Discussion Paper Series – CRC TR 224

Discussion Paper No. 495
Project B 06, B 07

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

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

January 2024

[1]University of Verona
[2]University of Mannheim & CEPR
[3]University of Southampton
[4]University of Mannheim
[5]University of Mannheim & ZEW

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

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

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

Alessia Campolmi† Harald Fadinger‡ Chiara Forlati§

Sabine Stillger¶ Ulrich J. Wagner‖

November 24, 2023

Abstract

To prevent carbon leakage induced by unilateral carbon pricing, the EU has designed a Carbon Border Adjustment Mechanism (CBAM) that taxes imports based on their carbon content. Since estimating the carbon content of imports is very complex, CBAM will be applied only to a few emission-intensive sectors. We argue that, as a consequence of its limited applicability, CBAM is unlikely to effectively eliminate leakage. We propose a simple alternative route towards leakage prevention with significantly lower information requirements and administrative burden which can be applied to *all* tradable sectors: the Leakage Border Adjustment Mechanism (LBAM). LBAM offsets the cost disadvantages of domestic producers relative to foreign competitors induced by unilateral carbon pricing by implementing import tariffs and, potentially, export subsidies that hold trade constant at the level before the introduction of carbon pricing. LBAM requires knowledge only about domestic product-specific output-to-emissions elasticities and import demand and export supply elasticities but does *not* depend upon information on the carbon content of imports. To quantify the welfare and emission effects of LBAM and to compare it to CBAM, we simulate a unilateral carbon-price increase in the EU using a granular structural trade model with 57 countries and 121 sectors. We find that LBAM is very effective in preventing leakage, while the EU CBAM is not.

*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. Funding by the Centre for Inclusive Trade Policy (CITP), by the German Federal Ministry of Education and Research (BMBF) through COMPLIANCE (grant 01LA1806C) and by the German Research Foundation (DFG) through CRC TR 224 (Projects B06 and B07), is gratefully acknowledged. Wagner received financial support from the European Research Council under the European Union's Horizon 2020 research and innovation programme (Grant agreement No. 865181).

†University of Verona

‡University of Mannheim and CEPR

§University of Southampton

¶University of Mannheim

‖University of Mannheim and ZEW

1 Introduction

In October 2023, the European Union (EU) has launched the Carbon Border Adjustment Mechanism (CBAM) as a supplementary measure to pricing carbon emissions under its Emissions Trading System (EU ETS). The main objective is to preserve the international competitiveness of European industrial and electricity firms as rapid increases in carbon prices have not been matched by similar regulation in Europe's trading partners.

CBAM first introduces an obligation for EU importers to provide a certification on the carbon content of imports in emissions-intensive sectors exposed to a significant risk of carbon leakage (aluminum, iron & steel, cement, fertilizers, electricity and hydrogen). Starting in 2026, EU importers in these sectors must pay a tax on the embedded carbon content of their imports corresponding to the carbon tax they would have paid to produce these goods in the EU. The main objectives of CBAM are to avoid carbon leakage, i.e., the replacement of EU production with dirty imports, and to correct for the absence of a foreign carbon tax. With the proper design, CBAM can even out distortions created by unilateral carbon pricing and would allow the EU to eliminate the free allocation of pollution rights to large polluters in sectors open to import competition, which violates the polluter-pays principle.

However, in its current design, CBAM faces a number of important problems. First, it necessitates the computation of detailed carbon contents of foreign imports at the producer level. Put differently, it requires knowing the exact carbon content of the foreign production process, including all intermediate inputs. This data requirement strikes us as far too ambitious to be realistic. Moreover, it implicitly creates a distortive non-tariff barrier to trade by shifting the burden of collecting data on carbon content to foreign firms. Crucially, foreign firms have obvious incentives to under-report the true carbon content of their production, necessitating expensive monitoring and a horrendous amount of bureaucracy. Finally, foreign multi-plant firms can easily reshuffle emissions in response to CBAM 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.

Most importantly, as currently designed, the CBAM is so complex that it can only be applied to a small number of sectors. For the concept to work as intended, however, *all* domestically and foreign-produced goods should be taxed on the basis of their carbon content. The fact that only imports in a small set of sectors are taxed, while others are not, induces a mis-allocation of resources. Under the proposed scheme, EU production of most goods could still be replaced by imported goods that are more carbon-intensive but less expensive. Similarly, EU producers can offshore production of final goods whose inputs fall under the current CBAM scheme and thereby circumvent it. For instance, instead of importing steel and paying the

CBAM fee, an EU car producer may decide to move car production abroad where steel is cheaper due to the absence of an ETS and then import the car without paying any CBAM fee.

In this paper, we address the question of how to design an alternative policy scheme that effectively prevents leakage without requiring any knowledge about foreign carbon intensities of production. We propose such a policy and provide a proof of concept for its implementation. The basic idea is to compute a product-specific leakage border adjustment mechanism (LBAM), consisting of a tax on imports (and, potentially, a corresponding subsidy for exports), which can easily be applied to all goods. This tax offsets the cost disadvantage relative to foreign producers that the EU ETS (or an alternative carbon pricing scheme like a tax or the planned ETS 2) imposes on domestic firms in the absence of similar regulations in foreign countries. LBAM implements product-specific import tariffs and, potentially, export subsidies that – absent other shocks to demand or supply – hold trade constant at the level before the introduction of carbon pricing. Thereby, LBAM avoids increases in domestic imports or reductions in domestic exports that would otherwise results from a domestic carbon-price increase (carbon leakage).

The key advantage of LBAM compared to CBAM is that it requires much less information and no costly monitoring and can thus be applied to *all* tradable sectors. While LBAM eliminates carbon leakage, it does not literally hold trade constant: shocks to demand and supply that are unrelated to changes in the domestic carbon price will affect imports and exports and such changes should not be neutralized by LBAM. Thus, to compute LBAM, we need to use an economic model to construct the counterfactual changes in imports and exports in response to a domestic carbon-price change in the absence of other shocks. We show that computing LBAM tariffs and export subsidies only requires information on (i) how domestic production costs change in response to changes in the price of carbon and (ii) how these cost changes are related to the substitution of demand between domestic and foreign producers. The only data required for implementing such a scheme are detailed product-level trade and absorption data (to estimate product-level import demand and export supply elasticities) and firm-level microdata for EU producers (to estimate product-specific elasticities of output with respect to carbon emissions). Unlike CBAM, this imposes no reporting burden on foreign firms and no monitoring burden on EU authorities.

To compute the sector-specific LBAMs, we build a tractable structural trade model with trade in differentiated products, many sectors and countries. We regard the EU as the domestic economy that unilaterally implements a carbon tax (or, equivalenly, an ETS) and a border adjustment mechanism. In our framework, consumers derive utility from a Cobb-Douglas aggregate of products, each consisting of differentiated 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 the export supply curves have sector-specific slopes. Given the short-run nature of our model, we assume that the number of firms is fixed. Production uses physical factors and energy as inputs and carbon emissions are contained in the energy input. Emissions are thus a by-product of production, can be reduced with carbon taxes, and are modeled as a global public bad, i.e., all countries are equally exposed to CO_2 emissions, regardless of where they are released.

Within this model, we first analyze the impacts of a substantial increase in the EU's domestic carbon price on welfare and emissions in the absence of any border adjustment mechanism. We also analyze several counterfactual scenarios where the carbon price increase is accompanied by different border adjustment mechanisms. In the first scenario, we consider an ideal CBAM that applies a carbon tax to imports of all goods according to each foreign exporter's carbon intensity. Second, we consider CBAM for a limited set of sectors, corresponding to the EU's current CBAM design. In the third scenario, the EU introduces an LBAM by setting product-specific taxes on imports that eliminate bilateral import-related leakage in all sectors. In the fourth scenario, the LBAM is extended to exports in the sense that the EU also grants product-specific export subsidies to prevent leakage in export markets.

To quantitatively assess the various policy scenarios, we calibrate a granular version of the model with 121 4-digit manufacturing sectors and 57 countries (the EU-27 and 56 other countries). We follow the methodology of Dekle et al. (2007), which allows us to reduce information requirements by replacing equilibrium objects in the initial equilibrium that depend on unknown parameters with trade and absorption data. We simulate an increase in the European ETS price from its 2018 level (around 15 US dollars) to its 2023 level (around 105 dollars). Conveniently, our model delivers very simple formulas for sectoral LBAMs, which allow computing the changes in import tariff (and export subsidies) required to eliminate leakage for any given change in the ETS price with readily available data. To compute the LBAMs that prevent leakage associated with this carbon price increase, we just need estimates of sector-specific price elasticities of import demand and export supply, output elasticities with respect to energy and physical inputs and absorption data. We leverage standard methodologies in demand and production function estimation: We estimate sector-level price elasticities of import demand and export supply from bilateral EU import data following the methodology proposed by Feenstra (1994); Broda & Weinstein (2006) and Soderbery (2015). We obtain sectoral output elasticities of energy and physical production factors by estimating sector-specific production functions using detailed firm-level micro-data for Germany (Ackerberg et al., 2015; Wooldridge, 2009). We construct absorption data by combining bilateral 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, which are difficult to obtain (Fowlie & Reguant, 2022). We use our model in combination with newly compiled, detailed data on energy prices and the average fuel mix of manufacturing companies to construct emissions intensities in each country.

We evaluate the effectiveness of policies in the scenarios above by computing the changes in EU and global carbon emissions and the EU consumer, producer and government surpluses associated with them. This allows us to compare the different policy schemes – and in particular LBAM and CBAM – in terms of their effects on EU welfare and global emissions.

We find that, in the absence of border adjustments, a seven-fold increase in the EU's carbon price from 15 to 105 US $ is associated with a less than 1 percent reduction in global emissions. This is due to a substantial amount of leakage reducing the effectiveness of the EU carbon price surge in reducing global emissions. Moreover, the ETS-price increase leads to a sizeable displacement of EU manufacturing production by dirty imports to the EU and by dirty exports of third countries to the rest of the world. An ideal CBAM that covers all sectors and taxes all imports based on their carbon content has substantially smaller welfare costs than an ETS price increase without border adjustment and gives 70% larger global emission reductions (1.43% reduction in global emissions). By contrast, the current EU proposal for a CBAM, which is limited to a few sectors, only marginally improves on the situation without border adjustment in terms of welfare, reducing global emissions and preserving EU manufacturing activity. Instead, an LBAM with import and export leakage border adjustment does much better and even comes close to the ideal CBAM in terms of welfare and global emission reductions. It implies 50% additional global emission reductions (a reduction of 1.28% of global emissions) compared to no BAM , while an LBAM limited to import border adjustment gives smaller additional reductions of 15% (0.97% of global emissions). Crucially, we find that the LBAM tariffs and export subsidies required to eliminate leakage are modest: the LBAM tariff is only 1.3 percent for the average sector, while the LBAM export subsidy amounts on average to 3.7 percent.

Finally, we extend our analysis to a climate club. This is motivated by the fact that some countries outside the EU – like the UK and Canada – are also discussing the adoption of a border adjustment mechanism to prevent leakage. The members of the carbon club share a common internal price of carbon and, potentially, a border adjustment vis-à-vis non-members. When Canada and the UK have a common carbon price 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 carbon 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.

2 Related Literature

By proposing a new approach to carbon leakage prevention, our paper adds to a rich literature on the environmental, competitive and welfare effects of unilateral climate policy. So far, this literature has mainly focused on either subsidizing domestic production or imposing carbon prices at the border (via import tariffs and export rebates) in industries that are at risk of carbon leakage. We shall briefly review such policies here with an emphasis on what our study adds to what we already know from previous work.[1]

Exemptions and rebates An effective yet rather blunt policy to maintain competitiveness of leakage-prone industries is to exempt them from carbon pricing altogether. For example, many EU member states granted generous rebates or exemptions on national energy or carbon taxes after efforts to harmonize taxation across the EU had failed in the 1990s (Pearce, 2006). While mitigating concerns about leakage, exemptions policy also takes away the incentive to reduce energy intensity and curb CO_2 emissions, as Martin et al. (2014a) show empirically for the UK.

Production subsidies in the form of free permits With the rise of cap-and-trade as the pre-dominant carbon pricing instrument, production subsidies to leakage-prone industries have emerged as the leading approach to leakage prevention. In no small part, this is because such subsidies can be granted implicitly by allocating pollution permits free of charge to firms and industries at risk of carbon leakage. Political feasibility is a given as most cap-and-trade schemes grant free permits based on historical emissions (grandfathering) in the initial stage. Following that stage, free permit allocation is continued subject to additional provisions on leakage risk and efficiency benchmarks.

The carbon markets in California and Canada grant free permits in proportion to the current period output. Output-based allocation (also referred to as output-based updating) has been shown to be effective at leakage prevention, but it dilutes the carbon price signal and thus leads to higher emissions and social costs (Fis-

[1] A caveat underlying this research, as well as the analysis in this paper, is that it only addresses competitiveness leakage. Fuel price leakage, i.e. the additional demand for fossil fuels in unregulated jurisdictions which results from prices falling due to climate policy in the regulated jurisdiction, is not considered here, despite its potential importance (Böhringer et al., 2022)

cher & Fox, 2007). Further economic costs arise due to foregone permit revenue which could otherwise be used to lower or abolish distortionary taxes (Bovenberg & de Mooij, 1994; Bovenberg & Goulder, 1996). In concentrated industries, output-based updating may exacerbate market power of incumbent firms with detrimental consequences for consumer welfare (Fowlie et al., 2012).

In the EU ETS, free permits are granted to leakage-exposed sectors in proportion to the installed capacity, though adjustments can be made in the event of exceptionally strong fluctuations in output. While akin to output-based updating, capacity-based allocation means that firms cannot influence permit allocations by changing output, thus limiting the impact of permit allocation on short-run production decisions (Meunier et al., 2014). In this sense, capacity-based updating in the EU ETS aims at preventing investment leakage rather than production leakage. Given the long time horizons involved, it is challenging to empirically test for investment leakage. The available evidence does not indicate that the EU ETS has caused significant investment leakage (Koch & Basse Mama, 2019; Borghesi et al., 2020). While industry associations attribute this outcome to free permit allocation and lobby for its continuation, research suggests that cheap abatement options for industrial emitters (Colmer et al., 2022) as well as a low priority of carbon costs in firms' assessment of where to produce (Martin et al., 2014b) might have played a more important role. Martin et al. (2014b) argue that free permits should only be granted to firms and industries where this has a marked negative impact on the expected carbon leakage.

Measuring leakage risk Directly related to instrument choice for leakage prevention is the question of which firms and industries should benefit from it. Existing carbon pricing schemes such as the carbon trading programs in the EU, California, and Canada have used simple metrics to identify industries that are at risk of carbon leakage. The key criteria are 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. Leakage prevention such as the subsidies described in the preceding paragraph are then granted to industries that exceed threshold values on one or both of these indicators.

Given widespread use of simple leakage indicators, recent research has attempted to quantify how well they can approximate more sophisticated indicators of leakage risk. 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. This does not mean that high TE sectors are vulnerable to leakage per se, however. Robust evidence consistent with carbon leakage has been found only for sectors that would rank high on both metrics, EI and TE. This is the conclusion of econometric work using US manufacturing data disaggreggated at the 4-digit level or higher (Aldy & Pizer, 2015; Fowlie et al., 2016; Fowlie & Reguant, 2022) and more qualitative research based on subjective measures of leakage risk elicited by interviewing managers of firms regulated in the EU ETS (Martin et al., 2014c). This casts doubt on the current practice in the EU ETS of granting free permits to manufacturing industries with high TE (>30%) but low carbon intensity.

It goes without saying that 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, which is part of the motivation for the more structural approach taken in this paper.

Border Carbon Adjustments A long-standing proposal for addressing carbon leakage has been to adjust prices of imports and exports at the border according to their domestic carbon tax liability (Markusen, 1975; Hoel, 1996). By taxing the carbon content of imports and rebating the carbon costs of exports, efficient border carbon adjustments seek to neutralize any cost 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).

A sizable economic literature has simulated effects of border carbon adjustments on emissions and welfare using computable general equilibrium models of the world economy, highlighting the advantages of border carbon adjustments over other leakage policies. A recent review of this literature is provided by Böhringer et al. (2022) who also discuss legal and implementation challenges of border carbon adjustments. Prominent criticisms include a possible violation of the Most-Favored Nations (MFN) Clause as well as practical difficulties associated with computing the approriate tariffs (Fischer & Fox, 2012; Cosbey et al., 2019). These factors, which we shall discuss in more detail below, explain why border carbon adjustments have not been implemented at full scale so far. However, California applies this instrument to electricity trades with its neighbor states (Fowlie et al., 2021). The EU's recent commitment to CBAM, which we describe in more detail below, marks a shift from the free trade paradigm towards a more pragmatic policy approach that balances trade and environmental objectives.

A more recent literature studies the empirical link between environmental regulation and emissions leakage through the lens of structural trade models. Aichele & Felbermayr (2015) find substantial emission leakage associated with the Kyoto protocol using a structural gravity model of trade. Larch & Wanner (2017) investigate 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.[2]

Turning to 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. 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 carbon club (Nordhaus, 2015) could achieve emissions reductions corresponding to up to 60% of the fully cooperative outcome, where member states of the carbon 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.[3]

While our model also satisfies structural gravity, it is much more granular. Moreover, compared to the CBAM literature, we propose a new policy experiment, LBAM. We assume that the EU unilaterally implements its share in global emission reductions agreed in the Paris agreements via an ETS and then we 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.

3 Unilateral Carbon Pricing and Leakage Protection in the EU

3.1 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-

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

[3] For an early analysis of how trade restrictions towards non-signatories can increase participation in a global environmental agreement (Barrett, 1997, see). Wagner (2016) empirically investigates the influence of trade restrictions on international cooperation for protecting the global ozone layer.

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.

Given the unilateral nature of the EU ETS, concerns about carbon leakage have been very influential in its design. In the very beginning, permits were allocated generously and free-of-charge to incumbent emitters. The overall cap has become more stringent since those early years, but free permit allocation, albeit less generous, continues to be used as the main instrument to prevent carbon leakage in manufacturing industries deemed at high leakage risk. This has drawn criticism for reasons discussed in the previous section, but also because it runs counter to the 'polluter-pays principle' underlying EU environmental policy (Martin et al., 2012). With the recent 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.

3.2 The Carbon Border Adjustment Mechanism (CBAM)

The CBAM is the EU's partial implementation of the theoretically efficient border carbon adjustment described above. For clarity, we shall maintain a clear distinction between the concept (carbon border adjustment) and this specific policy (CBAM) throughout this paper.

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.

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 design flaws that jeopardize its viability. Here we highlight three of them. First, CBAM requires a large bureaucracy which is expensive to maintain for the EU and likely creates a significant non-tariff barrier to trade (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).

It is not a new insight that political compromise can lead to policies that are a far cry from the economic idea underlying them. In the case of CBAM, however, we believe that the primary goal of preventing carbon leakage has fallen victim to the secondary goal of extending EU carbon pricing outside of EU boundaries. The focus of this paper is to 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.

3.3 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: The effect of a carbon tax on imports

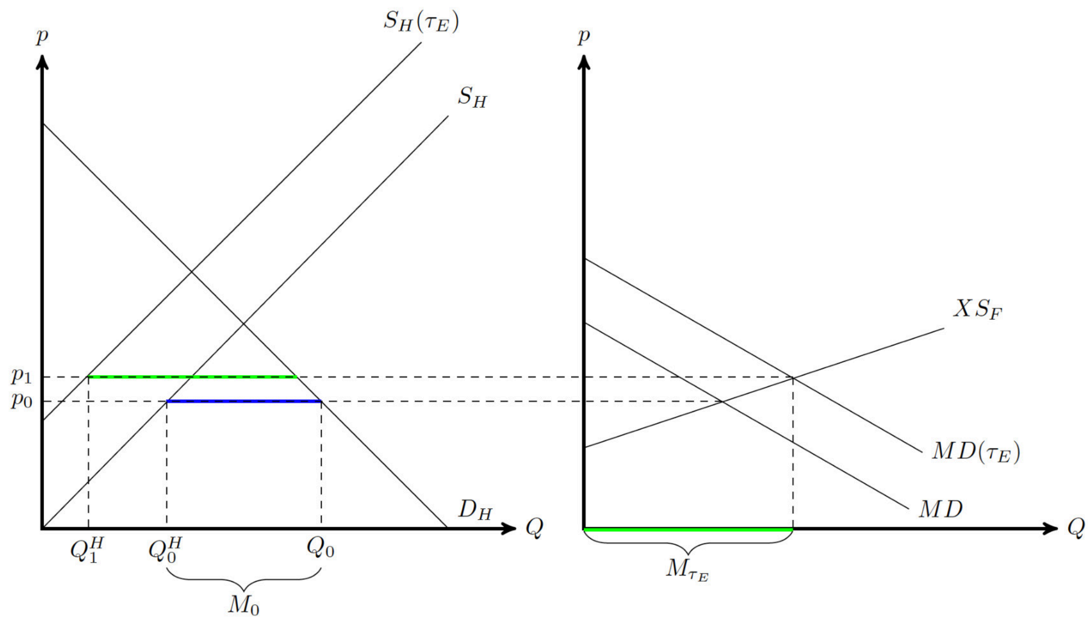
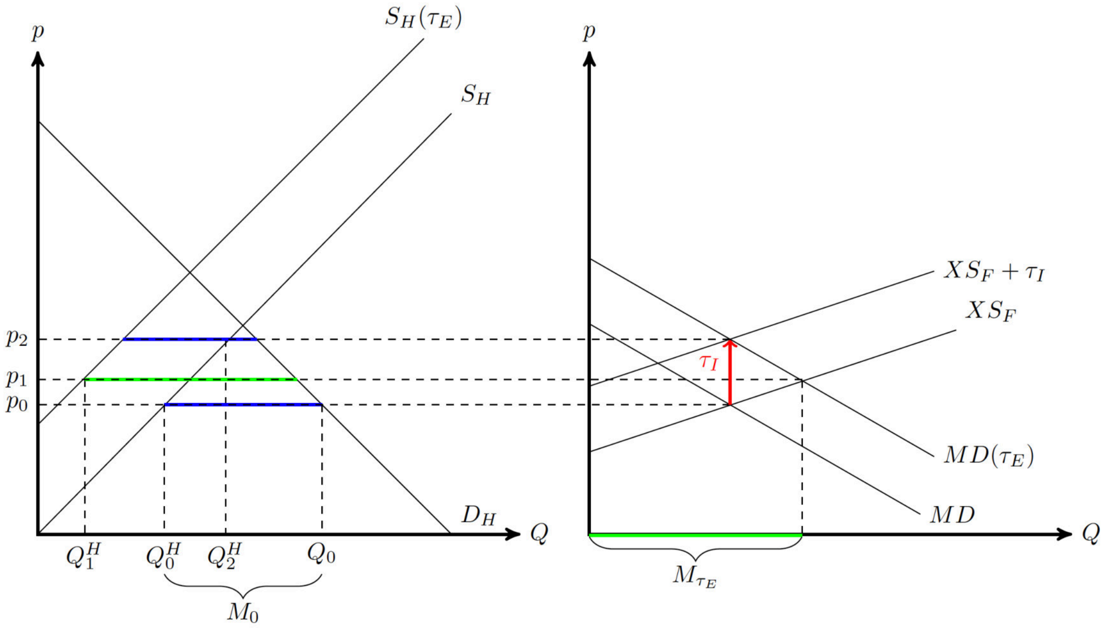


Figure 2: Sterilizing Imports with Leakage Border Adjustment



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.[4]

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.

[4] 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.

3.4 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.[5] This suggests a modification to the CBAM design whereby equal carbon intensities are assumed across sources (benchmarking). While also simplifying information requirements, 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 carbon 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 pro-

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

hibits 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.

4 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.

4.1 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

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

4.2 Production

For simplicity, we assume that production decisions are taken separately across markets.[6] 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.[7] 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. 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

[6]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.

[7]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.

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

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

where d_j denotes the rate of carbon emissions per unit of energy in country j.[8] 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.[9] 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

[8] 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.

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

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

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

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).

4.3 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.

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

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

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

4.4 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

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

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

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

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

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

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

4.5 Welfare

We compute the discrete changes in welfare induced by policy changes.[10] 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.

[10] 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.

Changes in welfare are given by[11]

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

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 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

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

[11] 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.

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.

5 Border Adjustment Mechanisms - 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 shall relax this assumption in Section 6 below). 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 4.5.

5.1 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*).

5.2 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.

5.3 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.

5.4 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.[12] 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

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

$\hat{\tau}_{Iijs} = 1$ 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:

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

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 5.1. Consequently, for these sectors, there is both import leakage and export leakage.

5.5 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:

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

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.

6 Policies with A Carbon 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. Following

Nordhaus (2015), we refer to this group of countries as the *carbon club*.

Without loss of generality, assume that countries J_C to J belong to the carbon club and countries 1 to $J_C - 1$ do not. The set of countries outside the carbon club is denoted by P (the set of polluting countries). If $J_C = J$ the carbon club only has a single member, i.e. there is no carbon club. We now discuss leakage and carbon border adjustment mechanisms.

6.1 A Carbon Club without Border Adjustments

We first consider a scenario where the carbon 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 carbon 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 carbon 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 carbon club's carbon tax. Demand for their exports increases due to an increase in the local price index.

6.2 A Carbon 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 carbon 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 carbon club.

6.3 A Carbon Club with Leakage Border Adjustment 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.

6.4 A Carbon 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.

7 Quantitative Analysis

We employ the quantitative trade model described in the previous sections to simulate the effects of a seven-fold increase in the EU carbon price, from \$15 to \$105 per ton of CO_2, under different assumptions about accompanying border carbon adjustments. To quantify the effects on trade, emissions, and welfare, we calibrate the model to the 2018 equilibrium using detailed data on all equilibrium objects and sector-specific parameters for 121 4-digit manufacturing industries located in 57 countries (the EU-27 and 56 of its trading partners[13]). We first describe the calibration in more detail before summarizing the results.

7.1 Calibration

7.1.1 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

[13]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.

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.[14] We set the initial levels of gross export taxes τ_{Xij} to unity because there is no systematic data on export taxes, and because export subsidies are forbidden under WTO rules.

Fourth, we need data for the carbon emission intensity of energy d_i by country. We source information on energy use in manufacturing by fuel type (coal, oil, natural gas, electricity) for the year 2018 from the International Energy Agency (IEA World Energy Statistics-World Energy Balances). 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).

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.

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

7.1.2 Parameters 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.

7.2 Simulation Results

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

7.2.1 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 5.4. The EU27 unilaterally change 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 5.4 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 5.2.

LBAM-X : In addition to import tariffs as in LBAM, the EU27 grants export subsidies that sterilize export-related leakage, as described in Section 5.3.

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 is very similar to the scenario without border adjustment. This is because CBAM-EU hardly prevents emissions leakage while further reducing consumer surplus compared to no adjustment. The ineffectiveness of CBAM-EU is a consequence of the granularity of our model and the fact that most sectors, many of which are quite energy-intensive, are not covered by CBAM-EU.

Third, our proposed LBAM welfare-dominates CBAM-EU and is more effective at preventing carbon leakage. The reductions in consumer surplus that result from the broader application of tariffs are more than offset by increased domestic profits and higher tariff revenues compared to CBAM-EU.

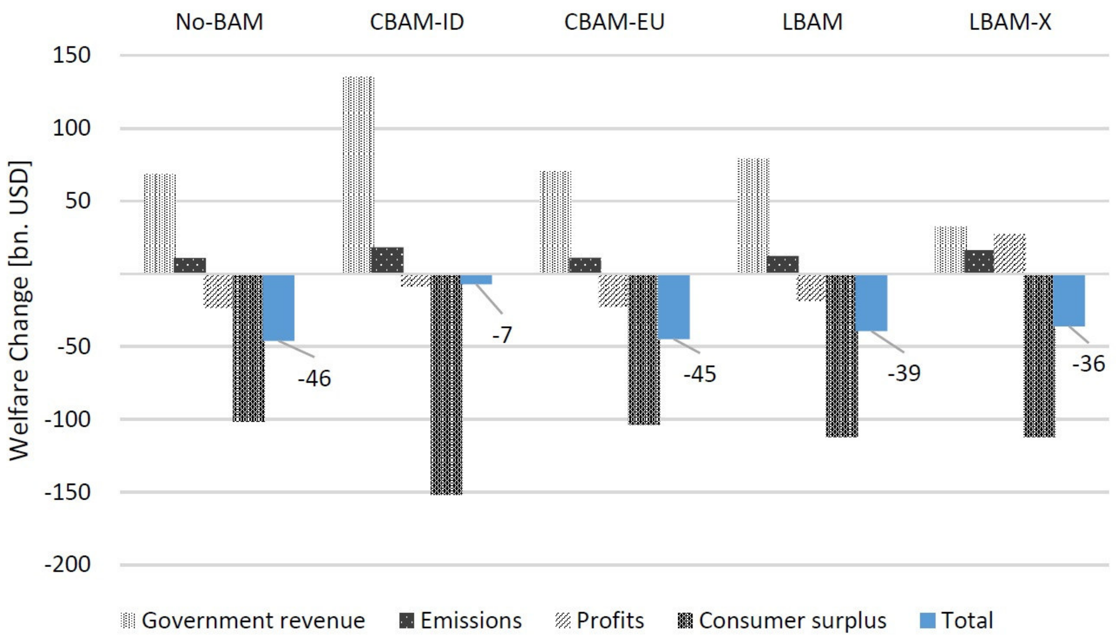
Fourth, not surprisingly, the CBAM-ID performs best in terms of welfare and global emissions reductions, but LBAM-X with import and export leakage adjustment comes quantitatively close.

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.

We start our more detailed discussion of these results with an inspection of the welfare effects depicted in Figure 3 (and also summarized in Panel A of Table 2). It is noteworthy that, unilaterally increasing the carbon tax to $105 is always welfare-detrimental for the EU. The reduction in total EU welfare is largest in the absence of any border adjustment, $46 bn. The associated increase in government revenue and the reduction in social costs of carbon emissions are outweighed by a fall in consumer surplus and reduced profits. In contrast, the CBAM-ID scenario has, with a difference, the smallest welfare cost of $ 7.0 bn. This reflects that 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.

However, since the potential gains of border carbon adjustments are not fully realized when applied to only a small set of industries, the current CBAM-EU has the worst performance of all border adjustment mechanisms and only slightly improves

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



welfare compared to No-BAM.The small welfare improvement of $1.2 bn of CBAM-EU over No-BAM 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 12.5% improvement over CBAM-EU. This is due to stronger emissions reductions, higher tax revenue, and smaller profit reductions. By contrast, 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. The total welfare loss under LBAM can be reduced by an additional 7.1 percentage points when eliminating export-related leakage with export subsidies (LBAM-X). The welfare loss of $36 bn puts this scenario second only to the CBAM-ID. The remaining welfare gap between the two policies is due to export subsidies substantially lowering government revenue, which is not fully offset by higher profits. Importantly, however, LBAM-X is the only border adjustment that results in emissions reductions that are very close to those that could be achieved by an unconstrained implementation of CBAM.

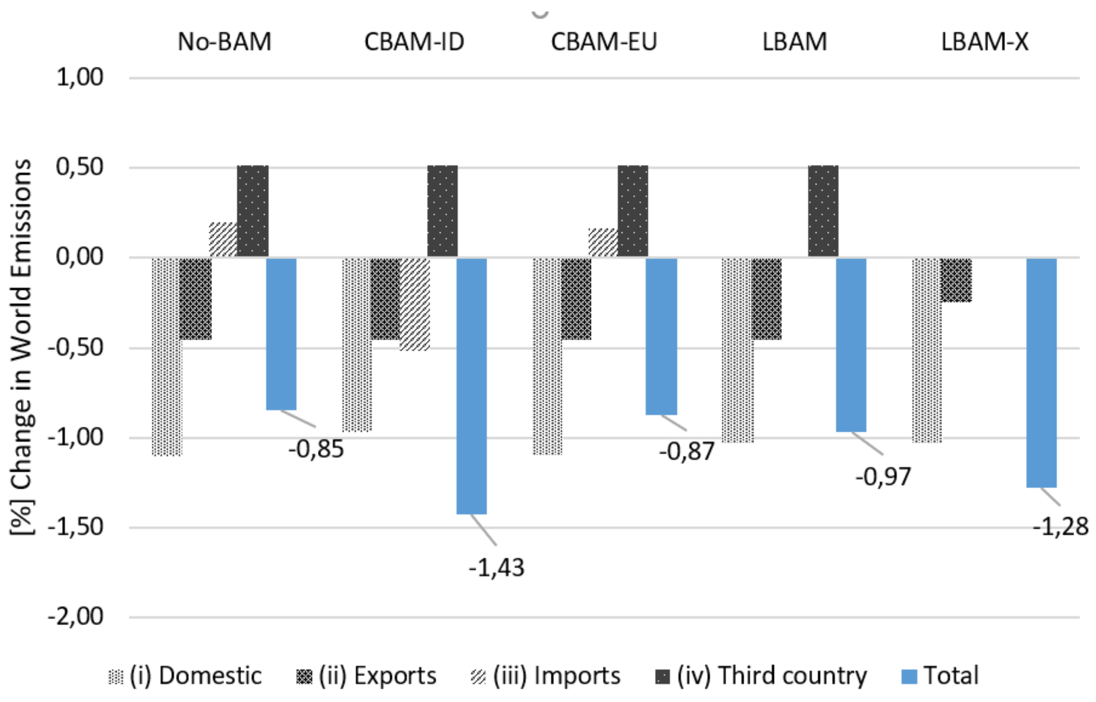
Panel A of Table 1 speaks more directly to this last point, by comparing the effects of different unilateral policy scenarios on EU and global emissions. In 2018, the EU accounted for about 8% of global emissions. Absent border adjustments (No-BAM), unilateral carbon pricing reduces manufacturing emissions in the EU by 29%, but only by 0.85% globally. This is the consequence of a significant leakage of EU emissions. Global emissions reductions could be 69% higher than that with an ideal CBAM-ID, even though EU emissions would fall somewhat less (26.7%). The actual CBAM-EU falls short of that, abating only 0.87% of global emissions, a

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 Carbon 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 Carbon 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 carbon club formed by the EU27, UK and Canada. In Panel C, the carbon 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 carbon club do not change their carbon prices.

Figure 4: Effects of Unilateral Carbon-Price Increase on Global Emissions



mere 3.4% improvement over No-BAM. CBAM-EU is not effective because in our granular model with 121 sectors there a many energy-intensive sectors which are not covered by border adjustment. The LBAMs fare much better in terms of reducing global emissions: Eliminating import leakage (LBAM) increases global emissions reductions by 14.7% compared to the No-BAM baseline scenario. A much stronger boost in global emissions reductions of 51%, however, comes with the simultaneous elimination of import and export leakage (LBAM-X). This is despite the fact that 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 decomposes global emission changes in response to unilateral EU policies using the decomposition developed in Section 5.5 above. In the No-BAM scenario the large reduction in emissions embodied in EU sales to its home market are partially offset by import leakage. Moreover, reduction in emissions embodied in EU exports are more than offset by increased emissions due to third-country leakage. Under CBAM-ID, emissions embodied in EU imports fall strongly, while export leakage is not sterilized. By contrast, under CBAM-EU import leakage is only marginally smaller than in the No-BAM scenario. In the LBAM scenario, import leakage is zero, while emission reductions embodied in EU domestic sales are slightly smaller than under No-BAM. Finally, under LBAM-X the large third-country leakage is additionally eliminated at the cost of slightly smaller emission reductions embodied in EU exports.

In conclusion, an LBAM not only helps to preserve EU manufacturing activity, it also substantially improves the global emission effects of EU policies. Moreover, note that policies that minimize local EU emissions generally do not minimize world emissions as a result of significant carbon leakage.

In Appendix Table A.1 we report the gross changes in EU bilateral imports associated with the different policies. In the No-BAM scenario, bilateral imports increase by 10% on average, with a maximum of 405%. Thus, import leakage is substantial. 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 go almost to zero in some sectors. The CBAM-EU scenario generates both these phenomena; average imports increase by almost 10%, but imports for some sector-country-pairs may drop by up to 50%. Finally, under the LBAM scenarios, bilateral imports are held constant, which eliminates import leakage.

The third panel of Appendix Table A.1 presents the associated gross tariff changes. For CBAM-ID, the average bilateral carbon tariff increase is around 8.3%, with a maximum of over 200%. In contrast, because CBAM-EU leaves imports in most sectors untaxed, the mean carbon tariff increase is just 0.3% and the maximum is 140%. Finally, the tariff increases required to hold imports constant under the LBAM scenarios are modest: the average tariff increase is 1.3% with a maximum of 8.6%. Given relatively high average trade elasticities, in most sectors modest tariff increases are sufficient to hold imports constant.

Finally, the second and fourth panels of Appendix Table A.1 report gross changes in exports and export subsidies under the various scenarios. In the absence of export subsidies, bilateral exports fall by 10% on average and by 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%.

7.2.2 Carbon Club

We now analyze policies adopted by a carbon club of countries that coordinate on a common carbon price. We consider two variants of such a club. The small club consists of the EU, Canada and the UK; the large club additionally contains the US. 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 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.

Panel B of Table 2 reports the welfare effects of those policies for the small club consisting of the EU, Canada and the UK. Welfare effects turn out to be quite similar

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 Carbon 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 Carbon 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 carbon club formed by the EU27, UK and Canada. In Panel C, the carbon 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 carbon club do not change their carbon prices.

to those of a unilateral EU policy change (Panel A). Without border adjustment, EU welfare falls by $43.3 bn (compared to $46 bn without the club). In comparison, EU welfare falls by $3.5 bn under the ideal CBAM and by $42.1 bn when all club members follow the current EU CBAM proposal. The LBAM scenarios lead to smaller EU welfare reductions of $36.4 bn with import tariffs and $32.6 bn with additional export subsidies. In Panel B of Table 1 we report the effect on EU emissions (column 1), on global emissions, and the percentage increase in global abatement achieved compared to the reference scenario of a unilateral EU carbon tax increase without border adjustment (column 3). Tax coordination with Canada and the UK alone gives an additional 22% reduction in global emissions compared to that reference scenario. If the club also coordinates on border adjustments, however, the additional abatement 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. We plot a decomposition of emission changes in Figure A.1 in the Appendix.

Results for the large carbon club are reported in Panel C of Tables 1 and 2. Given that the US account for around 17% of world emissions, global emissions fall substantially when the US joins the club and introduces a carbon tax. As a result, the total EU welfare change now becomes positive in all scenarios, and ranges from $19 bn (No-BAM) to $61 bn (CBAM-ID). LBAM yields intermediate welfare gains between $31 and $33 bn. Global emissions fall by between 5.93% (No-BAM) and 7.23% (CBAM-ID). Respectively, these figures correspond to 7 and 8.5 times the global abatement that the EU would have achieved unilaterally without border adjustment. Again, LBAM-X comes close to the ideal CBAM, yielding worldwide emission reductions of 6.71% – eight times the amount under the reference scenario. Observe that border adjustment continues to be important even in the presence of a club, because it provides incentives for other countries to join (Nordhaus, 2015). 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.

8 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 121 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.

References

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

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

Aldy, J. E. & Pizer, W. A. (2015). The competitiveness impacts of climate change mitigation policies. *Journal of the Association of Environmental and Resource Economists*, 2(4), 565–595.

Arkolakis, C., Costinot, A., & Rodríguez-Clare, A. (2012). New trade models, same old gains? *American Economic Review*, 102(1), 94–130.

Barrett, S. (1997). The strategy of trade sanctions in international environmental agreements. *Resource and Energy Economics*, 19(4), 345–361.

Borghesi, S., Franco, C., & Marin, G. (2020). Outward Foreign Direct Investment Patterns of Italian Firms in the European Union's Emission Trading Scheme. *The Scandinavian Journal of Economics*, 122(1), 219–256.

Bovenberg, L. A. & de Mooij, R. (1994). Environmental Levies and Distortionary Taxation. *American Economic Review*, 84, 1085–1089.

Bovenberg, L. A. & Goulder, L. (1996). Optimal Environmental Taxation in the Presence of Other Taxes: General Equilibrium Analyses. *American Economic Review*, 86, 985–1000.

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

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

Chen, Q., Chen, Z., Liu, Z., Suarez Serrato, J., & Yi Xu, D. (2023). *Regulating Conglomerates: Evidence from an Energy Conservation Program in China*. mimeo, Duke University.

Cherniwchan, J., Copeland, B. R., & Taylor, M. S. (2017). Trade and the environment: New methods, measurements, and results. *Annual Review of Economics*, 9(1), 59–85.

Colmer, J., Martin, R., Muûls, M., & Wagner, U. J. (2022). Does pricing carbon mitigate climate change? Firm-level evidence from the European Union Emissions Trading Scheme. CEPR Discussion Paper No. 16982.

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

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

Ellerman, D., Marcantonini, C., & Zaklan, A. (2016). The european union emissions trading system: Ten years and counting. *Review of Environmental Economics and Policy*, 10(1), 89–107.

Farrokhi, F. & Lashkaripour, A. (2021). Can trade policy mitigate climate change? *Working Paper*.

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

Fischer, C. & Fox, A. K. (2007). Output-based allocation of emissions permits for mitigating tax and trade interactions. *Land Economics*, 83(4), 575–599.

Fischer, C. & Fox, A. K. (2012). Comparing policies to combat emissions leakage: Border carbon adjustments versus rebates. *Journal of environmental economics and management.*, 64(2).

Fischer, C. & Fox, A. K. (2018). How trade sensitive are energy-intensive sectors? *AEA Papers and Proceedings*, 108, 130–135.

Fowlie, M., Petersen, C., & Reguant, M. (2021). Border carbon adjustments when carbon intensity varies across producers: Evidence from california. *AEA Papers and Proceedings*, 111, 401–05.

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

Fowlie, M., Reguant, M., & Ryan, S. P. (2012). Market-Based Emissions Regulation and Industry Dynamics.

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

Fowlie, M. L., Reguant, M., & Ryan, S. (2016). Measuring leakage risk. Report for the California Air Resources Board.

Gerster, A. & Lamp, S. (2022). Energy Tax Exemptions and Industrial Production. CRC TR 224 Discussion Paper No. 388.

Hintermann, B., Peterson, S., & Rickels, W. (2014). Explaining the European Carbon Price. *Review of Environmental Economics and Policy*, This edition.

Hoel, M. (1996). Should a carbon tax be differentiated across sectors? *Journal of public economics*, 59(1), 17–32.

Koch, N. & Basse Mama, H. (2019). Does the EU Emissions Trading System induce investment leakage? Evidence from German multinational firms. *Energy Economics*, 81, 479 – 492.

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

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

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

Martin, R., de Preux, L., & Wagner, U. J. (2012). The polluter-doesn't-pay principle. *CentrePiece*, (pp. 16–19).

Martin, R., de Preux, L. B., & Wagner, U. J. (2014a). The impact of a carbon tax on manufacturing: Evidence from microdata. *Journal of Public Economics*, 117, 1–14.

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

Martin, R., Muûls, M., de Preux, L. B., & Wagner, U. J. (2014c). On the Empirical Content of Carbon Leakage Criteria in the EU Emissions Trading Scheme. *Ecological Economics*, 105, 78–88.

Meunier, G., Ponssard, J.-P., & Quirion, P. (2014). Carbon leakage and capacity-based allocations: Is the eu right? *Journal of Environmental Economics and Management*, 68(2), 262–279.

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

Olley, S. & Pakes, A. (1996). The Dynamics of Productivity in the Telecommunications Equipment Industry. *Econometrica*, 64(6), 1263–1298.

Pearce, D. (2006). The political economy of an energy tax: The United Kingdom's Climate Change Levy. *Energy Economics*, 28(1), 149–158.

Rennert, K., Prest, B., Pizer, W., Newell, R., Anthoff, D., Kingdon, C., Rennels, L., Cooke, R., Raftery, A. E., Ševčíková, H., & Errickson, F. (2021). The social cost of carbon: Advances in long-term probabilistic projections of population, gdp, emissions, and discount rates. *Brookings Papers on Economic Activity*, Fall(Fall), 223–275.

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

Soderbery, A. (2015). Estimating Import Supply and Demand Elasticities: Analysis and Implications. *Journal of International Economics*, 96(1), 1–17.

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

Wagner, J. (2010). Estimated Capital Stock Values for German Manufacturing Enterprises Covered by the Cost Structure Surveys. *Journal of Contextual Economics – Schmollers Jahrbuch*, 130(3), 403–408.

Wagner, U. J. (2016). Estimating Strategic Models of International Treaty Formation. *The Review of Economic Studies*, 83(4), 1741–1778.

Weisbach, D., Kortum, S., & Wang, M. (2020). Optimal unilateral carbon policy. *Working Paper*.

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

Appendices

A Additional Tables and Figures

Table A.1: Trade Effects of Unilateral EU policies

	Mean	**Median**	**SD**	**Min**	**Max**
Gross Change in EU Bilateral Imports					
No-BAM	1.106	1.004	0.348	1	4.050
CBAM-ID	0.917	0.973	0.209	0	5.818
CBAM-EU	1.103	1.003	0.349	0.489	4.050
LBAM	1	1	0.000	1	1
LBAM-X	1	1	0.000	1	1
Gross Change in EU Bilateral Exports					
No-BAM	0.906	0.971	0.154	0.205	1
CBAM-ID	0.906	0.971	0.154	0.205	1
CBAM-EU	0.906	0.971	0.154	0.205	1
LBAM	0.906	0.971	0.154	0.205	1
LBAM-X	1	1	0.000	1	1
Gross Change in EU Tariffs					
No-BAM	1	1	0.000	1	1
CBAM-ID	1.083	1.057	0.088	1	2.056
CBAM-EU	1.003	1	0.017	1	1.392
LBAM	1.013	1.006	0.018	1	1.086
LBAM-X	1.013	1.006	0.018	1	1.086
Gross Change in EU Export Subsidies					
No-BAM	1	1	0.000	1	1
CBAM-ID	1	1	0.000	1	1
CBAM-EU	1	1	0.000	1	1
LBAM	1	1	0.000	1	1
LBAM-X	0.963	0.970	0.026	0.895	0.998

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 Carbon Club (EU, CAN, UK) on Global Emissions

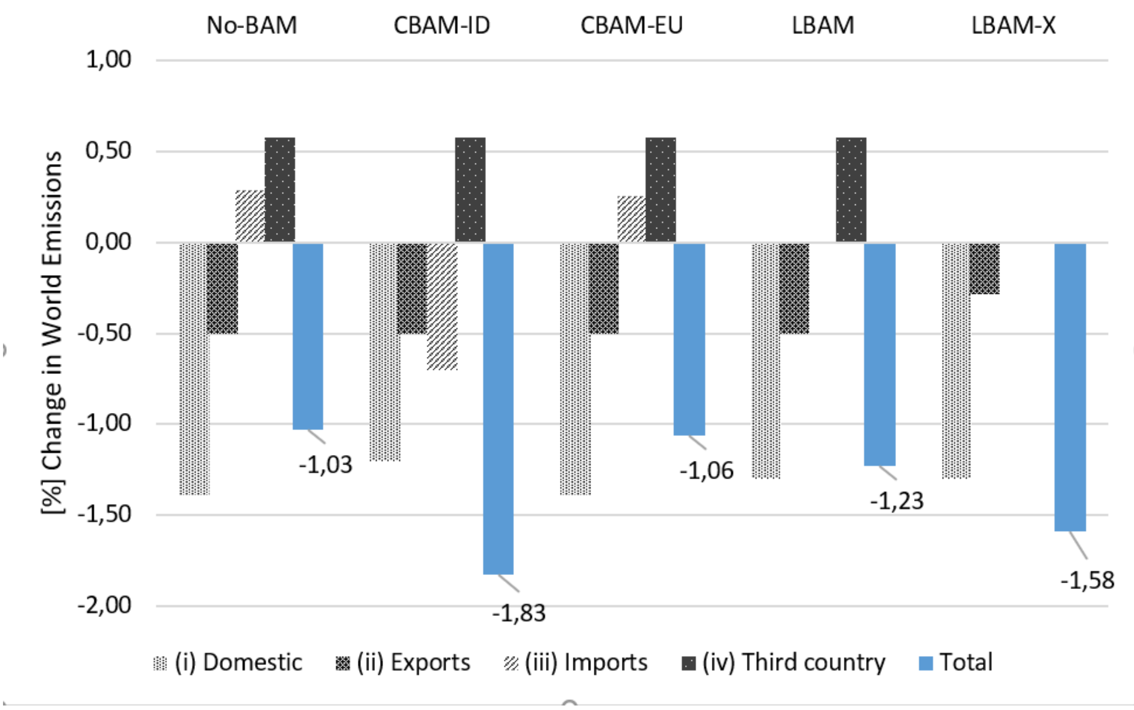
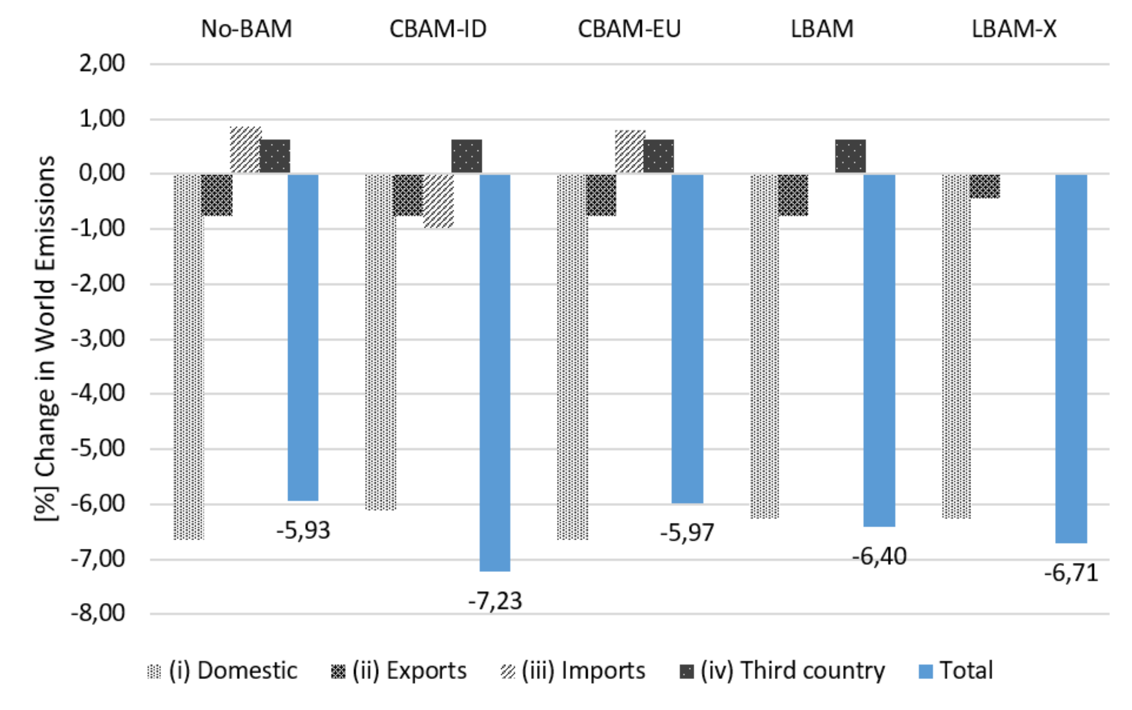


Figure A.2: Effects of Carbon-Price Increase by a Large Carbon Club (EU, CAN, UK, US) on Global Emissions



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 4.3, 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 4.5) in terms of observables.

Tax income in country i can be recovered as follows:

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

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

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

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:

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

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 $t_{Xjis} \equiv \frac{\tilde{\tau}_{Xjis} \tau_{Ijis}^{-1} \tau_{Xjis}^{-1} \eta_{js} \delta_{jis}}{\sum_{j\neq i}^{J} \tilde{\tau}_{Xjis} \eta_{js} \tau_{Ijis}^{-1} \tau_{Xjis}^{-1} \delta_{ijs}}$, 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 4.5, 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 4.1) 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 Carbon Club

Assume that countries from J_C to J belong to the carbon club and countries from 1 to $J_C - 1$ do not. The set of countries outside the carbon 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 Carbon Club without Border Adjustments

We now consider a situation where a set of countries introduce a common carbon tax (carbon 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:

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

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 Carbon 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)

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

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:

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

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 Carbon 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 Carbon 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:[15]

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

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

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.[16]

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 that supply and demand shocks are orthogonal, i.e. $\mathbb{E}(\epsilon_{ijst}^k \omega_{ijst}^k) = 0$. The sample analog of this condition leads to an estimation equation for σ_s and γ_s (Feenstra,

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

[16] 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.

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).