“Alternative Vertical Market Structures and CBAMs’”

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Abstract:

The European Union has recently applied carbon border adjustment mechanisms (CBAMs), linked to the EU carbon price, and targeted at “dirty” products such as steel and aluminum. A small number of models have highlighted the concentrated nature of these industries, emphasizing the idea that there are potentially two market failures to be accounted for, markups over marginal cost and externalities. To capture such effects, a vertical market model is derived, consisting of downstream domestic firms competing with imports subject to a CBAM, downstream production utilizing “dirty” upstream intermediate inputs. The model allows analysis of CBAM implementation in the presence of imperfect competition, the mechanisms associated with pass-through and pass-back between the vertical stages being captured, providing insights into the impact of CBAMs in a multi-market setting that captures the complexity of value chains.

Keywords: Vertical markets, leakage, carbon border adjustment mechanisms

JEL Codes: F13, Q54, Q56, Q58

1. Introduction

In a recent survey article, Copeland, Shapiro and Taylor (2022) present a series of stylized facts concerning interaction between trade and the environment. Three of these stylized facts provide important background for analysis of climate policy in the context of vertical market structures. First, based on total emission rates for carbon dioxide (CO_2) and the share of output traded, "dirty" industries are more exposed to trade than "clean" industries. Second, using Antràs *et al*.'s (2012) index of "upstreamness", i.e., how upstream an industry is from final consumption, Copeland *et al*. (2022) find "dirty" industries are located further upstream. The latter result is confirmed by Shapiro (2021) who finds a monotone relationship between upstreamness and CO_2 intensity, and that for most countries, import tariffs and non-tariff barriers (NBTs) are lower for dirty as compared to clean industries. Third, Copeland *et al*. (2022) report that by 2008 about 1.5 billion tons of global CO_2 emissions were embodied in the net imports of high-income countries, i.e., rich countries are increasingly outsourcing their greenhouse gas (GHG) emissions.

It seems unlikely importing countries explicitly consider CO_2 emissions when setting their trade policy, Shapiro's (2021) results providing further evidence for the well-known phenomenon of tariff escalation, a long-recognized issue in the trade literature (McCorriston and Sheldon, 2011). However, given CO_2 emissions contribute to climate change, this structure of protection can be thought of in terms of policymakers providing implicit subsidies to dirty upstream industries.[1] Shapiro (2021) estimates such subsidies range from \$85 to \$120 per ton of CO_2 emitted, which compares to a global social cost of \$40 per ton of CO_2. Necessarily, such a structure of protection provides an incentive to purchase downstream products domestically, while importing carbon-intensive upstream inputs which are then embodied in downstream products,

[1] In an earlier article, Helm, Hepburn, and Ruta (2012) also make the analytical argument that absence of carbon prices at the border are an implicit subsidy to production of dirty goods in unregulated markets.

thereby increasing global emissions. The latter point reinforces the argument that it is important to account for GHG emissions embodied in value chains (Copeland *et al*., 2022).

In principle, if a coalition of countries impose a carbon tax or some other climate policy instrument on upstream and downstream products, targeted at either direct or indirect CO_2 emissions, a system of carbon border adjustment mechanisms (CBAMs) could be implemented to address the dual issues of reduced competitiveness of domestic producers and any carbon leakage that would result from free riding of non-coalition countries (Copeland *et al*., 2021).[2] This argument has been evaluated analytically and empirically, but it is only recently that a group of rich countries, the European Union (EU), have decided to implement CBAMs, linked to their internal carbon price, and targeted at dirty imported upstream products such as cement, iron and steel, aluminum, fertilizers, organic chemicals, pulp and paper, and electricity (European Commission, 2021a; *Financial Times*, January 11, 2023).[3]

While empirical research on carbon leakage and CBAMs has typically focused on application of computable general equilibrium (CGE) models, e.g., Carbone and Rivers, 2017, and Böhringer Carbone and Rutherford (2018), the European Commission (2021a), and Deverajan, Go, Robinson, and Thierfelder (2022), a small number of industrial organization-type partial equilibrium models have highlighted the concentrated nature of the dirty upstream industries that will be targeted by the EU's CBAMs, e.g., cement: Ponssard and Walker (2008), Fowlie, Regaunt and Ryan (2016); iron and steel: Demailly and Quirion (2008); and aluminum: Sheldon and

[2] To be consistent with EU language, the term CBAMs is used throughout the current paper, but border measures for domestic carbon policy are also frequently referred to as border carbon adjustments (BCAs) (Grubb *et al*., 2022) and carbon tariffs (Carbone *et al*. 2018).
[3] While EU electricity imports only account for 1-2 percent of overall EU consumption on average, delivery into the EU through interconnectors has been expanding, Russia and Ukraine being the largest source of extra-EU imports. For example, net EU inflows of electricity from third countries with no carbon pricing increased by 17 Terrawatt hours (TWh) over the period 2017-19 (European Commission, 2021). See Abrell and Rausch (2016) for an analysis of EU electricity trade.

McCorriston (2017). The latter type of analysis emphasizes the idea that there are potentially two market failures to be accounted for, i.e., markups over marginal cost and externalities (Copeland *et al*., 2022). In addition, if vertical market structures characterized by successive oligopoly are accounted for, targeting of CBAMs at either upstream producers alone or both upstream and downstream producers, their expected welfare effects will be a function of both horizontal and vertical competitive interaction, as well as the nature of pass-through and pass-back effects.

To capture such effects, the approach taken in this paper is to build a model of successive oligopoly, that extends existing models dealing with trade policy issues in vertical market structures (Ishikawa and Spencer, 1999). At the downstream stage, domestic producers who pay a carbon tax compete with imports that may be subject to a CBAM targeted at embodied CO_2 emissions, while at the upstream stage, domestic producers who also pay a carbon tax compete with imports that may also be subject to a CBAM. The model allows analysis of either single-stage or simultaneous CBAM implementation in the presence of imperfect competition, the mechanisms associated with pass-through and pass-back between the vertical stages being captured. This provides insights into the impact of CBAMs in a vertical market structure and, in turn, market access and the motivation behind political opposition to CBAMs. For example, the model can be used to evaluate whether simultaneous implementation of CBAMs on upstream and downstream imports, has differential effects on market access and hence CO_2 emissions at each stage of the value chain.

The overall purpose of this paper is to highlight that, in dealing with one source of market failure (CO_2 emissions), a second market failure (the degree of competition) also matters in determining the outcomes of climate and trade policies. The insights from this framework also have implications for potential CBAMs in the food and agricultural sector given the upstream nature of agricultural production, where emissions are high, and where the issue of carbon pricing and associated CBAMs is an emerging issue for policymakers (Blandford, 2018; Martin, 2022; Glauber, 2022).

The remainder of the paper is outlined as follows: in section 2, the structure of the EU's CBAM system is outlined, followed in section 3 by a review of the economic and legal analysis of CBAMs. In section 4 a vertical market model is sketched out with the purpose of highlighting the complexity of introducing CBAMs into a multi-market system, while section 5 contains a summary and conclusion.

2. The European Union's Carbon Border Adjustment Mechanism (CBAM)

Parties to the 2015 Paris Agreement on climate change committed to limiting the increase in average global temperature to 1.5^0 C, that will require achieving carbon neutrality by 2050. Carbon pricing mechanisms, which include carbon taxation and/or emission trading systems (ETS), have been adopted or are expected to be adopted by at least 68 regional/national/sub-national jurisdictions as a strategy for reducing GHG emissions (Espa, Francois and van Asselt, 2022). However, as countries seek to become more aggressive in their application of climate policy, there are concerns there will be carbon leakage due to an increase in CO_2 emissions in jurisdictions that have either no or weaker climate policies in place.

In this context, the EU has recently introduced its revised climate policy, denoted the "Fit for 55 Package", designed to meet a 2030 target of reducing its GHG emissions by at least 55 percent compared to 1990 levels (European Commission, 2021a). The new policy consists of changes in the EU ETS combined with the introduction of CBAMs to be imposed on a defined set of imported products. The revised system consists of: (i) a reduction in the EU cap on CO_2 emissions, which will entail the progressive reduction of free emissions allowances currently granted to sectors most exposed to the risk of carbon leakage;[4] and (ii) importers of the covered set of products will be required to purchase non-tradable CBAM "certificates", their price reflecting the price of EU emissions allowances, with certificates being surrendered to cover the carbon emissions embodied in the imported products.[5]

The precise details of the CBAM mechanism are as follows (European Commission, 2021b): importers of covered products (cement, electricity, fertilizers, iron and steel, aluminum – see ANNEX I for disaggregated set of products) have to, (i) apply for authorization to import and set up a CBAM account with EU (Articles 4 and 5); (ii) by May 31 of each year submit a CBAM "declaration" showing total and verified carbon emissions embodied in the imports (Articles 6 and 7); (iii) purchase CBAM "certificates" at the weekly average price of emission allowances auctioned under the EU ETS (Articles 2-21); and (iv) surrender CBAM "certificates" to cover embodied emissions (Article 22). In addition, free allowances will gradually be phased out at the rate of 10 percent per year over the period 2026-2035 (Article 31). Finally, details for calculation of both direct and indirect CO_2 emissions are also provided, i.e., the EU CBAM is clearly designed to account for embodied carbon (ANNEX III).

The European Commission argues CBAMs are a "…necessary tool to mitigate the risk of carbon leakage as long as countries do not share the same ambition, or in other words that they do not have a similar carbon price in place…" (European Commission, 2021a, p.13.). The expectation is that under its revised climate policy, EU carbon prices will increase, creating an even larger difference to countries with less restrictive or no carbon pricing mechanisms, which in turn

[4] The EU shifted to a system of auctioning emissions allowances in 2008, but retained allocation of free allowances to industries facing compliance costs that would reduce their international competitiveness (Espa *et al.*, 2022). Note that electricity generating firms no longer receive free allowances but are required to buy them through auctions or on the secondary market (European Commission, 2021a).

[5] Rather than leveling down carbon pricing through a system of free allowances, CBAMs are designed to level up carbon costs for foreign producers while maintaining them on domestic producers (Espa *et al*., 2022; Pirlot, 2022).

increases the risk of carbon leakage – in other words, "…In the context of the "Fit for 55 Package, the CBAM is not a self-standing measure. It is a support measure aiming at enabling the climate ambition of the EU…" (European Commission, 2021a, p.12).

Before turning to a review of the economic and legal literature on CBAMs, it is important to note what the EU's revised climate policy does not include, as well as describe the alternative border policy instruments that were discussed and evaluated by the European Commission, but subsequently rejected. Although discussed in their impact assessment, the EU did not select a CBAM option including refunds of the carbon price on exported products (European Commission, 2021a). As the next section of the paper describes, public economic analysis has shown an optimal system of border tax adjustments (BTAs) for domestic excise taxes would mean levying them on imports and rebating them on exports. However, despite discussion of export rebates in the European Parliament, they were rejected on the grounds that the "…inclusion of refunds of a carbon price paid in the EU would undermine the global credibility of EU's raised climate ambitions and further risk to create frictions with major trade partners due to concerns regarding compatibility with WTO obligations…" (European Commission, 2021a, p.42). Essentially, there are concerns that allowing for export rebates would discourage carbon emission reductions in export-oriented sectors, and potentially be inconsistent the WTO's Agreement on Subsidies and Countervailing Measures (ASCM) (Espa *et al*., 2022).

In addition, the European Commission also rejected two other CBAM options: (i) a border carbon tax reflecting the EU carbon price combined with a default carbon intensity of the imported products (European Commission, 2021a, p.31); and (ii) a system of excise duties, similar to those applied to consumption of alcohol and tobacco products, would be levied on consumption in the EU of carbon-intensive products, irrespective of whether they are produced in the EU or imported.

At the border, an excise duty would be levied on imported materials or products containing a significant share of such materials, the excise duty being waived on exported materials and products (European Commission, 2021a, 35-36).

3. Economic and Legal Analysis of CBAMs

CBAMs are essentially climate policy-adapted versions of border tax adjustments (BTAs) for domestic excise taxes, economic analysis of BTAs not being especially new.[6] Formation of the European Economic Community (EEC) in the mid-1950s and its subsequent implementation of a harmonized system of value added tax (VAT), resulted in economic and legal discussion of adjustment at the border for such an internal tax system (Biermann and Brohm, 2005; Lockwood and Whalley, 2010). The central issue that arose was whether VAT should be applied on an origin or a destination basis. If the EEC had adopted the former, VAT would have applied to production, the tax would also have applied to exports, with no tax rebate at the border, and imports entering the EEC would have done so tax free. The original members of the EEC did in fact adopt the latter principle for taxation, VAT being applied to both domestic consumption and imports as they entered the EEC, and with VAT rebates on exports. Subsequently, as new countries acceded to the EEC, and later the EU, they also began applying BTAs for the internal application of VAT, and taxes on exports were rebated.

With implementation of the harmonized VAT tax system, concerns arose in the United States that its exports to the EEC were being subject to a trade barrier when entering the EEC, while at the same time VAT-free exports from the EEC were essentially receiving an export subsidy. Consequently, after completion of the Kennedy Round of the General Agreement on Tariffs and Trade (GATT) in 1967, and prior to the launch of the Tokyo Round in 1973, there was considerable

[6] This section draws partly on Sheldon (2010), and Sheldon and McCorriston (2017)

discussion in the United States as to whether the destination basis of VAT as applied in the EEC was a violation of GATT Article III. In the event, no dispute settlement case was initiated through the GATT by the United States, and there was no negotiation over the issue in the Tokyo Round. This outcome was essentially due to analysis by economists of the impact of a uniformly applied destination-based tax, as well as establishment in 1968 of a GATT Working Party on Border Tax Adjustments.

Lockwood and Whalley (2010) argue the principle for the use of BTAs is well-founded in the international public finance literature, with important analytical contributions by *inter alia*, Shibata (1967), Whalley (1979), Grossman (1980) and Lockwood, de Meza and Myles (1994). The principle is also captured in the WTO/GATT rules themselves: GATT Article II: 2(a) allows members of the WTO to place on the imports of any product, a BTA equivalent to an internal tax on the like product. However, under GATT Article III: 2, the BTA cannot be applied at a level greater than that applied directly or indirectly to the like domestic product, i.e., under World Trade Organization (WTO)/GATT rules, they must be neutral in terms of their impact on trade, their objective being to preserve competitive equality between domestic and imported products (WTO 1997).

The key questions raised by the WTO/GATT language concern whether BTAs are imposed on imported products that are similar to the domestic product and are neutral in terms of their impact on trade and thereby maintain the competitiveness of domestic producers. Goh (2004) and others note BTAs are normally implemented with respect to taxes on final products, e.g., domestic excise taxes are levied on products such as alcohol and cigarettes, and equivalent taxes are then levied at the border on imports of such products. In principle, however, there is nothing to prevent a country from also applying a BTA on an intermediate input used in production of a final product. The

United States already has such a tax regime in place applied to ozone-depleting chemicals (Barthold, 1994; Davie, 1995; Pauwelyn, 2012). An environmental excise tax was imposed in 1989/90 on the domestic production of a range of chlorofluorocarbons (CFCs), and a BTA was also applied to the import of such chemicals, as well as to the import of manufactured products that either contain CFCs or use them in their production process. While there has never been a GATT/WTO decision rendered on the CFC BTA, a 1987 GATT report in the *US-Superfund* dispute did permit the United States to impose a BTA on imports of chemical products embodying other chemicals that were already subject to a domestic environmental tax (GATT, 1987).

In this context, Poterba and Rotemberg (1995), and McCorriston and Sheldon (2005a) have evaluated application of neutral BTAs in settings where intermediate input and final product markets are respectively perfectly and imperfectly competitive.[7] Where markets are competitive the appropriate treatment for imports is straightforward: the BTA applied to a final product should equal the environmental excise tax applied to the upstream intermediate input times the extent to which the intermediate input enters the final product's cost function, a result that does not necessarily hold up where markets are imperfectly competitive.[8]

While analysis of BTAs has typically focused on preserving "…competitive equality in international trade…" (Demaret and Stewardson, 1994, p.14), economists have also analyzed how trade policy instruments might be used to counter international externalities such as carbon leakage, when one group of countries commits to cooperation over climate policy, while a second group free rides by not implementing climate policy (Copeland *et al*., 2022).[9] Early analysis by

[7] See McCorriston and Sheldon (2005b) for an analysis of the rebate of environmental taxes with imperfectly competitive markets.

[8] Under imperfect competition, McCorriston and Sheldon (2005a) show that neutrality of a BTA on a final product will depend on whether the nature of competition between firms is either strategic substitutes or complements, and the extent which the environmental excise tax is transmitted into an increase in final product costs.

[9] For early analysis of the leakage problem, see Hoel (1991), and Felder and Rutherford (1993).

Markusen (1975) shows that, in the absence of foreign country pollution policies, a home country should use environmental policy to target its own emissions, and an import tariff to target foreign emissions. The key result is that the optimal import tariff corresponds to the optimal pollution tax, conditional on the extent to which demand for the dirty product by non-regulating countries increases, given the import tariff drives down the price of the dirty good on the world market. A subsequent extension by Hoel (1996) shows a social optimum can be obtained if countries that form a coalition set common carbon taxes, and at the same time use import tariffs (export subsidies) on all energy-intensive traded products, the objective being to shift the terms of trade against free-riding countries, thereby reducing carbon leakage. Böhringer *et al*. (2018) explicitly analyze this argument in their CGE analysis, their results showing a reduction in leakage rates compared to a no-CBAM scenario, but there is also a re-routing of energy-intensive exports to unregulated markets. Related to this literature is analysis of the use of trade policies in a game-theoretic setting as an enforcement tool against non-regulating countries, e.g., Ederington (2003), Limao (2005), and Helm, Hepburn, and Ruta (2012). Other contributions include, *inter alia*, Copeland, 1996), Ishikawa and Kiyono (2006), Neary (2006), and Keen and Kotsogiannis (2014).

This analysis raises two important questions about the implementation of CBAMs: first, how important is carbon leakage, and second is there potential for CBAMs to be a form of "green protectionism" (Espa *et al*., 2022)?[10] A recent review by Grubb *et al*. (2022) indicates there is an extensive literature on the measurement of carbon leakage, but as the European Commission itself acknowledges, the evidence for its existence is not conclusive (European Commission, 2021a).[11]

[10] For example, see a recent consulting study on application of a CBAM in the US steel industry, which appears to have an explicitly protectionist objective (CRU International, 2021).
[11] For example, average leakage rates in CGE-type studies range between 10 and 30 percent for comparable climate policies (Böhringer *et al*., 2018)

Notwithstanding this, there is a view that increased stringency of climate policy will amplify both carbon leakage and competitiveness effects (OECD, 2020).

While the argument for using trade policy instruments to resolve a market failure is compelling theoretically, it has raised concerns that CBAMs could be used for protectionist ends and would therefore be constrained by current WTO/GATT rules (Holmes, Reilly and Rollo 2012) and, more generally, there is uncertainty about the compatibility of CBAMs and WTO/GATT rules and the associated design of these policies; for example, determining the carbon content of imported products from countries where environmental policies are either non-existent or are more lax than those applied in the importing country.

Staiger (2022) has recently analyzed how the GATT/WTO architecture might work if there are both trade and climate problems to be targeted. In a two-country setting with trade in a carbon-intensive product, it is shown that if both countries increase their carbon taxes, the importing country should raise its tariff while the other country should raise its export subsidy, the trade policy adjustments being referred to as BCAs. In other words, each country adjusts its trade policies to maintain their terms-of-trade, and hence the efficient level of market access.[12] Importantly, while the carbon tax increase for each country is targeted at its own production, BCAs do not depend on the carbon content of a country's trading partner, and in a multi-country version of the model, the BCAs would be non-discriminatory, satisfying the MFN principle. However, as Staiger (2022) also notes, applying additional BCA-type tariffs on top of existing tariff bindings would require countries initiating GATT Article XXVIII renegotiations with their trading partners, otherwise they could be subject to a violation complaint under GATT Article XXIII:1(a) for nullification or impairment of benefits.[13]

[12] See Bagwell and Staiger (1999) for a complete discussion of the terms-of-trade theory of the WTO/GATT.
[13] See Bagwell and Staiger (2001) for an earlier analysis of this argument.

There has been considerable discussion about the potential legal permissibility of CBAMs for domestic climate policy (Pauwelyn 2012; Cosbey *et al*., 2019; Espa *et al*., 2022) which is not repeated here. Importantly, two key aspects of the legal debate remain unresolved (Pauwelyn 2007). First it is unclear whether a CBAM will be allowed on imports of a final energy-intensive product, when the domestic carbon tax directly affects an input into its production which is not physically present in the final product. Pauwelyn (2012) argues convincingly that if the objective of a carbon tax on the upstream input, e.g., electricity, is to ensure that the price domestic consumers pay for an energy-intensive product such as aluminum reflects the social cost of producing the final product, then a CBAM on the imported final product should be permitted.

Second, it is also unclear whether WTO/GATT rules would apply in the case where domestic climate policy consists of a cap-and-trade system. Here Pauwelyn (2007) argues that if emission credits command a market price, then the obligation of electricity producers to hold emission credits up to the actual level of their carbon emissions qualifies as an internal tax. Assuming this internal tax is passed forward to domestic downstream producers/consumers, an appropriate CBAM can be implemented on imports of final products.

Focusing on the EU's CBAM proposal as written, Espa *et al*. (2022) provide a comprehensive analysis of the potential for it to be consistent or otherwise with WTO/GATT rules. Their overall conclusion is that as designed, the EU proposal may well violate the basic WTO/GATT rules on non-discrimination, i.e., GATT Articles I and III relating to most-favored nation (MFN) treatment and national treatment respectively, while at the same time compromising any environmental defense that could be made under GATT Article XX. Notwithstanding these concerns, the current paper proceeds upon the assumption that EU CBAMs combined with its emissions trading system will be found WTO/GATT legal.

4. A Vertical Market Model with CBAMs

Basic Set-Up

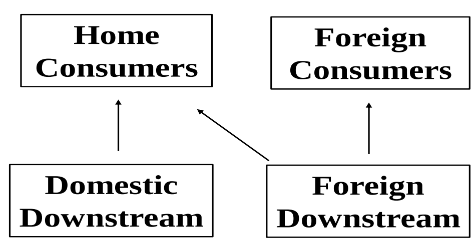
The objective of constructing a vertical market model is to focus on evaluating CBAMs in a multi-market setting consisting of domestic and foreign country upstream production of an intermediate input (e.g., electricity generation) used in downstream production of a final product (e.g., aluminum production). Specifically, there are three possible market structures: (a) the downstream product is traded but the intermediate input is not; (b) the intermediate input is traded but the downstream product is not; and (c) both downstream product and intermediate input are traded.

In the current paper, the focus is on market structure (a) which is divided into two cases to highlight possible multi-market effects: Case 1 where a carbon price is charged in both domestic and foreign countries, the domestic country targets a CBAM at imports of the downstream product from the foreign country, but production of the intermediate input in both domestic and foreign countries is excluded; and Case 2 where a CBAM is again targeted by the domestic country at imports of the downstream product from the foreign country, but production of the intermediate input in both domestic and foreign countries is included.

Case 1

The vertical market structure for Case 1 is illustrated in Figure 1:

Figure 1: Case 1 Vertical Market Structure



Given Figure 1, the following terminology is defined:

(i) Output: $Q^{D,D,H}$ is home downstream output, where superscripts *D*, *D* and *H* refer to downstream, domestic industry, and home consumers respectively; $Q^{D,F,H}$ is foreign downstream output in the domestic market, where superscripts *D*,*F*, and *H* refer to downstream, foreign industry, and home consumers respectively; $Q^{D,F,F}$ is foreign downstream output in the foreign market, where superscripts *D*,*F*, and *F* refer to downstream, foreign industry, and foreign consumers respectively. Domestic and foreign downstream products are treated as differentiated by home consumers, while foreign downstream products are treated as homogeneous by foreign consumers.

(ii) Downstream Emissions Intensity, Carbon Prices, and Carbon Costs: $\varepsilon^{D,D}$ and $\varepsilon^{D,F}$ are emissions intensities for the domestic and foreign downstream industries respectively; c_P^D and c_P^F are carbon prices in the domestic and foreign countries respectively, where $c_P^D \geq c_P^F$ with no free allowances in the domestic country;[14] $c_P^D \varepsilon^{D.D}(Q^{D,D,H})$ and $c_P^F \varepsilon^{D.F}(Q^{D,F,H} + Q^{D,F,F})$ are the total carbon costs for the domestic and foreign downstream industries respectively.

(iii) Leakage: carbon leakage in Case 1 is denoted as L^1,

$$L^1 = -\left[\varepsilon^{D,F}.d(Q^{D,F,H} + Q^{D,F,F}) / \varepsilon^{D,D}.dQ^{D,D,H} \right].$$

(iv) CBAMs: CBAMs targeted by the domestic country at imports of foreign downstream products can take different specifications, because while they are designed to correct for the domestic carbon price c_P^D, the level of foreign downstream emissions $\varepsilon^{D.F}(Q^{D,F,H} + Q^{D,F,F})$ are not necessarily known. Therefore, possible options for a CBAM are: (a) $CBAM = c_P^D$; (b)

[14] Free allowances will reduce the carbon price in the domestic country for the relevant set of industries.

$CBAM = (c_P^D - c_P^F)$; (c) $CBAM = c_P^D \varepsilon^{D,D}(Q^{D,D,H})$; (d) $CBAM = (c_P^D - c_P^F)\varepsilon^{D,D}(Q^{D,D,H})$; and (e) $CBAM = (c_P^D - c_P^F)\varepsilon^{D,F}(Q^{D,F,H} + Q^{D,F,F})$. Options (a)-(d) assume the level of foreign downstream emissions are unknown, giving rise to CBAMs that do not fully reflect carbon costs in the foreign country, while option (e) is a "true" CBAM given knowledge of $\varepsilon^{D.F}(Q^{D,F,H} + Q^{D,F,F})$.

(v) Inverse Demand Functions: home consumers, who treat domestic and foreign downstream products as differentiated, have the following inverse demand functions:

$$P_1^H = a_1^H - b_1 Q^{D,D,H} - KQ^{D,F,H} \tag{1}$$

$$P_2^H = a_2^H - b_2 Q^{D,F,H} - KQ^{D,D,H}, \tag{2}$$

where P_1^H and P_2^H are the home prices of the domestic and foreign downstream products, and b_1, b_2, and K are the own-price and cross-price parameters respectively.

The inverse demand function for foreign consumers of downstream products is:

$$P^F = a^F - b^F Q^{D,F,F} \tag{3}$$

where P^F is the foreign price of the foreign downstream product, and b^F is the own-price parameter.

(vi) Other Costs: P_I^D and P_I^F are the prices of domestic and foreign intermediate inputs respectively; t^{CBAM} is the tariff-equivalent of the CBAM, based on any of the above definitions; and, τ^D and τ^U are downstream and upstream tariffs that would reflect the extent of tariff escalation, but which are ignored for present purposes.

(vi) Profit Functions: the profit function of a representative domestic downstream firm i is given as:

$$\pi_i^{D,D,H} = \left[P_1^H - P_I^D - c_P^D \varepsilon^{D,D}(Q^{D,D,H})\right] q_i^{D,D,H}, \tag{4}$$

and the aggregate profit function for a representative foreign downstream firm j is given as:

$$\pi_j^{D,F} = \pi_j^{D,F,H} + \pi_j^{D,F,F}, \tag{5}$$

where:

$$\pi_j^{D,F,H} = \left[P_2^H - P_I^F - c_P^f \varepsilon^{D,F} (Q^{D,F,H} + Q^{D,F,F}) - t^{CBAM} \right] q_j^{D,F,H} \tag{6}$$

$$\pi_j^{D,F,F} = \left[P^F - P_I^F - c_P^f \varepsilon^{D,F} (Q^{D,F,H} + Q^{D,F,F}) \right] q_j^{D,F,F} \ . \tag{7}$$

Given the definitions in (i) through (vi), the first-order condition for a representative profit-maximizing domestic downstream firm *i* is given by:

$$\frac{\partial \pi_i^{D,D,H}}{\partial q_i^{D,D,H}} = P_1^H - P_I^D - c_P^D \varepsilon^{D,D} (Q^{D,D,H}) + (P_1^{H\prime} - c_P^D \varepsilon^{D,D} (Q^{D,D,H})') q_i^{D,D,H} \left(1 + \frac{\partial q_{-i}^{D,D,H}}{\partial q_i^{D,D.H}} \right), \tag{8}$$

and aggregating over the number of domestic downstream firms $i = 1, \ldots n^{D,D}$:

$$P_1^H - P_I^D - c_P^D \varepsilon^{D,D} (Q^{D,D,H}) + \left[P_1^{H\prime} - c_P^D \varepsilon^{D,D} (Q^{D,D,H})' \right] Q^{D,D,H} \theta^{D,D,H}, \tag{9}$$

where:

$$\theta^{D,D,H} = \frac{\left(1 + \frac{\partial q_{-i}^{D,D,H}}{\partial q_i^{D,D.H}} \right)}{n^{D,D}}, \tag{10}$$

and $\theta^{D,D,H}$, which varies between 0 and 1, represents the intensity of competition as perceived by domestic downstream firms.[15]

The first-order condition(s) for a representative profit-maximizing foreign downstream firm *j* selling to home consumers:

[15] See Weyl and Fabinger (2013) for a recent discussion of the intensity of competition parameter used here.

$$\frac{\partial \pi_j^{D,F,H}}{\partial q_j^{D,F,H}} = P_2^H - P_I^F - c_P^F \varepsilon^{D,F}(Q^{D,F,H} + Q^{D,F,F}) - t^{CBAM}$$
$$+\left[P_2^{H\prime} - c_P^F \varepsilon^{D,F}(Q^{D,F,H} + Q^{D,F,F})' \right] q_j^{D,F,H} \left(1 + \frac{\partial q_{-j}^{D,F,H}}{\partial q_j^{D,F.H}} \right) \tag{11}$$
$$- c_P^F \varepsilon^{D,F}(Q^{D,F,H} + Q^{D,F,F})' q_j^{D,F,F} \left(1 + \frac{\partial q_{-j}^{D,F,F}}{\partial q_j^{D,F.H}} \right),$$

and aggregating over the number of foreign downstream firms $j = 1, \ldots n^{D,F}$:

$$\begin{aligned} & P_2^H - P_I^F - c_P^F \varepsilon^{D,F}(Q^{D,F,H} + Q^{D,F,F}) - t^{CBAM} \\ & + \left[P_2^{H\prime} - c_P^F \varepsilon^{D,F}(Q^{D,F,H} + Q^{D,F,F})' \right] Q^{D,F,H} \theta^{D,F,H} , \\ & - c_P^F \varepsilon^{D,F}(Q^{D,F,H} + Q^{D,F,F})' Q^{D,F,F} \theta^{D,F,F} \end{aligned} \tag{12}$$

where:

$$\theta^{D,F,H} = \frac{\left(1 + \frac{\partial q_{-j}^{D,F,H}}{\partial q_j^{D,F.H}} \right)}{n^{D,F}} \text{ , and } \theta^{D,F,F} = \frac{\left(1 + \frac{\partial q_{-j}^{D,F,F}}{\partial q_j^{D,F.H}} \right)}{n^{D,F}} \tag{13}$$

The first-order condition(s) for a representative profit-maximizing foreign downstream firm *j* selling to foreign consumers:

$$\frac{\partial \pi_j^{D,F}}{\partial q_j^{D,F,F}} = P^F - P_I^F - c_P^F \varepsilon^{D,F}(Q^{D,F,H} + Q^{D,F,F})$$
$$+\left[P^{F\prime} - c_P^F \varepsilon^{D,F}(Q^{D,F,H} + Q^{D,F,F})' \right] q_j^{D,F,F} \left(1 + \frac{\partial q_{-j}^{D,F,F}}{\partial q_j^{D,F.F}} \right) \tag{14}$$
$$- c_P^F \varepsilon^{D,F}(Q^{D,F,H} + Q^{D,F,F})' q_j^{D,F,H} \left(1 + \frac{\partial q_{-j}^{D,F,H}}{\partial q_j^{D,F.H}} \right),$$

and aggregating over the number of foreign downstream firms $j = 1, \ldots n^{D,F}$:

$$\begin{aligned} & P^F - P_I^F - c_P^F \varepsilon^{D,F}(Q^{D,F,H} + Q^{D,F,F}) \\ & + \left[P^{F\prime} - c_P^F \varepsilon^{D,F}(Q^{D,F,H} + Q^{D,F,F})' \right] Q^{D,F,F} \theta^{D,F,F} . \\ & - c_P^F \varepsilon^{D,F}(Q^{D,F,H} + Q^{D,F,F})' Q^{D,F,H} \theta^{D,F,H} \end{aligned} \tag{15}$$

where $\theta^{D,F,H}$ and $\theta^{D,F,F}$ are given by (13).

Now let the carbon cost functions have a specific form:

$$c_P^D \varepsilon^{D,D}(Q^{D,D,H}) = c_P^D \varepsilon^{D,D}(\alpha^D + \beta^D Q^{D,D,H}), \tag{16}$$

$$c_P^F \varepsilon^{D,F}(Q^{D,F,H} + Q^{D,F,F}) = c_P^F \varepsilon^{D,F}[\alpha^F + \beta^F (Q^{D,F,H} + Q^{D,F,F})], \tag{17}$$

where $c_P^D \varepsilon^{D,D}(Q^{D,D,H})' = \beta^D c_P^D \varepsilon^{D,D}$, and $c_P^F \varepsilon^{D,F}(Q^{D,F,H} + Q^{D,F,F})' = \beta^F c_P^F \varepsilon^{D,F}$.

Then substitute the inverse demand function (1) into the first-order condition (9), along with the carbon cost function (15):

$$a_1^H - P_I^D - \chi_1 Q^{D,D,H} - KQ^{D,F,H} - c_P^D \varepsilon^{D,D}, \tag{18}$$

where $\chi_1 = \left[b_1(1+\theta^{D,D,H}) + \beta^D c_P^D \varepsilon^{D,D}(1+\theta^{D,D,H}) \right]$.

Substitute the inverse demand function (2) into the first-order condition (12), along with the carbon cost function (16):

$$a_2^H - P_I^F - t^{CBAM} - \chi_2 Q^{D,F,H} - KQ^{D,D,H} - c_P^F \varepsilon^{D,F} - \beta^F c_P^F \varepsilon^{D,F} Q^{D,F,F} \theta^{D,H,F}, \tag{19}$$

where $\chi_2 = \left[b_2(1+\theta^{D,H,F}) + \beta^F c_P^F \varepsilon^{D,F}(1+\theta^{D,H,F}) \right]$.

Substitute the inverse demand function (3) into the first-order condition (15), along with the carbon cost function (17):

$$a^F - P_I^F - \chi_3 Q^{D,F,F} - KQ^{D,F,H} - c_P^F \varepsilon^{D,F} - \beta^F c_P^F \varepsilon^{D,F} Q^{D,F,H} \theta^{D,F,H} \tag{20}$$

where $\chi_3 = \left[b_2(1+\theta^{D,F,F}) + \beta^F c_P^F \varepsilon^{D,D}(1+\theta^{D,H,F}) \right]$.

Finally, putting into matrix form:

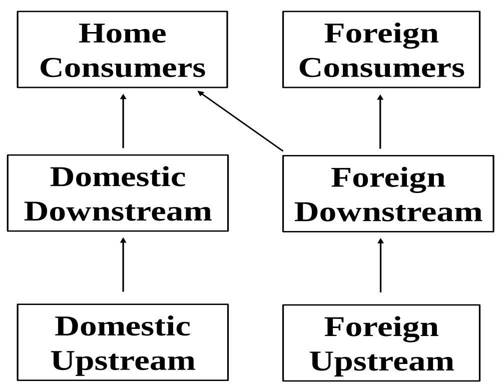
$$\begin{bmatrix} \chi_1 & K & 0 \\ K & \chi_2 & (1+\theta^{D,H,F})\beta^F c_P^F \varepsilon^{D,F} \\ 0 & (1+\theta^{D,F,F})\beta^F c_P^F \varepsilon^{D,F} & \chi_3 \end{bmatrix} \begin{bmatrix} Q^{D,D,H} \\ Q^{D,F,H} \\ Q^{D,F,F} \end{bmatrix} = \begin{bmatrix} a_1^H - P_I^D - c_P^D \varepsilon^{D,D} \\ a_2^H - P_I^F - c_P^F \varepsilon^{D,F} - t^{CBAM} \\ a^F - P_I^F - c_P^F \varepsilon^{D,F} \end{bmatrix}. \tag{21}$$

Three key observations can be drawn from the Case 1 equilibrium described in (21): first, carbon leakage L^1 as defined above depends on multimarket effects given that foreign downstream firms produce for the foreign market as well as export to the domestic market; second, given the policy instrument t^{CBAM} as defined above, it will not necessarily fully correct for carbon leakage; and third, the extent to which t^{CBAM} does not correct for carbon leakage will also interact with multimarket effects and the relative intensities of competition.

Case 2

The vertical market structure for Case 2 is illustrated in Figure 2:

Figure 2: Case 2 Vertical Market Structure



(i) Upstream Emissions Intensity, Carbon Prices, and Carbon Costs: $\varepsilon^{U,D}$ and $\varepsilon^{U,F}$ are emissions intensities for the domestic and foreign upstream industries respectively; as before, c_P^D and c_P^F are carbon prices in the domestic and foreign countries respectively; $c_P^D \varepsilon^{U,D}(Q^{U,D})$ and $c_P^F \varepsilon^{U.F}(Q^{U,F})$ are the total carbon costs for the domestic and foreign upstream industries respectively.

(ii) Leakage: carbon leakage in Case 2 is denoted as L^2,

$$L^2 = -\left[\{\varepsilon^{D,F}.d(Q^{D,F,H} + Q^{D,F,F})\} + \{\varepsilon^{U,F}.dQ^{U,F}\} / \{\varepsilon^{D,D}.dQ^{D,D,H}\} + \{\varepsilon^{U,D}.dQ^{U,D}\}\right] .$$

(iii) Technology: a Leontief-type technology is assumed so that: (a) $Q^{D,D,H} = \phi^D Q^{U,D}$; (b) $Q^{D,F,H} = \phi^F Q^{U,F,H}$; and (c) $Q^{D,F,F} = \phi^F Q^{U,F,F}$, with $Q^{U,F} = Q^{U,F,H} + Q^{U,F,F}$. ϕ is the input-output coefficient, typically set to 1 in vertical market models, but not restricted here to capture the idea multiple units of the intermediate input may be required to produce one unit of the downstream product.[16]

(iv) Upstream Costs: P_A^D and P_A^F are upstream costs of production.

(v) Inverse Derived Demand Functions: these are derived by re-arranging (18), (19) and (20):

$$P_I^D = a_1^H - \chi_1 Q^{D,D,H} - KQ^{D,F,H} - c_P^D \varepsilon^{D,D} \tag{22}$$

$$P_I^{F,H} = a_2^H - t^{CBAM} - \chi_2 Q^{D,F,H} - KQ^{D,D,H} - c_P^F \varepsilon^{D,F} - \beta^F c_P^F \varepsilon^{D,F} Q^{D,F,F} \theta^{D,H,F} \tag{23}$$

$$P_I^{F,F} = a^F - \chi_3 Q^{D,F,F} - KQ^{D,F,H} - c_P^F \varepsilon^{D,F} - \beta^F c_P^F \varepsilon^{D,F} Q^{D,F,H} \theta^{D,F,H} . \tag{24}$$

(vi) Profit Functions: the profit function of a representative domestic upstream firm *k* is given as:

$$\pi_k^{U,D} = (P_I^D - P_A^D - c_P^D \varepsilon^{U,D}(Q^{U,D}))q_k^{U,D} , \tag{25}$$

the first-order condition being given by:

$$\frac{\partial \pi_k^{U,D}}{\partial q_k^{U,D}} = P_I^D - P_A^D - c_P^D \varepsilon^{U,D}(Q^{U,D}) + \left[P_I^{D\prime} - c_P^D \varepsilon^{U,D}(Q^{U,D})' \right] q_k^{U,D} \theta_k^{U,D} , \tag{26}$$

and aggregating over the number of domestic upstream firms $k = 1,...n^{U,D}$:

$$P_I^D - P_A^D - c_P^D \varepsilon^{U,D}(Q^{U,D}) + \left[P_I^{D\prime} - c_P^D \varepsilon^{U,D}(Q^{U,D})' \right] Q^{U,D} \theta^{U,D} . \tag{27}$$

[16] For example, see Figure 1 in Stede *et al*. (2021), for production process data covering the steel and aluminum industries.

Given the inverse derived demand function (22), and noting again that: $Q^{D,D,H} = \phi^D Q^{U,D}$, $Q^{D,F,H} = \phi^F Q^{U,F,H}$, $Q^{D,F,F} = \phi^F Q^{U,F,F}$, and $\theta^{U,D} = \theta_k^{U,D} / n^{U,D}$, re-write the first-order condition as:

$$a_1^H - \chi_1 \phi^D Q^{U,D} - K\phi^F Q^{U,F,H} - c_P^D \varepsilon^{D,D} - P_D^A - \left[\phi^D \chi_1 \theta^{U,D} + \phi^F \beta^{U,D} \varepsilon^{U,D} \theta^{U,D}\right] Q^{U,D}, \quad (28)$$

which can be re-written as:

$$a_1^H - c_P^D \varepsilon^{D,D} - K\phi^F Q^{U,F,H} - P_D^A - \left[\phi^D (\chi_1 + \theta^{U,D} \chi_1) + \phi^F \beta^{U,D} \varepsilon^{U,D} \theta^{U,D}\right] Q^{U,D}. \quad (29)$$

The profit function of a representative foreign upstream firm *l* is given by:

$$\pi_l^{U,F} = \pi_l^{U,F,H} + \pi_l^{U,F,F}, \quad (30)$$

and given foreign downstream firms sell in both the domestic and foreign countries, there are two sources of derived demand for foreign upstream firms, (30) being re-written as:

$$\begin{aligned} \pi_l^{U,F} &= \left[P_I^{F,H} - P_A^F - c_P^F \varepsilon^{U,F}(Q^{U,F})\right] q_l^{U,F,H} \\ &+ \left[P_I^{F,F} - P_A^F - c_P^F \varepsilon^{U,F}(Q^{U,F})\right] q_l^{U,F,F} \end{aligned}. \quad (31)$$

Noting that $Q^{U,F} = Q^{U,F,H} + Q^{U,F,F}$:

$$\begin{aligned} \frac{\partial \pi_l^{U,F}}{\partial q_l^{U,F,H}} &= P_I^{F,H} - P_A^F - c_P^F \varepsilon^{U,F}(Q^{U,F}) + \left[P_I^{F,H\prime} - c_P^F \varepsilon^{U,F}(Q^{U,F})'\right] q_l^{U,F,H} \theta_l^{U,F,H} \\ &- c_P^F \varepsilon^{U,F}(Q^{U,F}) q_l^{U,F,F} \theta_l^{U,F,F} \end{aligned}, \quad (32)$$

and aggregating over the number of foreign upstream firms $l = 1, \ldots n^{U,F}$:

$$\begin{aligned} &P_I^{F,H} - P_A^F - c_P^F \varepsilon^{U,F}(Q^{U,F}) \\ &+ \left[P_I^{F,H\prime} - c_P^F \varepsilon^{U,F}(Q^{U,F})'\right] Q^{U,F,H} \theta^{U,F,H} \\ &- c_P^F \varepsilon^{U,F}(Q^{U,F}) Q^{U,F,F} \theta^{U,F,F} \end{aligned}, \quad (33)$$

Substitute in for $P_I^{F,H}$ and noting relation between upstream and downstream outputs:

$$
\begin{aligned}
&a_2^H - t^{CBAM} - c_P^F \varepsilon^{D,F} - P_F^A - K\phi^D Q^{U,D,H} \\
&-\chi_2 \phi^F Q^{U,F,H} - \beta^F c_P^F \varepsilon^{D,F} \phi^F Q^{U,F,F} \theta^{D,H,F} \\
&-\left[\phi^F \chi_2 + \beta^{U,F} c_P^F \varepsilon^{U,F}\right] \theta^{U,F,H} Q^{U,F,H} \quad , \\
&-c_P^F \varepsilon^{U,F} Q^{U,F,F} \theta^{U,F,F}
\end{aligned}
\tag{34}
$$

and re-writing as:

$$
\begin{aligned}
&a_2^H - t^{CBAM} - c_P^F \varepsilon^{D,F} - P_F^A - K\phi^D Q^{U,D,H} \\
&-\left[\phi^F \chi_2 (1+\theta^{U,F,H}) + \beta^{U,F} c_P^F \varepsilon^{U,F} \theta^{U,F,H}\right] Q^{U,F,H} \; . \\
&-c_P^F \varepsilon^{U,F} Q^{U,F,F} \theta^{U,F,F}
\end{aligned}
\tag{35}
$$

Also:

$$
\begin{aligned}
\frac{\partial \pi_l^{U,F}}{\partial q_l^{U,F,F}} = {} & P_I^{F,F} - P_A^F - c_P^F \varepsilon^{U,F}(Q^{U,F}) + \left[P_I^{F,H\prime} - c_P^F \varepsilon^{U,F}(Q^{U,F})'\right] q_l^{U,F,F} \theta_l^{U,F,F} \quad , \\
& - c_P^F \varepsilon^{U,F}(Q^{U,F}) q_l^{U,F,H} \theta_l^{U,F,H}
\end{aligned}
\tag{36}
$$

and aggregating over the number of foreign upstream firms $l = 1,...n^{U,F}$:

$$
\begin{aligned}
&P_I^{F,F} - P_A^F - c_P^F \varepsilon^{U,F}(Q^{U,F}) \\
&+\left[P_I^{F,H\prime} - c_P^F \varepsilon^{U,F}(Q^{U,F})'\right] Q^{U,F,F} \theta^{U,F,F} \; , \\
&-c_P^F \varepsilon^{U,F}(Q^{U,F}) Q^{U,F,H} \theta^{U,F,H}
\end{aligned}
\tag{37}
$$

Substitute in for $P_I^{F,H}$ and noting relation between upstream and downstream outputs:

$$
\begin{aligned}
&a^F - c_P^F \varepsilon^{D,F} - P_A^F - \chi_3 \phi^F Q^{U,F,F} \\
&-\left[\phi^F \chi_3 + \beta^{U,F} c_P^F \varepsilon^{U,F}\right] \theta^{U,F,F} Q^{U,F,H} \; , \\
&-c_P^F \varepsilon^{U,F} \phi^F Q^{U,F,H} \theta^{U,F,H}
\end{aligned}
\tag{38}
$$

and re-writing as:

$$
\begin{aligned}
&a^F - c_P^F \varepsilon^{D,F} - P_A^F - \left[\phi^F \chi_3 (1+\theta^{U,F,F}) + \beta^{U,F} c_P^F \varepsilon^{U,F} \theta^{U,F,F}\right] Q^{U,F,H} \; . \\
&-c_P^F \varepsilon^{U,F} \phi^F Q^{U,F,H} \theta^{U,F,H}
\end{aligned}
\tag{39}
$$

Simplifying the first-order conditions (29):

$$a_1^H - c_P^D \varepsilon^{D,D} - E_1 Q^{U,D} - K\phi^F Q^{U,F,H} - P_D^A, \tag{40}$$

where $E_1 = \left[\theta^F \chi_1 (1+\theta^{U,D}) + \beta^{U,D} c_P^D \varepsilon^{U,D} (1+\theta^{U,D})\right]$.

Simplifying the first-order condition (35):

$$\begin{gathered} a_2^H - t^{CBAM} - c_P^F \varepsilon^{D,F} - P_F^A - K\phi^D Q^{U,D,H} \\ -E_2 Q^{U,F,H} - c_P^F \varepsilon^{U,F} Q^{U,F,F} \theta^{U,F,F} \end{gathered}, \tag{41}$$

where $E_2 = \left[\phi^F \chi_2 (1+\theta^{U,F,H}) + \beta^{U,F} c_P^F \varepsilon^{U,F} (1+\theta^{U,F,H})\right]$.

Simplifying the first-order condition (39)

$$\begin{gathered} a^F - c_P^F \varepsilon^{D,F} - P_A^F - E_3 Q^{U,F,H} \\ -c_P^F \varepsilon^{U,F} \phi^F Q^{U,F,H} \theta^{U,F,H} \end{gathered}, \tag{42}$$

where $E_3 = \left[\phi^F \chi_3 (1+\theta^{U,F,F}) + \beta^{U,F} c_P^F \varepsilon^{U,F} (1+\theta^{U,F,F})\right]$.

Finally, putting into matrix form:

$$\begin{bmatrix} E_1 & \phi^F K & 0 \\ \phi^D K & E_2 & (1+\theta^{U,F,F}) c_P^F \varepsilon^{U,F} \\ 0 & (1+\theta^{U,F,H}) c_P^F \varepsilon^{U,F} & E_3 \end{bmatrix} \begin{bmatrix} Q^{U,D} \\ Q^{U,F,H} \\ Q^{U,F,F} \end{bmatrix} = \begin{bmatrix} a_1^H - c_P^D \varepsilon^{D,D} - P_A^D \\ a_2^H - c_P^F \varepsilon^{D,F} - P_A^F - t^{CBAM} \\ a^F - c_P^F \varepsilon^{D,F} - P_A^F \end{bmatrix}. \tag{43}$$

Three key observations can be drawn from the Case 2 equilibrium described in (43): first, because of the assumed Leontief technology, given by the parameters ϕ^D and ϕ^F, matrices (21) and (43) have similar structures; second, E_1, E_2, and E_3 all have the intensity of competition in the domestic and foreign upstream sectors, $\theta^{U,D}, \theta^{U,F,H}$ and $\theta^{U,F,F}$, plus via χ_1, χ_2, and χ_3, the intensity of competition in the domestic and foreign downstream sectors, $\theta^{D,D,H}, \theta^{D,F,H}$, and $\theta^{D,F,F}$; and third, the role of the intensity of competition in the domestic and foreign upstream stages also depends on the technology parameters ϕ^D and ϕ^F.

5. Summary and Conclusions

The recent introduction by the EU of carbon border adjustment mechanisms as part of its revised and more stringent climate policy, highlights the issue of carbon leakage and a focus on carbon-intensive manufacturing sectors such as steel, cement and aluminum. Under the EU's original emissions trading system, the latter sectors did not have to purchase allowances either through auction or the EU trading system. With policy revision, these sectors will now face the EU's internal carbon price, which is expected to increase over time, carbon leakage being targeted through application of CBAMs on imports.

In evaluating different methods for implementing CBAMs, the European Commission (2021a) repeatedly focused on the challenge of extending them to downstream products given the complexity of value chains and how a product is transformed in the later stages of those chains. In this paper, a vertical markets model is developed to highlight the very complexity described by the European Commission in its analysis of CBAMs. Specifically, the interest is in how carbon leakage and CBAMs operate through multi-market effects, and the relative intensities of competition in different markets. As shown in the paper, adding an intermediate input sector upstream to downstream production adds to the analysis of leakage and CBAMs in a number of important dimensions: first, the complexity of value chains matters; second competition at both the upstream and downstream stages matters; third, CBAMs at the downstream stage as modeled here, are likely to have back-shifting effects reducing intermediate input costs, the extent depending on the intensity of competition; and fourth, any issues relating to the definition of CBAMs are essentially exacerbated.

In terms of extensions to the current paper, the next steps in this research are as follows: first, the set of vertical market structures will be extended to include the cases where the intermediate input is traded and not the downstream product, and where both are traded; second, the market equilibria described in matrices (21) and (43) will be utilized to conduct more explicit comparative statics, and also carry out some numerical simulation of CBAMs being applied.

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