WORKING PAPERS

N° 1408

September 2023

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The economics of carbon leakage mitigation policies*

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September 2023

Abstract

In a trade model with endogenous emissions abatement, we investigate the impact of three policy instruments aimed at mitigating carbon leakage: free emission allowances, Carbon Border Adjustment Mechanism (CBAM) and CBAM with export rebates. We show that providing allowances for free does not alter the incentives to abate carbon emissions, but fosters the entry of more carbon intensive producers. It levels the "playing field" both domestically and internationally, and it may even reverse the carbon leakage. In contrast, the CBAM levels the playing field only domestically, and it may lead to an autarky equilibrium. To reverse the carbon leakage, the CBAM must be complemented with export rebates. We further show that the CBAM increases welfare for any share of free allowances, and identify the optimal share of free allowances with or without CBAM. Finally, we perform a calibration exercise on cement and steel sectors to simulate the effects of the CBAM recently adopted by the European Union. Our model predicts a scenario with reverse carbon leakage and significant welfare gains for both sectors.

Keywords: Carbon pricing, trade, carbon leakage, CBAM, free allowances, export rebates.
JEL codes: F13, F18, H23, Q52, Q54, Q58.

*We thank Raavi Aggarwal, Philippe Bontems, Ujjayant Chakravorty, Steve Cicala, Riccardo Liburdi, Matti Liski, Aude Pommeret, Katheline Schubert, as well as participants at many seminars and conferences for helpful suggestions and comments. We also thank Bhavita Ragoo for excellent research assistance. We thank the generosity of ISPRA in sharing their confidential anonymized plant-level dataset. This research was supported by the TSE Energy and Climate Center, the H2020-MSCA-RISE project GEOCEP-2020 GA No. 870245, and the grant ANR-17-EUR-0010 (Investissements d'Avenir program). All errors are our own.

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1 Introduction

Carbon pricing initiatives to tackle climate change have been flourishing worldwide. Several jurisdictions have capped greenhouse gas emissions from industrial producers by setting up emission trading schemes called ”cap-and-trade”. Examples include the European Union’s Emission Trading Scheme, the Regional Greenhouse Gas Initiative in the northeastern United States, California’s and Quebec’s joint cap-and-trade program, and China’s ETS (Schmalensee and Stavins, 2017, Almond and Zhang, 2021). Companies operating within the boundaries of these jurisdictions have to pay for their carbon emissions by buying emission allowances, which increases their production costs and, therefore, reduces their competitiveness relative to foreign firms. This creates an unlevel playing field, with repercussions for international trade flows and the climate. In fact, unilateral carbon pricing may lead to emission leakage: since greenhouse gases emitted outside the border of the emission trading market are not capped, the emission reductions induced by the cap-and-trade regulation can be more than offset by an increase of emissions from foreign competitors. Thus the emission trading scheme may not only harm a country’s competitiveness, but also fail to reduce carbon emissions globally.

Carbon leakage can be mitigated with three policy tools. First, the cost burden put by the carbon price on domestic firms can be lowered with rebates and subsidies based on output, abatement efforts or emissions intensities. Second, the cost of imported goods can be increased with a border charge through a Carbon Border Adjustment Mechanism (CBAM). Third, the cost of export can be reduced with rebates and subsidies on exported production (Fischer and Fox, 2012). The European Union (EU) has been recently adopting these policies, in the context of its Green Deal initiative to tackle climate change. A CBAM will enter into force in its transitional phase in October 2023. It will apply to imports of selected industries (aluminum, cement, hydrogen, fertilizers, iron and steel, and electricity). Imports will be charged a carbon tax on their carbon footprint, set equal to the average price of permits traded in the ETS. The CBAM will co-exist with free allowances during a transitory period, and it will replace them eventually (see European Commission, 2021a).

How do such anti-leakage policies impact international competition? Which policies improve welfare? What can be expected from the switch from free allowances to a CBAM for European industries? To answer these questions, we develop a two-country model of international trade in an industry producing an homogeneous good.[1] The carbon emission intensity can be reduced by investing in pollution abatement, which has a cost that is heterogeneous across producers. Carbon emissions are priced with an ETS domestically but not abroad.[2] We analyze the effects of free allowances, a CBAM and a CBAM with export rebates on trade, carbon emissions and welfare.

[1]The assumption of an homogeneous good allows us to compare the competitiveness of domestic and foreign producers by comparing costs. It is a reasonable approximation of reality for the raw products subject to the EU’s CBAM, such as aluminum, cement, hydrogen, iron and steel.

[2]We take the carbon price as exogenous throughout the paper.

We first characterize the equilibrium outcomes to understand how anti-leakage policies improve fair competition inside and outside the jurisdiction where the carbon is priced. We show that, by subsidizing output, free allowances level the playing field not only domestically but also on international markets. A higher share of free allowances can make domestic firms more competitive abroad, as long as they invest enough resources in pollution. Such "clean" firms end up exporting to the foreign country, which reverses the leakage problem by lowering the carbon-intensity of products consumed abroad. Since low-emission production at home replaces high-emission production abroad to serve the foreign market, global emissions are reduced, and carbon leakage is negative.[3]

We then analyze the effects of a CBAM. By charging the carbon content of imports, a CBAM levels the playing field domestically: both domestic and foreign firms pay the same cost per unit of CO_2 emitted. It increases the cost of imported products which reduces imports and therefore, mitigates carbon leakage. In addition, a CBAM can lead to an autarky equilibrium. This occurs whenever foreign firms are not competitive domestically because of the carbon tariff but, at the same time, domestic firms are not competitive abroad. Nevertheless, the CBAM *alone* does not level the playing field on international markets, as domestic firms exporting abroad are charged for their carbon emissions, while foreign firms are not. In other words, the CBAM reduces and sometimes eliminates carbon leakage, but alone it cannot reverse the leakage with exports.[4]

To level the playing field abroad, the CBAM should be complemented with export rebates. By assigning free allowances only on exported output, export rebates have two effects on the equilibrium outcome. First, under the leakage or autarky equilibria, consumers and firms pay the full carbon price (as there are no free allowances), and thus carbon emissions are lower than with free allowances. Second, reverse leakage is more likely because firms make a higher markup per output when they export. In other words, assigning free allowances only to exported output kills two birds with one stone: it makes firms pay the full cost of their carbon emissions and levels the playing field on international markets.

We then examine the welfare impact of leakage mitigation policies. We show that all allowances should be free without CBAM regardless of the equilibrium outcome, or with a CBAM with reverse leakage. Some allowances should be free with CBAM under carbon leakage if the carbon price is lower than the social cost of carbon. No allowance should be free with a CBAM if carbon is priced at its social cost except in the case of reverse leakage. We thus highlight another motive for providing free allowances (or subsidizing output): reducing carbon emissions abroad by substituting foreign goods with less carbon-intensive domestic ones on international markets.

[3]The term negative leakage has been introduced by Baylis, Fullerton, and Karney, 2014 in a different context of general equilibrium. It refers to the reduction of carbon emission outside the sectors where carbon is taxed through competition in for the same inputs.

[4]We also highlight that having free allowances increases carbon leakage if the carbon tariff is adjusted with the share of free allowances, as prescribed by the EU legislation for the transition period.

Moreover, we show that a CBAM is welfare enhancing for any share of free allowances. Intuitively, with CBAM, the supply curve in the domestic market reflects the social cost of production, including the carbon cost, and therefore, the harmfully impact of carbon emissions is internalized. Lastly, we stress that our results change substantially depending on how carbon emissions are accounted for in the social cost function. If the social planner cares only about greenhouse gases emitted within the jurisdiction where carbon is priced rather than global emissions, no allocation should be free and a CBAM should not be implemented.

In the last part of our analysis, we calibrate the model to quantify the impact of CBAM on international trade and welfare. We assume that the home country is the European Union, and focus on the two largest manufacturing sectors in which the CBAM will be implemented: cement and steel. We use Turkey as foreign country in the cement sector, and Russia in the steel sector, as these are the top exporters to EU in each industry (among the nations without a formal emissions trading scheme).[5] We combine publicly available data on production, international trade and emissions to calibrate the model to the year 2019 (before the Covid outbreak). We also use anonymized plant-level data on emissions intensity (in tons of CO2 per ton produced) from Italy, made available to us by ISPRA, a public agency that collects environmental data. We use this data to calibrate the abatement cost function and the moments of the distribution of abatement costs.[6]

Our quantitative analysis has three main results. First, increasing the share of free allowances under a CBAM changes the equilibrium outcome from leakage to reverse leakage in both industries. Second, export rebates are more effective in stimulating exports than free allowances. Lastly, the welfare gains from the CBAM are large and decreasing in the share of free allowances. They range between $0 - 122\%$ for cement and $0 - 33\%$ for steel. We also show that these results are generally robust to the calibration used for the abatement cost function and the emission factors.

Related literature. Economists have long advocated for the implementation of border carbon adjustment mechanisms to tackle carbon leakage. Border carbon adjustment mechanisms have been proposed as a theoretical solution to address carbon leakage, but their practical implementation raises concerns and challenges (see Cosbey et al., 2019, Ambec, 2022, Böhringer et al., 2022 for surveys). Most of the studies investigating the impact of unilateral carbon pricing, CBAM and other anti-leakage policies rely on numerical analysis with computable general equilibrium models (e.g. Branger and Quirion, 2014, Balistreri, Böringer, and Rutherford, 2018, Balistreri, Kaffine, and Yonezawa, 2019, Böhringer, Schneider, and Asane-Otoo, 2021, Clora and Yu, 2021, Magacho, Espagne, and Godin, 2022). They provide quantitative estimations but do not analytically characterize the eco-

[5]For instance, China is also among the top exporters to the EU, but it has a cap-and-trade system in place, which is not consistent with the assumption in our model that foreign firms do not pay a carbon tax.

[6]We conduct our analysis with the anonymized plant level data adhering to the confidentiality rules set by ISPRA. In particular, our analysis does not reveal any information about any given plant in the dataset.

nomic outcomes nor the optimality of anti-leakage policies depending on the economic environment as we do.

Earlier works like Markusen, 1975 have shown that unilateral carbon pricing can be optimal despite carbon leakage in a two-goods international trade model. Recently Balistreri, Böringer, and Rutherford, 2018 extended the Markusen model to characterize the optimal carbon tariff with a CBAM. They found that it should be lower than the Pigouvian carbon price because, in their framework, the CBAM increases supply in foreign markets, which lowers the foreign price, increases foreign consumption and, therefore, foreign emissions. We do not have this effect of the CBAM on foreign prices, because of the assumption of unlimited supply at constant marginal cost in foreign markets. Hence, our carbon tariff is set optimally at the carbon price when the latter is at its social cost. We complement Balistreri, Böringer, and Rutherford, 2018 analysis by investigating the optimality of other public policies such as free allowances and export rebates when carbon is priced efficiently. We show that welfare can be further increased by complementing the (Pigouvian) CBAM with free allowances or export rebates to supply less carbon-intensive products abroad and, therefore, reduce the carbon footprint of foreign consumption.

Recent studies (Kortum and Weisbach, 2021, Farrokhi and Lashkaripour, 2022, and Weisbach et al., 2023) have identified optimal carbon border adjustment policies using multi-sector models with heterogeneous goods and monopolistic competition à la Melitz (Melitz, 2003). The energy sector is central in Kortum and Weisbach, 2021 and Weisbach et al., 2023, and thus the optimal policy mix involves taxes on energy extraction and trade to mitigate the carbon leakage driven by the energy markets. In contrast, we do not model the energy sector, thus the carbon leakage arises from the reduced competitiveness of domestic firms. Importantly, we also allow for technological change through investment in pollution abatement, while Kortum and Weisbach, 2021 and Weisbach et al., 2023 do not. In addition, we complement their study by investigating the optimality of several leakage mitigation policies.

Two studies address carbon leakage through the relocation of manufacturing plants outside the jurisdiction where carbon is priced, a phenomenon sometime called "pollution offshoring" (Saussay and Zugravu-Soilita, 2023) or "pollution outsourcing" (Levinson, 2023). Martin et al., 2014 estimate with a calibrated model the number of allowances that should be assigned for free in the EU ETS to achieve a given risk of production plant relocation. Ahlvik and Liski, 2019 rely on mechanism design techniques to identify carbon policies when firms' relocation cost is private information. Our approach is different because leakage occurs through international trade, which is absent in both papers. We find out how different carbon leakage mitigation policies affect international trade outcomes. We then characterize the optimal anti-leakage policies (share of free allowances, CBAM) depending on international trade outcomes.

Our paper builds upon the previous literature on partial equilibrium models with trade, particularly Fischer and Fox, 2012 and Fowlie and Reguant, 2022.[7] Building on insights from Meunier, Ponssard, and Quirion, 2014, Fowlie and Reguant, 2022 focus on output subsidies as a policy instrument to mitigate carbon leakage. They characterize and estimate the optimal subsidy in a two-country model with one representative firm in each country. We also characterize the optimal output subsidy with and without CBAM. However, our formula is different because, in our model, domestic production is driven by the entry or exit of firms with heterogeneous pollution abatement efforts and emission-intensity.[8] Closer to our paper, Fischer and Fox, 2012 compare various anti-leakage policies, including carbon border adjustments, also in a model with two countries, one representative firm in each country, two differentiated goods and investment in pollution abatement. They analyse how the policies affect the economic outcome with a comparative statics analysis. In contrast, we characterize the economic outcomes as a function of endogenous parameters. We do that in a model where goods are perfect substitutes, which allows us to compare the competitiveness of firms on both sides of the border.

The rest of the paper proceeds as follow. We first develop a partial equilibrium model to investigate the economic effects of the carbon leakage mitigating policies (Section 2). Next we perform a welfare analysis and describe the optimal mixes of carbon pricing and free allowances with a CBAM (Section 3). Section 4 calibrates a parametric version of the model and performs policy simulations. Section 5 concludes.

2 A trade model with endogenous emissions abatement

In this section we develop a partial equilibrium model with two countries (a home country h and an aggregate of the rest of the world, which we call the foreign country f) that can freely trade an homogeneous polluting good. In the home country, carbon emissions are subject to a constant tax. The key feature of the model is that firms choose their optimal investment in carbon emissions abatement, and are heterogeneous in the cost of doing so. In this setting, we characterize the economic and welfare effects of a range of carbon leakage mitigation policies.

2.1 Framework

In the home country (h), production is supplied by a continuum of firms of mass 1, each of type θ. Each firm can produce q units of the good with constant marginal cost c_h. Producing the good emits CO_2 with an emission factor (also referred to as emission intensity or

[7] Böhringer, Fischer, and Rosendahl, 2014 also rely on a partial equilibrium model with trade. They compare the leakage rate and greenhouse emissions induced by several anti-leakage policies in a multi-country setting. However, they do not characterize the equilibrium, nor the optimal anti-leakage policy mix as we do.

[8] Cicala, Hémous, and Olsen, 2022 also model the entry and exit of firms with heterogeneous emission-intensity in their investigation of the impact of the certification process in a CBAM. However, they assume that all firms have same abatement cost while they are heterogeneous in our setting.

carbon footprint) normalized to 1. Firms can reduce the emission factor by a by investing into carbon emissions abatement. The cost of abating carbon emissions is firm specific. Firm of type θ invests $\theta C(a)$ to reach an emission factor of $1 - a$, with $0 < a < 1$. We assume $C(a)$ is increasing and strictly convex with $C'(1) = +\infty$, such that production is never fully carbon-free. We assume that the firm's abatement cost type θ is distributed according to a density g and a cumulative G, on the range $[\underline{\theta}, \overline{\theta}]$. We assume without loss of generality that $\overline{\theta}$ is larger than all the entry cutoffs we derive throughout our analysis. Examples of abatement strategies include improving energy efficiency or switching to decarbonated source of energy.[9] We interpret the abatement cost $C(a)$ as a set-up cost for a given production capacity, and it is increasing in the emission factor a. This cost is related to the firm's knowledge capital and technological portfolio, including patents, and cannot be transferred or imitated.[10]

The good is also produced in the foreign country (f) with unlimited supply at unit cost c_f and with an emission factor of $\gamma \geq 1$: this means that the production process abroad is at least as carbon intensive as the domestic one. This assumption is consistent with the general lack of carbon pricing that exists outside the European Union. While carbon emissions are free in the foreign country, they are priced in the home country at rate $\tau > 0$ per ton of CO_2. Carbon pricing increases the production cost with uncontrolled emissions in the home country from c_h to $c_h + \tau$. We assume that $c_f < c_h + \tau$: carbon pricing makes foreign firms more competitive than domestic ones without pollution abatement.

We assume perfect competition in the sense that firms are price-takers[11], and entry is free.[12] The demand function for the polluting good is $D(p_h)$, decreasing with the price p_h. We denote inverse demand with $P(Q)$ and consumers' surplus with $S(Q) = \int_0^Q P(x)dx$ where Q is the aggregate consumption in the home country.

We now examine three policy tools aimed at addressing carbon leakage: free allowances, a CBAM and a CBAM with export rebates.

[9] For instance, producing steel with the standard production process of combining iron and coke in a furnace has an emission factor of 2 tons of CO2 per ton of steel. It can be reduced by recycling steel, by sequestrating and storing the CO2 emissions from the coke combustion, or using hydrogen combined with with hydro or nuclear power instead of coal (see also McKinsey Report).

[10] Note that the model encompasses fully transferable abatement technologies in the specific case of only one type $\theta = \underline{\theta} = \overline{\theta}$, or of very high production capacity q.

[11] Home firms are price-takers even when they are exclusive producers of the good (e.g. when they export), as there is a continuum number of firms, so producers never have control over prices.

[12] Note that, since abatement costs are firm-specific, the entry of firms of a given type θ is bounded by the production capacity q. This assumption is without loss of generality, as production capacity can be high enough to fill up domestic demand. Note also that the entry or exit condition would be similar with random abatement, except that it would be ex-post similar to the productivity shock model in Hopenhayn, 1992.

2.2 Free emissions allowances

We first investigate how providing some emission allowances for free or subsidizing output affects the economy. In an emission trading scheme, firms receive a share α of free allowances per output with $0 \leq \alpha \leq 1$. Given the price of allowances τ, getting a share α of allowances for free reduces the cost of carbon pricing from τ to $(1-\alpha)\tau$ per output. The case $\alpha = 0$ corresponds to full carbon pricing while $\alpha = 1$ means that all allowances are free. By selling the allowances assigned for free in the ETS market, a firm obtains $\alpha\tau$ per output. A share α of free allowances is therefore equivalent to a subsidy $\alpha\tau$ per output. Our analysis encompasses both free allowances in an ETS and output subsidies in any carbon pricing mechanism.[13]

Given α, the profit of firm of type θ with an output market price p and a carbon price τ is:

$$\pi_\alpha(a,\theta) = [p - c_h - \theta C(a) + \alpha\tau - (1-a)\tau]q. \tag{1}$$

Each firm θ chooses how much to invest into abatement a to maximize its profit $\pi_\alpha(a,\theta)$. Differentiating $\pi_\alpha(a,\theta)$ with respect to a yields the following first order condition for an interior solution:

$$\theta C'(a) = \tau. \tag{2}$$

The firm θ invests in abatement up to equalize the marginal cost of abatement to the marginal benefit, i.e. the price of the carbon emission saved. Investment into abatement is thus driven by the carbon price regardless of the share of free allowances α. Without loss of generality, we assume that $\theta C'(0) < \tau$ to avoid corner solutions ($a^*(\theta) > 0$ for all θ), and thus the optimal abatement level is:

$$a^*(\theta) = C'^{-1}\left(\frac{\tau}{\theta}\right). \tag{3}$$

It is easy to show that, as long as some allowances are provided for free, some firms can benefit from the carbon pricing through their investment into emission abatement. Indeed, firm θ's optimal profit with 100% free allowances is $\pi_1(a^*(\theta),\theta) = [p - c_h - \theta C(a^*(\theta)) + a^*(\theta)\tau]q$, higher than the unregulated profit $\pi_1(0,\theta) = [p - c_h]q$ as long as $a^*(\theta)\tau > \theta C(a^*(\theta)$. The latter inequality holds by definition of $a^*(\theta)$ whenever $a^*(\theta) > 0$. More generally, a firm of type θ enjoys windfall profits from carbon pricing by receiving a share α of free allowances if $\alpha\tau + (1 - a^*(\theta))\tau > \theta C(a^*(\theta))$: in other words, the net trade of allowances more than offsets abatement costs. Importantly, when production costs are the same in the two countries, $c_h = c_f$, free allowances with abatement make some domestic firms more competitive than foreign firms. In the extreme case of all allowances for free ($\alpha = 1$), home producers are at the same level playing field as foreign ones, i.e. they have the same production cost with carbon pricing. However, by abating, home firms can become competitive abroad with their optimal abatement level $a^*(\theta)$.

[13] Note that with an output subsidy $\alpha\tau$, the parameter α is not bounded by 1. Also, with a carbon tax, α can be interpreted as the share of the tax revenue refunded to firms per unit of output.

Although the share of free allowances α does not impact how much a given firm θ invests into abatement $a^*(\theta)$, it determines which firms are profitable depending on their abatement cost type θ. Let us denote $K(\theta, \alpha)$ firm θ's production cost per output net of free allowances α with its optimal management strategy $a^*(\theta)$:

$$K(\theta, \alpha) = c_h + \theta C(a^*(\theta)) + (1 - a^*(\theta) - \alpha)\tau \tag{4}$$

We have $\frac{\partial K}{\partial \theta} = C(a^*(\theta)) > 0$ (due to the envelope theorem) and $\frac{\partial K}{\partial \alpha} < 0$: production cost is increasing with firm's abatement cost type and decreasing with the share of free allowances. Firm θ produces whenever it is profitable, that is whenever the selling price p exceeds the unit production cost: $p \geq K(\theta, \alpha)$. The active firm with the highest abatement cost earns zero profit. Let us define the cutoff type $\tilde{\theta}$. It is thus defined by the following zero profit condition (per output):

$$p - K(\tilde{\theta}, \alpha) = 0. \tag{5}$$

Since $\frac{\partial K}{\partial \theta} > 0$, all firms of type $\theta < \tilde{\theta}_\alpha$ earn infra-marginal profits per output $p - K(\theta, \alpha) > 0$. They produce up to their production capacity q and, therefore, the aggregate supply is $qG(\tilde{\theta})$.

Before examining the equilibrium outcomes under different trade regimes, we investigate how the cutoff type $\tilde{\theta}$ varies with α and τ. Differentiating (5) with respect to α and using (3) and (4) yields:

$$\frac{d\tilde{\theta}}{d\alpha} = \frac{\tau}{C(a^*(\tilde{\theta}))} > 0. \tag{6}$$

Increasing the share of free allowances α (or the output subsidy) increases firms' profits and thus entry. The cutoff type increases and so is total supply $qG(\tilde{\theta})$. Although increasing α does not modify the abatement effort $a^*(\theta)$, now firms with higher abatement cost types θ are supplying the good.

The impact of a higher carbon price on entry and exit is more ambiguous. Differentiating (5) with respect to τ and using (3) and (4), we obtain:

$$\frac{d\tilde{\theta}}{d\tau} = \frac{\alpha - (1 - a^*(\tilde{\theta}))}{C(a^*(\tilde{\theta}))} \tag{7}$$

The sign of (7) depends on whether the cutoff firm $\tilde{\theta}$ is a net seller or buyer in the allowance market.[14] The firm receives αq allowances while it needs $(1 - a^*(\tilde{\theta}_\alpha))q$ ones to comply with the regulation. If $\alpha < 1 - a^*(\tilde{\theta})$, the firm is short of allowances so it must buy the difference $(1 - a^*(\tilde{\theta}) - \alpha)q$. In this case, by (7), we have $\frac{d\tilde{\theta}}{d\tau} < 0$. In other words, a higher carbon price reduces the profits of all net buyers including firm $\tilde{\theta}$. The firm's type

[14] If the policy consists of a refunded carbon tax, the sign of (7) depends on whether the cutoff firm $\tilde{\theta}$ is a net contributor or beneficiary of the refunded tax system.

with zero profit $\tilde{\theta}$ is thus lower (i.e. with lower abatement costs), and home production $qG(\tilde{\theta})$ decreases. In contrast, if $\alpha > 1 - a^*(\tilde{\theta})$, firm $\tilde{\theta}$ is a net seller of allowances, and therefore benefits from carbon pricing. By (7), we have $\frac{d\tilde{\theta}}{d\tau} > 0$. A higher carbon price increases firm $\tilde{\theta}$'s profits (as well as the profit of all firms with lower abatement costs $\theta < \tilde{\theta}$ who are also net sellers). It thus favors entry into the industry, and therefore increases production $qG(\tilde{\theta})$ in the home country.

We summarize this comparative statics result in the following Lemma.

Lemma 1 *A higher carbon price favors entry (resp. exit) if the firm with the cut off type $\tilde{\theta}$ is a net seller (resp. buyer) of allowances.*

We now examine the equilibrium outcome under **autarky**. Without trade, the price is determined by domestic demand $p = P(qG(\tilde{\theta}_\alpha))$ which, together with the zero profit condition (5), determines the autarky cutoff that we denote $\tilde{\theta}_{A\alpha}$. It is thus defined by the following relationship:

$$P(qG(\tilde{\theta}_{A\alpha})) = K(\tilde{\theta}_{A\alpha}, \alpha). \tag{8}$$

Under **free trade**, competition from abroad drives down the equilibrium price to be equal to the foreign production cost. The equilibrium prices in the home and foreign countries are $p_h = p_f = c_f$. Providing that some domestic producers remain competitive at this price,[15] the cutoff firm type $\tilde{\theta}_\alpha$ is defined by replacing p by c_f in (5), which leads to:

$$c_f = K(\tilde{\theta}_\alpha, \alpha). \tag{9}$$

Domestic supply is $qG(\tilde{\theta}_\alpha)$. The home country imports or exports depending on how the price of the foreign good c_f compares with autarky price $P(qG(\tilde{\theta}_{A\alpha})$. If it is lower, then demand at this price, $D(c_f)$, exceeds domestic supply under autarky, and the good is imported. Conversely, if c_f is higher than the autarky price, foreign firms are not competitive in the home country, and the difference between domestic production and demand is exported.

We summarize this discussion in the following Proposition.

Proposition 1 *For a given share α of free allowances, define the autarky price as $p^{A\alpha} \equiv P(qG(\tilde{\theta}_{A\alpha}))$. The equilibrium outcomes are:*

(a) If $p^{A\alpha} > c_f$: carbon leakage.
Prices are $p_h = c_f = p_f$. Domestic production $qG(\tilde{\theta}_\alpha)$ is lower than consumption $D(c_f)$, the difference being imported.

(b) If $c_f > p^{A\alpha}$: reverse carbon leakage.
Prices are $p_h = c_f = p_f$. Domestic production $qG(\tilde{\theta}_\alpha)$ is higher than consumption $D(c_f)$, the difference being exported.

[15] This happens if the production cost of the most efficient producer is lower than the price, that is if $c_h + \underline{\theta}C(a^*(\underline{\theta})) + (1 - a^*(\underline{\theta}) - \alpha)\tau < c_f$.

In the case of no free allowances $\alpha = 0$, since domestic producers cannot compete with foreign ones, the autarky price $p^{A\alpha}$ is strictly higher than the price under free trade $p_h = p_f = c_f$. Hence only case (a) holds. The domestic supply is $qG(\tilde{\theta})$ where the cutoff firm type $\tilde{\theta}$ is such that $\alpha = 0$ in (9). The remaining domestic demand $D(c_f) - qG(\tilde{\theta})$ is imported. Emissions related to the imported good are leaked outside the home country's jurisdiction. In contrast, when a share α of allowances is assigned for free, domestic production costs are reduced, fostering entry. This translates into an increase of both cutoffs $\tilde{\theta}_{A\alpha}$ (under autarky) and $\tilde{\theta}_{\alpha}$ (under free trade) and, thus, an increase of supply. Under autarky, the price $p^{A\alpha}$ decreases, while it remains unchanged at c_f under free trade. Hence, increasing α not only reduces imports and, therefore emission leakage, by increasing domestic supply, but it may also reverse trade and leakage by shifting the economic outcome from (a) to (b).

Proposition 1 is illustrated in Figure 1. The (inverse) demand $P(Q)$ is graphed in red. The supply can be found by expressing the cutoff type in terms of domestic demand $Q = qG(\theta)$ into its production cost $K(\theta, \alpha)$. That is substituting $\theta = G^{-1}(Q/q)$ into $K(\theta, \alpha)$ to obtain $K(G^{-1}(Q/q), \alpha)$. It is graphed in blue for $\alpha = 0$ (full carbon pricing) and $\alpha > 0$ (free allowances). Point (A), where home demand and supply curves intersect, represents the equilibrium under autarky and without free allowances. When there is free trade but still no free allowances, the equilibrium shifts to (B): the demand is not fully satisfied by the domestic supply $qG(\tilde{\theta}_0)$ and the difference is imported. Increasing the share α of free allowances moves downward the supply curve from $K(\tilde{\theta}, 0)$ to $K(\tilde{\theta}, \alpha)$ as it makes home firms more competitive. The new equilibrium (C) corresponds to the case in which domestic firms are able to export. Domestic supply $qG(\tilde{\theta}_{\alpha})$ exceed domestic demand $D(c_f)$ and therefore the difference $qG(\tilde{\theta}_{\alpha}) - D(c_f)$ is exported. Hence, under free trade, while the supply curve $K(\tilde{\theta}, 0)$ without free allowances in Figure 1 leads to the economic outcome (a) with carbon leakage, assigning allowances for free can move down the supply curve to $K(\tilde{\theta}, \alpha)$ and, therefore, leads to the economic outcome (b) with reverse leakage.

2.3 Carbon Border Adjustment Mechanism

We now analyze the equilibrium outcome with the introduction of a CBAM. The CBAM imposes a tariff on imports based their carbon footprint γ and the carbon price τ. The tariff is $\gamma\tau$ for each good imported in the home country.

With a CBAM, the cost of supplying one unit of good for foreign firms is c_f abroad and $c_f + \gamma\tau$ in the home country. The equilibrium price abroad is $p_f = c_f$. The zero-profit condition which defines the cutoff type $\tilde{\theta}$ depends on which market is relevant for setting the price. If the home country is importing, domestic and foreign firms compete on the home county's market so that the equilibrium price is the highest production cost plus the carbon tariff, $p_h = c_f + \gamma\tau$. In contrast, if the home country exports the good, firms compete outside the home country's borders with an equilibrium price set by for-

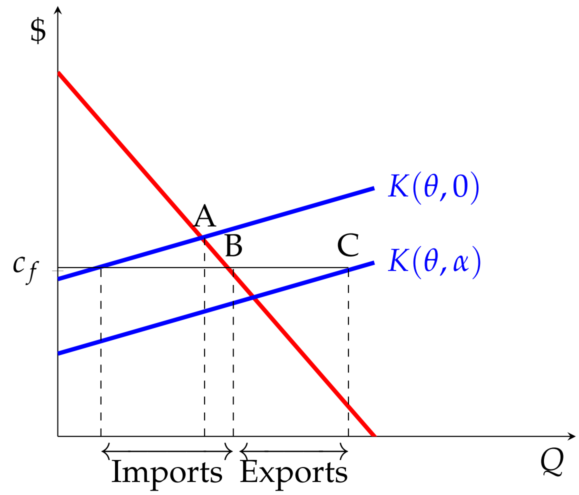

Figure 1: Equilibria with $\alpha = 0$ (full carbon pricing) and $\alpha > 0$ (free allowances). Point A is the equilibrium under autarky with $\alpha = 0$. Point B is the equilibrium under free trade with $\alpha = 0$. Point C is the equilibrium under free trade with a share $\alpha > 0$ of free allowances.

eign firm's production cost on international markets, $p_f = c_f$, which is unaffected by the carbon price. Hence, we can define a new cutoff type $\tilde{\theta}_{\gamma\alpha}$ under the case in which the home country imports with a zero profit condition with a domestic price $p_h = c_f + \gamma\tau$ as follows:

$$c_f + \gamma\tau = K(\tilde{\theta}_{\gamma\alpha}, \alpha). \tag{10}$$

When instead the home country exports in equilibrium, the cutoff type is defined by the zero-profit condition on foreign markets, that is with a market price $p_f = c_f$. Hence the cutoff type with exports is the free-trade one denoted $\tilde{\theta}_\alpha$ and defined in (9).

The economic outcomes with a CBAM and free allowances are described in the following proposition. The proof is in Appendix A.1.

Proposition 2 *Under a CBAM with a share α of free allowances, the equilibrium outcomes are:*

(a) If $p^{A\alpha} > c_f + \gamma\tau$: carbon leakage.
Prices are $p_h = c_f + \gamma\tau > p_f = c_f$. Domestic production $qG(\tilde{\theta}_{\gamma\alpha})$ is lower than consumption $D(c_f + \gamma\tau)$, the difference being imported.

(b) If $c_f + \gamma\tau > p^{A\alpha} > c_f$: no carbon leakage.
Prices are $p_h = p^{A\alpha} > p_f = c_f$. The home country supplies its own demand $qG(\tilde{\theta}_{A\alpha})$.

(c) If $c_f > p^{A\alpha}$: reverse carbon leakage.
Prices are $p_h = p_f = c_f$. Domestic production $qG(\tilde{\theta}_\alpha)$ is higher than consumption $D(c_f)$, the difference being exported.

Introducing a CBAM has three distinct effects on the equilibrium of the model. First, it increases the lower bound on the autarky price for case (a) by $\gamma\tau$. This implies that imports and thus carbon leakage are less likely, given the production and abatement costs. Second, it might lead to an autarky equilibrium, the new case (b). In fact, starting from case (a) of Proposition 1, the CBAM shuts down imports if $p^{A\alpha} \leq c_f + \gamma\tau$. This "no-trade" outcome occurs for two reasons. On one hand, foreign firms are no longer competitive domestically because of the CBAM. On the other hand, the share of free allowances α is not sufficiently high to make domestic firms competitive abroad. Producers are fully protected domestically but not competitive enough on international markets. Third, the CBAM increases the domestic price of the good by $\gamma\tau$ in cases (a) and (b). This favors entry as $\tilde{\theta}_{\gamma\alpha} > \tilde{\theta}_{\alpha}$ for any α, which thus increases domestic production compared to case (a) in Proposition 1.[16]

If the CBAM replaces free allowances, the equilibrium outcome described in Proposition is such that $\alpha = 0$. By removing free allowances, both the lower bound for carbon leakage (case a) and the autarky price increase. To see how replacing free allowances with a CBAM modifies the the equilibrium outcome, we illustrate Proposition with $\alpha = 0$ in Figure 2 below, and compare it with Figure 1.

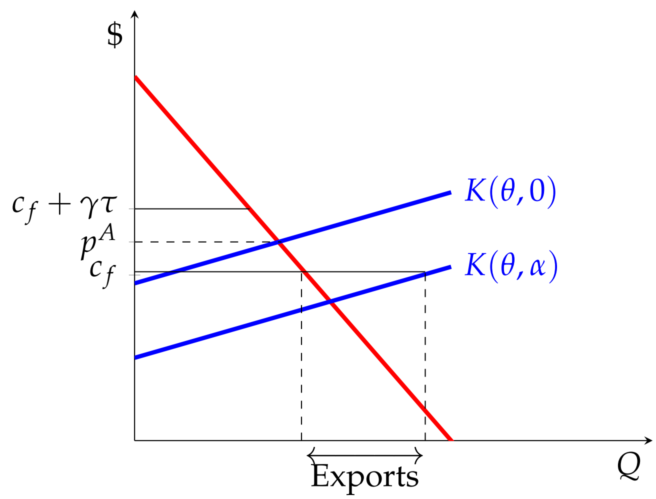

Figure 2: Equilibria with a CBAM.

Thanks to the CBAM, the full carbon price (i.e. no free allowances $\alpha = 0$) is implemented in equilibrium without carbon leakage in the case graphed in Figure 2. It is so because the autarky price with zero free allowances P^A is lower than the cost of imported goods $c_f + \gamma\tau$. The equilibrium outcome is the one described in case (b), namely autarky. The carbon tariff $\gamma\tau$ makes imported goods less competitive than domestic ones. The CBAM eliminated international trade and no carbon emission is leaked.

[16]Note that, in case (c) of reverse leakage, the CBAM has no effect on the economy, as nothing is imported. The equilibrium outcome is similar to the one of case (b) in Proposition 1.

Carbon emissions do leak if the line $c_f + \gamma\tau$ moves downward below the autarky price p^A (because of lower foreign production cost c_f or emission factor γ). Foreign products are competitive in the domestic market even with a CBAM and, they are therefore imported. Carbon emissions also leak if the supply curve $K(\theta, 0)$ moves upward and cross the the line $c_f + \gamma\tau$ (because of higher domestic production cost c_h or emission abatement costs $\theta C(a^*(\theta))$). Some home producers cannot compete with foreign producers in the domestic market despite the CBAM. Domestic products are replaced by foreign products in the home country.

With a CBAM, free allowances can reverse carbon leakage. It does so by moving downward the supply curve such that it crosses the demand function (in red) below the horizontal line c_f as for $K(\theta, \alpha)$ in Figure 2. It means that home producers are competitive both in the domestic and foreign markets. They produce at lower cost than their foreign competitors c_f. They are able to supply fully the domestic market as well as to export. Carbon emissions do not leak outside the home country. To the contrary, home products reduces emissions globally by replacing more carbon intensive foreign products abroad. Carbon leakage is negative.

Moreover, similarly to 1, we now examine how the carbon price impacts entry and exit in the industry with the CBAM. Differentiating (10) leads to

$$\frac{d\tilde{\theta}_{\gamma\alpha}}{d\tau} = \frac{\gamma + \alpha - (1 - a^*(\tilde{\theta}_{\gamma\alpha}))}{C(a^*(\tilde{\theta}_{\gamma\alpha}))}. \tag{11}$$

Comparing (11) with (7) shows that $\tilde{\theta}_{\gamma\alpha}$ is more likely to be increasing with τ than $\tilde{\theta}_\alpha$. Hence a carbon price increase is more likely to favor entry when a CBAM is implemented. It is so even if the firm of type $\tilde{\theta}_{\gamma\alpha}$ is a net buyer of emission permits. This happens because home producers benefit from an increase in the carbon price through an increase in the equilibrium price p_h, which might compensate for the net cost of purchasing allowances.

Before moving to analyzing export rebates, we highlight that free allowances are not effective in mitigating carbon leakage with a CBAM if the carbon tariff is adjusted to the share of free allowances, as prescribed in the EU's CBAM proposal during the transition period (Ambec, 2022). All producers, domestic and foreign, will pay the same share of carbon emission $1 - \alpha$ decreasing with the share of free allowance α. The carbon tariff is then set to $\gamma\tau(1 - \alpha)$ during the transition period, and, as α diminishes, it increases up to $\gamma\tau$. Adjusting the CBAM to the share of free allowances more than offsets the reduction of carbon leakage induced by free allowances. It reduces the cost of foreign products by $\gamma\alpha\tau$ while free allowances decrease the cost of domestic products by $\alpha\tau$. With a higher emission factor of foreign products $\gamma > 1$, since $\gamma\alpha\tau > \alpha\tau$, foreign producers obtains a higher cost reduction than domestic ones. Foreign producers become more competitive in the domestic market and thus import more in the home country, which results into more carbon leakage.[17] Carbon leakage turns out to be higher with free allowances. Put

[17]This can be formally shown by noticing that adjusting the carbon tariff to free allowances modifies the

differently, carbon leakage in the EU would be better addressed by removing right away free allowances while implementing the CBAM without the transition period.

2.3.1 CBAM and export rebates

We now examine how assigning free allowances only on exported output, a policy called "export rebates", impacts the equilibrium. The share of free allowances is a rebate on the carbon price on the export base. Export rebates with the CBAM makes climate policy vary with the geographical scope of the market. If the product is sold domestically, the firm has to buy all emissions permits at price τ but is able to sell at a potentially higher price thanks to the CBAM. If the product is exported, the firm gets a share α of allowances for free and a price equals to production cost of its foreign competitors.

Let us consider each of the possible economic outcomes (leakage, no leakage, reverse leakage) with export rebates. Under leakage, since no domestic firms export, no export rebates are provided, and firms buy all of their allowances, so $\alpha = 0$. The cutoff type in the home country market is thus $\tilde{\theta}_\gamma$ defined by equation (10). Under no leakage, the same logic applies because again domestic firms do not export. The cutoff type is defined by (8) with $\alpha = 0$. In contrast, under reverse leakage, the domestic firms are exporting so they receive export rebates. The zero-profit condition is given by (9) so that the cutoff type is $\tilde{\theta}_\alpha$. Proceeding similarly to the proof of Proposition 2, we obtain the following result. The proof is in Appendix A.2.[18]

Proposition 3 *Define the autarky price when $\alpha = 0$ as $p^A \equiv P(qG(\tilde{\theta}_A))$. With the CBAM and export rebates, the equilibrium outcomes are:*

(a) If $p^A > c_f + \gamma\tau$: carbon leakage.
Prices are $p_h = c_f + \gamma\tau > p_f = c_f$. Domestic production $qG(\tilde{\theta}_\gamma)$ is lower than consumption $D(c_f + \gamma\tau)$, the difference being imported.

(b) If $c_f + \gamma\tau > p^A > c_f + \alpha\tau$: no carbon leakage.
Prices are $p_h = p^A > p_f = c_f$. The home country supplies its own demand $qG(\tilde{\theta}_A)$.

(c) If $c_f + \alpha\tau > p^A$: reverse carbon leakage.
Prices are $p_h = c_f + \gamma\tau > p_f = c_f$. Domestic production $qG(\tilde{\theta}_\alpha)$ is higher than consumption $D(c_f + \gamma\tau)$, the difference being exported.

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domestic price with leakage from $c_f + \gamma\tau$ to $c_f + \gamma\tau(1-\alpha)$ in the left-hand side of (10). The supply function $K(\theta, \alpha)$ in the right-hand side being unchanged, the cutoff firm type $\tilde{\theta}_{\gamma\alpha}$ is reduced and so is domestic production $qG(\tilde{\theta}_{\gamma\alpha})$. Since the domestic price is lower, demand increases and imports are higher.

[18] Note that the choice between selling domestically or abroad is straightforward when $\alpha > \gamma$. By selling abroad a firm obtains $p_f + \alpha\tau$ per output while it gets p_h domestically. With equilibrium prices $p_f = c_f$ and $p_h \leq c_f + \gamma\tau$, exporting is more profitable for all firms (regardless of their type θ) when $c_f + \alpha\tau > c_f + \gamma\tau$, that is when $\alpha > \gamma$ with $\tau > 0$. In this case, all firms in the home country export their production, and demand is supplied by foreign firms.

We can compare Propositions 2 and 3 to understand how export rebates modify the equilibrium outcomes with a CBAM. The cutoff on autarky price p^A that distinguish between carbon leakage (case a) and no carbon leakage (case b) is then $c_f + \gamma\tau$ in both Propositions 2 and 3.The carbon leakage and no carbon leakage cases (a) and (b) respectively are identical because, since there is no export, the export rebate does not apply. What changes with export rebates is the lower bound on the autarky price P^A for which the equilibrium involves export and carbon leakage (case c). Since this lower bound on P^A increases by $\alpha\tau$, the economy moves from autarky to exports whenever $c_f > p^A > c_f + \alpha\tau$ with export rebates. By exporting, home producers obtain the rebate $\alpha\tau$ in addition to the foreign price c_f, which makes more of them profitable. They are thus able to export and, therefore, to reverse the leakage problem. The export rebate levels the playing field abroad by exempting home producers of a share α of their emission costs. It reduces gab the carbon cost paid for supplying the foreign market by $\alpha\tau$ per ton of CO2 equivalent.

3 Welfare analysis

3.1 Social welfare with climate cost

In this section we investigate how free allowances and the CBAM impact social welfare. The negative impact of carbon emissions is embedded in the social welfare through two terms: the social cost of carbon δ and carbon emitted by the sector globally E_W. The social cost of carbon assigns a value to each ton of CO2 equivalent greenhouse gases. It might differ from the carbon price if the latter is not at its first-best level. By assuming $\tau \leq \delta$, we do not rule out the possibility that carbon is under-priced.

Global emissions E_W are the sum of the domestic and foreign territorial emissions. Denoted E_T, the territorial emissions in the home country are:

$$E_T = q \int_{\underline{\theta}}^{\tilde{\theta}} (1 - a^*(\theta)) dG(\theta). \tag{12}$$

To compute the territorial emissions abroad, let D_f be the demand function in the foreign country. Consumption abroad occurs at price $p_f = c_f$ (irrespective of whether the good is produced locally or is imported from the home country). Total production in the foreign country is equal to foreign consumption net of trade, that is $D_f(c_f) + [D(p_h) - qG(\tilde{\theta})]$. Territorial emissions in the foreign country are thus $\gamma[D_f(c_f) + D(p_h) - qG(\tilde{\theta})]$. Therefore, global emissions are:

$$E_W = q \int_{\underline{\theta}}^{\tilde{\theta}} (1 - a^*(\theta)) dG(\theta) + \gamma[D_f(c_f) + D(p_h) - qG(\tilde{\theta})]. \tag{13}$$

The social welfare $\mathcal{W}$ adds up the consumers' surplus net of spending,[19] the producers'

[19] By consumers we mean not only final consumers but also producers using the good as an input, e.g. car manufacturers. The demand function reflects the private value of the good for all potential clients.

profits, transfers (the revenue collected from auctioning allowances and for pricing emissions at the border), net of the social cost of global emissions. Denoting δ the social cost of carbon (each ton of CO2 being valued δ) and E_W global emissions of the sector, the social welfare without CBAM is:

$$\begin{aligned}\mathcal{W} &= \underbrace{S(D(p_h)) - D(p_h)p_h}_{\text{Consumers' net surplus}} + \underbrace{\int_{\underline{\theta}}^{\tilde{\theta}} \pi_\alpha(a^*(\theta),\theta)dG(\theta)}_{\text{Producers surplus}} \\ &+ \underbrace{\int_{\underline{\theta}}^{\tilde{\theta}} q[1-a^*(\theta)-\alpha]\tau dG(\theta)}_{\text{Auction revenue}} \underbrace{-\delta E_W.}_{\text{Social cost of emissions}}\end{aligned}$$

With a CBAM, the revenue of collecting the carbon price on imports must be added up to the welfare: $\gamma\tau[D(p_h) - qG(\tilde{\theta})]$ with leakage (case (a) of Propositions 2 and 3), and $\gamma\tau D(p_h)$ under reverse leakage and export rebates (case (c) of Proposition 3). Substituting for the profits defined in equation (1), the auction revenue cancels out with the firms' allowances purchases, so that the welfare without CBAM or with CBAM and reverse leakage simplifies to:

$$\mathcal{W} = S(D(p_h)) - D(p_h)p_h + q\int_{\underline{\theta}}^{\tilde{\theta}}[p_h - c_h - \theta C(a^*(\theta))]dG(\theta) - \delta E_W. \tag{14}$$

With a CBAM and carbon leakage, instead we obtain:

$$\begin{aligned}\mathcal{W} &= S(D(p_h)) - D(p_h)p_h + q\int_{\underline{\theta}}^{\tilde{\theta}}[p_h - c_h - \theta C(a^*(\theta))]dG(\theta) \\ &+\gamma\tau[D(p_h) - qG(\tilde{\theta})] - \delta E_W.\end{aligned} \tag{15}$$

After the transfers cancel out, the home country's welfare can be decomposed into four terms: the consumer's surplus net of spending, the firms' profit gross of the regulation cost, the revenue for pricing the carbon intensity of imports with the CBAM, and the social impact of carbon emissions.

Before analysing the welfare impact of the different leakage mitigation policies depending on how emissions are accounted for, we examine the case of no leakage (and thus autarky), in which $D(p_h) = qG(\tilde{\theta})$ and the cutoff type is $\tilde{\theta}_{A\alpha}$ defined in (8). Substituting $q\int_{\underline{\theta}}^{\tilde{\theta}} p_h dG(\theta) = p_h qG(\tilde{\theta})$ in (15), and using $D(p_h) = qG(\tilde{\theta})$, the welfare in the no-leakage case boils down to:

$$\mathcal{W} = S(qG(\tilde{\theta}_{A\alpha})) - q\int_{\underline{\theta}}^{\tilde{\theta}_{A\alpha}}[c_h + \theta C(a^*(\theta)) + (1-a^*(\theta))\delta]dG(\theta) - \delta\gamma D_f(c_f) \tag{16}$$

Differentiating W with respect to α, and using (3), (4) and (8), we obtain:

$$\frac{d\mathcal{W}}{d\alpha} = -q[(1-a^*(\tilde{\theta}))[\delta-\tau] + \alpha\tau]g(\tilde{\theta})\frac{d\tilde{\theta}}{d\alpha}. \tag{17}$$

The above first-order condition shows that $\frac{d\mathcal{W}}{d\alpha} < 0$ when $\alpha > 0$ as long as $\tau \leq \delta$: the welfare decreases with the share of free allowances when the carbon price does not exceed the social cost of carbon. Therefore the optimal share of free allowances is a corner solution $\alpha^* = 0$ for every $\tau \leq \delta$. Unsurprisingly, without carbon leakage, full carbon pricing is optimal for any carbon price not exceeding the social cost of carbon.

3.2 Optimal share of free allowances

We examine the impact of free allowances on the home country's welfare. We focus on the leakage or reverse leakage cases of Proposition 1 and 2, as we have just addressed the no-leakage case. We sequentially consider the cases without and with a CBAM.

First, without CBAM, differentiating $\mathcal{W}$ in (14) with respect to α, and using (4) and (9), we obtain:

$$\frac{d\mathcal{W}}{d\alpha} = -q[(1 - a^*(\tilde{\theta}))(\delta - \tau) - \gamma\delta + \alpha\tau]g(\tilde{\theta})\frac{d\tilde{\theta}}{d\alpha}. \tag{18}$$

The first term into brackets in (18) is the social cost of the cutoff firm $\tilde{\theta}$'s emissions per output that are not internalized. The higher is the gap between the carbon price τ and the social cost of carbon δ, the higher is this term, which reduces welfare as the share of free allowances increases. This climate cost should be compared to the one of foreign production, namely $\gamma\delta$, the second term into brackets. This is because firm $\tilde{\theta}$'s production is replaced by foreign production if firm $\tilde{\theta}$ is not producing, and so are the carbon emissions. The welfare decreases with more home production - induced by a higher share of free allowances α - if the climate cost of home production not internalized by the cutoff firm $(1 - a^*(\tilde{\theta}))[\delta - \tau]$ exceeds the climate cost of foreign production.

Second, with a CBAM and leakage (case (a) of Propositions 2 and 3), differentiating (15 and using (4) and (10), we obtain:

$$\frac{d\mathcal{W}}{d\alpha} = -q[(1 - a^*(\tilde{\theta}) - \gamma)(\delta - \tau) + \alpha\tau]g(\tilde{\theta})\frac{d\tilde{\theta}}{d\alpha}, \tag{19}$$

With the CBAM, the climate cost is partly internalized by foreign firms when importing to the home country. Hence, the welfare impact of increasing home production with a higher share of free allowances depends solely on the difference between the emission intensity of the domestic and foreign products $1 - a^*(\tilde{\theta}) - \gamma$ for the climate cost not internalized $\delta - \tau$. If the cutoff firm produces less carbon intensive products than foreign firms, i.e. if $1 - a^*(\tilde{\theta}) < \gamma$, the welfare can be increased by fostering more home production through free allowances. The magnitude of this welfare increase is the climate cost not internalized by firms $\delta - \tau$.

Lastly, with CBAM and reverse leakage (case (c) of Propositions 2 and 3), differentiating the welfare with respect to α yields (18). By increasing exports, export rebates α substitute foreign products by home products in international markets. The carbon intensity of those foreign products being not priced, the carbon impact of this substitution should be evaluated by comparing $\delta - \tau$ with δ. Using (18) and (19), we prove the following result in Appendix A.3.

Proposition 4 *All allowances should be free without CBAM or with CBAM under reverse leakage. Some allowances should be free with CBAM under leakage if $\tau < \delta$ but none should be free if $\tau = \delta$. Under autarky, no allowance should be free if $\tau \leq \delta$.*

Proposition 4 characterizes the conditions for which free allowances or export rebates should be part of the carbon mitigation policies. When the domestic market is not protected by a CBAM, assigning allowances for free turns out to be welfare enhancing, because foreign products with higher emission-intensity are replaced with domestic products. Thus, global emissions decrease, improving welfare. This substitution effect with free allowances is also welfare enhancing with a CBAM under reverse leakage. The same applies with export rebates under reverse leakage.

In contrast, with a CBAM and leakage, free allowances improve welfare due to the substitution effect if the climate cost of production is only partly internalized with carbon pricing, that is if $\tau < \delta$. In contrast, with Pigou pricing $\tau = \delta$, free allowances are no longer optimal. Both consumers and producers (including the foreign ones) fully internalize the climate cost of their decisions, and the climate cost δ is embedded into the domestic price.[20]

Note that, in Appendix A.4, we also investigate to what extent our results hold when $\gamma < 1$, i.e. when foreign goods have lower carbon emissions than domestic ones. We show that free allowances and export rebates remain optimal as long as γ is not too low.

Finally, we can proceed similarly to investigate the optimal output subsidy s^* instead of share of free allowances α^* by setting $s = \alpha\tau$ in (18) or (19).[21] Without CBAM or with CBAM and reverse leakage, the welfare function being concave in s, the optimal subsidy s^* is found by equalizing the left-hand side of (18) to zero, which leads to:

$$s^* = \gamma\delta - (1 - a^*(\tilde{\theta}))(\delta - \tau). \tag{20}$$

If carbon is priced at its social cost ($\tau = \delta$), then (20) boils down to $s^* = \gamma\delta$. The subsidy should ideally compensate for the climate cost of foreign products. If the carbon price is constrained to be lower that the social cost of carbon ($\tau < \delta$), then the subsidy covers the net climate cost that is not internalized.

[20]Note that without CBAM, 100 % of allowances should be free even with Pigou carbon pricing because the climate cost are not internalized by consumers and foreign firms. Similarly, under CBAM and reverse leakage, exports should be subsidized with 100% free allowances on exported production because the climate cost of this sector is not internalized on international markets.

[21]Note that the term $\frac{d\tilde{\theta}}{d\alpha}$ should be replaced by $\frac{d\tilde{\theta}}{ds} = \frac{1}{C(a^*(\tilde{\theta}))}$ which is found by differentiating $c_f = c_h + \tilde{\theta}C(a^*(\tilde{\theta})) + (1 - a^*(\tilde{\theta}))\tau - s$ with respect to s and $\tilde{\theta}$.

3.3 Welfare impact of the CBAM

We now investigate whether implementing a CBAM improves welfare, conditional on the share of free allowances. We show the following proposition in Appendix A.5.

Proposition 5 *A CBAM is welfare-enhancing for any share of free allowances* α.

The CBAM is welfare-enhancing because it makes the domestic market internalize a part of, if not all, the climate externality. Imports are priced at a level closer to their social cost for any carbon price $\tau < \delta$, and at their social cost when $\tau = \delta$. Thus the domestic price incorporates at least part of the climate cost, and the firms that survive to competition are those with lowest emission factors. On the supply side, production costs are minimized at the industry level given the cost of one ton of CO2 emitted τ. On the demand side, only consumers who value the good more than the production cost of the less efficient active firm with the carbon price τ get it. The welfare is maximized when the carbon price reflects its social cost $\tau = \delta$.

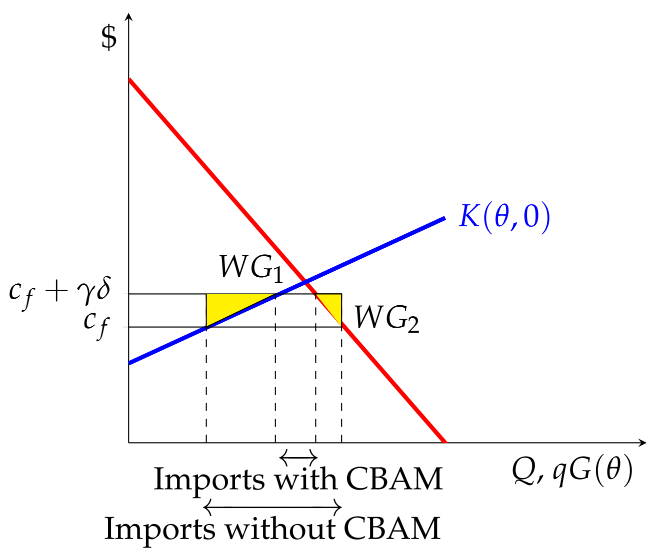

Figure 3: Welfare gains with CBAM, with $\tau = \delta$.

The welfare gain from implementing a CBAM in case of leakage is graphed in Figure 3 in the case $\tau = \delta$ and no free allowances. On the supply side, domestic supply $K(\theta, \alpha)$ internalizes the social cost of carbon through carbon pricing with or without CBAM. Foreign supply without CBAM (represented by the line c_f) does not, unless carbon is priced at the border, in which case the domestic supply is the line $c_f + \gamma\delta$. The area WG_1 is part of the welfare gain from setting up a CBAM. It adds up the difference of social surplus between imports $c_f + \gamma\delta$ and domestic production $K(\theta, \alpha)$ for all imports substituted by domestic production in the left-hand side of the graph. These imports are competitive without CBAM because their production cost c_f does not include the climate cost $\gamma\delta$. However, they are not optimal because $\gamma\delta$ should be added to the production cost. This is precisely what the CBAM is doing, which makes foreign products less competitive.

On the demand side, the equilibrium price with the CBAM c_f is lower than the product's social cost of production $c_f + \gamma\delta$. Consumers whose valuation of the good is in the range between c_f and $c_f + \gamma\delta$ buy the good, while they should not from an efficiency point of view. The area WG_2 is the welfare loss due to this misallocation: the difference between the consumers' valuation of the good and its social cost for all imports that should not be purchased. This loss is avoided by the CBAM, because it increases the equilibrium price at the product's social cost of production $c_f + \gamma\delta$. Overall, the main message of Proposition 5 is that, with global emissions, free allowances should be complemented with a CBAM or replaced by it.

It is worth to stress that the Pareto dominance of the CBAM relies on the assumption that the emission factor of foreign products γ is correct. Measuring the emission intensity of foreign products at the production plant is challenging in practice. For this reason, γ is often estimated based on a baseline technology and aggregated at the industry level. For instance, in the EU's CBAM project, a default emission factor is applied at the industry level for products whose carbon footprint is not certified by a reliable third party. In this case, the tariff on imports with a carbon price equals to its social cost $\gamma\delta$ is the not actual climate cost of foreign products but rather an approximation. This leads to two sources of inefficiency. First, the market outcome is distorted given the emission factors. On the supply side, competition in the domestic market does not select the less costly products regarding climate impact. The cost of supplying of products is no longer minimized. On the demand side, since the domestic price $p_h = c_h + \gamma\delta$ does not reflect the real social cost of the product, consumption is distorted. For instance, if γ is overestimated, the good is too expensive compared to its real social cost and not enough consumers buy it. The second source of inefficiency has to do with the incentive to reduce carbon emissions abroad. Although the foreign products' emission factor γ is exogenous in our model, in reality it is driven by firms' abatement investment, as we assume for domestic firm. Assigning the right emission factor at the plant level provides optimal incentives to invest into abatement with $\tau = \delta$ to reduce γ. In contrast, abatement investment would be distorted with a wrong approximation, diluted with an emission factor estimated at the industry level, or even absent if the emission factor relies on a baseline technology.

3.4 Territorial emissions

Although global emissions are the appropriate measure to determine the impact of economic activity on the climate, the discussion in the policy arena about emissions targets often refers to territorial emissions. For instance, to asses their compliance with the Paris agreement, countries report their emission inventories to the UNFCCC.[22]. In addition, the EU goal of reducing emission by 55% in 2030 compared to 1990, and to become neutral by 2050, refer to territorial net emissions that are computed yearly by the European union.

[22]See the guidelines in UNFCC reporting requirements.

For this reason, we now investigate the optimality of free allowances and the CBAM with territorial emissions instead of global emissions in the social welfare function. In Appendix A.6, we show the following result:

Proposition 6 *When the welfare function includes only domestic territorial emissions, it is never optimal to assign free allowances or export rebates for any $\tau \leq \delta$. Moreover, the CBAM should not be implemented.*

If only domestic territorial emissions are accounted for, allowances should not be free regardless if their are output-based or export-based. Intuitively, with a carbon price lower than its social cost, firms do not fully internalize the climate externality, and thus entry and production in the industry are over-optimal. Providing allowances for free or export rebates exacerbates this distortion. Instead, with a carbon price equals to the social cost of carbon, firm's private incentives are aligned with the social welfare, and entry and production are efficient with territorial emissions.

Furthermore, with territorial emissions, the CBAM should not be implemented. Since the CBAM reduces imports, it also increases domestic production and thus territorial emissions. In addition, the domestic price increases. Those two negative effect of the CBAM - higher territorial emissions and higher price - are not compensated by the higher inframarginal profits made by the domestic industry with a carbon price at the border.

4 Quantitative analysis

We now use our model to quantitatively investigate the economic impact of carbon leakage mitigation policy tools, with a specific focus on the CBAM. To this end, we first calibrate the model to a baseline year, 2019, and then we simulate several counterfactual scenarios.

4.1 Parametric assumptions

To calibrate our partial equilibrium model, we first impose some parametric assumptions on the abatement cost function $C(a)$, the abatement cost distribution, and the demand function of the representative consumer. In particular, we assume that

$$C(a) = \frac{1 - (1-a)^{1-\beta}}{1-\beta}, \tag{21}$$

where $\beta > 0$. This functional form implies that the abatement costs are convex: increasing the abatement level a (i.e. the fraction of emissions that is produced with clean energy) raises production costs at a rate that increases with a itself. Using this cost function, the first-order condition (2) that determines the optimal abatement level $a^*(\theta)$ for a firm of cost type θ writes:

$$(1 - a^*(\theta))^{-\beta} = \frac{\tau}{\theta}, \tag{22}$$

which leads to an optimal abatement level for firm θ of:

$$a^*(\theta) = 1 - \left(\frac{\tau}{\theta}\right)^{-\frac{1}{\beta}}.$$

We assume $\theta \leq \tau$ to make sure that $a^*(\theta) \geq 0$. We further assume that the inverse of θ (i.e. the abatement productivity) is drawn from a log-normal distribution with mean μ and variance σ^2. Lastly, we assume that consumer preferences are such that, in each sector, the inverse demand function is iso-elastic:

$$P = \left(\frac{Q}{A}\right)^{-\frac{1}{\epsilon}} \tag{23}$$

where $-\epsilon$ is the demand elasticity, Q is the sectoral demand, and A is an exogenous demand shifter. We assume that foreign consumers have the same demand function.

4.2 Model Calibration

We calibrate the model to 2019, the latest year before the Covid pandemic hit the world. We consider two manufacturing sectors that are the target of the CBAM proposed by the European Union: cement and steel.[23] We assume that the home country in our model is the European Union, while the foreign country is the top exporter to the EU in each sector. Specifically, we use Russia as the foreign country for steel, as Russia was the top exporter of these products to the EU in 2019 (according to trade data from UN Comtrade), among the countries that do not have a cap-and-trade system in place. Instead, we use Turkey as foreign country for cement.

We set τ to 25 €, the average price of carbon in 2019 in the ETS (European Court of Auditors, 2020). We obtain the average share of free allowances using data from the ETS (see EU ETS). The resulting α_s are close to 1, revealing that emissions abatement is heavily subsidized in both sectors. For our simulations, we relax the normalization that the domestic emission rate is 1. Instead, we use estimates from the environmental and engineering literature on the sectoral average emission rates (tons of CO2 emitted for each ton produced) in EU, Russia and Turkey.[24] We set the sectoral demand elasticities ϵ_s equal to

[23] The aluminum, electricity and fertilizers sectors are also the target of the proposal, but lack of comprehensive data prevents us to include them in our analysis.

[24] Estimates for average emission rates in the European Union are obtained from the Global Cement and Concrete Association, 2022 and Wörtler et al., 2013. Foreign sectoral average emission rates are based on Turkish estimates for cement (Maratou, 2021); global estimates for steel (World Steel Association, 2020).

previous estimates in the literature.[25]

We then turn to the estimation of the firms' technology parameters. To this end, we use plant-level data on emissions intensity from Italy, kindly made available to us by ISPRA, a public agency that collects environmental data.[26] We use this data to compute the emission intensity for each Italian plant (in tons of CO_2 per ton produced). We use this data set to calibrate the convexity parameter β and the mean and variance of the distribution of the abatement cost θ. To this end, we use the first-order condition (22) for the average firm with cost type $E[\theta]$. After normalizing the average abatement cost to 1, we obtain a simple expression linking emissions $e^*(\theta) = 1 - a^*(\theta)$ for all types θ to the carbon price τ:

$$E\left[(1 - a^*(\theta))^{-\beta}\right] = \tau. \tag{24}$$

To estimate β, we use the observed emissions per output e_i for all plants i and the observed carbon price τ, and minimize the following function

$$\beta = argmin \left\{ \frac{1}{F} \sum_i e_i^{-\beta} - \tau \right\}, \tag{25}$$

where F is the number of plants in our Italian sample (85 in 2019). Our results suggest that $\hat{\beta} = 1.6$. By inverting the F.O.C. above, we then back out the abatement cost type for manufacturing plant i:

$$\theta_i = \frac{\tau}{e_i^{-\hat{\beta}}}. \tag{26}$$

Using the cost types θ_i from (26), and assuming that the productivities (the inverse of θ) are drawn from a log-normal distribution, we estimate the mean and variance to be $\mu = -0.96$ and $\sigma^2 = 1.91$, respectively.[27] We obtain the production capacity q_s as the average quantity produced (expressed in tons) across all plants in each sector in EU.[28] We calibrate the foreign marginal cost, $c_{f,s}$, using the assumption of perfect competition maintained in our model, which implies that the observed import prices should be equal

[25]Demand elasticity estimates are from: Fowlie, Reguant, and Ryan, 2016 for cement and Reinaud, 2005 for steel. Note that these estimates are taken from the environmental literature, and are lower than the typical estimates from the trade literature (see e.g. Caliendo and Parro, 2015 and Adão, Arkolakis, and Esposito, 2019).

[26]We obtained the data thanks to a partnership between the Department of Economic and Statistical Sciences of the University of Naples Federico II and the Superior Institute of Environmental Protection and Research (ISPRA).

[27]The average of a log-normal distribution, with mean μ and variance σ^2, is $A = e^{\mu+\sigma^2/2}$, while its variance equals $V = \left(e^{\sigma^2} - 1\right) e^{2\mu+\sigma^2}$. Using the fact that the average of the implied productivities $1/\theta$ is $A = 1$, and that the observed variance is $V = 5.75$, we find $\sigma^2 = ln\left(\frac{V}{A^2} + 1\right) = 1.91$ and $\mu = ln(A) - \sigma^2/2 = -0.96$.

[28]Sources for quantity produced and number of plants by sector are: for cement, Cembureau, 2019 and Cemnet; for steel, European Commission, 2021b and BoldData.

to the foreign marginal cost of production. We use data on unit values per ton from CEPII and compute the average F.O.B. prices of the imports of EU from Russia and Turkey. We then multiply these import prices by the tariffs imposed by the EU on these goods, which we download from the World Bank WITS dataset, to obtain the foreign price $p_{f,s}$.[29]

We calibrate the domestic marginal costs of production by exploiting the fact that the home country (i.e. the EU) in 2019 was a net importer from the foreign country (i.e. either Russia or Turkey) in the two sectors considered in our analysis. Through the lens of our model, this means that for all the domestic producers, in equation (1) the equilibrium price is equal to the foreign price $p_{f,s}$. We normalize the profits of the marginal entrant, i.e. a firm with abatement level $a = 0$, in equation (1) to 0. Then, since the marginal cost of production, $c_{h,s}$ is the same across all firms, we can invert equation (1) for the marginal entrant in each sector and find $c_{h,s}$.[30]

Lastly, we calibrate the demand shifter A_s such that our model matches the observed import ratio (defined as imports divided by production) of the EU from the top exporter in each sector. In our model, when the home country is an importer, the import ratio equals:

$$Imp_s = \frac{Demand_s - Production_s}{Production_s} = \frac{A_s \left(p_{f,s}\right)^{-\epsilon_s} - q_s(1 - G(\tilde{\theta}_s))}{q_s(1 - G(\tilde{\theta}_s))},$$

where $\tilde{\theta}_s$ solves the zero-profit condition under free-trade:

$$p_{f,s} + \alpha_s \tau = c_{h,s} + \tilde{\theta}_s \frac{1 - \left(\frac{\tau}{\tilde{\theta}_s}\right)^{\frac{\beta-1}{\beta}}}{1 - \beta} + \left(\frac{\tau}{\tilde{\theta}_s}\right)^{-\frac{1}{\beta}} \tau.$$

We combine trade data from UN Comtrade with production data from UNIDO to compute the import ratio in 2019 for each sector, and find the demand shifter A_s such that the model matches the data. Table 1 below reports the relevant parameters by sector.

We discuss the robustness of our quantitative results with respect to the calibrated parameters in Appendix A.8.

4.3 The effects of carbon leakage mitigation policies

We now use the calibrated model to examine the impact of a CBAM, free allowances and export rebates on the trade equilibrium and welfare. We first look at the equilibrium prices under a scenario of a CBAM with a carbon price equal to 80 €, roughly the average price of carbon in the European ETS in 2022. Figure 4 plots, for each sector, the autarky

[29]The average tariffs were very low in 2019, being 0 and 0.28 percent for cement and steel, respectively.

[30]Note that all other entrants make positive profits, because they optimally abate emissions (depending on their heterogeneous abatement efficiency), but they all have the same marginal cost $c_{h,s}$.

	Cement	Iron & Steel
Carbon price (τ)	25	25
Share of free allowances (α)	0.99	0.98
Domestic emission rate	0.84	1.29
Foreign emission rate	0.86	1.83
Demand elasticity (ϵ)	-2	-0.9
Convexity parameter (β)	1.60	1.60
Average log-productivity (μ)	-0.96	-0.96
Variance log-productivity (σ^2)	1.91	1.91
Average capacity (q), in thous.	450	0.36
Foreign price (p_f)	185	2,406
Domestic cost (c_h)	185	2,405

Table 1: Parameters

price, the foreign price, and the foreign price under CBAM, for different values for the share of free allowances, α.

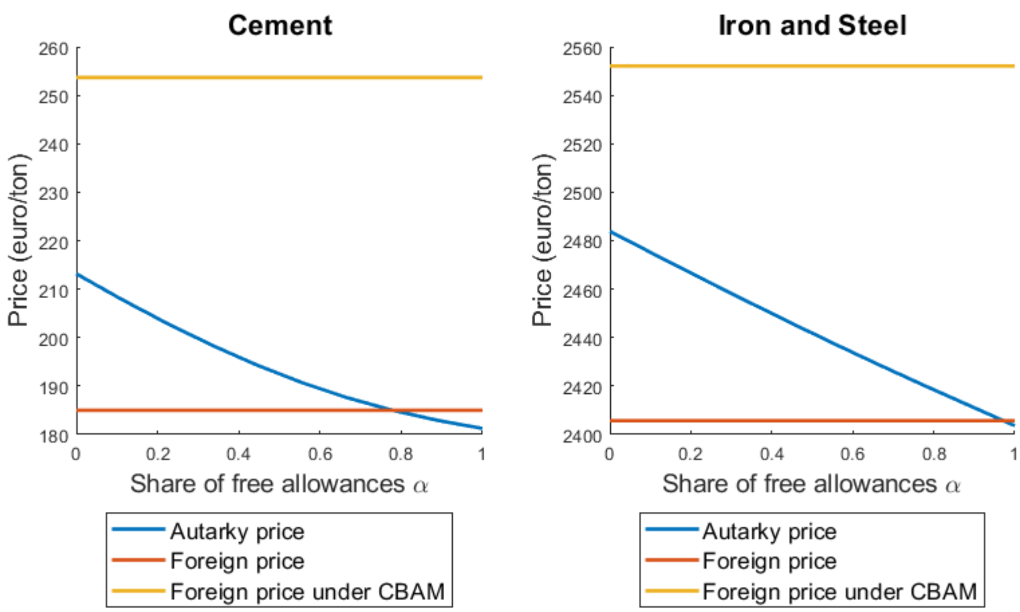

Figure 4: Equilibrium prices with CBAM, with $\tau = 80$.

Without a CBAM, in the cement sector (left panel) an increase in the share of free allowances lowers the autarky price. With low values of α, the autarky price is larger than the foreign price, and thus the home country imports in equilibrium (as in Proposition 1). With high values of α, instead, the home country exports the good. The introduction of a CBAM raises the price of foreign products (foreign price plus carbon tariff) above the autarky one, implying that the home country does not trade in equilibrium when α is low, as the autarky price lies between the foreign price and the foreign price plus the carbon tariff, consistent with Proposition 2. When the share of free allowances is sufficiently high (80%), the home economy switches to exporting, as the autarky price is lower than the foreign price. In the steel sector, a similar pattern emerges, but the economy switches to exporting only when the share of free allowances is close to 100%.[31]

Figure 5 considers the scenario where the cost of carbon is set to 230 €, an approximation of the social cost expected in 2030 in the EU.[32] We can see that, in both sectors, the introduction of a CBAM implies an autarky equilibrium for low values for α, as the autarky price lies between the foreign price and the foreign price plus the carbon tariff, consistent with Proposition 2. When the share of free allowances is sufficiently high, the equilibrium switches to reverse leakage, as the autarky price is lower than the foreign price. Interestingly, the minimal share of free allowances that is necessary to switch to reverse leakage is lower than in the case with $\tau = 80$: it is 50% for cement and 75% for steel. Therefore, with a higher cost of carbon (230 € instead of 80 €), a lower share of free allowances reverses the carbon leakage in both sectors.

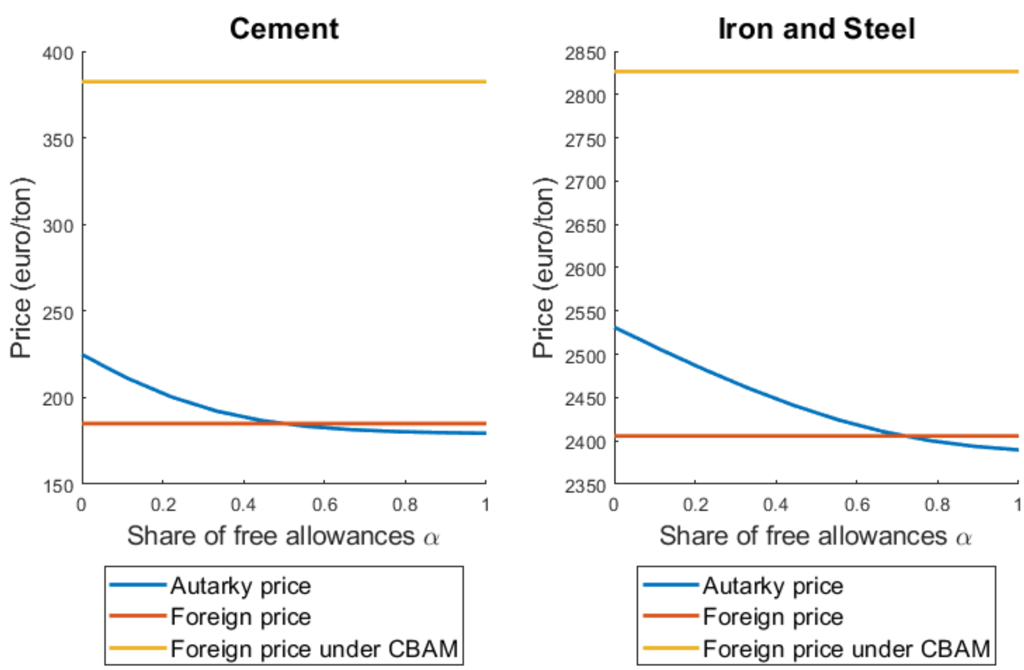

Figure 5: Equilibrium prices with CBAM, with $\tau = 230$.

[31]In Figure 12 in Appendix A.9 we report the same graph, but with a carbon price of 25 €, as in our calibration. We can see that without a CBAM, both sectors always import in equilibrium. With a CBAM the cement sector switches to exporting with a sufficiently high α, while steel keeps importing steel even under a CBAM.

[32]This number is in between the social cost of carbon expected for France (250, see estimate in Quinet, 2019) and the one expected for Germany (205, see estimate from Matthey and Bünger, 2019).

The fact that a higher cost of carbon τ increases exports may seem counterintuitive, as one would expect that a higher cost of carbon increases production costs and thus lowers production. However, in Lemma 1, we have shown that a higher cost of carbon may turn beneficial for domestic producers, if the marginal entrant is a "net seller of allowances," which occurs whenever $\alpha > 1 - a^*(\tilde{\theta}_\alpha)$. To show this mechanism more concretely, in Figure 13 in Appendix A.9 we plot the emission intensity of the marginal (or cutoff) entrant, $1 - a^*(\tilde{\theta}_\alpha)$, i.e. the firm with abatement cost θ equal to the entry cutoff $\tilde{\theta}_\alpha$, against the share of free allowances α. When α is higher than $1 - a^*(\tilde{\theta}_\alpha)$, which occurs to the right of the 45-degree line, the marginal entrant is a "net seller of allowances." In such case, increasing τ increases production and, if α is sufficiently high, the home country exports.

We next examine the economic impact of a CBAM combined with export rebates. In Figure 6 we display the equilibrium prices with a CBAM when the allowances are granted only to exports with a 230 €carbon price. In this scenario, the price schedules differ from when the allowances are given to any output. First, as shown in Proposition 3, the autarky price is found with $\alpha = 0$, and the relevant threshold that switches the equilibrium between autarky and export is now the foreign price c_f plus the export rebate $\alpha\tau$. It is increasing with α and, therefore, the red line is now upward sloping. Second, the autarky price does not depend on α, as domestic production does not grant free allowances. Hence, the blue line is now flat. Interestingly, both sectors never import in equilibrium, and switch from autarky to exporting at a lower α compared to the counterfactual in Figure 5. This suggests that export rebates are more effective in stimulating exports than production rebates, consistent with Proposition 3.

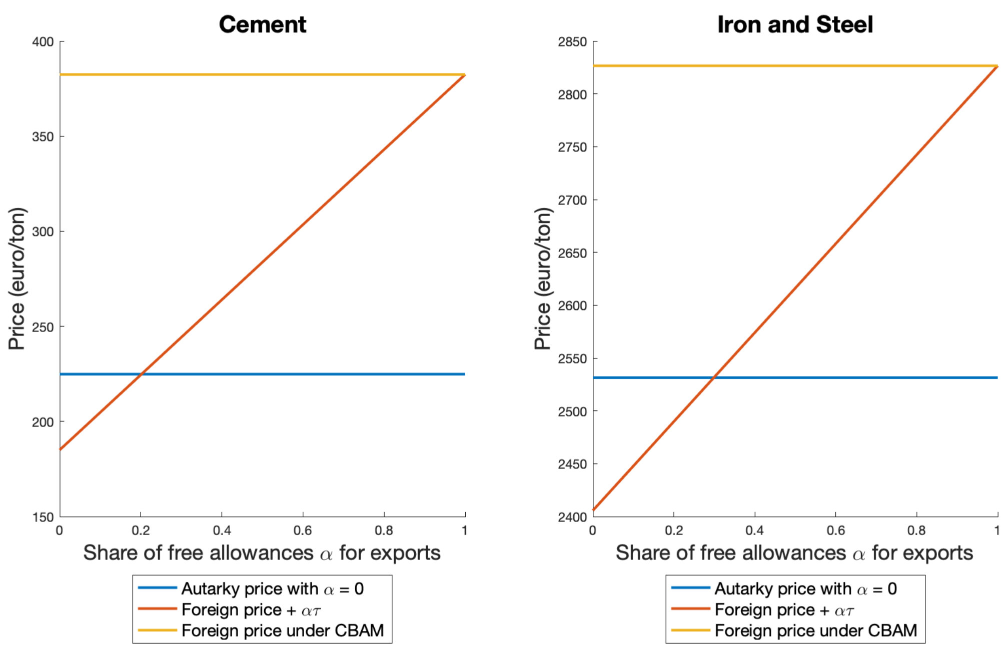

Figure 6: Equilibrium with CBAM and export rebates, with $\tau = 230$.

4.4 Welfare analysis

We now turn to the analysis of the effects of CBAM on total emissions and welfare. In Figure 7 we plot both the territorial emissions, using the expression in equation (12), and the global emissions, as in equation (13), setting the carbon price to 230 €. Two patterns emerge in both sectors. First, territorial emissions increase with the share of free allowances, because they foster production by lowering costs, raising carbon emissions. This is very similar to what occurs in a scenario without CBAM, as shown in Figure 14 in Appendix A.9. In contrast, global emissions first increase with α, but then decrease when the share of free allowances is sufficiently high. This happens because, as α gets larger, the home country exports the good abroad, as previously shown in Figure 5. When this occurs, the high-carbon emissions of foreign producers are replaced by low-carbon emissions of domestic producers, reducing global emissions, and thus carbon leakage. This differs to what happens without CBAM, as Figure 14 highlights how free allowances always significantly reduce global emissions, even when α is lower than 1.

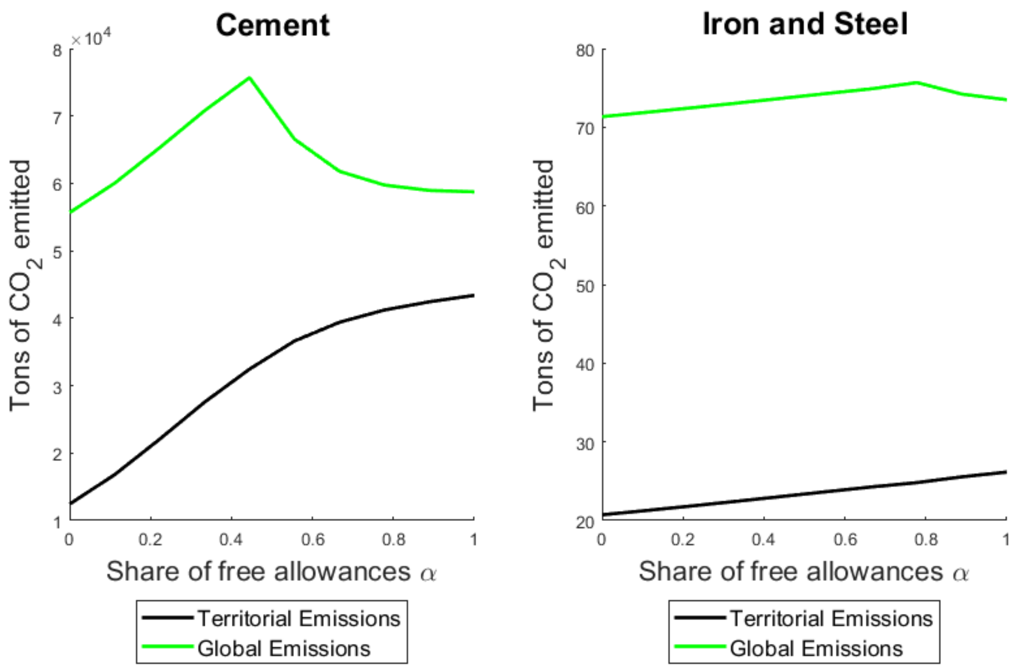

Figure 7: Emissions with CBAM, with $\tau = 230$.

Next, we look at the welfare effects of a CBAM, separately for each sector, using global emissions.[33] As before, we set the carbon price to $\tau = \delta = 230$, its Pigouvian rate. Figure 8 plots welfare for different shares of free allowances, normalizing to 1 the welfare with

[33] Starting from the demand in equation 23, the consumer surplus in sector k can be found as the integral of demand between the willingness to pay, p_0, and the equilibrium price p_h:

$$S_k = \int_{p_h}^{p_0} A_k P^{-\epsilon_k} dP = A_k \frac{1}{1-\epsilon_k} \left((p_0)^{1-\epsilon_k} - (p_h)^{1-\epsilon_k} \right).$$

$\alpha = 0$. Consistent with Proposition 4, trade-adjusted welfare is decreasing in the share of free allowances if the domestic economy is under autarky, as both sectors are for low levels of α. This is because under autarky the social optimum is attained with $\alpha = 0$, and any $\alpha > 0$ leads to over-production, and thus to an autarky price that is too low. In contrast, when the home country exports the good, giving more allowances for free is beneficial, and welfare is increasing in α. This happens because any extra production generated by a more generous subsidy is absorbed by the foreign country, without any negative effect on the export price (which always equals c_f).

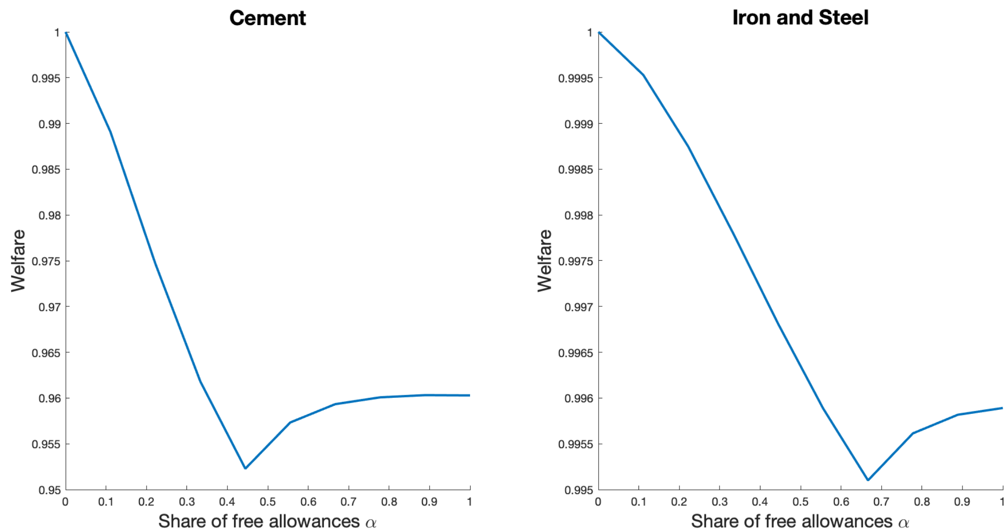

Figure 8: Welfare with CBAM, $\tau = \delta = 230$.

Finally, in Figure 9 we show that welfare with a CBAM is always higher or equal than welfare without CBAM, in both sectors.[34] In addition, welfare without CBAM is always increasing in α, as predicted by Proposition 4. This happens because giving more free allowances, when $\tau = \delta$, increases production but penalizes the resulting higher emissions with the appropriate social cost. Note that, for low levels of α, the economy is under carbon leakage without CBAM and in autarky with CBAM, and welfare with CBAM is strictly larger than without (as in case b of the proof of Proposition 5 in Appendix A.5).

Note that the lowest quantity that can be consumed is 1, so the willingness to pay is $p_0 = (A_k)^{\frac{1}{\epsilon_k}}$. Replacing it into the above we get the surplus in sector k:

$$S_k = \frac{A_k}{1-\epsilon_k}\left((A_k)^{\frac{1-\epsilon_k}{\epsilon_k}} - (p_h)^{1-\epsilon_k}\right).$$

We then use equations (14) or (15) to compute sectoral welfare.

[34] We again normalize to 1 the welfare with CBAM when $\alpha = 0$. Note that in our exercise we are computing the welfare gains from CBAM by simply comparing the welfare in the two equilibria. Thus we are not using a sufficient statistics approach that conditions on observables, as often done in the international trade literature (see e.g. Arkolakis, Costinot, and Rodríguez-Clare, 2012 and Esposito, 2020).

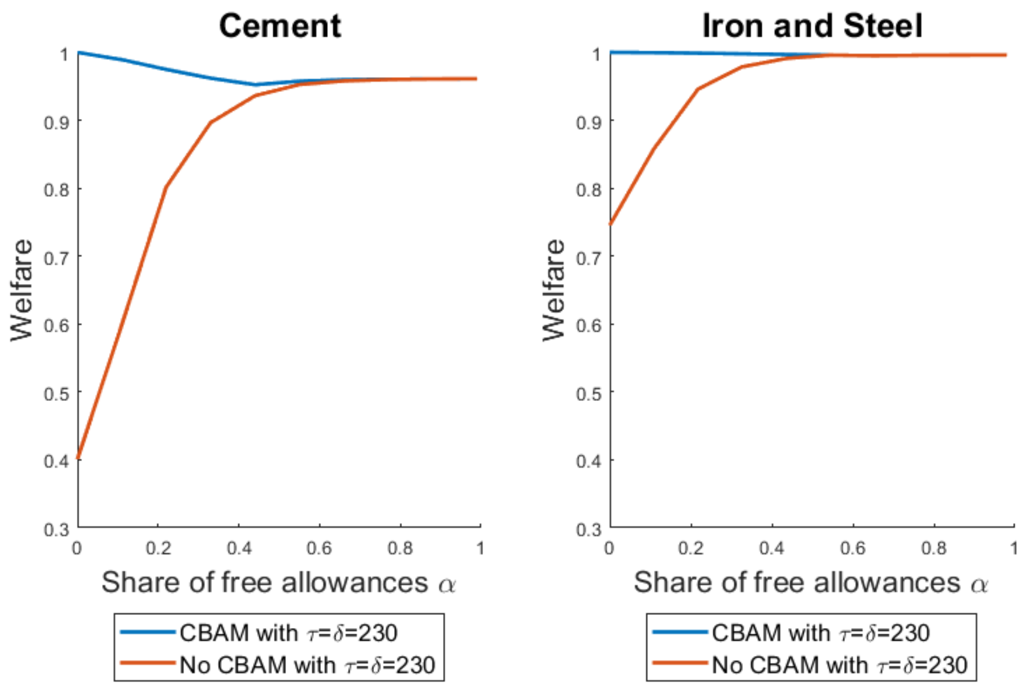

Figure 9: Welfare with and without CBAM, $\tau = \delta = 230$.

Instead, when α is high, there is reverse leakage both with and without CBAM (case c in the proof of Proposition 5). In this case, welfare is the same with or without CBAM because the equilibrium outcomes are the same. The CBAM is ineffective because no good is imported and the domestic price is the foreign price. Overall, welfare gains from CBAM are large and decreasing in the share of free allowances. They range between $0 - 122\%$ for cement and $0 - 33\%$ for steel.

5 Conclusions

How to limit carbon leakage driven by international trade? Should we exempt firms from paying their emission permits, or tax the carbon content of imports with a CBAM? What are the impacts of these leakage mitigation policies? We provide answers to these questions both analytically and quantitatively with a partial equilibrium model calibrated with European data. Although both free allowances and output subsidies are distortionary under autarky, they improve welfare in an open economy. By preserving the competitiveness of less carbon-intensive firms, both policies reduce the emission factor of products in the domestic market if the country imports and internationally if it exports. The CBAM does not help to export (i.e., it does not lead to reverse leakage), but free allowances and export rebates do. Providing free allowances on exports makes the export equilibrium more likely, reducing the emission intensity not only in the producing country but also abroad. It increases the welfare if this reduction of carbon intensity abroad is taken into account. A CBAM is welfare-enhancing for different reasons: either because it switches the economic outcome from imports to autarky, or makes firms (and consumers) pay the entire cost of their carbon emission under imports. Our simulations suggest that the EU would substantially gain from a CBAM in sectors like cement and steel.

To conclude, we discuss four important assumptions we have made in our analysis. First, we have analyzed carbon leakage mitigation policies taking the carbon price as exogenous. Studying the choice of the carbon price (or an emission target in an ETS) is beyond the scope of this paper as it would require setting up a political economy model. However, our model can still shed light on the effects of an exogenous change in the carbon price. We do that analytically in Appendix A.7. There, we formally show that the carbon price has three distinct effects on welfare: a price effect, an abatement effect, and an entry/exit effect. An interesting avenue for future research could be to quantify these channels in a setting with an endogenous carbon tax.

Second, our analysis relies on the assumption that each country-sector produces an homogeneous good. This leads to the equilibrium outcome in which the domestic country either imports, exports, or does not trade. However, in reality, even raw products such as aluminum, cement or steel may be differentiated in quality, shape and brands. This means that, within the same sector, some varieties are imported, while others are exported. While our model does not allow for intra-industry trade, it should be clear that what matters for our results is whether the home country is a net importer or exporter in a given sector, and not the product heterogeneity that may exist within a sector.

Third, by assuming that the good can be supplied internationally with constant marginal cost, we abstract for any effect of anti-leakage policies on the foreign price. With an increasing rather than flat supply curve in the foreign country, the substitution of foreign products by home products that is driven by free allowances and the CBAM would lower the foreign price. It would increase consumption abroad and, thus, mitigate the reduction of global emissions through a scale effect. Therefore, the welfare improvement from CBAM will be lower.

Fourth, the emission intensity of foreign products, γ, is exogenous in our model. Yet foreign firms might be able to reduce γ by investing in pollution abatement like their domestic competitors. For instance, as discussed in the EU proposal, this may require the existence of a certification process (as studied in Cicala, Hémous, and Olsen, 2022). Endogenizing γ with foreign investment in abatement would not change significantly our results. Providing that the imports are charged with firm-specific and well-evaluated emission factor, it would make the CBAM even more attractive by fostering decarbonization abroad. The optimality of free allowances and export rebates with a CBAM should be assessed by comparing the emission factors in both sides of the border, as we explain in Section 3.2. However, this comparison may turn out to be challenging in practice and we leave it for future research.

A Appendix

A.1 Proof of Proposition 2

Under the CBAM, autarky (no leakage) is the equilibrium outcome if the domestic price $p_h = P(qG(\tilde{\theta}_{A\alpha}))$ (with $\tilde{\theta}_{A\alpha}$ defined in (8)) is lower than the cost of imported products $c_f + \gamma\tau(1-\alpha)$ (to avoid imports) and higher than the foreign price $p_f = c_f$ (to avoid exports). Hence whenever $c_f < P(qG(\tilde{\theta}_{A\alpha})) < c_f + \gamma\tau$, the home country does not trade. Domestic firms supply domestic demand with $qG(\tilde{\theta}_A\alpha)$ units of the good.

If $c_f + \gamma\tau < P(qG(\tilde{\theta}_{A\alpha}))$, foreign products are competitive in the home country with the CBAM which charges $\gamma\tau$ per unit imported. The domestic price equals to the cost of imported products $p_h = c_f + \gamma\tau$. With this price in the home country, the cutoff firm's type is found by replacing $p = c_f + \gamma\tau$ in (5), which leads to (10) which defines $\tilde{\theta}_{\gamma\alpha}$. Domestic production is thus $qG(\tilde{\theta}_{\gamma\alpha})$. It supplies the home country with $D(c_f + \gamma\tau)$ units of the product, the rest $D(c_f + \gamma\tau) - qG(\tilde{\theta}_{\gamma\alpha})$ being imported.

If $P(qG(\tilde{\theta}_{A\alpha})) < c_f$, home production is competitive abroad. Home firm exports their production which is sold at price $p_h = p_h = c_f$. The cutoff firm's type is now found by replacing $p_h = c_f$ in (5), which leads to (9) which defines $\tilde{\theta}_\alpha$. Domestic production is $qG(\tilde{\theta}_\alpha)$, from which $D(c_f)$ is consumed domestically, the rest $qG(\tilde{\theta}_\alpha) - D(c_f)$ being exported.

A.2 Proof of Proposition 3

With an export rebate of $\alpha\tau$ and a CBAM, autarky (no leakage) is the equilibrium outcome if (i) the domestic price $p_h = P(qG(\tilde{\theta}_A))$, with $\tilde{\theta}_A$ defined in (8) with $\alpha = 0$, is lower than the cost of imported products $c_f + \gamma\tau$ (to avoid imports), and (ii) the revenue that domestic producers get per output exported $p_f + \alpha\tau = c_f + \alpha\tau$ is lower than by selling domestically at price $p_h = P(qG(\tilde{\theta}_A))$ (to avoid exports). Hence whenever $c_f + \alpha\tau < P(qG(\tilde{\theta}_{A\alpha})) < c_f + \gamma\tau$, the home country does not trade. Domestic firms supply domestic demand with $qG(\tilde{\theta}_A)$ units of the good.

If $c_f + \gamma\tau < P(qG(\tilde{\theta}_A))$, foreign products are competitive in the home country with the CBAM (which charges $\gamma\tau$ per unit imported). The domestic price equals to the cost of imported products $p_h = c_f + \gamma\tau$. With this price in the home country, the threshold firm's type with the highest abatement cost is found by replacing $p_h = c_f + \gamma\tau$ in (5), which leads to (10) which defines $\tilde{\theta}_\gamma$ with $\alpha = 0$. Domestic production is thus $qG(\tilde{\theta}_\gamma)$. It supplies the home country with $D(c_f + \gamma\tau)$ units of the product, the remaining demand $D(c_f + \gamma\tau) - qG(\tilde{\theta}_\gamma)$ being imported.

If $P(qG(\tilde{\theta}_A)) < c_f + \alpha\tau$, home producers can export. Their revenue is $c_f + \alpha\tau$ by exporting. If they sell in the home country, they obtain the market price in the home country which is set at the cost of imports products $c_f + \gamma\tau$. Since $P(qG(\tilde{\theta}_A)) < c_f + \gamma\tau$, then $qG(\tilde{\theta}_A) > D(c_f + \gamma\tau)$ and, therefore, the supply from home producers at price $p_h = c_f + \gamma\tau$ yields strictly positive profits. The zero profit condition is therefore met on exports. The cutoff firm is $\tilde{\theta}_\alpha$ defined in (9). Production in the home country is thus $qG(\tilde{\theta}_\alpha)$. Demand in the home country at this price is $D(c_f + \alpha\tau)$.

A.3 Proof of Proposition 4

First, consider the case without CBAM or with CBAM and reverse leakage. The welfare impact of free allowances $\frac{d\mathcal{W}}{d\alpha}$ is given by (18). We show by contradiction that $\frac{d\mathcal{W}}{d\alpha} > 0$ for every $\alpha < 1$. Suppose $\frac{d\mathcal{W}}{d\alpha} \leq 0$ for one α such that $0 < \alpha < 1$ at least. Then the term into bracket on the right-hand side in (18) should be weakly positive, which implies $\tau[\alpha - (1 - a^*(\tilde{\theta}))] \geq \delta[\gamma - (1 - a^*(\tilde{\theta}))]$. Since $\tau \leq \delta$, for the former inequality to hold, we must have $\alpha \geq \gamma$, which, combined with $\gamma \geq 1$, yields $\alpha \geq 1$, a contradiction. From $\frac{d\mathcal{W}}{d\alpha} > 0$ for every $\alpha < 1$, we conclude that the welfare increases with α up to $\alpha = 1$. Hence $\alpha^* = 1$.

Second, with a CBAM and leakage whereby $\frac{d\mathcal{W}}{d\alpha}$ is defined in (19), we have $\frac{d\mathcal{W}}{d\alpha}|_{\alpha=0} > 0$ if $\delta < \tau$ with $\gamma \geq 1 \geq 1 - a^*(\tilde{\theta})$ as assumed here. Furthermore, substituting $\tau = \delta$ into (19) yields:

$$\frac{d\mathcal{W}}{d\alpha} = -q\alpha\delta g(\tilde{\theta})\frac{d\tilde{\theta}}{d\alpha} < 0,$$

for every $\alpha > 0$ so that the welfare is always decreasing with α. Hence $\alpha^* = 0$ with Pigou carbon pricing with a CBAM and leakage.

A.4 The case with $\gamma < 1$

We briefly examine the efficiency of free allowances under the alternative assumption $\gamma < 1$. First, without CBAM or under CBAM and reverse leakage, $\frac{d\mathcal{W}}{d\alpha}|_{\alpha=0} > 0$ in (18) if $\delta < \tau$ and $\gamma\delta > (1 - a^*(\tilde{\theta}))[\delta - \tau]$. It implies that the welfare increases with α at zero and, therefore, $\alpha^* > 0$. Furthermore, substituting $\tau = \delta$ into (18) yields:

$$\frac{d\mathcal{W}}{d\alpha} = q\delta[\gamma - \alpha]g(\tilde{\theta})\frac{d\tilde{\theta}}{d\alpha}. \tag{27}$$

Since $\frac{d\mathcal{W}}{d\alpha} > 0$ if $\alpha < \gamma$ and $\frac{d\mathcal{W}}{d\alpha} < 0$ if $\alpha > \gamma$, which implies that $\mathcal{W}$ is increasing with α up to $\alpha = \gamma$ and decreasing with α for $\alpha > \gamma$. It is thus maximized at $\alpha^* = \gamma$.

Second, under CBAM and leakage, $\frac{d\mathcal{W}}{d\alpha}|_{\alpha=0} > 0$ in (19) if $\delta < \tau$ and $\gamma > 1 - a^*(\tilde{\theta})$. Hence $\alpha^* > 0$ in this case. If $\tau = \delta$, $\frac{d\mathcal{W}}{d\alpha}$ is given by (27) so that $\alpha^* = 0$.

A.5 Proof of Proposition 5

We consider in sequence the three cases described in Proposition 2.3.

(a) $p^{A\alpha} > c_f + \gamma\tau$: Leakage with and without CBAM.

The welfare without CBAM can be written as:

$$\begin{aligned} \mathcal{W} &= \int_0^{\tilde{\theta}_\alpha} [P(qG(\theta)) - c_h - \theta C(a^*(\theta)) - (1 - a^*(\theta))\delta] dG(\theta) \\ &\quad + \int_{qG(\tilde{\theta}_\alpha)}^{D(c_f)} [P(x) - c_f - \gamma\delta] dx - \delta\gamma D(c_f). \end{aligned} \tag{28}$$

The welfare with CBAM under leakage is:

$$\begin{aligned} \mathcal{W} &= \int_0^{\tilde{\theta}_{\gamma\alpha}} [P(qG(\theta)) - c_h - \theta C(a^*(\theta)) - (1 - a^*(\theta))\delta] dG(\theta)] \\ &\quad + \int_{qG(\tilde{\theta}_{\gamma\alpha})}^{D(c_f+\gamma\tau)} [P(x) - c_f - \gamma\delta] dx - \delta\gamma D(c_f). \end{aligned} \tag{29}$$

Since $\tilde{\theta}_{\gamma\alpha} > \tilde{\theta}_\alpha$ and $D(c_f) > D(c_f + \gamma\tau)$, the welfare difference with CBAM minus without CBAM (29)-(28) writes:

$$\begin{aligned} \Delta\mathcal{W} &= \int_{\tilde{\theta}_{\gamma\alpha}}^{\tilde{\theta}_\alpha} \underbrace{[c_f + \gamma\delta - c_h - \theta C(a^*(\theta)) - (1 - a^*(\theta))\delta]}_{(i)} dG(\theta)] \\ &\quad - \int_{D(c_f+\gamma\tau}^{D(c_f)} \underbrace{[P(x) - c_f - \gamma\delta]}_{(ii)} dx. \end{aligned} \tag{30}$$

First, by (9) and because $\theta C(a^*(\theta)) + (1 - a^*(\theta))\tau$ is increasing with θ, we have $c_f - c_h - \theta C(a^*(\theta)) > (1 - a^*(\theta) - \alpha)\tau$. The last inequality implies that (i) in (30) is higher than:

$$\gamma\delta - \alpha\tau - (1 - a^*(\theta))[\delta - \tau], \tag{31}$$

for every $\theta < \tilde{\theta}_\alpha$. Since $\gamma \geq 1 \geq \alpha$, (31) is weakly higher than $[\gamma - (1 - a^*(\theta))] \geq 0$, where the last inequality is due to he fact that $\gamma \geq 1 \geq 1 - a^*(\theta)$ for every θ and $\tau \leq \gamma$. Hence, (i) in (30) is strictly positive.

Second, for (ii) in (30), remark that $x > D(c_f + \gamma\tau)$ implies $P(x) < c_f + \gamma\tau$ by definition of $D(.) = P^{-1}(.)$ and $D'(.) < 0$. By $\tau \leq \delta$, $P(x) < c_f + \gamma\tau$ implies $P(x) < c_f + \gamma\delta$ for every $x > D(c_f + \gamma\tau)$. Hence the second integral in the right-hand side of (30) is strictly negative.

We conclude $\Delta\mathcal{W} > 0$.

(b) $c_f + \gamma\tau > p^{A\alpha} > c_f$: leakage without CBAM and no leakage with CBAM.

The welfare without CBAM is given by (28), while the welfare with CBAM under no leakage is given by

$$\mathcal{W} = \int_0^{\tilde{\theta}_{A\alpha}} [P(qG(\theta)) - c_h - \theta C(a^*(\theta)) - (1 - a^*(\theta))\delta] dG(\theta). \tag{32}$$

The welfare difference with and without CBAM (28) minus (32) is:

$$\begin{aligned} \Delta\mathcal{W} &= \int_{\tilde{\theta}_{\gamma\alpha}}^{\tilde{\theta}_{A\alpha}} [c_f + \gamma\delta - c_h - \theta C(a^*(\theta)) - (1 - a^*(\theta))\delta] dG(\theta) \\ &\quad + \int_{qG(\tilde{\theta}_{A\alpha})}^{D(c_f+\gamma\tau)} [P(x) - c_f - \gamma\delta] dx. \end{aligned}$$

Proceeding as for leakage case (a) shows that $\Delta\mathcal{W} > 0$.

(c) $c_f > p^{A\alpha}$: reverse leakage with and without CBAM.

The welfare is the same with or without CBAM for any given share of free allowances α because the equilibrium outcomes are the same. The CBAM is ineffective because no good is imported and the domestic price is the foreign price.

A.6 The case with only territorial emissions

Here we consider the case in which welfare depends only on domestic territorial emissions, and not on foreign emissions (including imports).

First, we investigate the impact of free allowances on welfare. Without a CBAM, differentiating $\mathcal{W}$ defined in (14) with E_T (instead of E_W) with respect to α yields:

$$\frac{d\mathcal{W}}{d\alpha} = q[p_h - c_h - \tilde{\theta} C(a^*(\tilde{\theta})) - \delta(1 - a^*(\tilde{\theta}))] g(\tilde{\theta}) \frac{d\tilde{\theta}}{d\alpha}. \tag{33}$$

Since $\frac{d\tilde{\theta}}{d\alpha} > 0$, a higher share of free allowances α favors entry, and firms with higher cost types θ become profitable. The term into brackets in (33) is the contribution of firm $\tilde{\theta}$'s output to the welfare: its mark-up $p_h - c_h - \theta C(a^*(\tilde{\theta}))$ net of the climate damage $\delta(1 - a^*(\tilde{\theta}))$ per unit of output. Since the zero profit condition trade equalizes the firm $\tilde{\theta}$'s mark-up to its regulation cost $(1 - a^*(\tilde{\theta}) - \alpha)\tau$ by (4) and (9), (33) can be written as:

$$\frac{d\mathcal{W}}{d\alpha} = -q[(1 - a^*(\tilde{\theta}))(\delta - \tau) + \alpha\tau] g(\tilde{\theta}) \frac{d\tilde{\theta}}{d\alpha}. \tag{34}$$

The two terms into brackets in (34) represent two inefficiencies of climate policy, when positive. The first term is the social cost of the cutoff firm $\tilde{\theta}$'s emissions per output that are not internalized. The higher is the gap between the carbon price τ and the social cost of carbon δ, the higher is this term, which reduces welfare as the share of free allowances increases. The second term is the subsidy per output with free allowances. Efficiency would require to equalize the regulation cost $(1 - a^*(\tilde{\theta}))\tau - \alpha\tau$ and the social cost of emissions $\delta(1 - a^*(\tilde{\theta}))$ for the cutoff $\tilde{\theta}$. However, since $\tau \leq \delta$, the optimal outcome is met only for $\tau = \delta$ and $\alpha = 0$ (no free allowances). With an under-priced carbon tax $\tau < \delta$, the welfare with territorial emissions is always decreasing for any $\alpha = 0$. Thus, providing free allowances worsens the inefficiency of not charging the social cost of carbon.

With a CBAM and leakage or reverse leakage, the negative impact of free allowances is even larger. Differentiating $\mathcal{W}$ defined in (15) with emissions E_T, and using (4) and (10), we obtain:

$$\frac{d\mathcal{W}}{d\alpha} = -q[(1 - a^*(\tilde{\theta}))(\delta - \tau) + \alpha\tau + \gamma\tau]g(\tilde{\theta})\frac{d\tilde{\theta}}{d\alpha}. \tag{35}$$

The equation shows that increasing the share of free allowances decreases further the welfare by reducing the revenue collected on pricing the carbon content of imports, which is captured by the last term into brackets, $\gamma\tau$.

Second, we analyse the impact of the CBAM on the welfare for any α with territorial emissions E_T in the welfare function.

(a) $p^{A\alpha} > c_f + \gamma\tau$: Leakage with and without CBAM.

The welfare without CBAM can be written as:

$$\begin{aligned} \mathcal{W} &= \int_0^{\tilde{\theta}_\alpha} [P(qG(\theta)) - c_h - \theta C(a^*(\theta)) - (1 - a^*(\theta))\delta] dG(\theta) \\ &\quad + \int_{qG(\tilde{\theta}_\alpha)}^{D(c_f)} [P(x) - c_f] dx \end{aligned} \tag{36}$$

The welfare with CBAM under leakage is:

$$\begin{aligned} \mathcal{W} &= \int_0^{\tilde{\theta}_{\gamma\alpha}} [P(qG(\theta)) - c_h - \theta C(a^*(\theta)) - (1 - a^*(\theta))\delta] dG(\theta)] \\ &\quad + \int_{qG(\tilde{\theta}_{\gamma\alpha})}^{D(c_f+\gamma\tau)} [P(x) - c_f] dx. \end{aligned} \tag{37}$$

Since $\tilde{\theta}_{\gamma\alpha} > \tilde{\theta}_\alpha$ and $D(c_f) > D(c_f + \gamma\tau)$, the welfare difference with CBAM minus without CBAM (37)-(36) writes:

$$\begin{aligned} \Delta\mathcal{W} &= \int_{\tilde{\theta}_{\gamma\alpha}}^{\tilde{\theta}_\alpha} \underbrace{[c_f - c_h - \theta C(a^*(\theta)) - (1 - a^*(\theta))\delta]}_{(i)} dG(\theta)] \\ &\quad - \int_{D(c_f+\gamma\tau)}^{D(c_f)} \underbrace{[P(x) - c_f - \gamma\delta]}_{(ii)} dx. \end{aligned} \tag{38}$$

First, by (9) and because $\theta C(a^*(\theta)) + (1 - a^*(\theta))\tau$ is increasing with θ, we have $c_f - c_h - \theta C(a^*(\theta)) - (1 - a^*(\theta) - \alpha)\tau < 0$ for every $\theta \leq \tilde{\theta}_\alpha$ which, since $\tau \leq \delta$, implies $c_f - c_h - \theta C(a^*(\theta)) - (1 - a^*(\theta) - \alpha)\tau < 0$ for every $\theta \leq \tilde{\theta}_\alpha$. Hence (i) in (38) is strictly negative for every $\theta \leq \tilde{\theta}_\alpha$ and so is the integral, i.e. the first right-hand term in (38).

Second, for (ii) in (30), remark that $x < D(c_f)$ implies $P(x) > c_f$ by definition of $D(.) = P^{-1}(.)$ and $D'(.) < 0$. Hence (ii) in (38) is strictly positive and so is the integral, i.e. the second right-hand term in (38).

We conclude $\Delta\mathcal{W} < 0$.

(b) $c_f + \gamma\tau > p^{A\alpha} > c_f$: leakage without CBAM and no leakage with CBAM.

The welfare without CBAM is given by (36), while the welfare with CBAM under no leakage is given by 32.

The welfare difference with and without CBAM (36) minus (32) is:

$$\Delta\mathcal{W} = \int_{\tilde{\theta}_{\gamma\alpha}}^{\tilde{\theta}_{A\alpha}} [c_f - c_h - \theta C(a^*(\theta)) - (1 - a^*(\theta))\delta] dG(\theta) + \int_{qG(\tilde{\theta}_{A\alpha})}^{D(c_f+\gamma\tau)} [P(x) - c_f] dx. \tag{39}$$

Proceeding as for (i) in (38) shows that $\Delta\mathcal{W} < 0$.

(c) $c_f > p^{A\alpha}$: reverse leakage with and without CBAM. The welfare is the same with or without CBAM for any given share of free allowances α because the equilibrium outcomes are the same. The CBAM is ineffective because no good is imported and the domestic price is the foreign price.

A.7 Impact of the carbon price

We now investigate the impact of the carbon price on the welfare with carbon leakage, accounting for territorial emissions first, and for the home country's contribution to total emissions next. Differentiating (15) with E_T instead of E_W with respect to τ and using (2) and (5) yields:

$$\begin{aligned} \frac{d\mathcal{W}}{d\tau} = & \underbrace{[qG(\tilde{\theta}) - D(p_h)]\frac{dp_h}{d\tau}}_{\text{Price effect}} \\ & \underbrace{+ q\int_{\underline{\theta}}^{\tilde{\theta}} [\delta - \tau]\frac{da^*(\theta)}{d\tau} dG(\theta)}_{\text{Abatement effect}} \\ & \underbrace{+ q[\tau(1 - a^*(\tilde{\theta}) - \alpha) - \delta(1 - a^*(\tilde{\theta}))]g(\tilde{\theta})\frac{d\tilde{\theta}}{d\tau}}_{\text{Entry or exit effect}}. \end{aligned} \tag{40}$$

A marginal increase of the carbon price has three impacts on the welfare. First, a higher carbon price might increase the price of the good p_h (in cases (a) and (b) but not (c)) which impacts positively firm's revenue but negatively consumer's spending. We call this channel the *price effect*. It corresponds to the right-hand term in the first line in (40). The price effect is negative if production $qG(\tilde{\theta})$ is lower than consumption $D(p_h)$, that is with imports (case (a)). It is nil under autarky (case (b)) since then $qG(\tilde{\theta}) = D(p_h)$: the increase of the good price is just a transfer from consumers to producers. With exports (case (c)), since $p_h = c_f$ (the domestic price is determined by the international price of the good), $\frac{dp_h}{d\tau} = 0$ so there is no price effect.

Second, pollution abatement improves the welfare by increasing pollution abatement. This *abatement effect* shows up the second line of (40). A marginal tax raise increases firm θ's abatement $a^*(\theta)$ by $\frac{da^*(\theta)}{d\tau} = \frac{1}{\theta C''(a^*(\theta))} > 0$, which reduces climate cost by δ while at the same time increases abatement cost by $\tau = \theta C'(a^*(\theta))$, where the last equality is due to (2). The abatement effect is nil with Pigou pricing $\tau = \delta$, and positive when carbon is under-priced $\tau < \delta$.

Third, a tax increase varies supply through entry or exit in the home country. We call this impact captured in the last line of (40) the *entry or exit effect*. As mentioned before, a higher tax favors entry if the threshold firm $\tilde{\theta}$ is a net seller of allowances (in which case $\frac{d\tilde{\theta}}{d\tau} > 0$), or induces some exists if it is a net buyer (then $\frac{d\tilde{\theta}}{d\tau} < 0$). The term into brackets in the third line of (40) is the difference between firm $\tilde{\theta}$'s regulatory cost $\tau(1 - a^*(\tilde{\theta})) - \tau\alpha$ and the climate cost $\delta(1 - a^*(\tilde{\theta}))$ per output. If the two coincide, e.g. under Pigou pricing $\tau = \delta$ and no free allowances $\alpha = 0$, the entry and exit effect is nil because firms internalize correctly the climate costs. Otherwise, the sign of the entry or exit effect depends upon both the difference between the regulatory and climate cost of firm $\tilde{\theta}$'s production, and firm $\tilde{\theta}$'s net position of in the allowance market (buyer or seller). If the regulation cost is too low - because carbon is under-priced $\tau < \delta$ and/or some allowances are free $\alpha > 1$ - then the entry and exit effect is negative when a higher carbon price favors entry, which turns out to be the case if the threshold firm is a net seller of allowances (i.e. if $\alpha > 1 - a^*(\tilde{\theta})$). In contrast, it is positive when a higher carbon price make firms exit the industry, that is if the threshold firm is a net buyer of allowances (i.e. if $\alpha < 1 - a^*(\tilde{\theta})$).

With global emissions E_W in the welfare, differentiating (15) with respect to τ and using

(2) and (5) yields:

$$\frac{d\mathcal{W}}{d\tau} = \underbrace{[qG(\tilde{\theta}) - D(p_h) - \delta\gamma D'(p_h)]\frac{dp_h}{d\tau}}_{\text{Price effect}} + \underbrace{q\int_{\underline{\theta}}^{\tilde{\theta}}[\delta - \tau]\frac{da^*(\theta)}{d\tau}dG(\theta)}_{\text{Abatement effect}} + \underbrace{q[\tau(1-a^*(\tilde{\theta})) - \alpha) - \delta(1-a^*(\tilde{\theta}) - \gamma)]g(\tilde{\theta})\frac{d\tilde{\theta}}{d\tau}}_{\text{Entry or exit effect}}. \tag{41}$$

Compared to the case with territorial emissions in (40), the above relationship differs in two ways. First, the price effect takes into account the social gain of reduced emissions from lower consumption in the home country, i.e. the last term into brackets of the right-and term in the first line of (41). An increase of p_h with a marginally higher τ decreases demand by $-D'(p_h)$ in cases (a) (with imports), which reduces emissions by γ and has social value δ. The marginal climate gain from the price increase with imports is therefore $-\delta\gamma D'(p_h) > 0$. Second, the entry or exit effect measures the carbon impact of the threshold firm's output relative to the foreign alternative rather in absolute term, i.e. with $1 - a^*(\theta) - \gamma$ rather than $1 - a^*(\theta)$. It therefore lower and can even be even be positive if $1 - a^*(\theta) < \gamma$, in which case firm $\tilde{\theta}$'s production improves the welfare by replacing more carbon-intensive foreign products.

A.8 Robustness of the quantitative analysis

In this section, we gauge the robustness of our quantitative results with respect to the calibrated parameters. First, we estimate β using different years. Using the Italian plant-level data for years other than 2019, we find $\hat{\beta} = 1.48$ for 2018 (using the average τ of 15 observed in that year), and $\hat{\beta} = 0.76$ for 2017 (using the average τ of 5).[35] In Figure 10 we plot the welfare under CBAM in each sector (as in Figure 8) using the β estimated in different years.

The graph shows that the welfare is close to the baseline welfare for any level for α, but is increasing in the convexity parameter β. Intuitively, when the cost function is more convex, the abatement costs are on average higher, thus the welfare gain arising from the CBAM "protecting" domestic producers from foreign competition becomes larger.

Second, we evaluate the robustness of our results with respect to the values for domestic and foreign emissions. We set $\gamma = 1$, which means that the foreign emission factors are equal to the domestic ones, before abatement.

[35] If instead we use the same τ as in 2019, we find $\hat{\beta} = 1.67$ in 2018 and $\hat{\beta} = 1.09$ in 2017.

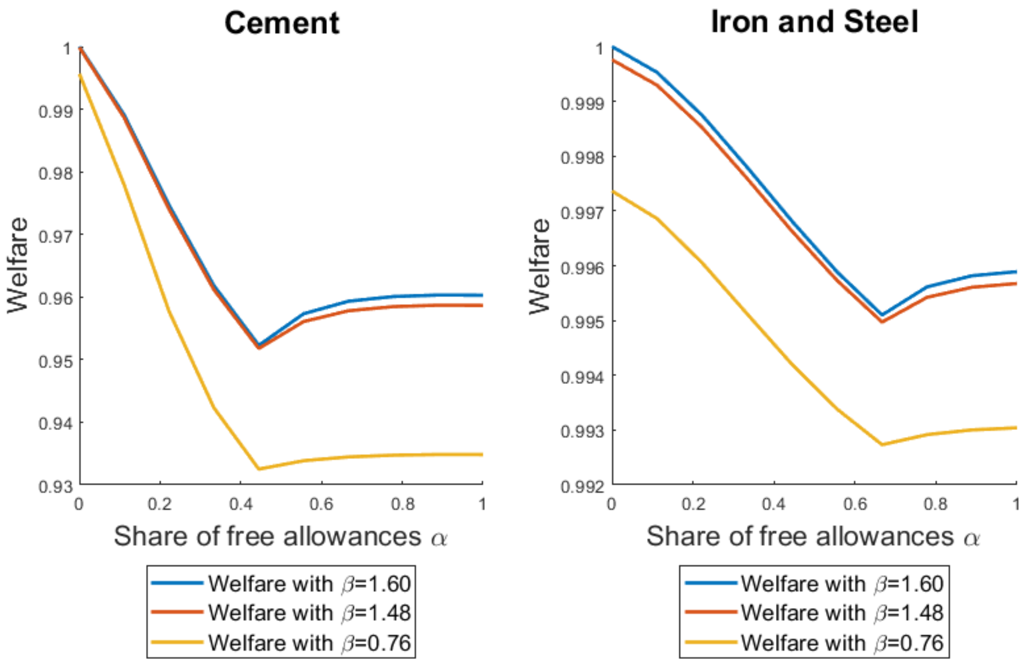

Figure 10: Welfare with CBAM with β calibrated in different years.

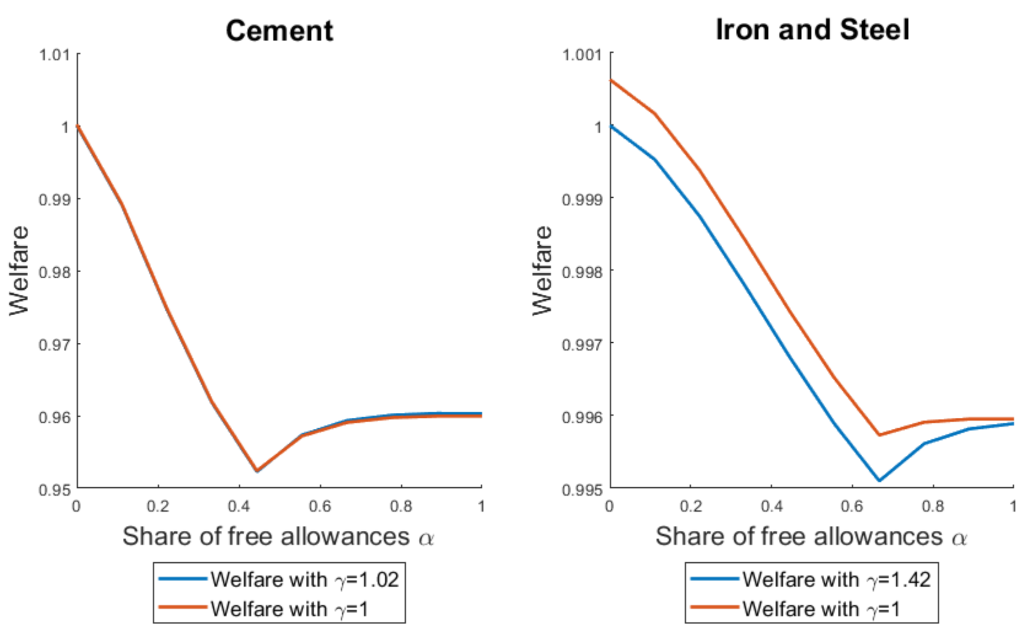

Figure 11: Welfare with CBAM with $\gamma = 1$.

In Figure 11, we can see that the welfare under CBAM is essentially the same as in the baseline for cement, while it is a bit higher for the steel sector. This is because in the steel sector global emissions are significantly lower than in the baseline, as γ goes from 1.42 to 1.

Overall, these robustness exercises indicate that our welfare results are not driven, neither qualitatively nor quantitatively, by the specific point estimates that we impose in our baseline calibration.

A.9 Additional Figures

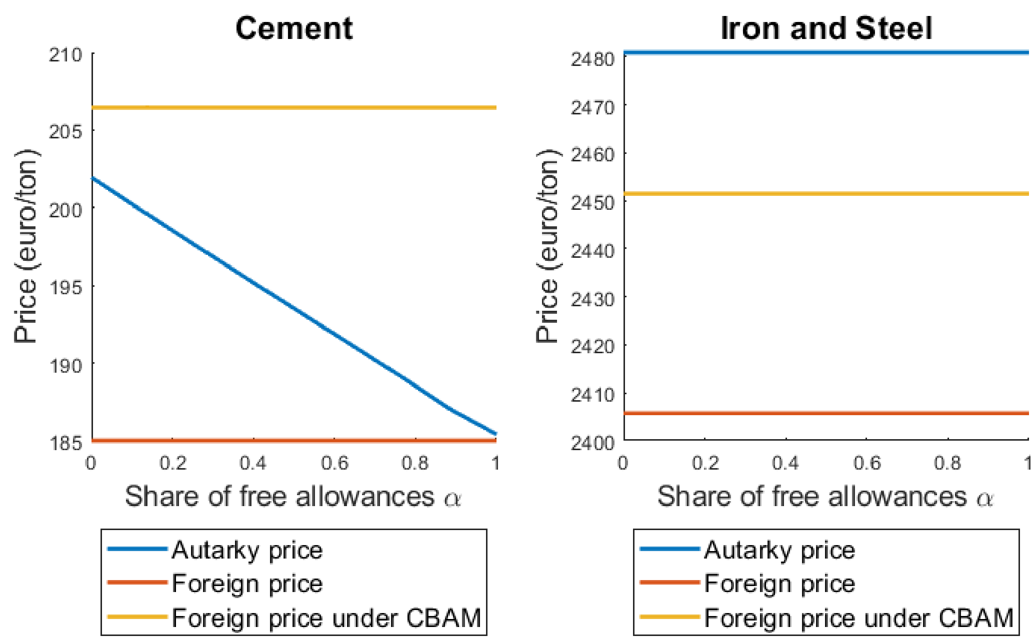

Figure 12: Equilibrium prices with CBAM, with $\tau = 25$.

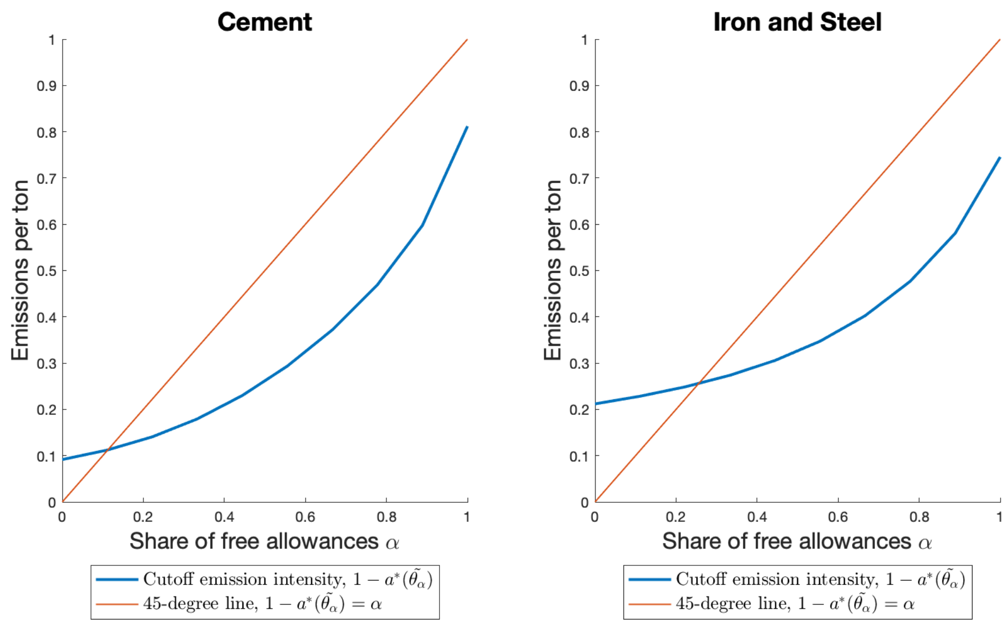

Figure 13: Cutoff emission intensity with CBAM, with $\tau = 230$.

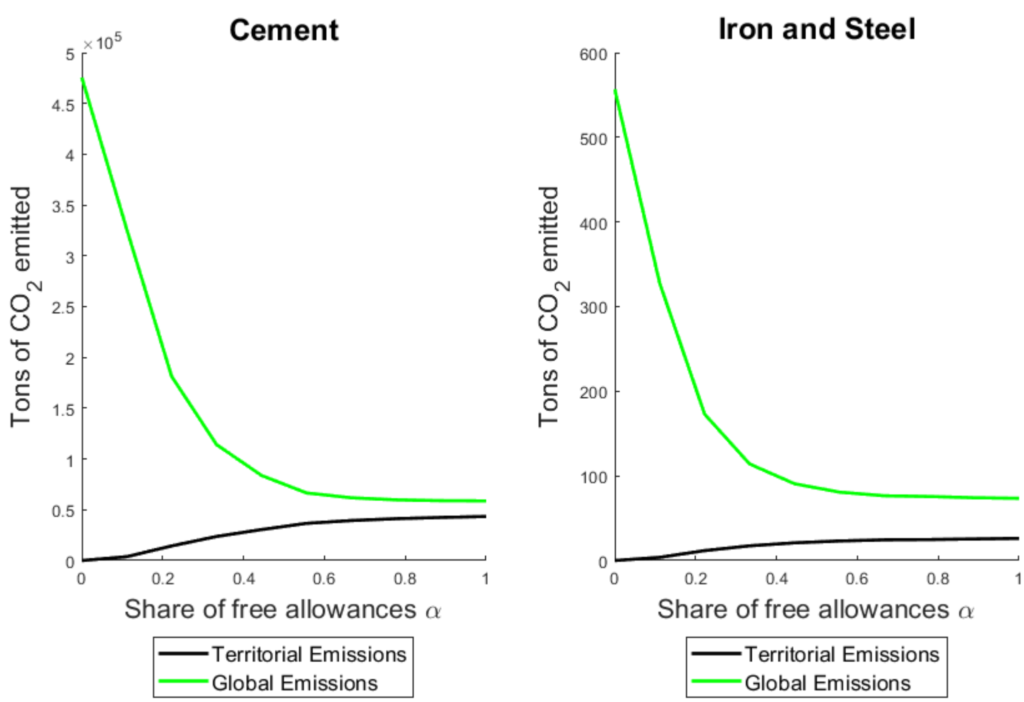

Figure 14: Emissions without CBAM, with $\tau = 230$.

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