Most-Favored Nations (MFN) Clause (Fischer & Fox, 2012; Cosbey et al., 2019). Such legal and implementation challenges explain why border carbon adjustments have not been implemented at full scale so far.[4] The EU's recent commitment to CBAM constitutes a paradigm shift towards a more pragmatic policy approach that balances trade and environmental objectives. This sets the stage for rethinking the design of border carbon adjustments, as we do in this paper.

Our approach to use a structural trade model follows recent empirical research on environmental regulation and emissions leakage. Aichele & Felbermayr (2015) employ a structural gravity model of trade to estimate carbon leakage induced by the Kyoto Protocol, the world's first binding climate treaty. Larch & Wanner (2017) investigate

[4] California adjusts for embedded carbon in electricity trades with its neighbor states (Fowlie et al., 2021).

the emission and welfare effects of carbon tariffs in a structural multi-sector structural gravity model of the world economy. Shapiro & Walker (2018) develop a quantitative heterogeneous-firm trade model to quantify the role of regulation in reducing air pollution emissions from US manufacturing.[5] Sogalla (2023) uses this type of model, augmented by a fossil fuel sector and scale economies, to quantify the effects of CBAM on leakage and welfare, and how those metrics vary with key design features of the policy.

Further research has analyzed the design of *optimal* border carbon adjustments. Weisbach et al. (2020) study unilaterally optimal extraction, production and border adjustment taxes in a general equilibrium model of trade with two countries. Their optimal tax mix consists of an extraction tax on energy production, a tax on trade in energy, and an export subsidy on goods. In constrast to their work, we do not model energy leakage (energy supply-side policies), and focus on production leakage. We also do not consider unilaterally optimal policies that generally harm foreign countries. Instead, we sterilize the impact of the domestic carbon tax on the rest of the world. Farrokhi & Lashkaripour (2021) use a structural multi-sector, multi-country gravity model and derive unilaterally optimal carbon taxes, production taxes and border adjustment taxes. In their model, border taxes are motivated both by carbon leakage and by terms-of-trade motives. These authors find that non-cooperative policies deliver just 1% of world emission reductions achievable under global cooperation. In contrast, partial cooperation in a climate club (Nordhaus, 2015) could achieve emissions reductions corresponding to up to 60% of the fully cooperative outcome, where member states of the climate club adopt a globally optimal carbon tax and levy unilaterally optimal border taxes vis-à-vis non-members. Taking tariffs as given, non-member states join the club if this makes them better off.[6] We also analyze the formation of climate clubs, but we assume that the club's border taxes are focused on leakage prevention rather than welfare maximization.

To sum up, while our analysis is closely related to these papers, the main contribution of this paper is to propose a new policy instrument, LBAM, that prevents carbon leakage and is feasible given the current legal and information constraints that plague border carbon adjustments. To do so, we build a quantitative trade model that satisfies structural gravity as previous work but is much more granular. The key conceptual distinction from research on optimal policies is that we take as given the EU's commitment to unilaterally increase carbon prices (as a way to meet its obligations under the Paris Accord) and consider border adjustments that keep the EU imports and exports constant. Thus, in contrast to unilaterally optimal or Nash policies, LBAM does not impose any negative externalities on other countries.

[5]See Cherniwchan et al. (2017) for a review of the literature on heterogeneous-firm models of trade and the environment.

[6]Barrett (1997) shows how trade restrictions towards non-signatories can increase participation in a theoretical analysis of global environmental agreements. Wagner (2016) empirically investigates the influence of trade restrictions on international cooperation for protecting the global ozone layer.

The remainder of this paper is structured as follows. The next section provides background on EU climate policy and a sketches the design of our proposed policy instrument. Section 3 introduces the economic model used to analyze different leakage policies adopted by the EU or by a climate club, described in Section 4. Section 5 explains the calibration and presents our quantitative results. Section 6 concludes.

2 Unilateral Carbon Pricing and Leakage Protection in the EU

2.1 Carbon Pricing in the Emissions Trading System

The EU electricity sector and energy-intensive manufacturing industries have been subject to carbon pricing since 2005, when the EU launched its Emissions Trading System (EU ETS) for CO_2 and other greenhouse gases. Designed as a cap-and-trade policy, the ETS limits total emissions by issuing a fixed number of European Union Allowances (EUA) each year. Demand for those emission permits comes from regulated emitters who must cancel one EUA for each ton of CO_2 equivalent they emit in a given year. The EUA price is established in auctions and via bilateral trades. Permit prices during the initial years of the policy were mostly below 20 € and only rarely exceeded 30 € (Ellerman et al., 2016; Hintermann et al., 2014). However, between October 2020 and February 2023, the permit price has climbed from under 30 € to over over 100 €, and has rarely fallen below 80 € since. With the arrival of higher carbon prices, and against the background of increased ambition for carbon reduction targets set out in its 2020 Green Deal, the EU Commission recognized a need for better leakage protection and proposed the introduction of a Carbon Border Adjustment Mechanism in July 2021.

2.2 Free Permit Allocation to Sectors at Risk of Carbon Leakage

Given the unilateral nature of the EU ETS, concerns about preventing carbon leakage have been very influential in its design. Initially, permit were given free-of-charge to all incumbent emitters to offset compliance costs. Since 2013, free permit allocation is being gradually phased out except in manufacturing industries deemed at high leakage risk (currently 69 sectors and sub-sectors). Eligible firms receive free permits in proportion to their production capacity and industry specific carbon intensity benchmarks. Unlike output-based updating practiced in the Californian and Canadian carbon markets, whereby free emissions permits are granted in proportion to current-period output,[7] EU permit al-

[7]Output-based updating can effectively prevent leakage but it also dilutes the carbon price signal, leading to higher emissions and social costs (Fischer & Fox, 2007). In concentrated industries, output-based updating may exacerbate market power of incumbent firms with detrimental consequences for consumer welfare (Fowlie et al., 2012).

locations are updated only in the event of exceptionally strong fluctuations in output. Since firms cannot influence their permit allocations by changing output in the short run, capacity-based updating aims to prevent carbon leakage that operates via new investment decisions rather than production decisions (Meunier et al., 2014). It is challenging to empirically test for investment leakage, given the long time horizons involved, but the evidence available so far does not indicate that the EU ETS has caused significant investment leakage (Koch & Basse Mama, 2019; Borghesi et al., 2020; Dechezleprêtre et al., 2022). Industry associations attribute this outcome to free permit allocation and lobby for its continued use even when CBAM tariffs will be in force (CEFIC, 2022). However, cheap abatement options for industrial emitters (Colmer et al., 2024), very low carbon prices as well as a low priority of carbon costs in firms' assessment of where to produce (Martin et al., 2014b) go a long way to explain the absence of leakage.

With the introduction of CBAM, the EU plans to limit the eligibility for and amount of free permit allocation. This responds to the long-standing criticism from civil society that transferring pollution rights to incumbent polluters turns the polluter-pays principle on its head. It also recognizes economic disadvantages and practical problems of this particular leakage prevention policy. Allocating permits free-of-charge is costly as it foregoes revenue that could otherwise be used to lower or abolish distortionary taxes (Bovenberg & de Mooij, 1994; Bovenberg & Goulder, 1996). Such costs are only justified if receiving those permits actually reduces a firm's leakage propensity, which is unobservable (Martin et al., 2014b; Ahlvik & Liski, 2022). Consequently, choosing which firms and industries should benefit from free permit allocation has been a key issue in with this policy.

The EU ETS and other carbon markets have been relying on two simple metrics to identify industries that are at risk of carbon leakage: energy (or emissions) intensity (EI) and trade exposure (TE). EI is typically measured as the cost of energy or emissions (for a fixed carbon price) divided by value added. TE is measured as the sum of exports and imports divided by the sum of domestic production and exports. Eligibility for free permit allocation is determined at the industry level according to threshold values on one or both of these indicators. Given their widespread use, academics have attempted to quantify how well those simple metrics approximate actual leakage risk.[8] Econometric evidence consistent with carbon leakage has been found only for sectors that would rank high on both metrics, EI and TE (Aldy & Pizer, 2015; Fowlie et al., 2016; Fowlie & Reguant, 2022). Martin et al. (2014c) elicit qualitative measures of leakage risk in interviews with managers of firms regulated in the EU ETS. Based on their findings, the EU could raise billions of euros in auction revenues annually without increasing aggregate leakage risk if it eliminated free permit allocation to industries with high trade exposure but low carbon

[8] Fowlie & Reguant (2018) discuss the conceptual imperfections of these indicators and suggest ways of obtaining improved, empirically grounded estimates of carbon leakage. Fischer & Fox (2018) show that more sophisticated measures of trade sensitivity are positively correlated with the simple TE metric, at least within the set of EITE sectors.

intensity.[9]

2.3 The Carbon Border Adjustment Mechanism (CBAM)

CBAM denotes the EU's particular implementation of the concept of a border carbon adjustment (Markusen, 1975; Hoel, 1996). For clarity, we shall maintain a clear distinction between the concept (carbon border adjustment) and this specific policy (CBAM) throughout this paper. By taxing the carbon content of imports and rebating the carbon costs of exports in accordance with the domestic carbon tax, efficient border carbon adjustments offset the competitive disadvantage that unilateral carbon pricing confers on domestic producers. This instrument is appealing because it establishes a level playing field for competition on domestic and export markets, thus removing incentives for relocating production. Moreover, it potentially improves the global cost-effectiveness of carbon pricing by extending its scope to producers abroad (Böhringer et al., 2022).

CBAM applies the idea of a carbon border adjustment to EU imports in five industries –iron and steel, cement, fertilizers, aluminum, hydrogen and electricity– all of which pay carbon prices and are considered at high risk of carbon leakage due to the high carbon intensity of the production processes. EU importers of those goods will have to buy a so-called CBAM certificate for each ton of CO_2 emissions embodied in them. The price of CBAM certificates will be updated weekly to reflect the current EUA price, meaning that imported varieties of those goods are subject to similar carbon prices as their EU counterparts. This establishes the level playing field between imports and domestic production, the key element of border carbon adjustments.

The cost of CBAM certificates will be deducted by any amount that non-EU producers have already paid in their country for the carbon used in the production of the imported goods. This creates an incentive for non-EU countries to green their production processes; it also rewards international coordination on carbon pricing initiatives.

CBAM certificates will be required for imports from 2026 onwards, but a reporting system has already been launched in October 2023. This early roll-out is necessary due to the enormous amount of information needed before the financial adjustments can be implemented. Of central importance is that EU importers calculate the actual embedded CO_2 emissions at the plant level in the origin country. Given the obvious incentives to under-report emissions, an effective monitoring and verification process will have to be put in place. Also, under certain conditions, importers unable to report their carbon intensity can fall back on averages computed for the exporting country or for EU producers.

[9] Leakage risk also varies with the carbon cost shock under consideration. Evidence from ex-post analyses, which is necessarily based on moderate energy and (if available) carbon prices, suggests that the their effect on competitiveness indicators such as output, value added, or employment is small Aldy & Pizer (2015) or insignificant (Gerster & Lamp, 2022; Martin et al., 2014a). Extrapolating such results to considerably higher carbon prices is subject to substantial uncertainty, providing further motivation for the structural approach taken in this paper.

CBAM is based on a powerful economic principle, and its sheer announcement already marks a turning point for global climate policy. However, CBAM also has a number of severe shortcomings that jeopardize its viability. First, CBAM requires a large bureaucracy which is expensive to maintain for the EU and bound to erect a new non-tariff barrier to trade for its trading partners (Cosbey et al., 2019). Second, due to its very limited coverage of goods, CBAM distorts the allocation of production because it does not tax carbon embedded in imported products that are higher up in the value chain (e.g. steel contained in imported cars). Third, the CBAM design is unfit to fix this problem because scaling it up to cover all traded goods and sectors will also scale the disadvantages associated with a large bureaucracy (point 1). Fourth, the policy encourages opportunistic evasion practices, such as re-routing of imports via 'clean' third countries and reshuffling of EU-bound production via cleaner production plants.

Taken together, these shortcomings casts significant doubt on the effectiveness of CBAM at preventing carbon leakage. It appears that this primary goal has fallen victim to the secondary goal of extending EU carbon pricing outside of EU boundaries. We propose to drop this secondary goal and derive an alternative border adjustment that effectively prevents leakage while keeping bureaucracy, compliance costs, and trade distortions to a minimum. We sketch the idea behind this alternative proposal in the next subsection before analyzing it in a full fledged model.

2.4 Leakage Border Adjustment (LBAM) in a Nutshell

The basic idea of LBAM can be explained in a simple supply and demand diagram depicted in Figure 1. Under free trade, Home is a net importer in a specific sector (say, steel), which is characterized by perfect competition and an increasing marginal cost (=supply) curve, S_H. The difference between Home's demand (D_H) and supply curves for any given price p gives Home's import demand curve, depicted as the curve MD. Foreign is characterized by an upward-sloping export supply curve XS_f, given by the horizontal difference between its own, upward-sloping supply and downward-sloping demand curves . Given free trade, the initial equilibrium obtains at the world price p_0 where domestic demand Q_0 is larger than domestic supply Q_0^H and hence the difference equals Home's initial equilibrium imports M_0 from Foreign.

Consider now that Home unilaterally levies a carbon tax τ_E. This tax increases Home's marginal production cost for any given quantity and thus Home's supply curve shifts up to $S_H(\tau_E)$. In the new equilibrium, the price rises to p_1 and Home's imports increase to M_{τ_E} because domestic producers are now less competitive than before, relative to foreign producers. Increased import demand $\Delta M = M_{\tau_e} - M_0$ induces carbon leakage if, as is assumed here, production is more carbon intensive in Foreign than in Home. Absent other differences in regulation, prices or endowments between the two countries that would favor a lower carbon intensity in Foreign, the mere difference in carbon taxation suffices to justify this assumption. Consequently, a domestic carbon tax shifts some of the domestic emissions to the rest of the world. Moreover, the terms of trade move against Home because the world price of imports increases to p_1. This generates an additional welfare loss for Home.

Figure 1: Effect of a Carbon Tax on Imports

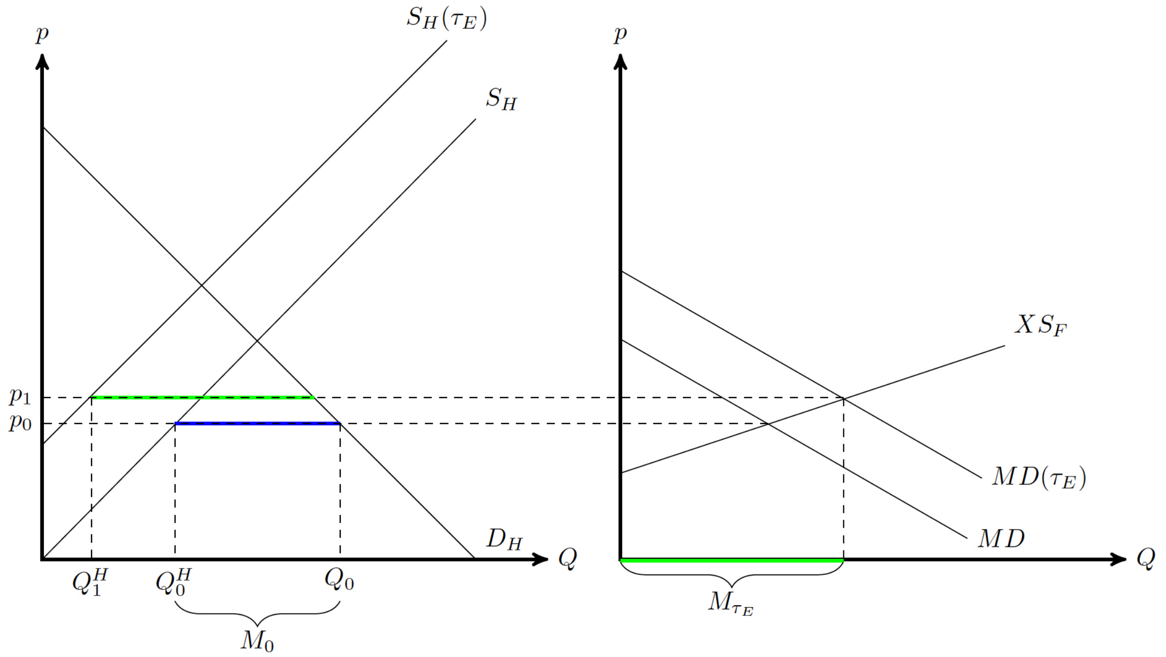
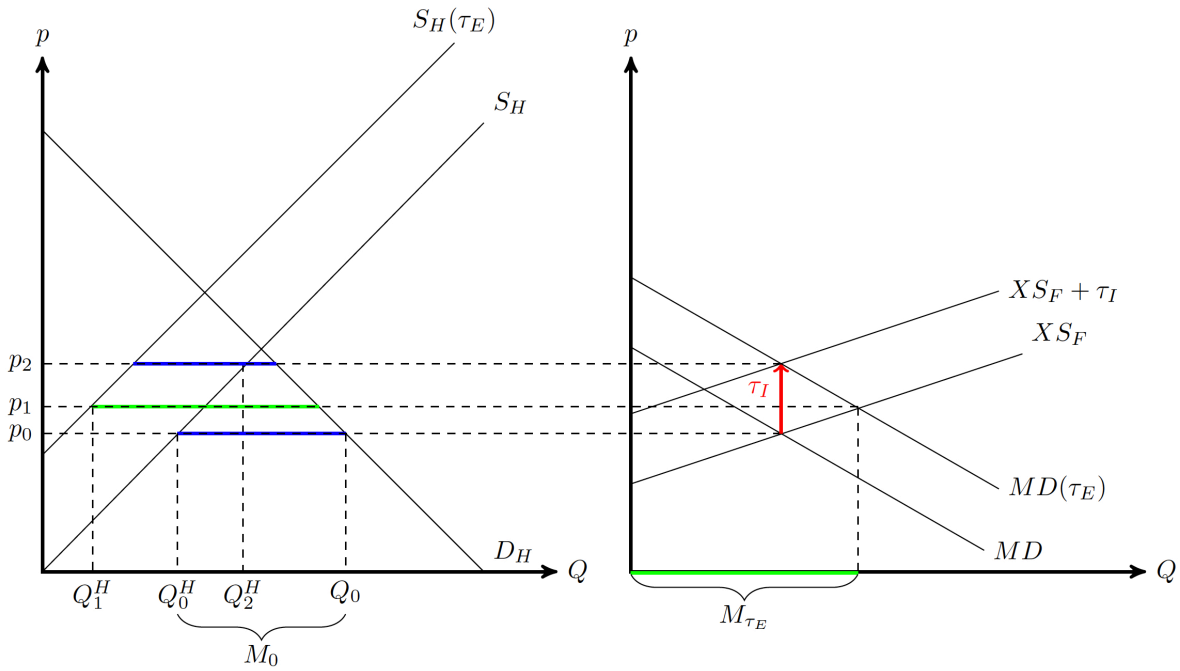


Figure 2: Sterilizing the Import Change with Leakage Border Adjustment



To avoid leakage, Home can introduce a tariff τ_I that brings import demand back to the initial situation M_0. This situation is depicted in Figure 2. The LBAM tariff just offsets the cost disadvantage of domestic producers generated by the domestic carbon tax. Home consumers now face a higher tariff-inclusive price, which induces them to demand less imports. This is depicted by an upward shift of the Foreign export supply curve to $XS_F + \tau_I$. Given the higher domestic price, domestic production rises compared to the situation without LBAM. The correct level of the tariff thus returns the level of imports and the world price to their initial levels M_0 and p_0. Production adjusts to a level that is higher than without the tariff but lower than without the carbon tax. Note that global emissions fall by more under this scenario compared to the situation without LBAM because domestic production is cleaner than foreign production by assumption, even though Home's emissions fall by less because it produces more.[10]

We emphasize that the simplicity of our proposed LBAM tariff is deliberate and dramatically reduces information requirements compared to CBAM. To see this, note that the computation of τ_I requires only three pieces of information for each good: (i) the slope of the domestic import demand, (ii) the slope of the foreign export supply curve, and (iii) by how much the domestic supply curve shifts in response to the carbon tax. Knowledge of these objects suffices to design a non-discriminatory tariff that holds imports and, hence, the carbon content of imports, constant. This knowledge is much easier to obtain than reliable information on embodied carbon at a myriad of foreign production sites, which is essential to the proposed CBAM.

2.5 Implementation challenges: CBAM vs. LBAM

Restricting trade to prevent carbon leakage is not an easy task for policy makers. Drawing on earlier, more comprehensive reviews of the numerous legal and practical obstacles to implementing border carbon adjustments (Cosbey et al., 2019; Böhringer et al., 2022), this subsection highlights those challenges that have markedly different implications for CBAM and LBAM.

Until recently, it has been widely held that border carbon adjustments like CBAM would likely violate WTO rules. Discriminating between imports with different carbon intensities is a key element of this policy yet it violates the Most-Favored-Nation (MFN) clause which requires that the same tariff rate must be applied to all trading partners.[11] This suggests a modification to the CBAM design whereby equal carbon intensities are assumed across sources (benchmarking). While also simplifying information requirements,

[10] A symmetric argument applies to Home's export market. The introduction of a carbon tax would require an export subsidy that eliminates the cost disadvantage that Home's carbon tax imposes on Home producers when competing with Foreign producers in export markets. The LBAM export subsidy simply holds exports constant at the level before the carbon tax was introduced.

[11] Cosbey et al. (2019) cite the conservation of exhaustible natural resources as a potential cause for and MFN exemption under GATT Article XX.

the modified CBAM would fail on both its objectives as it would neither establish the level playing field for competition nor equalize marginal incentives for abating CO_2. Moreover, modified CAM would create incentives for tariff arbitrage: exporters from a dirty country that face a high CBAM tariff could first export to a third destination on which the EU sets a lower CBAM tariff and then export from that destination to the EU.

By contrast, these issues do not arise with LBAM tariffs and subsidies because they do not discriminate across sources; they simply offset import and export leakage. As argued by Staiger (2022), LBAM tariffs on imports are compatible with the MFN principle, because they just preserve the level of market access to the domestic market that foreign countries had before the introduction of the domestic carbon pricing scheme. Without border adjustment that sterilizes imports, imports from countries without an equivalent carbon tax would rise and this constitutes a market-access favor that was never meant to be given.

LBAM does discriminate between trading partners that do (members of a climate club) and those that do not have equivalent carbon pricing policies. This is a logical distinction because the risk of carbon leakage vanishes when trading partners have equally stringent carbon prices. The discrimination can also be justified with the MFN principle because non-members have a cost advantage relative to club members and the LBAM tariff just offsets it. The LBAM tariff holds imports from all origin countries constant at the level before the carbon-tax increase in the club. In addition, not taxing club members while maintaining border adjustment vis-à-vis non member provides an incentive for coordinated carbon pricing policies across countries (Barrett, 1997; Nordhaus, 2015).

Likewise, the WTO Agreement on Subsidies and Countervailing Measures presents legal challenges for both CBAM and LBAM when applied to exports, because it prohibits export subsidies. While indirect taxes can be legally rebated on exports under this agreement, this is not the case for regulation costs like those arising under an ETS (Cosbey et al., 2019). From an economic perspective the legal view is not very meaningful because an ETS and a carbon tax are equivalent. Moreover, one can argue that LBAM export subsidies should be legal when applied to destinations without equivalent carbon pricing since they merely preserve existing market access by compensating for the cost disadvantage of domestic producers and thus do not harm foreign producers (Staiger, 2022).

Legal challenges aside, a fundamental problem with the practical implementation of CBAM lies in its vast information requirements, as was pointed out above. As we have already noted there, LBAM tariffs are not susceptible to such problems due to the much lower information requirements. There are several ramifications of this aspect. First, LBAM is robust to reshuffling, which is the redirection of the lowest-carbon production for export to carbon-regulating countries while higher-carbon production remaining for unregulated consumption (Cosbey et al., 2019). Foreign firms have an incentive to engage in reshuffling under CBAM because this lowers the tariff burden, but not under LBAM.

Second, accounting for indirect emissions embodied in factor inputs exacerbates information requirements under CBAM. Unless the value chain is very short, these emissions account for an important part of the carbon intensity of products. Domestic producers are exposed to this because of carbon prices paid by electricity firms and by domestic producers' intermediates. If the CBAM proposal were to be extended to all sectors (which is desirable to avoid distortions along the value chain), indirect emissions ought to be part of the carbon intensity measure that constitutes the basis for the border adjustment. However, this presents further measurement issues and challenges. By contrast, computing LBAM does not require any knowledge of foreign indirect emissions along the supply chain and domestic indirect emissions are automatically taxed under an ETS.

3 Theoretical Model

We solve a many-country model with countries denoted by $j = 1, ..., J$. To facilitate a simple computation of border adjustment mechanisms that are linked to the current ETS price, the model deliberately abstracts from general-equilibrium effects that operate via changes in factor prices. There is a continuum of tradable sectors indexed by s. In each sector, there is a fixed number of firms that operate under monopolistic competition à la Dixit-Stiglitz with differentiated varieties. The first subindex denotes the location of consumption and the second one the location of production.

3.1 Consumers

We assume quasi-linear utility between a tradable outside sector and Cobb-Douglas aggregate of a continuum of differentiated tradable sectors s. Moreover, consumers obtain negative utility from global emissions. The utility function of the representative consumer in country i is thus given by

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

where

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

is a CES aggregator across the continuum of differentiated varieties ω in sector s. The term $c_{ijs}(\omega)$ denotes the consumption by country i of an individual sector-s variety ω produced in country j. N_{ijs} is the (exogenous) measure of varieties produced by country j available in country i in sector s. The elasticity of substitution across varieties, ε_s, is sector-specific and larger than unity. Denote by e_s worldwide emissions of sector s and θ

denotes the social marginal cost of emissions. After aggregating consumption of varieties by sector s and country pair ij,

$$C_{ijs} \equiv \left[\int_0^{N_{ijs}} c_{ijs}(\omega)^{\frac{\varepsilon_s - 1}{\varepsilon_s}} d\omega \right]^{\frac{\varepsilon_s}{\varepsilon_s - 1}}$$

we can write country i's sector-s consumption as a CES aggregator of the country-specific aggregate bundles C_{ijs}

$$C_{is} = \left[\sum_{j=1}^{J} C_{ijs}^{\frac{\varepsilon_s - 1}{\varepsilon_s}} \right]^{\frac{\varepsilon_s}{\varepsilon_s - 1}}$$

Maximizing utility (1) subject to the budget constraint

$$p_{i0} C_{i0} + \sum_{j=1}^{J} \int_s \int_0^{N_{ijs}} p_{ijs}(\omega) c_{ijs}(\omega) d\omega ds = I_i$$

where I_i is income of country i, yields the following demand function for individual varieties

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

We also obtain the demand function of country i for the aggregate bundle sourced from country j

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

as a function of the demand for the aggregate sector s bundle

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

Substitution yields

$$C_{ijs} = P_{ijs}^{-\varepsilon_s} P_{is}^{\varepsilon_s - 1} \eta_{is}, \tag{5}$$

where

$$P_{ijs} = \left[\int_0^{N_{ijs}} p_{ijs}(\omega)^{1-\varepsilon_s} d\omega \right]^{\frac{1}{1-\epsilon_s}}$$

and

$$P_{is} = \left[\sum_{j=1}^{J} P_{ijs}^{1-\varepsilon_s} \right]^{\frac{1}{1-\epsilon_s}}. \tag{6}$$

3.2 Production

For simplicity, we assume that production decisions are taken separately across markets.[12] Production y_{ijs} of a firm located in country j for market i in sector s is given by the following Cobb-Douglas production function

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

where z_{ijs} is the energy use associated with the production, l_{ijs} is a composite physical input (factors other than energy) and ϕ_{ijs} is a productivity shifter. Note that we assume potentially non-constant returns to scale. In case $\alpha_s + \beta_s < 1$ (decreasing returns – DRS), we obtain an upward sloping export supply curve, while when $\alpha_s + \beta_s = 1$ (constant returns - CRS) the export supply curve is horizontal.[13] The corresponding total cost function is given by

$$TC_{ijs} = \left(\frac{y_{ijs}}{\phi_{ijs}}\right)^{\frac{1}{\alpha_s+\beta_s}} p_{Zj}^{\frac{\beta_s}{\alpha_s+\beta_s}} (\alpha_s + \beta_s), \tag{7}$$

where p_{Zj} is the (exogenous) price of energy in country j.[14]

Note that 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. Due to these assumptions the model abstracts from equilibrium effects on factor prices and can be solved sector by sector. The 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 $\gamma_s \equiv \frac{1}{\alpha_s+\beta_s} - 1$. Note that $\gamma_s = 0$ implies CRS and $\gamma_s > 0$ implies decreasing RS.

Energy use gives rise to more or less carbon emissions, depending on the prevailing mix of fossil and renewable energy sources in a given country. Therefore, carbon emissions embodied in goods produced by sector s in country j for market i can be computed as

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

[12]Such a 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. (2023) provide detailed evidence that Chinese multi-plant firms shift emissions from regulated to unregulated plants.

[13]In principle, we could also allow for increasing returns, i.e. $\alpha_s + \beta_s > 1$, but our empirical estimates imply that this is never the case. An alternative setup would be to assume constant marginal costs, heterogeneous firms and free entry. However, in this case the increase in export supply would be driven by the extensive margin, which seems unrealistic in the short run.

[14]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).

where d_j denotes the rate of carbon emissions per unit of energy in country j.[15] Shepard's Lemma provides an expression for z_{ijs},

$$z_{ijs}(p_{Zj}, y_{ijs}) = \frac{\partial TC_{ijs}}{\partial p_{Zj}} = \beta_s \left(\frac{y_{ijs}}{\phi_{ijs}} \right)^{1+\gamma_s} p_{Zj}^{-\alpha_s(1+\gamma_s)}. \tag{8}$$

Hence the emission intensity of exports from country j to country i sector s is given by:

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

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

We also need to specify the relationship between energy prices and the carbon emission tax τ_{Ej} that a country may decide to levy. Let $\tilde{p}_{Zj}$ be the energy price in country j net of carbon taxes. We assume a per-unit carbon tax of τ_{Ej} Dollars per unit of carbon emissions.[16] Then the price of a unit of energy gross of the carbon tax is given by $p_{Zj} = \tilde{p}_{Zj} + d_j \tau_{Ej}$. Thus, the carbon tax increases the price of energy by more in countries with higher carbon emission intensity d_j (e.g., when the local energy mix contains a lot of fossil fuels and little solar energy).

We assume that there are iceberg trade costs τ_{ijs} for shipping a sector-s variety from j to i. Tariffs on imports by country i on origin country j in sector s are denoted by τ_{Iijs}, taxes on exports by country j on exports to destination country i in sector s are denoted as τ_{Xijs}. When $i = j$, so that we consider goods produced and sold in the same market, there are neither trade taxes nor transport costs i.e., $\tau_{ijs} = \tau_{Iijs} = \tau_{Xijs} = 1$.

Firms in country i are monopolists for their variety and optimally set a markup over their marginal cost. The consumer price of a sector-s variety produced in country i and consumed by country j is then given by

$$p_{jis} = \tau_{jis} \tau_{Ijis} \tau_{Xjis} \mu_s \left(\frac{y_{jis}}{\phi_{jis}} \right)^{\gamma_s} p_{Zi}^{\beta_s(\gamma_s+1)} \phi_{jis}{}^{-1}, \tag{9}$$

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

Total profits of sector s in country i are given by

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

[15] Consistent with our focus on partial-equilibrium, short-run analysis, we assume that d_j is fixed and does not respond to carbon pricing. In the longer run, the energy sector will likely respond to higher prices of ETS allowances and CBAM certificates by reducing d_j.

[16] All nominal variables in the model are to be considered in US Dollars.

where

$$\Pi_{jis} = N_{jis}(\tau_{Ijis}^{-1}\tau_{Xjis}^{-1}p_{jis}c_{jis} - TC_{jis}) = N_{jis}\left[\mu_s - \frac{1}{1+\gamma_s}\right]\left(\frac{y_{jis}}{\phi_{jis}}\right)^{\gamma_s+1} p_{Zi}^{\beta_s(\gamma_s+1)}$$

are the profits that country-i sector-s firms earn in each market j. Note that the last equality follows from conditions (7) and (9).

3.3 Equilibrium

We impose market clearing for each sector. As shown in Appendix B, we obtain the following three equations which allow us to find a closed-form solution for y_{ijs}, p_{ijs} and P_{is} for all i, j and s.

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

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

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

3.4 Equilibrium in Changes

We rewrite the equilibrium conditions in terms of gross changes in the outcome variables. For any such variable X, we denote by $\hat{X} = \frac{X'}{X}$ the gross change from the initial equilibrium value X to the new equilibrium outcome X'. This notation allows us to express changes in the equilibrium outcomes in terms of changes in policy instruments (taxes) and objects that are observable to us, such as initial trade shares. The derivations of these expressions are relegated to Appendix B.

To begin, note that changes in the carbon tax are positively related to changes in the price of energy via the relationship $\hat{p}_{Zj} = \frac{\tilde{p}_{Zj}+d_j\hat{\tau}_{Ej}\tau_{Ej}}{\tilde{p}_{Zj}+d_j\tau_{Ej}}$. Then from condition (10) and (11) it follows that

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

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

Note that conditions (13) and (14) hold for all i, j and s and that $\hat{c}_{ijs} = \hat{C}_{ijs} = \hat{y}_{ijs}$. Changes in the domestic sector-s price index (6) can be written as

$$\hat{P}_{is}^{\frac{(1+\gamma_s)(1-\varepsilon_s)}{\gamma_s\varepsilon_s+1}} = \sum_{j=1}^{J}\delta_{ijs}\hat{p}_{Zj}^{\beta_s\frac{(\gamma_s+1)(1-\varepsilon_s)}{\gamma_s\varepsilon_s+1}}\left(\hat{\tau}_{Iijs}\hat{\tau}_{Xijs}\right)^{\frac{1-\varepsilon_s}{\gamma_s\varepsilon_s+1}}, \tag{15}$$

where δ_{ijs} is the expenditure share of country i on goods imported from country j (i.e.,

$\delta_{ijs} \equiv \frac{P_{ijs}C_{ijs}}{P_{is}C_{is}}$). This expression gives us an explicit solution for the change in the sector-s consumer price index. Combining condition (15) with (13) and(14) allows us to 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, parameters (β_s, γ_s, ε_s) and observable trade shares only. Eq.(5) implies that

$$\hat{C}_{is} = \hat{P}_{is}^{-1}.$$

Finally, changes in emissions are given by

$$\hat{e}_{ijs} = \left(\frac{\hat{y}_{ijs}}{\hat{p}_{Zj}^{\alpha_s}}\right)^{1+\gamma_s} = \hat{y}_{ijs}^{1+\gamma_s}\hat{p}_{Zj}^{\beta_s(1+\gamma_s)-1}. \tag{16}$$

3.5 Welfare

We compute the discrete changes in welfare induced by policy changes.[17] With quasilinear utility, the marginal utility of income is unity. Thus, if we take the outside good as the numéraire and define it as money, changes in indirect utility correspond to the amount of money consumers need to receive/pay in order to stay indifferent to the policy change.

Welfare is given by utility

$$W_i = C_{i0} + \int_s \eta_{is} \log C_{is} d_s - \theta \int_s e_s ds = I_i + \int_s \eta_{is} \log C_{is} d_s - \int_s P_{is} C_{is} ds - \theta \int_s e_s ds,$$

where the equality follows from substituting the demand function for the outside good C_{i0} into the utility function. Income is defined as $I_i = w_i L_i + \int_s \Pi_{is} ds + \int_s T_{is} d_s$, (labor income plus profits plus tax income). 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 (profits), labor income, tax income and the disutility from global emissions.

Changes in welfare are given by[18]

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

where we have used the fact that $\widehat{P_{is}C_{is}} = 1$. We have already computed $\hat{C}_{is}$ in the previous section. In Appendix C we show how to compute $\hat{\Pi}_{is}$, Π_{is}, $\hat{T}_{is}$, T_{is} and $\hat{e}_s$, e_s in

[17] In Appendix C we provide the derivation of the welfare formulae as well as an explanation of how to apply those formulas when the initial level of tax revenues is zero for some ijs combinations.

[18] In contrast to what is usually done in the literature (see, e.g., Arkolakis et al., 2012, who compute relative welfare changes), because of quasi-linear utility we compute the absolute welfare difference between the situations before and after the policy change.

terms of observables. In particular, profit changes/levels are given by

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

where $\sigma_{jis} = \frac{\tau_{Ijis}^{-1}\tau_{Xjis}^{-1}\eta_{js}\delta_{jis}}{\sum_{j=1}^{J}\tau_{Ijis}^{-1}\tau_{Xjis}^{-1}\eta_{js}\delta_{jis}}$ are the sales shares in each market net of trade taxes. Changes in tax income in country i is given by

$$\int_s (\hat{T}_{is} - 1) T_{is} ds = \int_s (\hat{T}_{Eis} - 1) T_{Eis} ds + \int_s (\hat{T}_{Iis} - 1) T_{Iis} ds + \int_s (\hat{T}_{Xis} - 1) T_{Xis} ds,$$

where T_{Eis}, T_{Iis} and T_{Xis} are the sector s tax revenues from the carbon tax, import tariffs and export taxes. These objects can be written as

$$\hat{T}_{Eis} = \hat{\tau}_{Ei} \hat{p}_{Zi}^{\beta_s(1+\gamma_s)-1} \sum_{j=1}^{J} \sigma_{jis} \hat{y}_{jis}^{(1+\gamma_s)} \qquad T_{Eis} = \beta_s \mu_s^{-1} d_i \tau_{Eis} p_{Zi}^{-1} \sum_{j=1}^{J} \tau_{Ijis}^{-1} \tau_{Xjis}^{-1} \eta_{js} \delta_{jis}$$

$$\hat{T}_{Iis} = \sum_{j \neq i}^{J} \hat{p}_{Zj}^{\beta_s(1+\gamma_s)} t_{Iijs} \hat{\tilde{\tau}}_{Iijs} \hat{\tau}_{Xijs} \hat{y}_{ijs}^{(1+\gamma_s)} \qquad T_{Iis} = \eta_{is} \sum_{j \neq i}^{J} \tilde{\tau}_{Iijs} \tau_{Iijs}^{-1} \delta_{ijs}$$

$$\hat{T}_{Xis} = \hat{p}_{Zi}^{\beta_s(1+\gamma_s)} \sum_{j \neq i}^{J} t_{Xjis} \hat{\tilde{\tau}}_{Xjis} \hat{y}_{jis}^{(1+\gamma_s)} \qquad T_{Xis} = \sum_{j \neq i}^{J} \eta_{js} \tilde{\tau}_{Xjis} \tau_{Iji}^{-1} \tau_{Xji}^{-1} \delta_{jis},$$

where $\tilde{\tau}_{Iijs} \equiv \tau_{Iijs} - 1$ and $\tilde{\tau}_{Xijs} \equiv \tau_{Xijs} - 1$. Moreover, $t_{Iijs} \equiv \frac{\tilde{\tau}_{Iijs}\tau_{Iijs}^{-1}\delta_{ijs}}{\sum_{j\neq i}^{J}\tilde{\tau}_{Iijs}\tau_{Iijs}^{-1}\delta_{ijs}}$ and $t_{Xjis} \equiv \frac{\tilde{\tau}_{Xjis}\tau_{Ijis}^{-1}\tau_{Xjis}^{-1}\eta_{js}\delta_{jis}}{\sum_{j\neq i}^{J}\tilde{\tau}_{Xjis}\eta_{js}\tau_{Ijis}^{-1}\tau_{Xjis}^{-1}\delta_{ijs}}$ are the tax revenue shares of each import/export market in total import/export tax revenue.

Changes in global emissions can be written as

$$\hat{e}_s = \sum_{i=1}^{J} \sum_{j=1}^{J} \hat{e}_{jis} \frac{N_{jis} e_{jis}}{\sum_{i=1}^{J} \sum_{j=1}^{J} N_{jis} e_{jis}}. \tag{17}$$

Then, using conditions (8) and (9) again, we obtain

$$\hat{e}_s = \sum_{i=1}^{J} \hat{p}_{Zi}^{\beta_s(1+\gamma_s)-1} \sum_{j=1}^{J} \tilde{\sigma}_{jis} \hat{y}_{jis}^{(1+\gamma_s)} \qquad e_s = \beta_s \mu_s^{-1} \sum_{i=1}^{J} p_{Zi}^{-1} d_i \sum_{j=1}^{J} \tau_{Ijis}^{-1} \tau_{Xjis}^{-1} \eta_{js} \delta_{jis}, \tag{18}$$

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.

4 Border Adjustment Mechanisms and Policy Scenarios

This section characterizes the workings of various border adjustment mechanisms using the equilibrium-in-changes notation introduced above. All scenarios have in common that carbon pricing is unilateral, i.e., the domestic economy raises the domestic carbon tax while all other countries do not implement any policies. We relax this assumption in Section 4.3 below, where a climate club of countries jointly implements a carbon tax increase and, possibly, a joint border adjustment mechanism.

In the baseline scenario without any border adjustment, the environmental effectiveness of the carbon tax is low because clean domestic production is displaced by dirty imports in the home market (*import leakage*) and by dirty exports from other countries in third markets (*export leakage*). The various border adjustment mechanisms we consider reign in leakage to different degrees. Our proposed leakage border adjustment mechanism (LBAM) is designed to sterilize changes in imports and, potentially, exports induced by changes in the domestic carbon tax. We derive the LBAM import tariff and LBAM export subsidy that keep imports and exports constant at the levels before the carbon-tax increase. Due to the structure of our model, the LBAM tariff and subsidy can be set independently from one another. We also characterize tariffs on the carbon content of imports consistent with the EU's carbon border adjustment mechanism (CBAM), as well as a broader variant of CBAM that applies to all sectors.

For each scenario, we characterize the changes in the policy variables and their impact on prices and production. With these outcomes in hand, the welfare consequences of these policies, as well as their impact on emissions, can be evaluated using the equations derived in Section 3.5.

4.1 Unilateral Increase in the Carbon Tax

4.1.1 A Unilateral Carbon Tax without Border Adjustments

A unilateral carbon-tax increase raises the costs of domestic producers relative to foreign competitors in the domestic and foreign markets and thereby causes import and export leakage. Changes in policy variables are thus given by $\hat{\tau}_{Ei} > 1$ while $\hat{\tau}_{Ej} = 1$ for all $j \neq i$ and $\hat{\tau}_{Iijs} = \hat{\tau}_{Xijs} = 1$ for all i and j. Consequently, the energy prices change according to $\hat{p}_{Zi} = \frac{\tilde{p}_{Zi} + d_i \hat{\tau}_{Ei} \tau_{Ei}}{\tilde{p}_{Zi} + d_i \tau_{Ei}}$ and $\hat{p}_{Zj} = 1$ for all $j \neq i$.

We compute the changes in equilibrium variables induced by this policy. By conditions (13) and (15):

$$\hat{y}_{iis} = \hat{p}_{Zi}^{\frac{-\beta_s \ (\gamma_s+1)\varepsilon_s}{1+\varepsilon_s\gamma_s}} \hat{P}_{is}^{\frac{\varepsilon_s-1}{1+\varepsilon_s\gamma_s}} \tag{19}$$

That is, given that $\gamma_s \geq 0$, holding constant changes in the price index $\hat{P}_{is}$, an increase in the domestic carbon tax reduces sales of domestic producers in their home market ($\hat{y}_{iis} < 1$). The decrease is larger, the stronger the degree of decreasing returns γ_s , the larger the cost share of emissions β_s, and the larger the elasticity of demand ε_s. Substituting the (positive) price index change from condition (15) into eq. (19) allows us to write the equilibrium response in sales of domestic producers in their home market to an increase in the carbon tax by $\hat{\tau}_{Ei}$ as

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

Given that $\varepsilon_s < 1$ this expression is smaller than unity because the direct negative effect of higher producer prices dominates the positive effect on sales operating via an increase in the price index. Intuitively, domestic producers' sales to their home market fall in industry equilibrium because consumers substitute away from domestic varieties when their prices increase.

By contrast, imports increase because the domestic price index goes up in response to the increased carbon tax, reflecting the reduced competitiveness of domestic producers.

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

A domestic carbon-tax increase raises the price of domestic relative to foreign varieties: when holding output constant, a 1-percent increase in the carbon tax increases domestic producer prices by $\beta_s(\gamma_s + 1)$ percent, leading consumers to substitute buy more foreign varieties. In the presence of decreasing returns ($\gamma_s > 0$), the resulting contraction in domestic production reduces domestic marginal costs, while the expansion in foreign production required to satisfy higher domestic demand for foreign varieties increases foreign marginal cost with an elasticity γ_s. This dampens the equilibrium response of imports somewhat. Overall, the increase in the domestic carbon tax induces *import leakage*: As long as domestic production is cleaner than abroad, increased imports mean that clean domestic production is replaced by dirty foreign production, increasing global emissions.

The domestic carbon tax has a symmetric effect on exports because domestic producers now face higher costs in foreign markets and foreign consumers substitute away from domestically produced varieties towards cheaper foreign-produced ones. The export conditions (13) and (15) imply

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

Thus, domestic exports fall in response to an increase in the domestic carbon tax. This increases global emissions as long as domestic production is cleaner than foreign production, because clean domestic production is replaced by dirty foreign production (*export leakage*).

4.1.2 A Unilateral Carbon Tax with Import Leakage Border Adjustment

We now consider a scenario where country i unilaterally introduces a carbon-tax increase ($\hat{\tau}_{Ei} > 1$ while $\hat{\tau}_{Ej} = 1$ for all $j \neq i$) and simultaneously introduces a tariff that keeps imports within each sector s constant at the level before the carbon-tax increase in order to prevent import leakage. We will show that any tariff that (i) prevents import leakage and (ii) does not discriminate between partner countries (most-favored-nation principle) must hold bilateral imports from each origin country constant. We thus first consider a tariff that holds bilateral imports constant and then show that this tariff is the only non-discriminatory tariff that also holds aggregate imports in the sector constant.

In this scenario, $\hat{C}_{ijs} = \hat{c}_{ijs} = \hat{y}_{ijs} = 1$ for all j in response to $\hat{\tau}_{Ei} > 1$. We are looking for the set of tariff changes $\hat{\tau}_{Iijs} > 1$ that make this work. In Appendix D we first show that tariffs changes are going to be independent of the partner country i.e., $\hat{\tau}_{Iijs} = \hat{\tau}_{Iis}$ for all j. Next, we show that the tariff change that keeps bilateral imports constant within each sector satisfies the following equation:

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

Given $\hat{\tau}_{Ei}$, this is one implicit equation in $\hat{\tau}_{Iis}$ that can be easily solved numerically. Observe that computing the optimal tariff change that prevents bilateral import leakage 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 on domestically produced varieties *before* the carbon tax increase δ_{ii}. By contrast, it does not require any information on the carbon content of imports. Since the LBAM tariff holds the level of bilateral imports constant and does not change the foreign carbon intensity of production it automatically holds the carbon content of imports constant, too.

By virtue of holding bilateral imports constant, the tariff changes in eq. (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 in Appendix D that there exist no other non-discriminatory tariffs that hold aggregate imports constant.

4.1.3 A Unilateral Carbon Tax with Export Leakage Border Adjustment

We next consider a scenario where country i unilaterally implements a carbon-tax increase ($\hat{\tau}_{Ei} > 1$ while $\hat{\tau}_{Ej} = 1$ for all $j \neq i$) and simultaneously introduces an export subsidy that keeps exports within each sector s constant at the level before the carbon-tax increase in order to prevent export leakage. Recall that 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.

We assume that the export subsidy $\hat{\tau}_{Xjis} < 1$ is set so as to keep bilateral exports of country i fixed, i.e. $\hat{C}_{jis} = \hat{c}_{jis} = \hat{y}_{jis} = 1$ for all j, in response to $\hat{\tau}_{Ei} > 1$ in country i. In Appendix D we show that this is the case when $\hat{\tau}_{Xjis}$ satisfies

$$\hat{\tau}_{Xjis}^{\frac{-\varepsilon_s(1+\gamma_s)}{\gamma_s\varepsilon_s+1}} = \delta_{jis}\hat{p}_{Zi}^{\beta_s(\gamma_s+1)}\hat{\tau}_{Xjis}^{\frac{1-\varepsilon_s}{\gamma_s\varepsilon_s+1}} + (1-\delta_{jis})\hat{p}_{Zi}^{\frac{\beta_s(\gamma_s+1)^2\varepsilon_s}{\gamma_s\varepsilon_s+1}} \tag{22}$$

A simple yet elegant solution to this equation is a non-discriminatory export subsidy that exactly offsets the pass-through of higher energy prices to exports, $\hat{p}_{Zi}^{\beta_s(\gamma_s+1)}$. Setting the LBAM subsidy to $\hat{\tau}_{Xi} = \hat{p}_{Zi}^{-\beta_s(\gamma_s+1)}$ prevents price changes in the destination markets, irrespective of the export destination. Since the price index does not change ($\hat{P}_{js} = 1$), domestic producers do not change their exports ($\hat{y}_{jis} = 1$) and, hence, bilateral exports remain constant. Moreover, holding bilateral exports constant without discrimination is equivalent to holding total exports constant without discrimination. The only information required to compute the export-leakage offsetting subsidy is the output elasticity of carbon β_s and the export supply elasticity γ_s.

4.1.4 A Unilateral Carbon Tax with Carbon Border Adjustment

In our framework, the EU's CBAM proposal can be characterized as a tax imposed by country i on the carbon content of imports from a country j for a subset of sectors. This policy requires knowledge of the carbon intensity of foreign production, because it taxes each unit of imported carbon at the same rate as a unit of domestic carbon.[19] We assume that the initial carbon price in foreign countries is zero. CBAM increases the energy price in those countries by an amount consistent with the domestic carbon tax, i.e. $\hat{p}_{Zij} = 1 + \frac{d_j\hat{\tau}_{Ei}\tau_{Ei}}{p_{Zj}}$, but only for goods that are exported to country i and the sectors s affected by CBAM (otherwise, $\hat{p}_{Zij} = 1$). In our model, we can implement the carbon tariff 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, i.e., $\hat{\tau}_{Xijs} = 1$ for all s and j. We use these assumptions in equations (13)-(15) to compute $\hat{y}_{ijs}$, $\hat{p}_{ijs}$, $\hat{c}_{ijs}$, $\hat{C}_{ijs}$, $\hat{P}_{is}$ and $\hat{C}_{is}$. Specifically:

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

[19] Our model abstracts from imperfect information and assumes that the carbon content of foreign production can be perfectly observed.

for all j and all s covered by CBAM.

Thus, domestic production and imports from all countries fall in response to a carbon-tax increase in combination with CBAM. Prices of all varieties increase in response to the carbon-tax increase and more so for varieties produced in locations with a more carbon-intensive energy mix. This induces consumers to reduce consumption of all varieties, both domestic and imported ones, and to shift their consumption mix away from carbon-intensive locations. Since the EU's CBAM proposal does not include export subsidies (not even for the small set of sectors covered by it), there is export leakage. Domestic producers face a cost disadvantage in export markets and domestic exports are replaced by third-country exports.

For the set of sectors not covered by CBAM, the situation is identical to the situation without border adjustment considered in Section 4.1.1. Consequently, for these sectors, there is both import leakage and export leakage.

4.2 Emission Responses to Unilateral Policies

We now dig deeper into the global emission responses to unilateral policy changes. Specifically, the global emission changes of each sector associated with unilateral policy changes (condition (18)) can be further decomposed as follows:

$$\begin{aligned}\hat{e}_s = & \underbrace{\hat{p}_{Zi}^{\beta_s(1+\gamma_s)-1}\tilde{\sigma}_{iis}\hat{y}_{iis}^{1+\gamma_s}}_{\substack{\textbf{(i)}\ \textit{Emission changes due to}\\ \textit{a change in production of domestically}\\ \textit{consumed and produced goods}}} + \underbrace{\hat{p}_{Zi}^{\beta_s(1+\gamma_s)-1}\sum_{j\neq i}^{J}\tilde{\sigma}_{jis}\hat{y}_{jis}^{1+\gamma_s}}_{\substack{\textbf{(ii)}\ \textit{Emission changes due to}\\ \textit{changes in domestic exports}}} \\ & + \underbrace{\sum_{j\neq i}^{J}\tilde{\sigma}_{ijs}\hat{p}_{Zj}^{\beta_s(1+\gamma_s)-1}\hat{y}_{ijs}^{1+\gamma_s}}_{\substack{\textbf{(iii)}\ \textit{Emission changes due to}\\ \textit{changes in domestic imports}}} + \underbrace{\sum_{k\neq i}^{J}\sum_{j\neq i}^{J}\tilde{\sigma}_{jks}\hat{y}_{jks}^{1+\gamma_s}}_{\substack{\textbf{(iv)}\ \textit{Emission changes due to}\\ \textit{changes in production of goods consumed}\\ \textit{and produced in the rest of the world}}}\end{aligned} \tag{23}$$

This decomposition of the change in global emissions distinguishes between the impact of domestic policy changes on domestic and foreign emissions.

Effect on emissions embedded in domestic production – (i) and (ii): By increasing the cost of energy inputs, a rise in the domestic carbon tax directly reduces the emissions embodied in each unit of production of domestically produced goods in country i, both for the domestic market and for exports. Moreover, since production for the domestic market falls in response to a domestic carbon-tax increase ($\hat{y}_{iis} < 1$), so do emissions. Finally, the same mechanism reduces domestic emissions from exports ($\hat{y}_{jis} < 1$) unless an LBAM export subsidy is provided. In the presence of an LBAM export subsidy that sterilizes exports, emissions embodied in exports fall exclusively because exports become cleaner.

Import Leakage – (iii): In the absence of import-related border adjustments, emissions embedded in imports by country i increase in response to a carbon-tax increase. Consumers in country i substitute domestically produced goods with imported goods because these become relatively cheaper. Tariffs on imports can avoid this effect. The LBAM tariff on imports holds the term constant at the initial share of world emissions accounted for by emissions embedded in EU imports. By contrast, CBAM actually makes this term smaller because it taxes imports more heavily when they come from origins where production is more carbon intensive than in country i.

Third-Country Leakage – (iv): As the prices of goods imported from country i increase because of the unilateral carbon-tax increase, foreign consumers substitute these imports with varieties produced in third countries. Thus, emissions embodied in the production of varieties produced by the rest of the world rise. Third-country leakage can be eliminated with LBAM export subsidies (but not with import tariffs).

Note that different border adjustment mechanisms vary in their effect on terms (i)-(iv). First, compared to a carbon-tax increase without border adjustment, LBAM and CBAM on imports reduce term (i) by less because they preserve more domestic production. This is efficient from a global perspective if domestic production is less emission intensive than foreign production. We will show below that this is true in the data. Second, by eliminating import leakage, LBAM on imports holds term (iii) constant, while CBAM makes it smaller. Finally, import-related leakage border adjustment has no effect on export leakage and third-country leakage (terms (ii) and (iv)). As we will show in the empirical section below, these terms are quantitatively large. This makes LBAM on exports desirable because it is the only policy that can address these types of leakage.

4.3 Carbon Tax Increase With a Climate Club

We now consider a set of countries that jointly introduce a carbon tax and, possibly, a common border adjustment mechanism vis-à-vis the rest of the world. Without loss of generality, assume that countries J_C to J belong to the climate club and countries 1 to $J_C - 1$ do not. The set of countries outside the climate club is denoted by P (the set of polluting countries). If $J_C = J$ the climate club only has a single member, i.e. there is no climate club.

4.3.1 Climate Club without Border Adjustments

We first consider a scenario where the climate club introduces a common carbon tax but does not apply any border adjustments. In this case $\hat{\tau}_{Ej} > 1$ and $\hat{p}_{Zj} = 1 + \frac{d_j \tau_{Ej} \hat{\tau}_{Ej}}{p_{Zj}}$ for all $j \geq J_C$, $\hat{\tau}_{Ej} = 1$ for all $j < J_C$ and $\hat{\tau}_{Iijs} = \hat{\tau}_{Xijs} = 1$ for all i and j .

For all countries $j \geq J_C$ in the climate club, changes in production for the domestic market and in exports to market i can be recovered from condition (13) and are equal to

$$\hat{y}_{ijs} = \hat{p}_{Zj}^{\frac{-\beta_s \ (\gamma_s+1)\varepsilon_s}{1+\varepsilon_s\gamma_s}} \hat{P}_{is}^{\frac{\varepsilon_s-1}{1+\varepsilon_s\gamma_s}} \tag{24}$$

This condition holds for all i, independently of whether the importing country i is a club member or not.

By contrast, changes in production for all markets i by countries j outside the club ($j < J_C$) are given by

$$\hat{y}_{ijs} = \hat{P}_{is}^{\frac{\varepsilon_s-1}{1+\varepsilon_s\gamma_s}} \tag{25}$$

From eq. (15), the change in the aggregate sectoral price index P_{is} is given by

$$\hat{P}_{is}^{\frac{(1+\gamma_s)(1-\varepsilon_s)}{\gamma_s\varepsilon_s+1}} = \sum_{j=1}^{J_C-1} \delta_{ijs} + \sum_{j=J_C}^{J} \delta_{ijs}\hat{p}_{Zj}^{\frac{\beta_s(\gamma_s+1)(1-\varepsilon_s)}{\gamma_s\varepsilon_s+1}} \tag{26}$$

for all i. Thus, the aggregate sectoral price level increases in all countries with the introduction of carbon taxes in the club because goods produced by club members become more expensive. The more members the climate club has, the larger is this effect.

From condition (24) we see that the effect of an increase of the carbon tax on club members' sales to any destination i (members and non-members) is negative because consumers substitute away from varieties produced by club members as these become relatively more expensive.

By contrast, from condition (25) we see that sales of polluting countries to any given destination unambiguously rise in response to an increase in the climate club's carbon tax. Demand for their exports increases due to an increase in the local price index.

4.3.2 Climate Club with a Leakage Border Adjustment on Imports

Next, we consider a scenario where countries in the club introduce a border adjustment mechanism vis-à-vis non-members that sterilizes import leakage to the polluting countries. In this case, $\hat{\tau}_{Ej} > 1$ and $\hat{p}_{Zj} = 1 + \frac{d_j\tau_{Ej}\hat{\tau}_{Ej}}{p_{Zj}}$ for all $j \geq J_C$ whereas $\hat{\tau}_{Ej} = 1$ for all $j < J_C$. Moreover, $\hat{\tau}_{Iijs} > 1$ for all $i \geq J_C$ and $j < J_C$ and $\hat{\tau}_{Iijs} = 1$ in all other markets. We assume that there is no export border adjustment so that $\hat{\tau}_{Xijs} = 1$ for all i and j.

In Appendix E.2, we show that club members charge a non-discriminatory tariff to offset import leakage vis-à-vis polluting countries, which is given by

$$\hat{\tau}_{Iis}^{\frac{-\varepsilon_s(1+\gamma_s)}{\gamma_s\varepsilon_s+1}} = \sum_{j=J_C}^{J} \delta_{ijs}\hat{p}_{Zj}^{\frac{\beta_s(\gamma_s+1)(1-\varepsilon_s)}{\gamma_s\varepsilon_s+1}} + \hat{\tau}_{Iis}^{\frac{1-\varepsilon_s}{\gamma_s\varepsilon_s+1}} \sum_{j=1}^{J_C-1} \delta_{ijs}. \tag{27}$$

Notice that this expression looks very similar to the one that determines the unilateral LBAM tariff, cf. eq. (21), the only difference being the weights. Moreover, the non-discriminatory tariff that avoids import leakage in the presence of a climate club is independent of whether or not (i) we assume that the tariff stabilizes aggregate or bilateral imports, and (ii) the other club members also levy a tariff to avoid import leakage. Hence, coordination of border adjustment in the club is not necessary to determine the import-leakage-offsetting tariff, provided that rules of origin prevent arbitrage within the climate club.

4.3.3 Climate Club with Leakage Border Adjustments on Imports and Exports

As a variation on the previous scenario, we now consider that all club members sterilize leakage related to their imports from and exports to the set of polluting economies. Formally, we assume that $\hat{\tau}_{Ej} > 1$ and $\hat{p}_{Zj} = 1 + \frac{d_j \tau_{Ej} \hat{\tau}_{Ej}}{p_{Zj}}$ for all $j \geq J_C$, $\hat{\tau}_{Ej} = 1$ for all $j < J_C$. Moreover, $\hat{\tau}_{Iijs} > 1$ and $\hat{\tau}_{Xjis} < 1$ for all $i \geq J_C$ and $j < J_C$ and $\hat{\tau}_{Iijs} = \hat{\tau}_{Xjis} = 1$ in all other markets. Since tariffs offsetting import leakage are independent of taxes offsetting export leakage, import tariffs for all $i \geq J_C$ and $j < J_C$ are still set according to condition (27) in all sectors. In Appendix E.3, we show that the LBAM export subsidy that club members grant for exports to polluting countries is given by $\hat{\tau}_{Xji} = \hat{p}_{Zi}^{-\beta_s(\gamma_s+1)}$ for all $i \geq J_C$ and $j < J_C$ and all s. Hence, as in the case of unilateral carbon pricing, the export subsidy that holds exports constant does not discriminate between non-members, does not depend on the export destination, and simply eliminates the pass-through of the domestic carbon tax on exports.

4.3.4 Climate Club with Carbon Border Adjustment

Finally, we consider a CBAM imposed by the club on non-member coutries, i.e. a tax on the carbon content of imports from a country $j < J_C$ to country $i \geq J_C$ for a subset of sectors. As above, we assume that the initial level of the carbon price in the set of polluting countries is zero. Under this assumption, the change in the energy price for imports from country j associated with a discriminatory carbon tariff on imports of country i from a non-member country j that equals the domestic carbon tax is given by $\hat{p}_{Zij} = 1 + \frac{d_j \hat{\tau}_{Ei} \tau_{Ei}}{p_{Zj}}$ for the subset of sectors covered by CBAM and 1 for those sectors not covered. We implement CBAM by setting a tariff equal to $\hat{\tau}_{Iijs} = \hat{p}_{Zij}^{\beta_s(\gamma_s+1)}$ for all $i \geq J_C$ and s with CBAMs and $\hat{\tau}_{Iijs} = 1$ for all sectors without CBAM. Other instruments of trade policy are not used and therefore $\hat{\tau}_{Xijs} = 1$ for all s and j. The equilibrum changes in production for each market are provided in Appendix E.4.

5 Quantitative Analysis

We simulate the effects of a seven-fold increase in the EU carbon price, from \$15 to \$105 per ton of CO_2, on trade, emissions, and welfare under different assumptions about accompanying border carbon adjustments. To this end, we calibrate the structural trade model described in the previous section to the 2018 equilibrium using detailed data on all equilibrium objects and sector-specific parameters for 131 four-digit manufacturing industries located in 57 countries (the EU-27 and 56 of its trading partners[20]). We first describe the calibration in more detail before summarizing the results.

5.1 Calibration

5.1.1 Data sources

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 obtained 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.[21] 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,

[20]These countries are Afghanistan, Albania, Armenia, Australia, Azerbaijan, Bangladesh, Belarus, Bosnia and Herzegovina, Brazil, Canada, China, Colombia, Costa Rica, Ecuador, Fiji, Georgia, Hong Kong, Iceland, India, Indonesia, Israel, Jordan, Kazakhstan, Kenya, Kyrgyzstan, Malaysia, Mauritius, Mexico, Moldova, Mongolia, Myanmar, Nepal, New Zealand, North Macedonia, Norway, Oman, Panama, Peru, Philippines, Qatar, Russian Federation, Rwanda, Saudi Arabia, Senegal, Singapore, South Korea, Sri Lanka, State of Palestine, Switzerland, Ukraine, United Arab Emirates, United Kingdom, Tanzania, United States, Uzbekistan, Zimbabwe.

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

electricity) for the year 2018 from the International Energy Agency (IEA World Energy Statistics-World Energy Balances). 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. 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). For me details, see Appendix G.1.

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. Since information for many countries is missing in this data source, we complement it with information from several other reports. 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 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. With information on fuel prices and energy mixes in manufacturing in hand, we compute the country-specific energy price index p_{Zi} as the average energy price weighted by the fuel shares. For me details, see Appendix G.2.

5.1.2 Parameter estimation

To estimate price elasticities of demand ε_s and the returns to scale parameters γ_s for each 4-digit product, we adopt estimation approaches suggested by Feenstra (1994), Broda & Weinstein (2006) and Soderbery (2015). Their method requires data on import values and quantities at the 4-digit level for each importing country. We source bilateral EU import values and quantities at the 4-digit NACE Rev. 2. level for the period 2005-2019 from Eurostat's COMEXT and convert the data to 4-digit ISIC Rev. 4. We explain the estimation procedure in detail in Appendix F.1.

Output elasticities of energy β_s and physical production factors α_s are obtained from econometrically estimated production functions using German firm-level data from AFiD. The estimates are obtained at the 4-digit WZ level and then converted to the ISIC Rev.4 classification. For more details, see Appendix F.2

Finally, we set the disutility of carbon emissions, θ, equal to 60$ per ton of carbon, which is at the lower end of recent estimates of the social cost of carbon (Rennert et al., 2021). While the value of this parameter affects the absolute welfare gains/losses arising from the EU's policies, it does not change their relative welfare ranking.

5.2 Simulation Results

We report simulation results separately for scenarios where the EU acts unilaterally and as part of a carbon club.

5.2.1 Unilateral EU Policies

In all unilateral policy simulations, countries outside the EU27 keep their tax instruments unchanged, i.e., $\hat{\tau}_{Iji} = \hat{\tau}_{Xij} = \hat{\tau}_{Ej} = 1$ for $j \neq$ EU27. Within the EU27, the carbon tax paid by domestic producers rises from \$15 to \$105 per ton. This roughly corresponds to the change from the initial average carbon price to its all-time high in 2023.

We compare the following policy scenarios:

No-BAM: No border adjustment. Apart from the carbon tax change, there are no other unilateral tax changes in the EU27.

CBAM-ID: 'Ideal' implementation of the CBAM described in Section 4.1.4. The EU27 unilaterally changes their import tariffs so as to tax the carbon content of imports in *all* sectors.

CBAM-EU: Current implementation of CBAM as described in Section 4.1.4, applied only to aluminum, iron and steel, fertilizers, cement.

LBAM: Tariffs on imports that eliminate bilateral import-related leakage in all sectors, as described in Section 4.1.2.

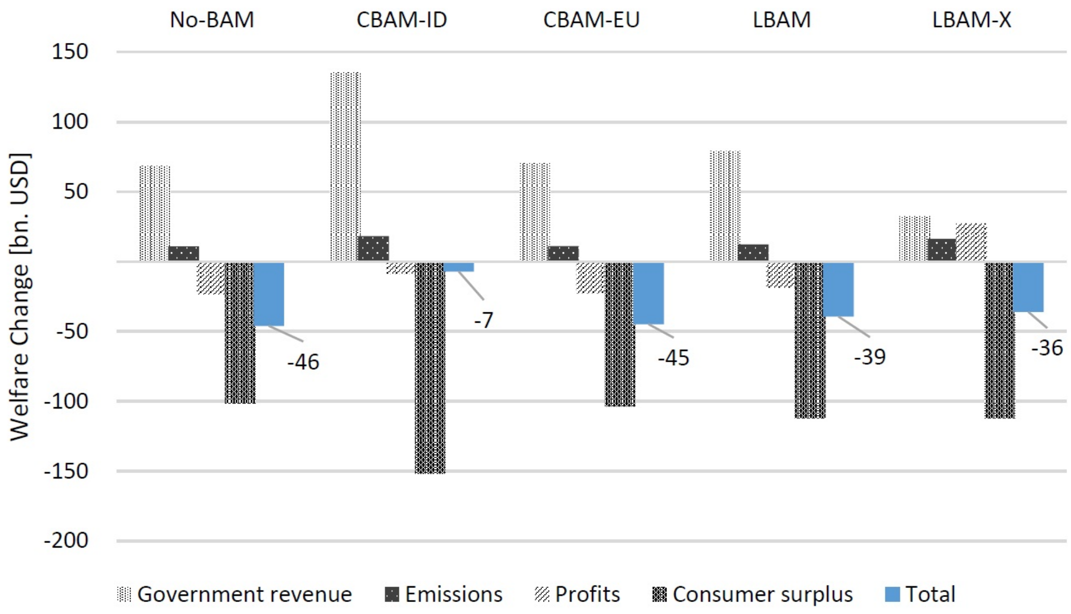
LBAM-X : In addition to import tariffs as in LBAM, the EU27 grants export subsidies that sterilize export-related leakage, as described in Section 4.1.3.

Tables 1 and 2 report the results of these simulations for the various outcomes of interest. There are five main lessons:

First, unilateral carbon pricing is always welfare detrimental to the EU. This is because losses in profits and consumer surplus are only partly compensated by gains in tax revenues and avoided social costs of carbon.

Second, the EU's current CBAM proposal performs worse than any other border adjustment we consider and only marginally improves on the scenario without border adjustment. This is because CBAM-EU hardly prevents emissions leakage while further reducing consumer surplus compared to no adjustment. CBAM's focus on a few, very energy-intensive sectors means that it exempts the bulk of imports in the many other sectors that, as our granular model reveals, can also be quite emission intensive.

Figure 3: Effects of Unilateral Carbon Price Increase On EU Welfare



Notes: The figure shows welfare changes (in 2018 US$) following a unilateral increase in the EU carbon price from $15 to $105 per ton, assuming a social marginal cost of emissions of $ 60 per ton. Welfare changes are computed in the absence of any border adjustment (No-BAM) and with one of four policies: CBAM-ID – Ideal carbon border adjustment across all sectors; CBAM-EU – Current CBAM implementation in the EU; LBAM – Leakage Border Adjustment Mechanism applied to imports only; LBAM-X – Leakage Border Adjustment Mechanism applied to imports and exports. All other taxes are held fixed.

Third, LBAM welfare-dominates CBAM-EU and is more effective at preventing carbon leakage. While applying LBAM tariffs across all sectors reduces consumer surplus, it also increases domestic profits and generates higher tariff revenues compared to CBAM-EU.

Fourth, not surprisingly, the CBAM-ID performs best in terms of welfare and global emissions reductions, but LBAM-X with import and export leakage adjustment comes quantitatively close.

Fifth, export subsidies turn out to be quantitatively important for increasing the effectiveness of EU Carbon taxes. This is so because they eliminate not just the direct export leakage, but also indirect export leakage via third countries.

Welfare We begin our discussion of results with an inspection of the welfare effects, depicted in Figure 3 (and also summarized in Panel A of Table 2). In line with the 'tragedy of the commons' increasing the carbon tax to $105 unilaterally is always welfare-detrimental for the EU. The reduction in welfare is largest in the absence of any border adjustment, $46 bn, as the associated reductions in consumer surplus and profits outweigh increases in government revenue and avoided social costs of carbon emissions. In contrast, the CBAM-ID scenario has, with a difference, the smallest welfare cost of $ 7.0 bn. This is because CBAM-ID generates both the largest emission reductions and the largest government revenues. At the same time, this policy also induces the largest reductions in consumer surplus due to large increases in consumer prices and small losses in producer surplus.

The EU's CBAM implementation, however, falls short of realizing those potential benefits because it covers just a handful of industries. The small welfare improvement of CBAM-EU over No-BAM of $1.2 bn is driven mostly by higher profits and somewhat lower emissions.

Both leakage border adjustment mechanisms offer substantial welfare improvements over CBAM-EU. When targeting import leakage only (LBAM), the total welfare loss of unilateral carbon pricing amounts to only $39.3 bn, a 15% improvement over No-BAM (vs. 3% with CBAM-EU). This is due to stronger emissions reductions, higher tax revenue, and smaller profit reductions. LBAM tariffs induce a somewhat larger decrease in consumer surplus as they are levied in all leakage-prone sectors, not just a handful of industries. When additionally eliminating export leakage with export subsidies (LBAM-X), the EU's welfare costs of unilateral climate action falls to $36 bn. This is a 22% improvement over No-BAM and puts this scenario second only to the ideal CBAM, although a considerable welfare gap remains. The main reason for this is that CBAM-ID transfers considerable rents from taxing relatively dirty production abroad, whereas LBAM does not. In spite of this difference, LBAM-X yields similar global emissions reductions as those achievable with an unconstrained implementation of CBAM, as we will see next.

Global Emissions Panel A of Table 1 summarizes the effects of unilateral carbon pricing on carbon emissions. In 2018, the EU accounted for about 8% of global emissions. Absent border adjustments (No-BAM), unilateral carbon pricing reduces EU manufacturing emissions by 29%, but global emissions only by 0.85%. If carbon leakage could be deterred with the ideal CBAM-ID, global emissions reductions could be 69% higher than that, but the actual CBAM-EU delivers a mere 3% improvement over No-BAM. CBAM-EU is not effective because, as our granular model with 131 sectors reveals, many energy-intensive varieties are not subject to any border adjustment in this regime. LBAM scenarios do considerably better in terms of reducing global emissions: Eliminating import leakage (LBAM) increases global emissions reductions by 15% compared to the No-BAM scenario. This percentage more than triples with additional elimination of export leakage (LBAM-X). LBAM-X thus closes three quarters of the gap to CBAM-ID, even though emissions abatement within the EU (24%) is lower than in any other scenario. Export subsidies are such an effective lever to increase the effectiveness of EU carbon taxation because they not only eliminate direct import leakage but also indirect export leakage via third-country-effects.

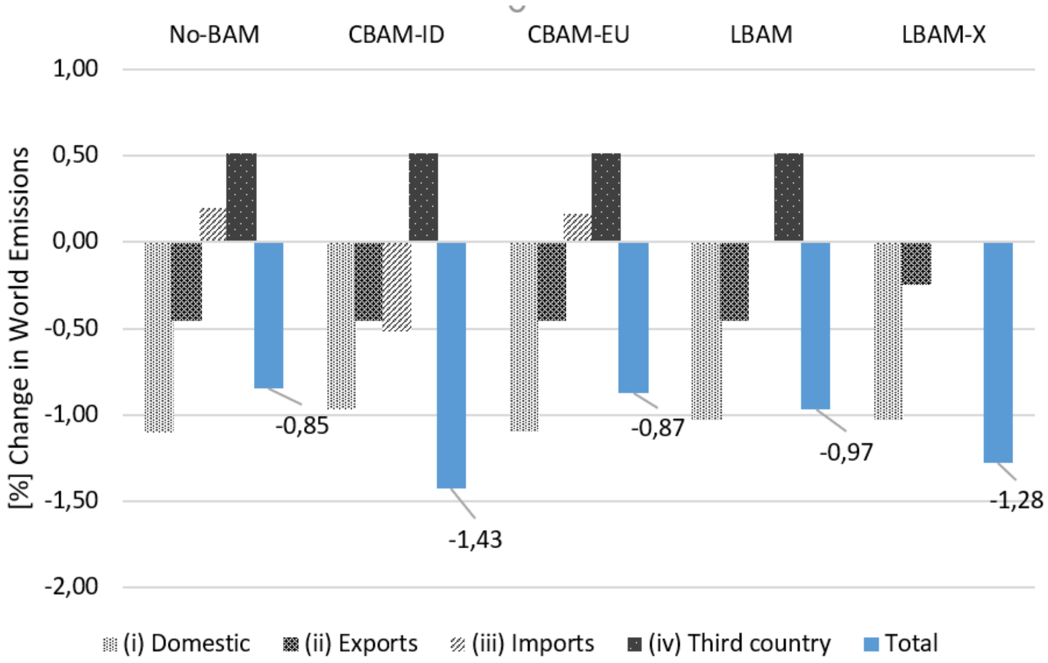
Figure 4 illustrates this by decomposing global emission changes in response to unilateral EU policies, as explained in Section 4.2 above. In the No-BAM scenario, large

Table 1: Policy-Induced Changes in EU and Global Emissions

	Δ Emissions (% of 2018 level) EU	Global	Additional Reduction in Global Emissions (% of Reference)
A. Unilateral Carbon Pricing in EU27			
No-BAM (Reference)	-29.0	-0.85	-
CBAM-ID	-26.7	-1.43	68.7
LBAM-X	-24.0	-1.28	51.0
LBAM	-27.8	-0.97	14.7
CBAM-EU	-28.9	-0.87	3.4
B. Small Climate Club: EU27, Canada, and UK			
CBAM-ID	-26.0	-1.83	116.1
LBAM-X	-24.2	-1.58	87.4
LBAM	-27.4	-1.23	45.1
CBAM-EU	-28.4	-1.06	25.2
No-BAM	-28.5	-1.03	21.5
C. Large climate club: EU27, Canada, UK, USA			
CBAM-ID	-24.4	-7.23	755.2
LBAM-X	-23.5	-6.71	694.1
LBAM	-25.6	-6.40	657.0
CBAM-EU	-27.9	-5.97	606.4
No-BAM	-28.1	-5.93	601.3

Notes: The table reports simulated changes in CO_2 emissions in the EU (column 1) and globally (column 2), relative to 2018, following an increase in the carbon price from \$15 to \$105 per ton. Column 3 reports the percentage improvement in global emissions abatement relative to the the case of Unilateral carbon pricing by the EU27 without border adjustments. In Panel A, this carbon price increase is implemented only in the EU27. In Panel B, the carbon price increase is implemented by a climate club formed by the EU27, UK and Canada. In Panel C, the climate club additionally comprises the United States. For each pricing coalition, we compute the welfare consequences in the absence of any border adjustment (No-BAM) and with one of four policies: CBAM-ID – Ideal carbon border adjustment across all sectors; CBAM-EU – Current CBAM implementation in the EU; LBAM – Leakage Border Adjustment Mechanism applied to imports only; LBAM-X – Leakage Border Adjustment Mechanism applied to imports and exports. All other taxes are held fixed. Countries outside the climate club do not change their carbon prices.

Figure 4: Effects of Unilateral Carbon-Price Increase on Global 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 are computed for five scenarios: No border adjustment (No-BAM), with carbon border adjustment on either all sectors (CBAM-ID) or on CBAM regulated industries only (CBAM-EU), with a Leakage Border Adjustment Mechanism applied to imports (LBAM) or to both imports and exports (LBAM-X). Emissions changes are due to changes in (i) EU production for the home market, (ii) EU production for the export market, (iii) foreign production for the EU market (import leakage), and (iv) foreign production for other foreign markets (third-country leakage).

reductions of emissions embodied in EU domestic sales are partially offset by import leakage. Worse, reductions in emissions embodied in EU exports are *more than offset* as those exports are being replaced by more carbon-intensive production in the rest of the world (third-country leakage). Under CBAM-ID, emissions embodied in EU imports fall strongly, but export leakage is not sterilized. CBAM-EU does not prevent export leakage either and only marginally reduces import leakage compared to No-BAM. In contrast, LBAM is designed to sterilize import leakage and LBAM-X additionally sterilizes third-country leakage. These leakage-preventing effects more than compensate for smaller reductions in emission embodied in EU domestic sales and/or EU exports in those scenarios.

To sum up our results thus far, policies that minimize local EU emissions generally do not minimize world emissions as a result of significant carbon leakage. LBAM not only helps to preserve EU manufacturing activity, it also substantially improves the global emission effects of EU policies. To complete our analysis of theses policy scenarios, we turn to their effects on trade flows, tariffs, and export subsidies next.

Imports and Tariffs Percent changes in EU bilateral imports associated with the different policies are summarized in Panel A of Appendix Table A.1. In the No-BAM scenario, bilateral imports increase by 10% on average, and by up to 305% in some sectors. Thus, unilateral carbon pricing shifts comparative advantage to dirty producers and induces substantial import leakage. In contrast to this, CBAM-ID actually *reduces* imports compared to no carbon pricing. The average import reduction is 8%, but imports from very carbon-intensive partners virtually go to zero in some sectors.[22] CBAM-EU gives rise to both these phenomena; average imports increase by almost 10%, but imports for some sector-country-pairs drop by up to one half. These results explain why there is widespread international opposition against CBAM; the policy decreases welfare of poorer countries by limiting access to EU markets. In contrast, LBAM holds bilateral imports constant at pre-policy levels, raising tariffs by just enough to eliminate import leakage.

The magnitudes of such tariff changes are reported in Panel B of Appendix Table A.1. Implementing CBAM-ID raises bilateral tariffs by 5.6% for the median sector and by 8.3% on average, yet it more than doubles tariff rates in some sectors. As CBAM-EU leaves imports in most sectors untaxed, the mean carbon tariff increase is just 0.3%, but it can be as high as 39.2% for some sectors. The tariff increases required to hold imports constant under the LBAM scenarios are smaller, with 0.6% in the median sector, 1.3% on average and a maxium of 8.6%. Given relatively high average trade elasticities, in most sectors modest tariff increases are sufficient to hold imports constant.

Exports and Export Subsidies Percent changes in exports and export subsidies under the various scenarios are reported in Panels C and D of Appendix Table A.1, respectively. In the absence of export subsidies, bilateral exports fall by almost 10% on average and up to 80% in the most impacted sector-country pairs. Thus, export leakage induced by the domestic carbon tax increase can be very large. However, given high trade elasticities, a 3.7% export subsidy in LBAM-X suffices to hold exports constant in the average sector and the maximum export subsidy required to hold exports constant is 10.5%.

5.2.2 Policies with a Climate Club

We now analyze policies adopted by a group of countries that coordinate on a common carbon tax. We consider two variants of such a climate club. The small club consists of the EU, Canada and the UK; the large club additionally contains the US.[23] In all simulations, countries outside the club keep their tax instruments unchanged, i.e., $\hat{\tau}_{Iji} = \hat{\tau}_{Xij} = \hat{\tau}_{Ej} = 1$ for $j < J_C$. The carbon tax adopted by the club members is assumed to increase by the

[22] Conversely, the coherent taxation of embedded emissions leads to increased EU imports of cleaner goods in a small number of country-sector pairs.

[23] This would require the US to levy an explicit carbon tax or the recognition of alternative US climate policies as equivalent to the club's carbon price. Currently, the implied average US carbon price in the CBAM industries is estimated at less than \$1 per ton (Clausing & Wolfram, 2023).

same amount as above, from \$15 to \$105 per ton of carbon. We maintain the same labels for the policies, but they now refer to border adjustments adopted by the club.

A Climate Club with the UK and Canada Panel B of Table 2 reports the welfare effects of the various policies for the small climate club. The total reduction in EU welfare is smaller than when raising the carbon price unilaterally (Panel A), but the ranking of policies does not change. With no border adjustment, EU welfare falls by \$43.3 bn compared to only \$3.5 bn with an ideal CBAM. Again, CBAM-EU improves welfare by just \$1.2 bn compared to No-BAM. The LBAM scenarios lead to significantly smaller welfare reductions of \$36.4 bn with import tariffs and \$32.6 bn with additional export subsidies.

Not surprisingly, coordinating carbon taxes within the small club is also good for the planet. As reported in Panel B of Table 1, the small climate club abates 22% more emissions globally, relative to the reference scenario of EU unilateral policies without border adjustments. By also coordinating their border adjustments mechanisms, the additional abatement achieved by the club can be as high as 116% (with CBAM-ID) or as low as 25% (with CBAM-EU). Incremental emissions reductions brought about by LBAM are 45% when targeting imports only. This figure almost doubles to 87.4% under LBAM-X, thus closing three quarters of the gap to global abatement under CBAM-ID.[24]

A Climate Club with the US, Canada, and the UK US accession to the climate club is a game changer in terms of both emissions and welfare (Panels C of Tables 1 and 2, respectively). Given its share of 17% in world emissions, the introduction of a carbon tax in the US leads to global emissions reductions between 5.93% without any border adjustments and 7.23% with the ideal CBAM-ID. Put differently, emissions abatement by the large climate club exceeds EU unilateral efforts by a factor of 7 to 8.5. As a result, EU welfare from carbon pricing now increases across all scenarios, by at least \$19 bn (No-BAM) and up to \$61 bn (CBAM-ID). LBAM yields intermediate welfare gains between \$31 and \$33 bn. These welfare differences across policies are economically significant, and they give rise to the same ranking as in the previous cases. When it comes to global emissions, however, the relative differences between the various adjustments become smaller in the large climate club. As a larger share of world emissions is subject to carbon pricing, the scope for carbon leakage declines. Notwithstanding this effect, the design of the border adjustment mechanism continues to matter even with a larger club due to its effect on the welfare of third countries that ponder accession to the climate club (Nordhaus, 2015; Barrett, 1997). The larger the club, the stronger the incentives for countries to join because non-members face tariffs on their exports to members and export subsidies of members in their home markets.

[24]Figure A.1 in the Appendix plots a decomposition of emission changes.

Table 2: Policy Induced Changes in EU Welfare

	Government Revenue	Consumer Surplus	Profits	Emissions	Total
A. Unilateral Carbon Pricing in EU27					
No-BAM	68.6	-101.7	-23.6	10.7	-46.0
CBAM-ID	135.5	-151.8	-8.8	18.1	-7.0
CBAM-EU	70.4	-103.6	-22.7	11.1	-44.8
LBAM	79.2	-112.1	-18.7	12.3	-39.3
LBAM-X	32.6	-112.1	27.3	16.2	-36.0
B. Small Climate Club: EU27, Canada, and UK					
No-BAM	69.5	-105.4	-20.5	13.0	-43.3
CBAM-ID	129.7	-151.1	-5.4	23.2	-3.5
CBAM-EU	71.1	-107.1	-19.6	13.5	-42.1
LBAM	78.8	-114.6	-16.2	15.6	-36.4
LBAM-X	39.3	-114.6	22.6	20.1	-32.6
C. Large Climate Club: EU27, Canada, UK, USA					
No-BAM	70.5	-114.1	-11.3	74.1	19.3
CBAM-ID	117.1	-149.1	3.2	90.3	61.6
CBAM-EU	72.1	-115.7	-10.4	74.6	20.5
LBAM	80.5	-123.2	-6.4	80.0	30.9
LBAM-X	54.0	-123.2	18.6	83.9	33.3

Notes: The table reports simulated changes in money metric welfare, expressed in 2018 US$, following an increase in the carbon price from $15 to $105 per ton. In Panel A, this carbon price increase is implemented only in the EU27. In Panel B, the carbon price increase is implemented by a climate club formed by the EU27, UK and Canada. In Panel C, the climate club additionally comprises the United States. For each pricing coalition, we compute the welfare consequences in the absence of any border adjustment (No-BAM) and with one of four policies: CBAM-ID – Ideal carbon border adjustment across all sectors; CBAM-EU – Current CBAM implementation in the EU; LBAM – Leakage Border Adjustment Mechanism applied to imports only; LBAM-X – Leakage Border Adjustment Mechanism applied to imports and exports. All other taxes are held fixed. Countries outside the climate club do not change their carbon prices.

6 Conclusion

In this paper we have proposed a new leakage border adjustment mechanism (LBAM) with minimal information requirements. The traditional border carbon adjustment, of which the EU's carbon border adjustment mechanism (CBAM) is a prominent example, requires information on the carbon content of imports, which is very hard to obtain. This limits the practical application of CBAM to a small number of products. In contrast, LBAM just requires estimates of the elasticities of import demand and export supply and the domestic output elasticity with respect to carbon emissions. As a consequence, it can be easily applied to all tradable sectors without creating an excessive administrative burden.

The main idea behind LBAM is to set import tariffs and, potentially, export subsidies, that hold imports and exports constant at the levels before the domestic carbon-price change. We have shown, using a detailed quantitative trade model with 57 countries and 131 sectors, that a broad implementation of border adjustment is key to effectively avoid leakage: As the EU's CBAM applies to only a few carbon-intensive sectors, it hardly improves welfare and emissions compared to a situation without border adjustment. This is so, because the vast majority of sectors, many of which are carbon-intensive, are not covered by the EU's CBAM. Moreover, because our model abstracts from implementation and screening costs associate with CBAM, it still over-states the emission and welfare effects of CBAM. Because LBAM targets all leakage-prone industries, it increases the effectiveness of unilateral carbon pricing at reducing global emissions by up to 50%. This is accomplished by a tariff designed to exactly offset any displacement of domestic production by foreign imports due to carbon pricing. We have shown that export border adjustment via subsidies that hold exports constant is particularly effective in avoiding carbon leakage that arises from consumers in third countries substituting from goods produced in the EU to goods from other origin countries where production is more carbon intensive.

Finally, we have argued that, in contrast to carbon border adjustment, LBAM is likely compatible with WTO rules. LBAM does not discriminate between trade partners and it does not make them worse off. It merely holds imports and exports constant at the levels before the unilateral introduction of carbon pricing, thereby sterilizing market-access effects (larger imports, less exports) that would otherwise occur.

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Appendices

A Additional Tables and Figures

Table A.1: Trade Effects of Unilateral EU policies

	Mean	**Median**	**SD**	**Min**	**Max**
A. Percent Change in EU Bilateral Imports					
No-BAM	10.6	0.4	34.8	0	305.0
CBAM-ID	-8.3	-2.7	20.9	-100	481.8
CBAM-EU	10.3	0.0	34.9	-51.1	305.0
LBAM	0.0	0.0	0.0	0.0	0.0
LBAM-X	0.0	0.0	0.0	0.0	0.0
B. Percent Change in EU Tariffs					
No-BAM	0.0	0.0	0.0	0.0	0.0
CBAM-ID	8.3	5.7	8.8	0.0	105.6
CBAM-EU	0.3	0.0	1.7	0.0	39.2
LBAM	1.3	0.6	1.8	0.0	8.6
LBAM-X	1.3	0.6	1.8	0.0	8.6
C. Percent Change in EU Bilateral Exports					
No-BAM	-9.4	-2.9	15.4	-79.5	0
CBAM-ID	-9.4	-2.9	15.4	-79.5	0
CBAM-EU	-9.4	-2.9	15.4	-79.5	0
LBAM	-9.4	-2.9	15.4	-79.5	0
LBAM-X	0.0	0.0	0.0	0.0	0.0
D. Percent Change in EU Export Subsidies					
No-BAM	0.0	0.0	0.0	0.0	0.0
CBAM-ID	0.0	0.0	0.0	0.0	0.0
CBAM-EU	0.0	0.0	0.0	0.0	0.0
LBAM	0.0	0.0	0.0	0.0	0.0
LBAM-X	-3.7	-3.0	2.6	-10.5	-0.2

Notes: The table reports simulated gross changes in EU bilateral imports, exports, import tariffs and export subsidies following a unilateral increase in the EU carbon price from \$15 to \$105 per ton. We compute changes in the absence of any border adjustment (No-BAM) and with one of four policies: CBAM-ID – Ideal carbon border adjustment across all sectors; CBAM-EU – Current CBAM implementation in the EU; LBAM – Leakage Border Adjustment Mechanism applied to imports only; LBAM-X – Leakage Border Adjustment Mechanism applied to imports and exports. All other taxes are held fixed.

Figure A.1: Effects of Carbon-Price Increase by a Small climate club (EU, CAN, UK) on Global Emissions

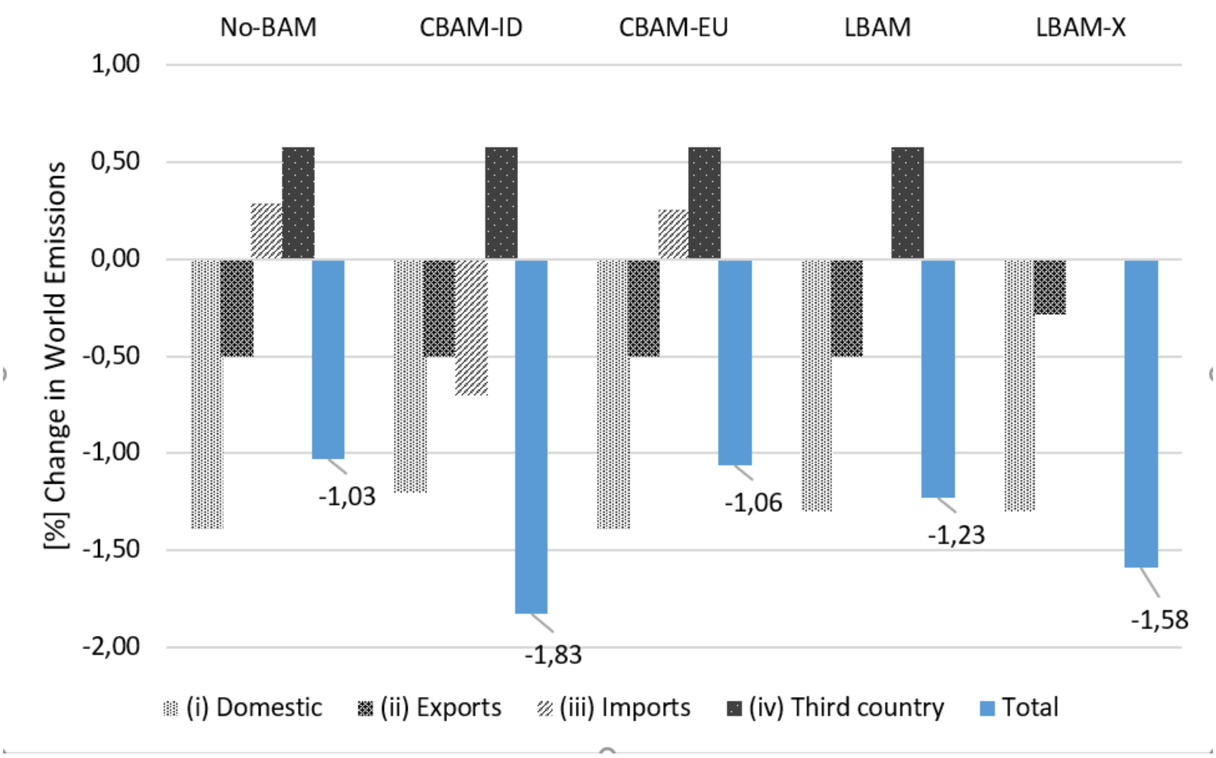
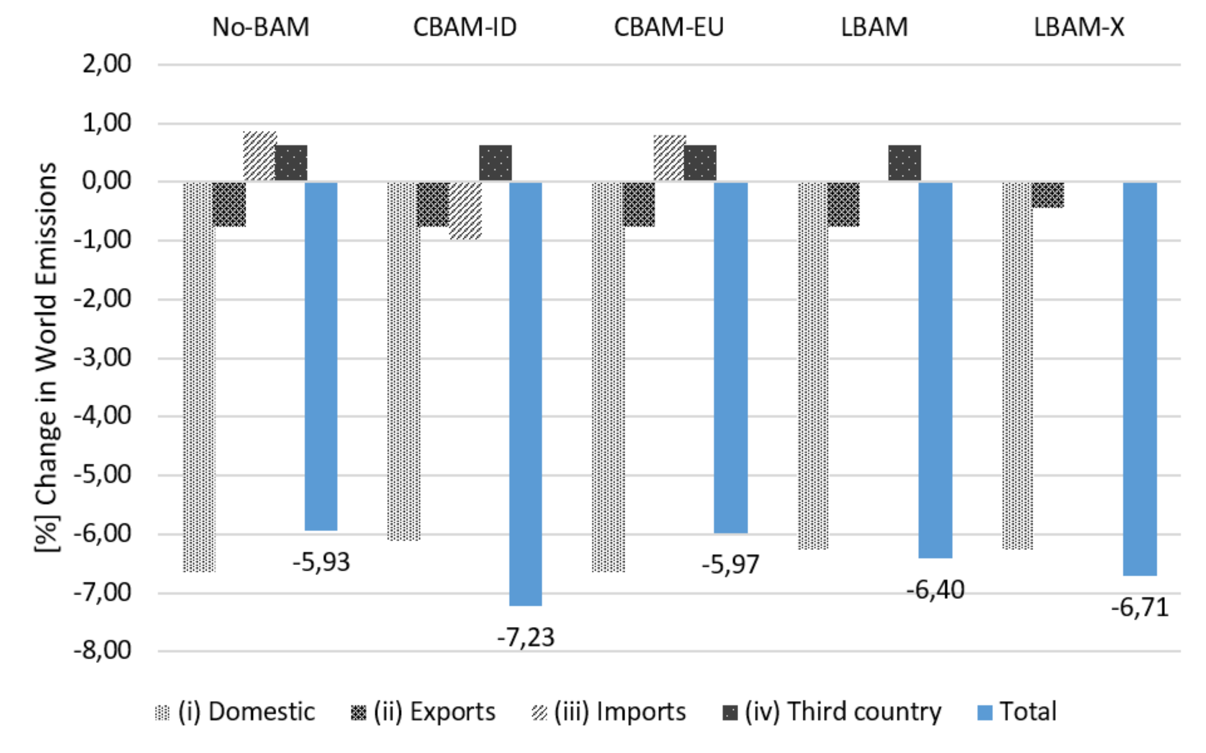


Figure A.2: Effects of Carbon-Price Increase by a Large climate club (EU, CAN, UK, US) on Global Emissions



B Equilibrium

Using conditions (2), (3) and (4), we obtain the following market clearing conditions:

$$y_{ijs} = \tau_{ijs} c_{ijs} = \tau_{ijs} p_{ijs}^{-\varepsilon_s} P_{is}^{\varepsilon_s - 1} \eta_{is} \tag{28}$$

which hold for all i, j and s and where P_{is} is the ideal price index in sector s, which – according to (6) – can be written as:

$$P_{is}^{1-\varepsilon_s} = \sum_{j=1}^{J} N_{ijs} p_{ijs}^{1-\varepsilon_s} \tag{29}$$

Substituting condition (9) into condition (28) we obtain condition (10). Next, condition (10) can be substituted again into condition (9) to get (11). Finally, substituting condition (11) into the sectoral price index (29), we obtain condition (12).

It is useful to also define total imports:

$$C_{iIs}^{\frac{\varepsilon_s - 1}{\varepsilon_s}} \equiv \sum_{j \neq i} C_{ijs}^{\frac{\varepsilon_s - 1}{\varepsilon_s}} \tag{30}$$

B.1 Equilibrium in changes

From condition (28) we get:

$$\hat{c}_{ijs} = \hat{p}_{Zj}^{-\beta_s \frac{(\gamma_s + 1)\varepsilon_s}{\gamma_s \varepsilon_s + 1}} \left(\hat{\tau}_{Iijs} \hat{\tau}_{Xijs} \right)^{\frac{-\varepsilon_s}{\gamma_s \varepsilon_s + 1}} \hat{P}_{is}^{\frac{\varepsilon_s - 1}{\gamma_s \varepsilon_s + 1}} \tag{31}$$

Since $C_{ijs} = N_{ijs}^{\frac{\varepsilon_s}{\varepsilon_s - 1}} c_{ijs}$, we obtain:

$$\hat{C}_{ijs} = \hat{p}_{Zj}^{-\beta_s \frac{(\gamma_s + 1)\varepsilon_s}{\gamma_s \varepsilon_s + 1}} \left(\hat{\tau}_{Iijs} \hat{\tau}_{Xijs} \right)^{\frac{-\varepsilon_s}{\gamma_s \varepsilon_s + 1}} \hat{P}_{is}^{\frac{\varepsilon_s - 1}{\gamma_s \varepsilon_s + 1}} \tag{32}$$

Condition

$$P_{is}^{1-\varepsilon_s} = \sum_{j=1}^{J} P_{ijs}^{1-\varepsilon_s} \tag{33}$$

in changes becomes:

$$\hat{P}_{is}^{1-\varepsilon_s} = \sum_{j=1}^{J} \left(\frac{P'_{ijs}}{P_{ijs}} \frac{P_{ijs}}{P_{is}} \right)^{1-\varepsilon_s} \tag{34}$$

This can also be written as:

$$\hat{P}_{is}^{1-\varepsilon_s} = \sum_{j=1}^{J} \hat{p}_{ijs}^{1-\varepsilon_s} \left(\frac{P_{ijs}}{P_{is}} \right)^{1-\varepsilon_s} \tag{35}$$

Note that from (5) $P_{ijs} C_{ijs} = P_{ijs}^{1-\varepsilon_s} P_{is}^{\varepsilon_s - 1} \eta_{is}$ and $P_{is} C_{is} = \eta_{is}$. Therefore we get:

$$\hat{P}_{is}^{1-\varepsilon_s} = \sum_{j=1}^{J} \delta_{ijs} \hat{p}_{ijs}^{1-\varepsilon_s} \tag{36}$$

This equation states that changes in the ideal sector-s consumer price index are given by a weighted average of the changes in the individual consumer prices where the weights are the corresponding expenditure shares. Substituting condition (14) into condition (36), we get:

$$\hat{P}_{is}^{1-\varepsilon_s} = \sum_{j=1}^{J} \delta_{ijs} \left[\hat{p}_{Zj}^{\beta_s \frac{\gamma_s+1}{\gamma_s\varepsilon_s+1}} (\hat{\tau}_{Iijs}\hat{\tau}_{Xijs})^{\frac{1}{\gamma_s\varepsilon_s+1}} \hat{P}_{is}^{\frac{\gamma_s(\varepsilon_s-1)}{\gamma_s\varepsilon_s+1}} \right]^{(1-\varepsilon_s)} \tag{37}$$

This leads to (15). Finally, we need to compute changes in aggregate imports as this will be needed to for some policy scenarios. From (30) it follows that:

$$\hat{C}_{iIs}^{\frac{\varepsilon_s-1}{\varepsilon_s}} = \sum_{j\neq i} \delta_{ijs}^{I} \hat{c}_{ijs}^{\frac{\varepsilon_s-1}{\varepsilon_s}} = \sum_{j\neq i} \delta_{ijs}^{I} \left[\hat{p}_{Zj}^{-\beta_s \frac{(\gamma_s+1)\varepsilon_s}{\gamma_s\varepsilon_s+1}} (\hat{\tau}_{Iijs}\hat{\tau}_{Xijs})^{\frac{-\varepsilon_s}{\gamma_s\varepsilon_s+1}} \hat{P}_{is}^{\frac{\varepsilon_s-1}{\gamma_s\varepsilon_s+1}} \right]^{\frac{\varepsilon_s-1}{\varepsilon_s}} \tag{38}$$

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, $P_{iIs}C_{iIs} = \sum_{i\neq j} P_{ijs}C_{ijs}$, and where the last equality follow from (31).

C Welfare

A shown in section 3.3, aggregate sector-s profits in country i are given by:

$$\Pi_{is} = \sum_{j=1}^{J} \Pi_{jis} \tag{39}$$

where

$$\Pi_{jis} = N_{jis}(\tau_{Ijis}^{-1}\tau_{Xjis}^{-1} p_{jis}c_{jis} - TC_{jis}) = N_{jis}[\mu_s - (1+\gamma_s)^{-1}] \left(\frac{y_{jis}}{\phi_{ijs}}\right)^{\gamma_s+1} p_{Zi}^{\beta_s(\gamma_s+1)}$$

Profits in changes are defined as:

$$\hat{\Pi}_{jis} = \hat{y}_{jis}^{\gamma_s+1} \hat{p}_{Zi}^{\beta_s(\gamma_s+1)} \tag{40}$$

Moreover:

$$\hat{\Pi}_{is} = \frac{\Pi'_{is}}{\Pi_{is}} = \frac{\sum_{j=1}^{J} \Pi'_{jis}}{\sum_{j=1}^{J} \Pi_{jis}} = \sum_{j=1}^{J} \hat{\Pi}_{jis} \frac{\Pi_{jis}}{\sum_{j=1}^{J} \Pi_{jis}} \tag{41}$$

Note that $\Pi_{jis} = N_{jis}\tau_{Ijis}^{-1}\tau_{Xjis}^{-1} p_{jis}c_{jis}[1-\mu_s^{-1}(1+\gamma_s)^{-1}] = \tau_{Ijis}^{-1}\tau_{Xjis}^{-1} P_{jis}C_{jis}\ [1-\mu_s^{-1}(1+\gamma_s)^{-1}]$. Then, the profit shares are equal to:

$$\frac{\Pi_{jis}}{\sum_{j=1}^{J} \Pi_{jis}} = \sigma_{jis} \equiv \frac{\tau_{Ijis}^{-1}\tau_{Xjis}^{-1}\eta_{js}\delta_{jis}}{\sum_{j=1}^{J} \tau_{Ijis}^{-1}\tau_{Xjis}^{-1}\eta_{js}\delta_{jis}} \tag{42}$$

where σ_{ijs} are the *sales shares* in each market, measured before trade taxes are applied. Hence we can write the expression for profits in changes and in levels (derived in section 3.5) in terms of observables.

Tax income in country i can be recovered as follows:

$$\int_s (\hat{T}_{is}-1)T_{is}ds = \int_s (\hat{T}_{Eis}-1)T_{Eis}ds + \int_s (\hat{T}_{Iis}-1)T_{Iis}ds + \int_s (\hat{T}_{Xis}-1)T_{Xis}ds \quad (43)$$

where T_{Eis}, T_{Iis} and T_{Xis} are the sector s tax revenues from the carbon tax, import tariffs and export taxes, respectively:

$$\begin{aligned} T_{Eis} &\equiv \tau_{Ei}\sum_{j=1}^{J} N_{jis}e_{jis} \\ T_{Iis} &\equiv \sum_{j\neq i}^{J}(\tau_{Iijs}-1)N_{ijs}\tau_{Iijs}^{-1}p_{ijs}c_{ijs} \\ T_{Xis} &\equiv \sum_{j\neq i}^{J}(\tau_{Xjis}-1)N_{jis}\tau_{Ijis}^{-1}\tau_{Xjis}^{-1}p_{ji}c_{jis} \end{aligned} \quad (44)$$

Define $\tilde{\tau}_{Iijs} \equiv \tau_{Iijs}-1$ and $\tilde{\tau}_{Xijs} \equiv \tau_{Xijs}-1$ and recall that if $Y \equiv \sum_{j=1}^{J} y_j$ then $\hat{Y} \equiv \frac{\sum_{j=1}^{J} y_j'}{\sum_{j=1}^{J} y_j} = \sum_{j=1}^{J}\hat{y}_j \frac{y_j}{\sum_{j=1}^{J} y_j}$. As a result:

$$\begin{aligned} \hat{T}_{Eis} &= \sum_{j=1}^{J}\hat{\tau}_{Ei}\hat{e}_{jis}\frac{N_{jis}e_{jis}}{\sum_{j=1}^{J}N_{jis}e_{jis}} \\ \hat{T}_{Iis} &= \sum_{j\neq i}^{J}\hat{\tilde{\tau}}_{Iijs}\hat{\tau}_{Iijs}^{-1}\hat{p}_{ijs}\hat{c}_{ijs}\frac{\tilde{\tau}_{Iijs}\tau_{Iijs}^{-1}N_{ijs}p_{ijs}c_{ijs}}{\sum_{j\neq i}^{J}\tilde{\tau}_{Iijs}\tau_{Iijs}^{-1}N_{ijs}p_{ijs}c_{ijs}} \\ \hat{T}_{Xis} &= \sum_{j\neq i}^{J}\hat{\tilde{\tau}}_{Xjis}\hat{\tau}_{Ijis}^{-1}\hat{\tau}_{Xjis}^{-1}\hat{p}_{jis}\hat{c}_{jis}\frac{\tilde{\tau}_{Xjis}\tau_{Ijis}^{-1}\tau_{Xjis}^{-1}N_{jis}p_{jis}c_{jis}}{\sum_{j\neq i}^{J}\tilde{\tau}_{Xjis}\tau_{Ijis}^{-1}\tau_{Xjis}^{-1}N_{jis}p_{jis}c_{jis}} \end{aligned} \quad (45)$$

Moreover define $t_{Iijs} \equiv \frac{\tilde{\tau}_{Iijs}\tau_{Iijs}^{-1}\delta_{ijs}}{\sum_{j\neq i}^{J}\tilde{\tau}_{Iijs}\tau_{Iijs}^{-1}\delta_{ijs}}$ and $t_{Xjis} \equiv \frac{\tilde{\tau}_{Xjis}\tau_{Ijis}^{-1}\tau_{Xjis}^{-1}\eta_{js}\delta_{ijs}}{\sum_{j\neq i}^{J}\tilde{\tau}_{Xjis}\eta_{js}\tau_{Ijis}^{-1}\tau_{Xjis}^{-1}\delta_{ijs}}$, which are the tax revenue shares of each import/export market in total import/export tax revenue. Then, by condition (8) we have:

$$e_{jis} = d_i z_{jis} = d_i\beta_s\left(\frac{y_{jis}}{\phi_{jis}}\right)^{1+\gamma_s} p_{zi}^{[\beta_s(1+\gamma_s)-1]}$$

and by condition (9) we have:

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

Combining these conditions we get:

$$e_{jis} = \beta_s d_i p_{Zi}^{-1}\tau_{Ijis}^{-1}\tau_{Xjis}^{-1}\mu_s^{-1}p_{jis}c_{jis} = \beta_s d_i p_{Zi}^{-1}\tau_{Ijis}^{-1}\tau_{Xjis}^{-1}\mu_s^{-1}\eta_{js}\delta_{jis}$$

Combining this with (44) and (45) we obtain the expression found in section 3.5, namely:

$$\hat{T}_{Eis} = \hat{\tau}_{Ei}\hat{p}_{Zi}^{\beta_s(1+\gamma_s)-1}\sum_{j=1}^{J}\sigma_{jis}\hat{y}_{jis}^{(1+\gamma_s)} \qquad T_{Eis} = \beta_s\mu_s^{-1}d_i\tau_{Eis}p_{Zi}^{-1}\sum_{j=1}^{J}\tau_{Ijis}^{-1}\tau_{Xjis}^{-1}\eta_{js}\delta_{jis}$$

$$\hat{T}_{Iis} = \sum_{j\neq i}^{J}\hat{p}_{Zj}^{\beta_s(1+\gamma_s)}t_{Iijs}\hat{\tilde{\tau}}_{Iijs}\hat{\tau}_{Xijs}\hat{y}_{ijs}^{(1+\gamma_s)} \qquad T_{Iis} = \eta_{is}\sum_{j\neq i}^{J}\tilde{\tau}_{Iijs}\tau_{Iijs}^{-1}\delta_{ijs}$$

$$\hat{T}_{Xis} = \hat{p}_{Zi}^{\beta_s(1+\gamma_s)}\sum_{j\neq i}^{J}t_{Xjis}\hat{\tilde{\tau}}_{Xjis}\hat{y}_{jis}^{(1+\gamma_s)} \qquad T_{Xis} = \sum_{j\neq i}^{J}\eta_{js}\tilde{\tau}_{Xjis}\tau_{Iji}^{-1}\tau_{Xji}^{-1}\delta_{jis}.$$

C.1 Computation of welfare changes

The computation of welfare changes induced by different policy experiments requires handling zero initial tax revenues for at least some ijs combinations (actually all of them in case of export taxes). Dealing with that issue is actually quite simple since it suffices to rewrite the expression for the welfare changes induced by changes in tax revenues (43) as follows:

$$\int_s(\hat{T}_{is}-1)T_{is}ds = \int_s(\hat{T}_{Eis}-1)T_{Eis}ds + \int_s(T_{Iis}^{'}-T_{Iis})ds + \int_s(T_{Xis}^{'}-T_{Xis})ds$$

where

$$T_{Iis}^{'} = \eta_{is}\sum_{j\neq i}^{J}\frac{\tau_{Iijs}^{'}-1}{\tau_{Iijs}^{'}}\delta_{ijs}^{'}$$

$$T_{Xis}^{'} = \sum_{j\neq i}^{J}\eta_{js}\frac{\tau_{Xjis}^{'}-1}{\tau_{Ijis}^{'}\tau_{Xjis}^{'}}\delta_{jis}^{'}$$

and

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

D Leakage Border Adjustment Mechanism (LBAM) - Simple rules

D.1 A Unilateral Carbon Tax without Border Adjustments

We first consider a scenario, where only country i introduces a carbon tax and there is no border adjustment mechanism. In this case only $\hat{\tau}_{Ei} > 1$ and $\hat{\tau}_{Iijs} = \hat{\tau}_{Ej} = 1$ for all $j \neq i$.

We compute the changes in equilibrium variables and the components of welfare changes induced by this policy.

By conditions (13) and (15):

$$\hat{y}_{iis} = \hat{p}_{Zi}^{\frac{-\beta_s\ (\gamma_s+1)\varepsilon_s}{1+\varepsilon_s\gamma_s}}\hat{P}_{is}^{\frac{\varepsilon_s-1}{1+\varepsilon_s\gamma_s}} \tag{46}$$

$$\hat{y}_{ijs} = \hat{P}_{is}^{\frac{\varepsilon_s-1}{1+\varepsilon_s\gamma_s}} \tag{47}$$

and

$$\hat{P}_{is}^{\frac{(1+\gamma_s)(1-\varepsilon_s)}{1+\varepsilon_s\gamma_s}} = \delta_{iis}\hat{p}_{Zi}^{\frac{\beta_s(1+\gamma_s)(1-\varepsilon_s)}{1+\varepsilon_s\gamma_s}} + \sum_{j\neq i}^{J}\delta_{ijs} \tag{48}$$

which – since $\sum_{j\neq i}^{J}\delta_{ijs} = 1-\delta_{iis}$ – can be rewritten as

$$\hat{P}_{is}^{\frac{(1+\gamma_s)(1-\varepsilon_s)}{1+\varepsilon_s\gamma_s}} = \delta_{iis}\hat{p}_{Zi}^{\frac{\beta_s(1+\gamma_s)(1-\varepsilon_s)}{1+\varepsilon_s\gamma_s}} + 1-\delta_{iis} \tag{49}$$

As a consequence, if country i does not sterilize leakage and increases the carbon emissions tax by $\hat{\tau}_{Ei}$, imports from country j rise as follows:

$$\hat{y}_{ijs} = \left[\delta_{iis}\hat{p}_{Zi}^{\frac{\beta_s(1+\gamma_s)(1-\varepsilon_s)}{1+\varepsilon_s\gamma_s}} + 1-\delta_{iis}\right]^{\frac{-1}{1+\gamma_s}} > 1 \tag{50}$$

where the last condition can be obtained by combing (20) and (49). (50) is unequivocally larger than unity (as can be seen from (20)) , since $\epsilon_s > 1$: a domestic carbon tax increases the price of domestic relative to foreign varieties: when holding output constant, a 1-percent increase in the energy price increases domestic producer prices by $\beta_s(\gamma_s+1)$ percent and this leads consumers to substitute their demand towards foreign varieties. In the presence of decreasing returns ($\gamma_s > 0$), the resulting reduction in domestic production reduces domestic marginal costs, while the increase in foreign production which is required to satisfy higher domestic demand for foreign varieties, increases foreign marginal cost with an elasticity γ_s, thus cushioning the effect somewhat.

At the same time the change in the carbon tax changes the production of the domestically produced and consumed varieties in sector s as follows:

$$\hat{y}_{iis} = \hat{p}_{Zi}^{\frac{-\beta_s\ (\gamma_s+1)\varepsilon_s}{1+\varepsilon_s\gamma_s}} \left[\delta_{iis}\hat{p}_{Zi}^{\frac{\beta_s(1+\gamma_s)(1-\varepsilon_s)}{1+\varepsilon_s\gamma_s}} + 1-\delta_{iis}\right]^{\frac{-1}{1+\gamma_s}} \tag{51}$$

This expression is smaller than unity as long as the impact of the carbon tax on the price of domestically produced varieties is stronger than on the aggregate price index.

Finally, the domestic carbon tax also has an effect on exports because domestic producers now face higher costs in foreign markets and foreign consumers will substitute away from domestically produced varieties. The export conditions (13) and (15) imply:

$$\hat{y}_{jis} = \hat{p}_{Zi}^{\frac{-\beta_s\ (\gamma_s+1)\varepsilon_s}{1+\varepsilon_s\gamma_s}} \hat{P}_{js}^{\frac{\varepsilon_s-1}{1+\varepsilon_s\gamma_s}} \tag{52}$$

where:

$$\hat{P}_{js}^{\frac{(1+\gamma_s)(1-\varepsilon_s)}{1+\varepsilon_s\gamma_s}} = \delta_{jis}\hat{p}_{Zi}^{\frac{\beta_s(1+\gamma_s)(1-\varepsilon_s)}{1+\varepsilon_s\gamma_s}} + 1-\delta_{jis} \tag{53}$$

Hence, we obtain:

$$\hat{y}_{jis} = \hat{p}_{Zi}^{\frac{-\beta_s\ (\gamma_s+1)\varepsilon_s}{1+\varepsilon_s\gamma_s}} \left[\delta_{jis}\hat{p}_{Zi}^{\frac{\beta_s(1+\gamma_s)(1-\varepsilon_s)}{1+\varepsilon_s\gamma_s}} + 1-\delta_{jis}\right]^{\frac{-1}{1+\gamma_s}} \tag{54}$$

as in the main text. Thus, exports will fall ($\hat{y}_{jis} < 1$) as long as the impact of the domestic carbon tax on the prices of domestic exporters is stronger than its impact on the foreign price index.

The welfare effects of this policy can be computed as follows. First, we consider the effects on consumption in the differentiated sector $\hat{C}_{is}$. Plugging in conditions (53) into condition $\hat{C}_{is} = \hat{P}_{is}^{-1}$ (recovered in section 3.1) we get

$$\hat{C}_{is} = \left[\delta_{iis}\hat{p}_{Zi}^{\frac{\beta_s(\gamma_s+1)(1-\varepsilon_s)}{\gamma_s\varepsilon_s+1}} + 1 - \delta_{iis}\right]^{\frac{\varepsilon_s\gamma_s+1}{(\varepsilon_s-1)(1+\gamma_s)}} \tag{55}$$

which says that the aggregate sectoral consumption index falls in response to the introduction of a carbon tax.

D.2 A Unilateral Carbon Tax with Unilateral Import Border Adjustment

Given condition (13), we obtain:

$$\hat{y}_{ijs} = \hat{\tau}_{Iijs}^{\frac{-\varepsilon_s}{\gamma_s\varepsilon_s+1}} \hat{P}_{is}^{\frac{\varepsilon_s-1}{\gamma_s\varepsilon_s+1}} = 1 \Rightarrow \hat{\tau}_{Iijs}^{\frac{-\varepsilon_s(1+\gamma_s)}{\varepsilon_s\gamma_s+1}} = \hat{P}_{is}^{\frac{(1+\gamma_s)(1-\varepsilon_s)}{\varepsilon_s\gamma_s+1}} \tag{56}$$

Hence, this implies that $\hat{\tau}_{Iijs} = \hat{\tau}_{Iis}$ for all j, i.e. tariffs are independent of the partner country.

Moreover, using condition (15) we get:

$$\hat{\tau}_{Iis}^{\frac{-\varepsilon_s(1+\gamma_s)}{\gamma_s\varepsilon_s+1}} = \delta_{iis}\hat{p}_{Zi}^{\beta_s\frac{(\gamma_s+1)(1-\varepsilon_s)}{\gamma_s\varepsilon_s+1}} + \sum_{j\neq i}^{J} \delta_{ijs}\hat{\tau}_{Iis}^{\frac{1-\varepsilon_s}{\gamma_s\varepsilon_s+1}}$$

Since $\sum_{j\neq i}^{J} \delta_{ijs} = 1 - \delta_{ii}$ this can be rewritten as (21).

Given $\hat{\tau}_{Ei}$ (and thus $\hat{p}_{Zi}$), this is one implicit equation in $\hat{\tau}_{Iis}$. In order to stabilize bilateral imports, the domestic tariff should stabilize the effects on the demand of imported varieties and the related prices. Without a tariff, bilateral imports would increase in response to the domestic carbon tax, as consumers substitute away from domestic varieties, which become more expensive. A tariff is required to offset this effect. The tariff that stabilizes bilateral imports is a weighted average of two effects where the weights are the expenditure shares on domestic versus imported varieties: first, the effect of the carbon tax on the price of domestically produced goods and second, the effect of the tariff on the price of imported varieties from other countries.

We now look at the impact of the carbon tax on the domestic production of varieties for the domestic market. Notice that combining conditions (19) and (56) we obtain the following condition

$$\hat{y}_{iis} = \hat{p}_{Zi}^{\frac{-\beta_s\varepsilon_s(1+\gamma_s)}{1+\varepsilon_s\gamma_s}} \hat{\tau}_{Iis}^{\frac{\varepsilon_s}{1+\varepsilon_s\gamma_s}} \tag{57}$$

Thus, domestic production for the domestic market falls ($\hat{y}_{ii} < 1$), as long as the direct negative effect of the carbon tax is larger than the effect on foreign competitors' prices via the tariff. However, the fall in domestic production for the domestic market is smaller than without the compensating tariff.

Moreover, the impact on domestic exports under this policy scheme is given by:

$$\hat{y}_{jis} = \hat{p}_{Zi}^{\frac{-\beta_s\varepsilon_s(1+\gamma_s)}{1+\varepsilon_s\gamma_s}} \hat{P}_{js}^{\frac{\varepsilon_s-1}{\gamma_s\varepsilon_s+1}}, \tag{58}$$

where by condition (15):

$$\hat{P}_{js}^{\frac{(1+\gamma_s)(1-\varepsilon_s)}{\varepsilon_s\gamma_s+1}} = \delta_{jis}\hat{\tau}_{Iis}^{\frac{1-\varepsilon_s}{\gamma_s\varepsilon_s+1}} + (1-\delta_{jis}) \tag{59}$$

Thus exports fall (and thus export leakage is positive) in response to the domestic carbon tax and there is no mechanism to compensate for this effect.

Consider a scenario where tariffs on imports are set in order to keep changes in aggregate imports equal to zero, i.e. $\hat{C}_{iI} = 1$.

Then given condition (38)

$$1 = \sum_{j\neq i}^{J} \delta_{ijs}^{I} \left[\hat{\tau}_{Iijs}^{\frac{-\varepsilon_s}{\gamma_s\varepsilon_s+1}} \hat{P}_{is}^{\frac{\varepsilon_s-1}{\gamma_s\varepsilon_s+1}} \right]^{\frac{\varepsilon_s-1}{\varepsilon_s}} \Rightarrow \hat{P}_{is}^{-\frac{(\varepsilon_s-1)^2}{(\gamma_s\varepsilon_s+1)\varepsilon_s}} = \sum_{j\neq i}^{J} \delta_{ijs}^{I} \hat{\tau}_{Iijs}^{\frac{1-\varepsilon_s}{\gamma_s\varepsilon_s+1}} \tag{60}$$

At the same time from condition (15) it follows:

$$\hat{P}_{is}^{\frac{(1+\gamma_s)(1-\varepsilon_s)}{\gamma_s\varepsilon_s+1}} = \delta_{iis}\hat{p}_{Zi}^{\frac{\beta_s(\gamma_s+1)(1-\varepsilon_s)}{\gamma_s\varepsilon_s+1}} + \sum_{j\neq i}^{J} \delta_{ijs}\hat{\tau}_{Iijs}^{\frac{1-\varepsilon_s}{\gamma_s\varepsilon_s+1}} \tag{61}$$

Combining the last two conditions we obtain condition (**??**). This is the condition that needs to hold in order to keep aggregate imports constant. Notice that when the tariffs on imports of country i are the same for all trade partners condition (**??**) can be rewritten as condition (21).

D.3 A Unilateral Carbon Tax with Unilateral Export Border Adjustment: Keeping Bilateral Exports Fixed

In this case $\hat{C}_{jis} = \hat{c}_{jis} = \hat{y}_{jis} = 1$ for all j in response to $\hat{\tau}_{Ei} > 1$ only for country i. Find the set of $\hat{\tau}_{Xjis}$ that make this work.

From the akin of condition (13) it follows:

$$\hat{y}_{jis} = \hat{p}_{Zi}^{\frac{-\beta_s(\gamma_s+1)\varepsilon_s}{\gamma_s\varepsilon_s+1}} \hat{\tau}_{Xjis}^{\frac{-\varepsilon_s}{\gamma_s\varepsilon_s+1}} \hat{P}_{js}^{\frac{\varepsilon_s-1}{\gamma_s\varepsilon_s+1}} = 1 \Rightarrow \hat{p}_{Zi}^{\frac{-\beta_s(\gamma_s+1)\varepsilon_s}{\gamma_s\varepsilon_s+1}} \hat{\tau}_{Xjis}^{\frac{-\varepsilon_s}{\gamma_s\varepsilon_s+1}} = \hat{P}_{js}^{\frac{1-\varepsilon_s}{\gamma_s\varepsilon_s+1}}$$
$$\Rightarrow \hat{p}_{Zi}^{\frac{-\beta_s(\gamma_s+1)^2\varepsilon_s}{\gamma_s\varepsilon_s+1}} \hat{\tau}_{Xjis}^{\frac{-\varepsilon_s(1+\gamma_s)}{\gamma_s\varepsilon_s+1}} = \hat{P}_{js}^{\frac{(1+\gamma_s)(1-\varepsilon_s)}{\gamma_s\varepsilon_s+1}} \tag{62}$$

Moreover given condition (15) under this policy scheme we get:

$$\hat{P}_{js}^{\frac{(1+\gamma_s)(1-\varepsilon_s)}{\gamma_s\varepsilon_s+1}} = \delta_{jis}\hat{p}_{Zi}^{\frac{\beta_s(\gamma_s+1)(1-\varepsilon_s)}{\gamma_s\varepsilon_s+1}} \hat{\tau}_{Xjis}^{\frac{1-\varepsilon_s}{\gamma_s\varepsilon_s+1}} + (1-\delta_{jis}) \tag{63}$$

Combining the last two conditions we obtain condition (22).

E Policies with A climate club

Assume that countries from J_C to J belong to the climate club and countries from 1 to $J_C - 1$ do not. The set of countries outside the climate club is denoted with P (the set of polluting countries). Then, we define the imports and the exports in sector s of country i from the set of *polluting* countries P as C_{iPs}, C_{Pis} respectively. These objects are defined as:

$$C_{iPs}^{\frac{\varepsilon_s-1}{\varepsilon_s}} = \sum_{j=1}^{J_C-1} C_{ijs}^{\frac{\varepsilon_s-1}{\varepsilon_s}} = \sum_{j=1}^{J_C-1} N_{ijs} \left(\frac{y_{ijs}}{\tau_{ijs}} \right)^{\frac{\varepsilon_s-1}{\varepsilon_s}} \tag{64}$$

$$C_{Pis}^{\frac{\varepsilon_s-1}{\varepsilon_s}} = \sum_{j=1}^{J_C-1} C_{jis}^{\frac{\varepsilon_s-1}{\varepsilon_s}} = \sum_{j=1}^{J_C-1} N_{jis} \left(\frac{y_{jis}}{\tau_{jis}} \right)^{\frac{\varepsilon_s-1}{\varepsilon_s}} \tag{65}$$

where the last equality follows from (2), (3) and (28). Similarly, we can define the aggregate sector-s price index of goods imported by country i from the set of polluting countries P as:

$$P_{iPs}^{1-\varepsilon_s} = \sum_{j=1}^{J_C-1} P_{ijs}^{1-\varepsilon_s} = \sum_{j=1}^{J_C-1} N_{ijs} p_{ijs}^{1-\varepsilon_s}$$

We want to show that in equilibrium the following condition holds:

$$C_{ijs} = \left(\frac{P_{ijs}}{P_{iDs}} \right)^{-\varepsilon_s} C_{iDs} \tag{66}$$

for all $i = J_C, .., J$ and $j = 1, .., J_C - 1$. Consider that by condition (3):

$$C_{ijs} = \left(\frac{P_{ijs}}{P_{iks}} \right)^{-\varepsilon_s} C_{iks} \Rightarrow P_{iks}^{1-\varepsilon_s} C_{ijs}^{\frac{\varepsilon_s-1}{\varepsilon_s}} = P_{ijs}^{1-\varepsilon_s} C_{iks}^{\frac{\varepsilon_s-1}{\varepsilon_s}} \tag{67}$$

Summing this condition over j we get:

$$P_{iks}^{1-\varepsilon_s} \sum_{j=1}^{J_C-1} C_{ijs}^{\frac{\varepsilon_s-1}{\varepsilon_s}} = C_{iks}^{\frac{\varepsilon_s-1}{\varepsilon_s}} \sum_{j=1}^{J_C-1} P_{ijs}^{1-\varepsilon_s} \tag{68}$$

for all for all $i = J_C, .., J$ and $k = 1, .., J_C - 1$, which leads to:

$$P_{iks}^{1-\varepsilon_s} C_{iPs}^{\frac{\varepsilon_s-1}{\varepsilon_s}} = C_{iks}^{\frac{\varepsilon_s-1}{\varepsilon_s}} P_{iPs}^{1-\varepsilon_s} \tag{69}$$

Rearranging this last condition we get condition (67).

Finally we need to recover the changes in aggregate imports. From condition (64):

$$\hat{C}_{iPs}^{\frac{\varepsilon_s-1}{\varepsilon_s}} = \sum_{j=1}^{J_C-1} \left(\frac{C'_{ijs}}{C_{ijs}} \frac{C_{ijs}}{C_{iPs}} \right)^{\frac{\varepsilon_s-1}{\varepsilon_s}} \tag{70}$$

$$\hat{C}_{iPs}^{\frac{\varepsilon_s-1}{\varepsilon_s}} = \sum_{j=1}^{J_C-1} \hat{c}_{ijs}^{\frac{\varepsilon_s-1}{\varepsilon_s}} \left(\frac{C_{ijs}}{C_{iPs}} \right)^{\frac{\varepsilon_s-1}{\varepsilon_s}} \tag{71}$$

Notice that by condition (66) this last condition can be written as:

$$\hat{C}_{iPs}^{\frac{\varepsilon_s-1}{\varepsilon_s}} = \sum_{j=1}^{J_C-1} \hat{c}_{ijs}^{\frac{\varepsilon_s-1}{\varepsilon_s}} \frac{P_{ijs}C_{ijs}}{P_{iPs}C_{iPs}} \tag{72}$$

$$\hat{C}_{iPs}^{\frac{\varepsilon_s-1}{\varepsilon_s}} = \sum_{j=1}^{J_C-1} \delta_{ijs}^{P} \hat{c}_{ijs}^{\frac{\varepsilon_s-1}{\varepsilon_s}} \tag{73}$$

Note that $\delta_{ijs}^{P} \equiv \frac{P_{ijs}C_{ijs}}{P_{iPs}C_{iPs}}$ represents the share of imports of country i from country j in total *polluting* imports.

In the case of aggregate exports of country i towards the polluting countries we get:

$$\hat{C}_{Pis}^{\frac{\varepsilon_s-1}{\varepsilon_s}} = \sum_{j=1}^{J_C-1} \left(\frac{C'_{jis}}{C_{jis}} \frac{C_{jis}}{C_{Pis}} \right)^{\frac{\varepsilon_s-1}{\varepsilon_s}} \tag{74}$$

$$\hat{C}_{Pis}^{\frac{\varepsilon_s-1}{\varepsilon_s}} = \sum_{j=1}^{J_C-1} \hat{c}_{jis}^{\frac{\varepsilon_s-1}{\varepsilon_s}} \left(\frac{C_{jis}}{C_{Pis}} \right)^{\frac{\varepsilon_s-1}{\varepsilon_s}} \tag{75}$$

In this case finding an expression for $\hat{C}_{Pis}$ in terms of observables is tricky. Notice however that if assume that $\hat{c}_{jis}$ is equal across all j then the expression above collapses to $\hat{C}_{Pis} = \hat{c}_{jis}$.

E.1 A Climate Club without Border Adjustments

We now consider a situation where a set of countries introduce a common carbon tax (climate club) but do not apply any border adjustments. In this case $\hat{\tau}_{Ej} > 1$ and $\hat{p}_{Zj} = 1 + \frac{d_j \tau_{Ej} \hat{\tau}_{Ej}}{p_{Zj}}$ for all $j \geq J_C$, $\hat{\tau}_{Ej} = 1$ for all $j < J_C$ and $\hat{\tau}_{Iijs} = \hat{\tau}_{Xijs} = 1$ for all i and j .

For all countries in the club ($j \geq J_C$) changes in production for the domestic market and in exports to market i can be recovered from condition (13) and are equal to:

$$\hat{y}_{ijs} = \hat{p}_{Zj}^{\frac{-\beta_s \ (\gamma_s+1)\varepsilon_s}{1+\varepsilon_s\gamma_s}} \hat{P}_{is}^{\frac{\varepsilon_s-1}{1+\varepsilon_s\gamma_s}} \tag{76}$$

This condition holds for all i i.e., independently of whether the importing country i is a club member or not.

By contrast, changes in production for all markets i by countries j outside the club ($j < J_C$) are given by the following condition:

$$\hat{y}_{ijs} = \hat{P}_{is}^{\frac{\varepsilon_s-1}{1+\varepsilon_s\gamma_s}} \tag{77}$$

Finally, by condition (15), the change in the aggregate sectoral price index P_{is} is given by:

$$\hat{P}_{is}^{\frac{(1+\gamma_s)(1-\varepsilon_s)}{\gamma_s\varepsilon_s+1}} = \sum_{j=1}^{J_C-1} \delta_{ijs} + \sum_{j=J_C}^{J} \delta_{ijs} \hat{p}_{Zj}^{\frac{\beta_s(\gamma_s+1)(1-\varepsilon_s)}{\gamma_s\varepsilon_s+1}} \tag{78}$$

for all i.

E.2 A Climate Club with a Leakage Border Adjustment on Imports

We now consider a scenario in which countries in the club introduce a border adjustment mechanism vis-a-vis non-members that sterilizes import leakage to the polluting countries. In this case $\hat{\tau}_{Ej} > 1$ and $\hat{p}_{Zj} = 1 + \frac{d_j \tau_{Ej} \hat{\tau}_{Ej}}{p_{Zj}}$ for all $j \geq J_C$ and $\hat{\tau}_{Ej} = 1$ for all $j < J_C$. Moreover, $\hat{\tau}_{Iijs} > 1$ for all $i \geq J_C$ and $j < J_C$ and $\hat{\tau}_{Iijs} = 1$ in all other markets. Finally, we assume that there is no export border adjustment, i.e. $\hat{\tau}_{Xijs} = 1$ for all i and j.

To determine the tariffs which sterilize leakage associated with imports of the the club from non-members, we first calculate the change in aggregate imports by combining (13) and (72)

$$1 = \sum_{j=1}^{J_C-1} \delta_{ijs}^P \left[\hat{\tau}_{Iijs}^{\frac{-\varepsilon_s}{\gamma_s \varepsilon_s + 1}} \hat{P}_{is}^{\frac{\varepsilon_s - 1}{\gamma_s \varepsilon_s + 1}} \right]^{\frac{\varepsilon_s - 1}{\varepsilon_s}} \Rightarrow \hat{P}_{is}^{-\frac{(\varepsilon_s - 1)^2}{(\gamma_s \varepsilon_s + 1)\varepsilon_s}} = \sum_{j=1}^{J_C-1} \delta_{ijs}^P \hat{\tau}_{Iijs}^{\frac{1-\varepsilon_s}{\gamma_s \varepsilon_s + 1}} \tag{79}$$

Note that changes in aggregate imports are zero, i.e. $\hat{C}_{iPs} = 1$. Moreover, by condition (15) we have

$$\hat{P}_{is}^{\frac{(1+\gamma_s)(1-\varepsilon_s)}{\gamma_s \varepsilon_s + 1}} = \sum_{j=J_C}^{J} \delta_{ijs} \hat{p}_{Zj}^{\frac{\beta_s(\gamma_s+1)(1-\varepsilon_s)}{\gamma_s \varepsilon_s + 1}} + \sum_{j=1}^{J_C-1} \delta_{ijs} \hat{\tau}_{Iijs}^{\frac{1-\varepsilon_s}{\gamma_s \varepsilon_s + 1}}. \tag{80}$$

Using the previous condition to substitute out the left-hand side we obtain:

$$\left[\sum_{j=1}^{J_C-1} \delta_{ijs}^P \hat{\tau}_{Iijs}^{\frac{1-\varepsilon_s}{\gamma_s \varepsilon_s + 1}} \right]^{\frac{\varepsilon_s(1+\gamma_s)}{(\varepsilon_s - 1)}} = \sum_{j=J_C}^{J} \delta_{ijs} \hat{p}_{Zj}^{\frac{\beta_s(\gamma_s+1)(1-\varepsilon_s)}{\gamma_s \varepsilon_s + 1}} + \sum_{j=1}^{J_C-1} \delta_{ijs} \hat{\tau}_{Iijs}^{\frac{1-\varepsilon_s}{\gamma_s \varepsilon_s + 1}} \tag{81}$$

Imposing non-discrimination ($\hat{\tau}_{ijs} = \hat{\tau}_{is}$ for all $j < J_C$) this condition can be written as:

$$\hat{\tau}_{Iis}^{\frac{-\varepsilon_s(1+\gamma_s)}{\gamma_s \varepsilon_s + 1}} = \sum_{j=J_C}^{J} \delta_{ijs} \hat{p}_{Zj}^{\frac{\beta_s(\gamma_s+1)(1-\varepsilon_s)}{\gamma_s \varepsilon_s + 1}} + \hat{\tau}_{Iis}^{\frac{1-\varepsilon_s}{\gamma_s \varepsilon_s + 1}} \sum_{j=1}^{J_C-1} \delta_{ijs} \tag{82}$$

E.3 A Climate Club with Leakage Border Adjustment on Imports and Exports

Here we consider a situation where all club members sterilize leakage related to their imports and exports from the set of polluting economies.

In this case $\hat{\tau}_{Ej} > 1$ and $\hat{p}_{Zj} = 1 + \frac{d_j \tau_{Ej} \hat{\tau}_{Ej}}{p_{Zj}}$ for all $j \geq J_C$, $\hat{\tau}_{Ej} = 1$ for all $j < J_C$. Moreover, $\hat{\tau}_{Iijs} > 1$ and $\hat{\tau}_{Xjis} < 1$ for all $i \geq J_C$ and $j < J_C$ and $\hat{\tau}_{Iijs} = \hat{\tau}_{Xjis} = 1$ in all other markets. Hence, we assume that all countries in the club decide to sterilize the effects of the carbon tax on on imports and exports. Since tariffs offsetting import leakage are independent of taxes offsetting export leakage, import tariffs for all $i \geq J_C$ and $j < J_C$ are still set according to condition (27) in all sectors. It remains to determine the export subsidies towards the polluting countries (15). We assume $\hat{c}_{jis} = 1$ for all $i \geq J_C$ and $j < J_C$. Then also $\hat{y}_{jis} = 1$ for all $i \geq J_C$ and $j < J_C$, since $\hat{c}_{jis} = \hat{y}_{jis}$. Therefore, by condition (13):

$$1 = \hat{y}_{jis} = \hat{p}_{Zi}^{-\beta_s \frac{(\gamma_s+1)\varepsilon_s}{\gamma_s \varepsilon_s + 1}} \hat{\tau}_{Xjis}^{\frac{-\varepsilon_s}{\gamma_s \varepsilon_s + 1}} \hat{P}_{js}^{\frac{\varepsilon_s - 1}{\gamma_s \varepsilon_s + 1}}$$

This leads to

$$\hat{P}_{js}^{\frac{1-\varepsilon_s}{\gamma_s\varepsilon_s+1}} = \hat{p}_{Zi}^{-\beta_s\frac{(\gamma_s+1)\varepsilon_s}{\gamma_s\varepsilon_s+1}}\hat{\tau}_{Xjis}^{\frac{-\varepsilon_s}{\gamma_s\varepsilon_s+1}} \tag{83}$$

At the same time, by condition (15) we have that under this policy scheme the following is true:

$$\hat{P}_{js}^{\frac{(1+\gamma_s)(1-\varepsilon_s)}{\gamma_s\varepsilon_s+1}} = \sum_{i=1}^{J_C-1}\delta_{jis} + \sum_{i=J_C}^{J}\delta_{jis}\hat{p}_{Zis}^{\frac{\beta_s(\gamma_s+1)(1-\varepsilon_s)}{\gamma_s\varepsilon_s+1}}\hat{\tau}_{Xjis}^{\frac{1-\varepsilon_s}{\gamma_s\varepsilon_s+1}} \tag{84}$$

Combining this condition with condition (83) above we obtain:

$$\hat{p}_{Zis}^{\frac{\beta_s(\gamma_s+1)}{\gamma_s\varepsilon_s+1}}\hat{\tau}_{Xjis}^{\frac{-\varepsilon_s(1+\gamma_s)}{\varepsilon_s\gamma_s+1}} = \sum_{i=1}^{J_C-1}\delta_{jis} + \sum_{i=J_C}^{J}\delta_{jis}\hat{p}_{Zis}^{\frac{\beta_s(\gamma_s+1)(1-\varepsilon_s)}{\gamma_s\varepsilon_s+1}}\hat{\tau}_{Xjis}^{\frac{1-\varepsilon_s}{\gamma_s\varepsilon_s+1}} \tag{85}$$

for all $i \geq J_C$ and $j < J_C$ and all s. This formula is akin to condition (22). One solution to this set of equations is again $\hat{\tau}_{Xji} = \hat{p}_{Zi}^{-\beta_s(\gamma_s+1)}$ for all $i \geq J_C$ and $j < J_C$ and all s.

E.4 A Climate Club with Carbon Border Adjustment

We now consider a CBAM imposed by the club on non-member coutries, i.e. a tax on the carbon content of imports from a country $j < J_C$ to country $i \geq J_C$ for a subset of sectors.

Like before, we assume again that the initial level of the carbon price in the set of polluting countries is zero. Under this assumption, the change in the energy price for imports from country j associated with a carbon tariff on imports of country i that equals the domestic carbon tax is given by $\hat{p}_{Zij} = 1 + \frac{d_j\hat{\tau}_{Ei}\tau_{Ei}}{p_{Zj}}$ for the subset of sectors covered by CBAM and 1 for those sectors not covered. We implement CBAM by setting a tariff equal to $\hat{\tau}_{Iijs} = \hat{p}_{Zij}^{\beta_s(\gamma_s+1)}$ for all $i \geq J_C$ and s with CBAMs and $\hat{\tau}_{Iijs} = 1$ for all sectors without CBAM. Moreover, the other trade instruments are not used and therefore $\hat{\tau}_{Xijs} = 1$ for all s and j. Under these assumptions equations (13)-(15) imply:

$$\hat{y}_{ijs} = \hat{p}_{Zij}^{\frac{-\beta_s(\gamma_s+1)\varepsilon_s}{\gamma_s\varepsilon_s+1}}\hat{P}_{is}^{\frac{\varepsilon_s-1}{\gamma_s\varepsilon_s+1}} \tag{86}$$

for all i and $j \geq J_C$ and all s with CBAM. Moreover, in the sectors where imports are taxed on the basis of their carbon content, condition (86) also applies to the club's imports from non-members ($j < J_C$ and $i \geq J_C$). By contrast, changes in production in sectors not covered by CBAM or by countries outside the club for their domestic market or for exports towards the rest of the world (i.e., with all $i < J_C$, all $j < J_C$) are given by:

$$\hat{y}_{ijs} = \hat{P}_{is}^{\frac{\varepsilon_s-1}{\gamma_s\varepsilon_s+1}} \tag{87}$$

This last condition implies that there is still export leakage to third countries whose imports from non-members increase. Finally, changes in aggregate prices are equal to:[25]

$$\hat{P}_{is}^{\frac{(1+\gamma_s)(1-\varepsilon_s)}{\gamma_s\varepsilon_s+1}} = \sum_{j=1}^{J} \delta_{ijs} \hat{p}_{Zij}^{\beta_s \frac{(\gamma_s+1)(1-\varepsilon_s)}{\gamma_s\varepsilon_s+1}} \quad i \geq J_C \tag{88}$$

$$\hat{P}_{is}^{\frac{(1+\gamma_s)(1-\varepsilon_s)}{\gamma_s\varepsilon_s+1}} = \sum_{j=1}^{J_C-1} \delta_{ijs} + \sum_{j=J_C}^{J} \delta_{ijs} \hat{p}_{Zij}^{\beta_s \frac{(\gamma_s+1)(1-\varepsilon_s)}{\gamma_s\varepsilon_s+1}} \quad i < J_C \tag{89}$$

F Parameter Estimation

F.1 Demand Elasticities and Returns to Scale

Our estimation of demand elasticities ϵ_s and the returns to scale parameter γ_s follows the methodology developed by Feenstra (1994), Broda & Weinstein (2006) and, in particular, Soderbery (2015). Rewriting the demand equation (3) in terms of market shares $\delta_{ijs} \equiv P_{ijs}C_{ijs}/(P_{is}C_{is})$ 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

$$\Delta^k \ln \delta_{ijst} = \Delta \log \delta_{ijst} - \Delta \log \delta_{ikst} = (1-\varepsilon_s)\Delta^k \log p_{ijst} + \epsilon_{ijst}^k \tag{90}$$

where ϵ_{ijst}^k are unobservable demand shocks.[26]

To derive the empirical analog of the supply equation (9), we write the price of a country-j, sector-s firm in market i as a function of the market share

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

Taking logs yields:

$$\begin{aligned}(1+\gamma)\log p_{ijs} &= \log(\tau_{ij}\tau_{Iijs}\tau_{Xijs}) + \beta_s(\gamma_s+1)\log \tau_{Ej} - (1+\gamma_s)\log(\phi_{ijst}) \\ &\quad + \log \mu + \gamma \log \delta_{ijst} + \gamma \log \eta_{ist}\end{aligned}$$

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

$$\Delta^k \log P_{ijst} = \Delta \log P_{ijst} - \Delta \log P_{ikst} = \frac{\gamma_s}{1+\gamma_s}\Delta^k \log \delta_{ijst} + \omega_{ijst}^k \tag{91}$$

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

[25] With some abuse of notation in what follows we assume that $p_{Zjj} = P_{Zj}$

[26] 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.

that supply and demand shocks are orthogonal, i.e. $\mathbb{E}(\epsilon^k_{ijst}\omega^k_{ijst}) = 0$. 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 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.

Table F.1 reports summary statistics for our estimates of demand elasticities and returns to scale.

F.2 Output Elasticities

We estimate gross-output Cobb-Douglas production functions for four-digit NACE industries with labor, capital, materials and energy as inputs using administrative data for the German manufacturing industries (AFiD). More specifically, we combine plant-level data on energy use and electricity consumption with a representative firm-level survey on gross output, labor, depreciation rates and intermediate inputs for the years 2005 - 2017. We estimate the capital stock using the method proposed by Wagner (2010). Labor is defined as the number of workers.

Our estimator of choice is Wooldridge (2009), which is robust to the critique by Ackerberg et al. (2015) and estimates the moment conditions proposed by Olley & Pakes (1996) and Levinsohn & Petrin (2003) jointly using GMM. Compared to Ackerberg et al. (2015) this method puts restrictions on the underlying data generating process and is slightly less general, but it is computationally less expensive.

For each four-digit NACE industry, we estimate a four-factor production function using either materials or energy as proxy variables and using the first and/or second lag of variables as instruments. 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. 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 four-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. Finally, we rescale output elasticities to make them compatible with the returns to scale estimate obtained in section F.1 above. We report summary statistics of the production function coefficients in Table F.1 below.

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

Variable	N	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

Source: Research Data Center of the Federal Statistical Office and Statistical Offices of the Länder (survey years 2005-2017).

G Data

G.1 Imputation of Fuel Consumption

Table G.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 G.2 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%.

G.2 Imputation of Fuel Prices

Table G.3 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 including 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 G.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 G.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

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Table G.2: Summary Statistics Fuel Shares

Variable	N	Mean	Median	Min	Max	SD	% imputed
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

Table G.3: 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

t statistics in parentheses

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Table G.4: Summary Statistics Fuel Prices

Variable	N	Mean	Median	Min	Max	SD	% imputed
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

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ET-AF-24-003-EN-N

Publications Office
of the European Union

DOI 10.2873/336612
ISBN 978-92-68-12942-5