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The economics of carbon leakage mitigation policies[☆]

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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, a Carbon Border Adjustment Mechanism (CBAM), and a CBAM with export rebates. We show that providing free allowances does not alter the incentives to abate carbon emissions, but, instead fosters the entry of more carbon intensive producers. This "levels the playing field" both domestically and internationally, and may even reverse carbon leakage. In contrast, a CBAM only levels the playing field domestically, and may lead to an autarky equilibrium. To reverse carbon leakage, a CBAM must be complemented with export rebates. We further show that a CBAM and export rebates improve welfare for any carbon price, and we identify the optimal share of free allowances with or without a 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.

1. Introduction

Carbon pricing initiatives to tackle climate change have recently 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 (ETS), 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 located in these jurisdictions have to pay for their carbon emissions by buying emission allowances, increasing their production costs, and therefore reducing their competitiveness relative to foreign firms. This creates an *uneven* playing field, with repercussions for international trade flows and the climate. In fact, unilateral carbon pricing may lead to carbon 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 (see Aichele and Felbermayr (2012)).

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Carbon leakage can be mitigated using three policy tools. First, the cost burden due to the carbon price on domestic firms can be lowered with rebates and subsidies based on output, abatement efforts, or emission 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 exports can be reduced with rebates and subsidies on exported production (Fischer and Fox, 2012). The European Union (EU) has recently been adopting these policies in the context of its Green Deal initiative to tackle climate change. A CBAM entered into its transitional phase in the EU in October 2023 on imports of selected industries (aluminum, cement, hydrogen, fertilizers, iron and steel, and electricity). Imports are charged a carbon tax on their carbon footprint, set equal to the average price of permits traded in the ETS. This CBAM will co-exist with free allowances during a transitory period, and will eventually replace them (see European Commission (2021a)).

How do anti-leakage policies impact international competition? How do they affect welfare? What will the impact of a CBAM on European industries be? 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 at an exogenous pricedomestically, but not abroad.

We first characterize the equilibrium outcomes to understand how anti-leakage policies improve fair competition, both inside and outside the jurisdiction in which 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 enough resources are invested in dealing with pollution. Such "clean" firms end up exporting to a 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.

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. This 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, a 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 cannot alone reverse the leakage with exports.[2]

To level the playing field abroad, a CBAM should be complemented with export rebates. By assigning free allowances on exported output only, 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 have 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 a CBAM, regardless of the equilibrium outcome, or with a CBAM with reverse leakage. Some allowances should be free with a 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.

Moreover, we show that a CBAM is welfare enhancing for any share of free allowances, and for any carbon price below or equal to the social cost of carbon emissions. Intuitively, with a CBAM, the supply curve in the domestic market reflects the social cost of production, including the carbon cost, at least partially for sub-optimal carbon pricing and fully if carbon is priced at its social cost. The harmful impact of carbon emissions is therefore internalized at least partially or fully, depending on the carbon price. We also show that export rebates further improve welfare by "decarbonating" foreign consumption for different carbon prices that do not exceed the social cost of carbon.

In the last part of our analysis, we calibrate the model to quantify the impact of a CBAM on international trade and welfare. We assume that the home country is the EU, and focus on the two largest manufacturing sectors in which a CBAM is implemented: cement and steel. We use Turkey as the foreign country for the cement sector and Russia for the steel sector, as these are the top exporters to the EU in each industry (among the nations without a formal ETS).[3] We combine publicly available data on production, international trade and emissions to calibrate the model to the year 2019 (before the global COVID-19 pandemic). We also use anonymized plant-level data on emissions intensity (in tons of CO_2 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.[4]

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[1] The homogeneity assumption allows us to compare the competitiveness of domestic and foreign firms by looking directly at production costs. For industries subject to the CBAM introduced by the EU, this seems a reasonable assumption, as these industries mostly produce raw materials.

[2] We also show that free allowances actually *increase* carbon leakage if the carbon border tariff is adjusted by the share of free allowances, as prescribed by the EU legislation for the transition period.

[3] 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.

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

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, as expected from our theory. Lastly, the welfare gains from a CBAM are large for both sectors and decreasing in the share of free allowances. We also show that these results are generally robust to the calibration used for the abatement cost function and the emission factors.

Related literature. Carbon leakage is a concern for both scholars and policymakers. Several studies aim to measure the magnitude of carbon leakage where carbon is priced. Fischer and Fox (2012) estimate the impact of a carbon price implemented unilaterally by the US with regard to several energy intensive industries. According to their estimates, a carbon price of \$50 per ton of CO_2 leads to substantial carbon emission leakage rates, ranging from 2% to 58%. Fowlie and Reguant (2022) analyze the leakage risk across 312 manufacturing sectors in the US and find an average leakage rate of 46% with a carbon price of \$25 per ton of CO_2. Empirically, Aichele and Felbermayr (2012) find large carbon leakage effects following the implementation of the Kyoto Protocol. Other studies focusing on the EU ETS find limited or no leakage (Bushnell et al., 2013; Wagner et al., 2014; Naegele and Zaklan, 2019).

Economists have long advocated for the implementation of border carbon adjustment mechanisms to tackle carbon leakage (see Cosbey et al. (2019), Ambec (2022) and Böhringer et al. (2022) for surveys).[5] 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 et al. (2018, 2019) and Böhringer et al. (2021)). They provide quantitative analyses, however, they do not analytically characterize the properties of the equilibrium nor the optimality of anti-leakage policies as we do in this paper.

Earlier works, such as Markusen (1975), have shown that unilateral carbon pricing can be optimal despite carbon leakage in a two-goods international trade model. Balistreri et al. (2018) extended the Markusen model to characterize the optimal carbon tariff with a CBAM. They found that it should be lower than the social cost of carbon 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 same effect of a 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 equals the social cost of carbon.

Recent studies Kortum and Weisbach (2021), Farrokhi and Lashkaripour (2022), and Weisbach et al. (2023) have identified the optimal policy mix to address carbon leakage using multi-sector models with heterogeneous goods and monopolistic competition (Melitz, 2003). The optimal policy mix involves a carbon tax equal to the social cost of carbon, taxes on imports (based on their carbon content, as in a CBAM), a tax on energy, and export subsidies. In contrast to this literature, we investigate the welfare effects of an anti-leakage policy instruments in second-best settings where the optimal policy mix is not implemented. Notably, we extend the welfare analysis to sub-optimal carbon pricing. We show that a CBAM is welfare-enhancing for *any* carbon price, even if it is below the social cost of carbon. In addition, this is the case even when some free allowances are assigned, or when production is subsidized. Moreover, we show that welfare can be improved further if a CBAM is complemented with export rebates for any carbon price below or equal to the social cost of carbon.[6]

Two studies address carbon leakage through the relocation of manufacturing plants outside the jurisdiction in which carbon is priced, a phenomenon sometimes called "pollution offshoring" (Saussay and Zugravu-Soilita, 2023) or "pollution outsourcing" (Levinson, 2023). Martin et al. (2014) use a calibrated model to estimate the number of allowances that should be freely assigned in the EU ETS in order to achieve a given level of plant relocation. Ahlvik and Liski (2019) identify carbon policies when firms' relocation costs are 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 depending on the equilibrium within international markets.

Our paper builds upon existing partial equilibrium models with trade, particularly Fischer and Fox (2012) and Fowlie and Reguant (2022).[7] Fowlie and Reguant (2022) characterize and estimate the optimal subsidy in a two-country model, with one representative firm in each country. Similarly, we also characterize the optimal output subsidy with and without a 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] Fischer and Fox (2012) compare various anti-leakage policies, including carbon border adjustments, in a model with differentiated goods and investment in pollution abatement. In contrast, we characterize the economic outcomes in a model where goods are perfect substitutes, which allows us to compare the competitiveness of firms on both sides of the border.

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[5] Empirical studies on the effects of carbon leakage include Branger et al. (2016), Healy et al. (2018), Naegele and Zaklan (2019) and Dechezleprêtre et al. (2022).

[6] It is worth mentioning that our approach differs from Kortum and Weisbach (2021), Farrokhi and Lashkaripour (2022), and Weisbach et al. (2023) in at least three dimensions. First, in our paper, the welfare impact of anti-leakage policy instruments is analyzed without any constraints on the foreign country's welfare, nor with strategic interactions among countries. Second, we do not model the energy sector, thus the carbon leakage arises from the reduced competitiveness of domestic firms. Third, we allow for technological change through investment in pollution abatement, while those papers do not.

[7] Böhringer et al. (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 et al. (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 the same abatement costs, while they are heterogeneous in our setting.

The rest of the paper proceeds as follows. We first develop a partial equilibrium model to investigate the economic effects of carbon leakage mitigating policies in Section 2. Next, in Section 3, we perform a welfare analysis and describe the optimal mixes of carbon pricing and free allowances with a CBAM. 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 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 a decarbonated source of energy.[9] We interpret the abatement cost $C(a)$ as a set-up cost for a given production capacity, which 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 $\gamma \geq 1$: 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 EU. 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.

2.2. Free emissions allowances

We first investigate how providing some emission allowances free-of-charge 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 and a benchmark emission factor of 1, getting a share α of allowances for free reduces the cost of carbon pricing from τ to $(1-\alpha)\tau$ per output.[13] The case $\alpha = 0$ corresponds to full carbon pricing, while $\alpha = 1$ means that all allowances are free. By selling the allowances assigned free-of-charge in the ETS market, a firm obtains $\alpha\tau$ per output. A share α of free allowances is thus equivalent

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[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 CO_2 per ton of steel. It can be reduced by recycling steel, by sequestrating and storing the CO_2 emissions from the coke combustion, or using hydrogen combined 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).

[13] Note that since the number of free allowances is based on past emissions, the firm's current abatement effort a does not impact them. This grandfathering principle applies to most ETS, including the EU ETS, see Directive 2009/29/EC (European Parliament, 2009) or Martin et al. (2014). Although the current abatement effort likely affects the number of allowances a firm would obtain in the future, we abstract for the dynamic impact of abatement on future allowances. The model also does not feature a New Entrant Reserve (NER) provision, that in the EU ETS reserves a higher share of free allowances for new entrants.

to a subsidy $\alpha\tau$ per output. Therefore, our analysis encompasses both free allowances in an ETS and output subsidies in any carbon pricing mechanism.[14]

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 free, some firms can benefit from the carbon pricing through their investment into emissions 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 where all allowances are free ($\alpha = 1$), home producers are on the same level playing field as foreign ones, that is, they have the same production costs with carbon pricing. However, by abating, home firms can become competitive abroad with their optimal abatement level $a^*(\theta)$.

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 $\frac{\partial K}{\partial \alpha} < 0$: the production cost is increasing with the 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.[15] 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 and 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 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),

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[14] 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.

[15] 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.

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,[16] 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 the 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.

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 of the home country's jurisdiction. In contrast, when a share α of allowances is assigned free-of-charge, 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 Fig. 1. The (inverse) demand $P(Q)$ is shown 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 shown in blue for $\alpha = 0$ (full carbon pricing) and $\alpha > 0$ (free allowances). Point (A), where home demand and supply curves intersect, representing 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 the supply curve downward 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 $qG(\tilde{\theta}_\alpha)$ exceeds 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 Fig. 1 leads to the economic outcome (a) with carbon leakage, assigning free allowances can move the supply curve down 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 that 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 country'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 foreign firm's production costs on

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

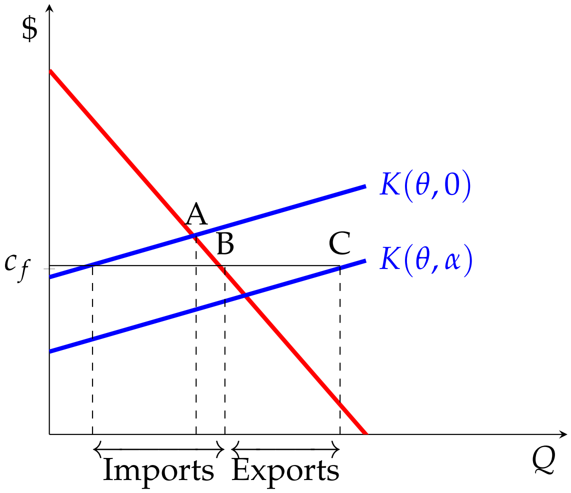

Fig. 1. Equilibria with $\alpha = 0$ (full carbon pricing) and $\alpha > 0$ (free allowances). Point A is the equilibrium under autarky with $\alpha = 0$. Point B is the equilibrium under free trade with $\alpha = 0$. Point C is the equilibrium under free trade with a share $\alpha > 0$ of free allowances.

international markets, $p_f = c_f$ (which is unaffected by the carbon price). Hence, we can define a new cutoff type $\tilde{\theta}_{\gamma\alpha}$, whereby 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, which is 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 the 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.[17]

If the CBAM replaces free allowances, the equilibrium outcome described in Proposition 2 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 equilibrium outcome, we illustrate Proposition with $\alpha = 0$ in Fig. 2, and compare it with Fig. 1.

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 Fig. 2. This 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 therefore no carbon emission is leaked.

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

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[17] 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 that in case (b) in Proposition 1.

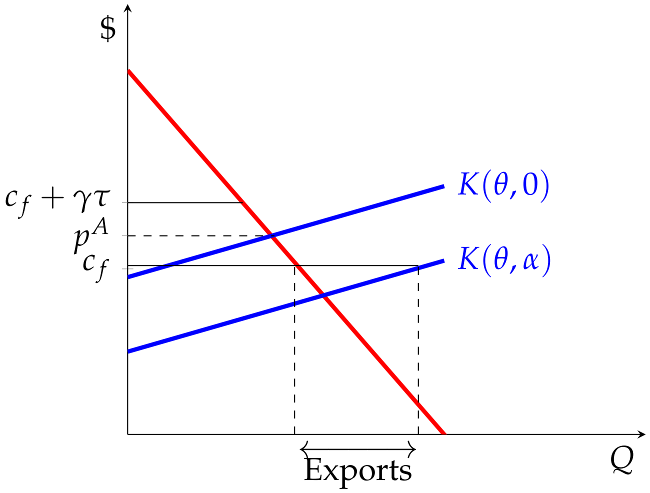

Fig. 2. Equilibria with a CBAM.

imported. Carbon emissions also leak if the supply curve $K(\theta,0)$ moves upward and crosses the line $c_f+\gamma\tau$ (due to 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 the supply curve downward, such that it crosses the demand function (in red) below the horizontal line c_f, as for $K(\theta,\alpha)$ in Fig. 2. This means that home producers are competitive both in the domestic and foreign markets. They produce at a lower cost than their foreign competitors c_f, and are able to fully supply the domestic market, as well as the export market. Carbon emissions do not leak outside the home country. On the contrary, home products reduce emissions globally by replacing more carbon intensive foreign products abroad. Carbon leakage is negative.

Moreover, similarly to Lemma 1, we now examine how the carbon price impacts entry and exit in the industry with a 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 occurs 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 obtain 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 in more carbon leakage.[18] Carbon leakage turns out to be higher with free allowances. In other words, carbon leakage in the EU would be better addressed by immediately removing free allowances while implementing the CBAM without a 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 of the export base. Export rebates with a CBAM causes climate policy to vary in relation to 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 free-of-charge and a price equal to the production cost of its foreign competitors.

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[18] This can be formally shown by noting that adjusting the carbon tariff to free allowances modifies the domestic price with leakage from $c_f+\gamma\tau$ to $c_f+\gamma\tau(1-\alpha)$ on the left-hand side of (10). The supply function $K(\theta,\alpha)$ on the right-hand side is unchanged, the cutoff firm type $\tilde{\theta}_{\gamma\alpha}$ is reduced, as is domestic production $qG(\tilde{\theta}_{\gamma\alpha})$. Since the domestic price is lower, demand increases and imports are higher.

Let us consider each of the possible economic outcomes ((a) leakage, (b) no leakage, (c) 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 Eq. (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.[19]

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.

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 distinguishes between carbon leakage (a) and no carbon leakage (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 causes more of them to be 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 the gap that the carbon cost paid for supplying the foreign market by $\alpha\tau$ per ton of CO_2 equivalent.

3. Welfare analysis

3.1. Social welfare with climate cost

In this section, we investigate how free allowances and a CBAM impact social welfare. The negative impact of carbon emissions is embedded into 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 CO_2 equivalent greenhouse gases. This 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,[20] the producers' 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 CO_2 being valued δ) and E_W global emissions of the sector, the social welfare without a CBAM is:

$$\mathcal{W} = \underbrace{S(D(p_h)) - D(p_h)p_h}_{\text{Consumers' net surplus}} + \underbrace{\int_{\underline{\theta}}^{\tilde{\theta}} \pi_\alpha(a^*(\theta), \theta)dG(\theta)}_{\text{Producers surplus}}$$

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[19] 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.

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

$$+\underbrace{\int_{\underline{\theta}}^{\tilde{\theta}} q[1-a^*(\theta)-\alpha]\tau dG(\theta)}_{\text{Auction revenue}} \quad \underbrace{-\delta E_W}_{\text{Social cost of emissions}}.$$

With a CBAM, the revenue of collecting the carbon price on imports must be added 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 Eq. (1), the auction revenue cancels out with the firms' allowance purchases, so that the welfare with or without a 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 analyzing 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 results in:

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

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 Propositions 1 and 2, in the same way that we have addressed the no-leakage case. We consider the cases with and without a CBAM.

First, without a 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 in brackets in (18) is the social cost of the cutoff firm $\tilde{\theta}$'s emissions per output that are not internalized. The higher the gap between the carbon price τ and the social cost of carbon δ, the higher this term, which reduces welfare as the share of free allowances increases. This climate cost should be compared to that of foreign production, namely $\gamma\delta$, the second term in brackets. This is because firm $\tilde{\theta}$'s production is replaced by foreign production if firm $\tilde{\theta}$ is not producing, as 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 Proposition 2), 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 a 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 that is not internalized by firms $\delta-\tau$.

Lastly, with a CBAM and reverse leakage (case (c) of Proposition 2), differentiating the welfare with respect to α yields (18). By increasing free allowances, exports substitute foreign products with home products in international markets. The carbon intensity of those foreign products not being priced means that 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 with or without a CBAM under reverse leakage. Some allowances should be free with a CBAM under leakage if $\tau < \delta$ however, none should be free if $\tau = \delta$. Under autarky, no allowance should be free when $\tau \le \delta$.*

Proposition 4 characterizes the conditions under which free allowances should be part of the carbon mitigation policies. When the domestic market is not protected by a CBAM, assigning allowances free-of-charge turns out to be welfare enhancing, because foreign products with a 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.

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, using Pigou pricing $\tau = \delta$, free allowances are no longer optimal. Both consumers and producers (including foreign ones) fully internalize the climate cost of their decisions, and the climate cost δ is embedded into the domestic price.[21]

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 remain optimal as long as γ is not too low.

Finally, we can proceed similarly to investigate the optimal output subsidy s^*, instead of the share of free allowances α^*, by setting $s = \alpha\tau$ in (18) or (19).[22] With or without a 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) reduces 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.

3.3. Welfare impact of a CBAM

We now investigate whether implementing a CBAM improves welfare, conditional on the share of free allowances. We also assess the efficiency of export rebates when a CBAM is implemented. We show the following proposition in Appendix A.5.

Proposition 5. *A CBAM is welfare-enhancing for any α and $\tau \le \delta$. Welfare is further improved if the CBAM is complemented with export rebates.*

A CBAM is welfare-enhancing because it makes the domestic market internalize a part, if not all, of 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 the lowest emission factors. On the supply side, production costs are minimized at the industry level given the cost of one ton of CO_2 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 receives it. The welfare is maximized when the carbon price reflects its social cost $\tau = \delta$.

The welfare gain from implementing a CBAM in case of leakage is shown in Fig. 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 a CBAM. Foreign supply without a CBAM (represented by the line c_f) does not internalize this social cost, 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 on the left-hand side of the graph. These imports are competitive without a 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 achieving, causing foreign products to be less competitive.

On the demand side, the equilibrium price with a 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, which is 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 key message of Proposition 5 is that in terms of global emissions, free allowances should be complemented with a CBAM, or replaced by it.

Export rebates further improve welfare because they substitute away carbon-intensive foreign products with low-carbon domestic products in international markets. Unlike free allowances, they do so only when they are effective, that is, under reverse leakage. Furthermore, since export rebates are only applied to exported production, they do not distort the domestic market where carbon is priced.

Lastly, before moving to the quantitative analysis, it is worth discussing two issues related to the real-world implementation of a CBAM. First, note that the Pareto dominance of a CBAM relies on the assumption that the emission factor of foreign products γ is appropriately measured. If this is not the case, the market outcome would be distorted. In practice, measuring the emission intensity

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[21] Note that without a CBAM, 100% of allowances should be free, even with Pigou carbon pricing, because the climate costs are not internalized by consumers and/or foreign firms.

[22] 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 $\tilde{\theta}$.

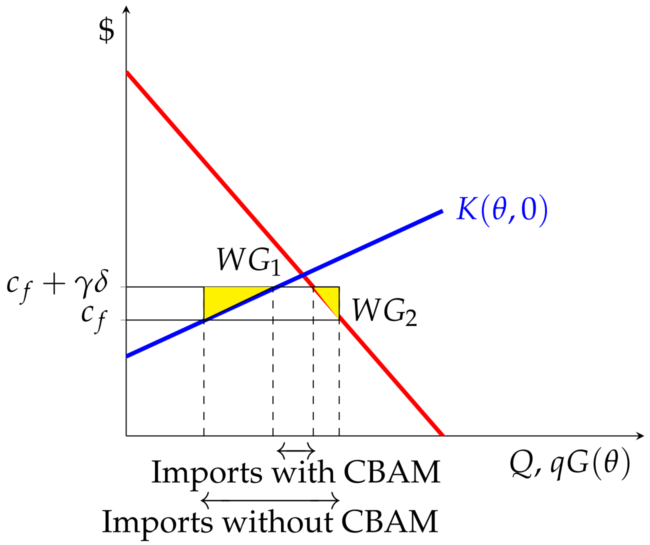

Fig. 3. Welfare gains with CBAM, with $\tau = \delta$.

of foreign products at the production plant is challenging. For this reason, in the EU's CBAM legislation, a default emission factor is applied at the industry level for products whose carbon footprints are not certified by a reliable third party. Second, although global emissions are the appropriate measure by which to determine the impact of economic activity on the climate, discussions in the policy arena about emissions targets often refer to territorial emissions.[23] In our working paper (Ambec et al., 2023), we show that if territorial emissions only are taken into account, a CBAM actually lowers welfare. This occurs because the CBAM increases domestic production and thus territorial emissions, as well as the domestic price. Those two negative effects are not offset by the higher infra-marginal profits made by the domestic industry with a carbon price at the border.

4. Quantitative analysis

We now use our model to investigate the economic impact of carbon leakage mitigation policy tools, with a specific focus on a CBAM. To this end, we first calibrate the model and then simulate several counterfactual scenarios. Given that ours is a partial equilibrium model, we see this exercise as an helpful illustration of the mechanisms used in our framework, rather than a comprehensive assessment of the effects of these policies on the European economy.

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:

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

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[23] For instance, to assess their compliance with the Paris Agreement, countries report their emission inventories to the UNFCCC (see UNFCC). In addition, the EU's goal of reducing emissions by 55% in 2030, compared to 1990, and to become neutral by 2050, refers to territorial net emissions that are computed yearly by the EU.

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 last year before the COVID-19 pandemic impacted the world. We consider two manufacturing sectors that are the target of a CBAM proposed by the EU: cement and steel.[24] We assume that the home country in our model is the EU, 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. We use Turkey as the 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, showing 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 CO_2 emitted for each ton produced) in EU, Russia and Turkey.[25] We set the sectoral demand elasticities ϵ_s equal to previous estimates in the literature.[26]

We then turn to the estimation of the firms' technology parameters. To this end, we use plant-level data on emissions intensity from Italy, made available to us by ISPRA, a public agency that collects environmental data.[27] We use this data to compute the emission intensity for each Italian plant (in tons of CO_2 per ton produced). We also 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:

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

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 show that $\hat{\beta} = 1.6$. By inverting the FOC 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.[28] We obtain the production capacity q_s as the average quantity produced (expressed in tons) across all plants in each sector within the EU.[29] 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 to the foreign marginal cost of production. We use data on unit values per ton from CEPII and compute the average FOB 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 downloaded from the World Bank WITS dataset, to obtain the foreign price $p_{f,s}$.[30]

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[24] The aluminum, electricity and fertilizers sectors are also targets of the proposal, but the lack of comprehensive data prevents us from including them in our analysis.

[25] Estimates for average emission rates in the EU are obtained from 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) and global estimates for steel (World Steel Association, 2020).

[26] Demand elasticity estimates are from Fowlie et al. (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 et al. (2019)).

[27] We gratefully 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).

[28] 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 $\mu = ln(A) - \sigma^2/2 = -0.96$.

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

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

Table 1
Parameters.

	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	2406
Domestic cost (c_h)	185	2405

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 Eq. (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 Eq. (1) to 0. Then, since the marginal cost of production, $c_{h,s}$ is the same across all firms, we can invert Eq. (1) for the marginal entrant in each sector and find $c_{h,s}$.[31]

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 the 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 trade equilibrium and welfare.

Fig. 4 considers the scenario where the cost of carbon is set to €162, which is the most recent estimate of the social cost of carbon.[32] For each sector, the figure plots the autarky price, the foreign price, and the foreign price under a CBAM for different values for the share of free allowances, α. 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 (60%), the home economy switches to exporting, as the autarky price is lower than the foreign price. In the steel sector a similar pattern emerges, however, the economy switches to exporting only when the share of free allowances is above 80%.

Interestingly, the minimal share of free allowances that is necessary to switch the equilibrium to reverse leakage is higher the lower the carbon price. As shown in Fig. 9 in Appendix A.7, when the carbon price is €120, the minimum α that implies exporting is 70% for cement and 90% for steel; when τ is €80 instead, it becomes 80% for cement and 98% for steel. Therefore, when the carbon price is higher, the home country is more likely to export.

The fact that a higher cost of carbon τ increases exports may seem counter-intuitive, 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

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[31] 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 $c_{h,s}$.

[32] The preferred estimate of the social cost of carbon in Rennert et al. (2022) is $185 in 2020 U.S. dollars. Using the average exchange rate in 2020 between the euro and the dollar, we obtain $185/1.1422 = €162.

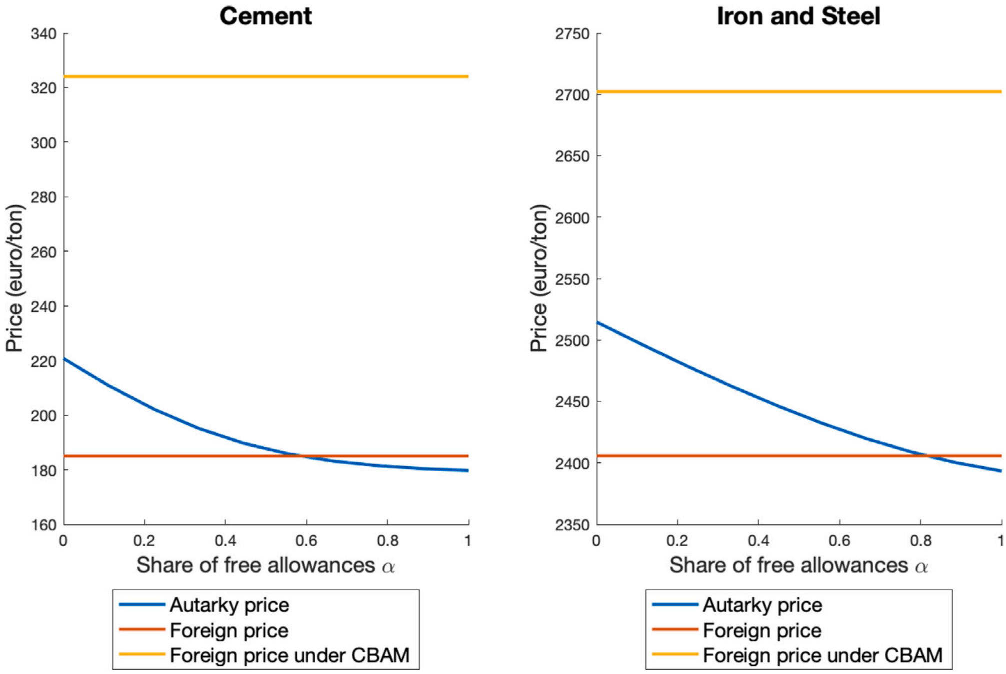

Fig. 4. Equilibrium prices with CBAM, with $\tau = 162$.

may become 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 demonstrably, in Fig. 10 in Appendix A.7, we plot the emission intensity of the marginal (or cutoff) entrant, $1 - a^*(\tilde{\theta}_\alpha)$; that is, 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 a 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 Fig. 5, we display the equilibrium prices with a CBAM when the allowances are granted only to exports. 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 autarky price line is now flat. Interestingly, both sectors never import in equilibrium, and they switch from autarky to exporting at a lower α compared to the counterfactual in Fig. 4. This suggests that export rebates are more effective in stimulating exports than production rebates, consistent with Proposition 3.

4.4. Welfare analysis

We now turn to the analysis of the effects of a CBAM on total emissions and welfare. Throughout the section, we set the carbon price to €162 as before, which is the social cost of carbon. In Fig. 6, we plot both the territorial emissions, using the expression in Eq. (12), and the global emissions, as in Eq. (13). Two patterns emerge in both sectors. First, territorial emissions increase with the share of free allowances, because they foster production by lowering costs, and thus raising carbon emissions. This is very similar to what occurs in a scenario without a CBAM, as shown in Fig. 11 in Appendix A.7. In contrast, global emissions first increase with α, but then decrease when the share of free allowances is sufficiently high. This occurs because, as α gets larger, the home country exports the good abroad, as previously shown in Fig. 4. Following this, 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 occurs without a CBAM, as Fig. 11 highlights how free allowances always significantly reduce global emissions, even when α is lower than 1.

Next, we look at the welfare effects of a CBAM, separately for each sector, using global emissions.[33] Fig. 7 plots welfare for different shares of free allowances, normalizing to 1 the welfare with $\alpha = 0$. Consistent with Proposition 4, trade-adjusted welfare

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[33] Starting from the demand in Eq. (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:

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

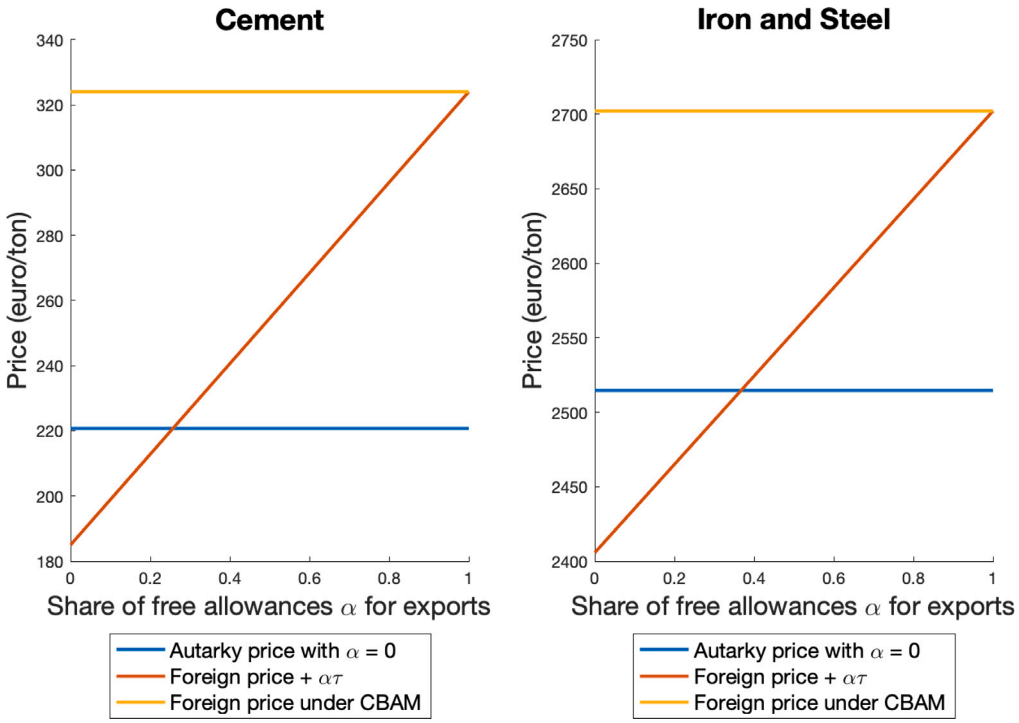

Fig. 5. Equilibrium with CBAM and export rebates, with $\tau = 162$. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

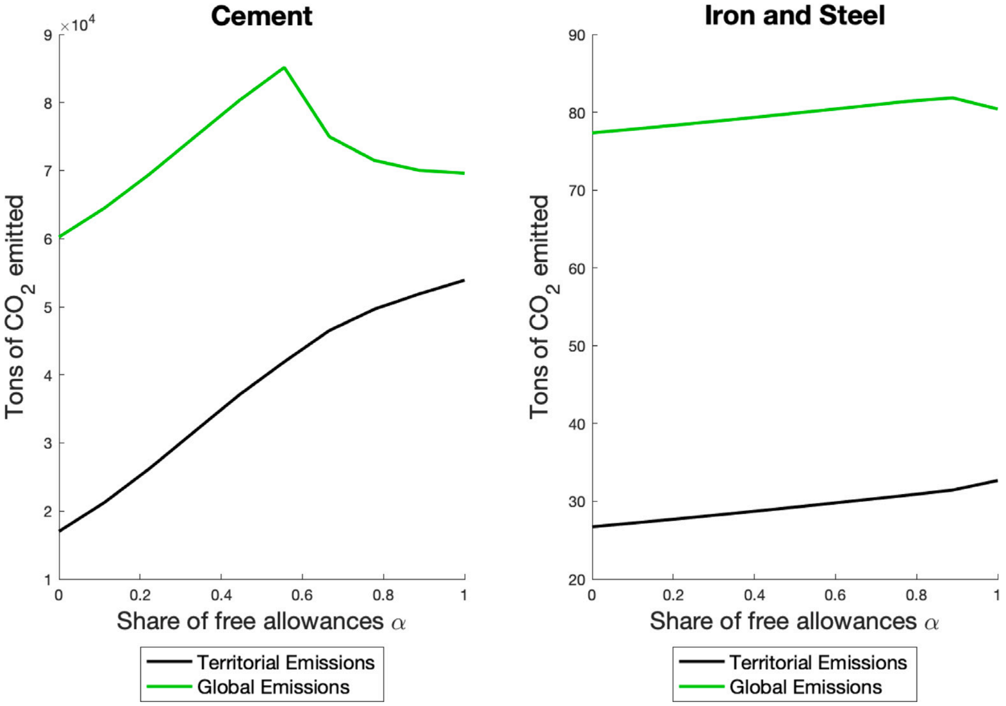

Fig. 6. Emissions with CBAM, with $\tau = 162$.

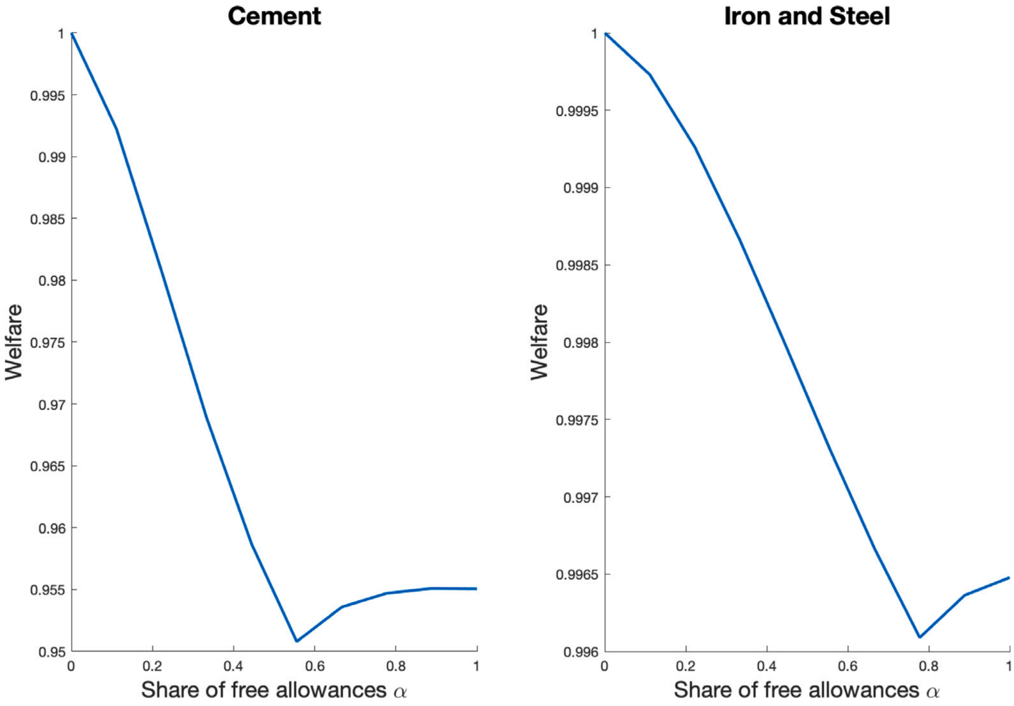

Fig. 7. Welfare with CBAM, $\tau = \delta = 162$.

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 free allowances is beneficial, and welfare is increasing in α. This occurs 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).

Finally, in Fig. 8, we show that welfare with a CBAM is always higher than or equal to welfare without a CBAM, in both sectors.[34] In addition, welfare without a CBAM is always increasing in α, as predicted by Proposition 4. This occurs 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 a CBAM and in autarky with a CBAM, and welfare with a CBAM is strictly larger than without (as in case (b) of the proof of Proposition 5 in Appendix A.5). Instead, when α is high, there is reverse leakage both with and without a CBAM (case (c)in the proof of Proposition 5). In this case, welfare is the same with or without a 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 a CBAM are large and decreasing in the share of free allowances. They range between $0 - 85\%$ for cement and $0 - 19\%$ for steel.

5. Conclusions

How can carbon leakage driven by international trade be limited? Should firms be exempt from paying their emission permits, or should the carbon content of imports be taxed 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 distorted 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. A CBAM does not assist the export process (i.e., it does not lead to

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

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

We then use Eqs. (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 a CBAM by simply comparing the welfare in the two equilibria. Thus, we are not using a sufficient statistics approach that conditions on observables, as is often seen in the international trade literature (see e.g., Arkolakis et al. (2012) and Esposito (2020)).

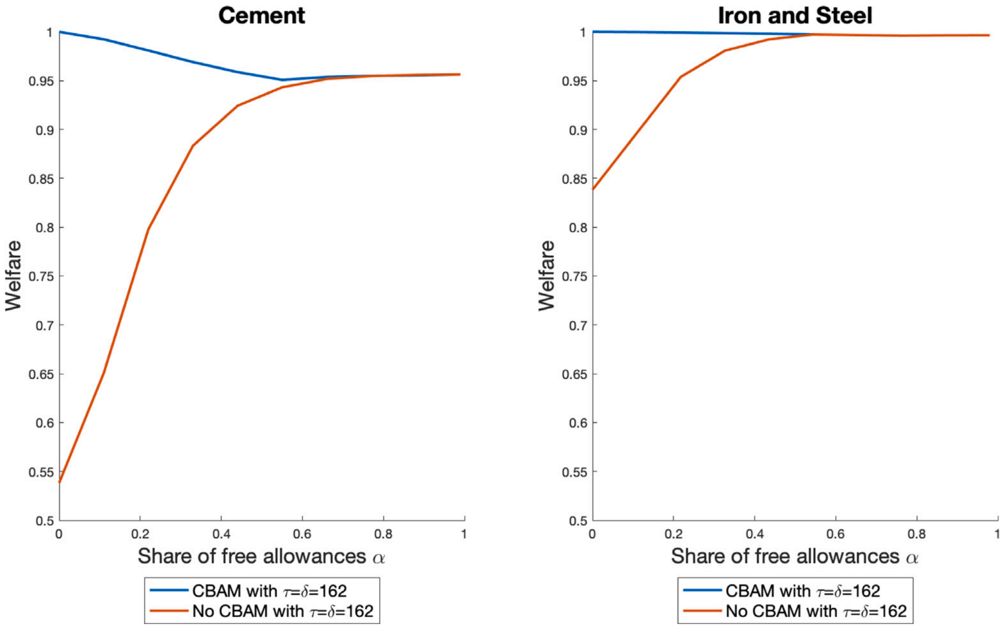

Fig. 8. Welfare with and without CBAM, $\tau = \delta = 162$.

reverse leakage), however 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 internationally. Furthermore, it increases the welfare of a producing country. A CBAM is welfare-enhancing for different reasons: either because it switches the economic outcome from imports to autarky, or it makes firms (and consumers) pay the entire cost of their carbon emission under imports. Our simulations suggest that the EU would gain substantially from a CBAM in sectors such as cement and steel.

To conclude, we discuss several important assumptions made in our analysis. First, we analyze 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 us to set up a political economy model. However, our study can still shed light on the effects of an exogenous change in the carbon price. We do so analytically in Appendix A.6, where 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 by quality, shape, and brand. 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 is important for our results is whether the home country is a net importer or exporter in a given sector, rather than the product heterogeneity that may exist within a sector. In the same vein, by focusing on only one sector in partial equilibrium, we abstract for spillover effects across sectors. In particular, we do not model the pass-through on prices along the supply chain of the product (e.g., for inputs such as labor or energy) or on complementary or substitute products (e.g., wood instead of cement in the construction sector). Inter-sectoral spillover effects can be modeled and evaluated using computable general equilibrium models.

Third, by assuming that the good can be supplied internationally with a constant marginal cost, we abstract for any effect of anti-leakage policies on the foreign price. With an increasing rather than a flat supply curve in the foreign country, the substitution of foreign products by home products, driven by free allowances and a CBAM, would lower the foreign price. It would also 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. Nonetheless, foreign firms might be able to reduce γ by investing in pollution abatement, as their domestic competitors do. For instance, as discussed in the EU proposal, this may require the existence of a certification process (as studied in Cicala et al. (2022)). Endogenizing γ with foreign investment in abatement would not significantly change our results. Providing that the imports are charged with firm-specific and well-evaluated emission factors, it would cause a CBAM to be 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 on both sides of the border, as we explain in Section 3.2. However, this comparison may be challenging to implement in practice and we leave it for future research.

Lastly, our single-sector model does not differentiate between direct and indirect emissions. The EU CBAM mandates the reporting of both direct and indirect emissions per product (scope 2). In contrast, in the EU ETS, only direct emissions (scope 1) from manufacturing plants are accounted for. Emissions from inputs in the production process, such as electricity, are not included. This asymmetry in the scope of emissions between foreign and domestic products is only an issue if indirect emissions from domestic production are not priced. This is generally not the case for electricity production, since thermal power plants have to comply with EU ETS, however, it could be the case for other inputs produced by manufacturing plants exempted from complying with the EU ETS. Investigating this feature of the EU policy would require extending our model to multiple sectors. We think this is an interesting avenue for future research.

CRediT authorship contribution statement

Stefan Ambec: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Federico Esposito:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Antonia Pacelli:** Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Investigation, Formal analysis, Data curation, Conceptualization.

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.

(a) $p^{A\alpha} > c_f + \gamma\tau$: Leakage with and without CBAM.
The welfare without CBAM can be written as:

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

The welfare with CBAM under leakage is:

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

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:

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

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:

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

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.

As for export rebates, they are effective only is case (c) of Proposition 3, in which case the welfare $\mathcal{W}$ is defined in (14). Differentiating (14) with respect to α, and using (4) and (9), yields (18). In A.3 we show that $\frac{d\mathcal{W}}{d\alpha} > 0$ for every $\alpha < 1$. Hence $\mathcal{W}$ increases with export rebates $\alpha > 0$.

A.6. 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:

$$\begin{aligned}\frac{d\mathcal{W}}{d\tau} = & \underbrace{[qG(\tilde\theta) - D(p_h)]\frac{dp_h}{d\tau}}_{\text{Price effect}} \\ & + \underbrace{q\int_{\underline{\theta}}^{\tilde\theta}[\delta-\tau]\frac{da^*(\theta)}{d\tau}dG(\theta)}_{\text{Abatement effect}} \\ & + \underbrace{q[\tau(1-a^*(\tilde\theta)-\alpha) - \delta(1-a^*(\tilde\theta))]g(\tilde\theta)\frac{d\tilde\theta}{d\tau}}_{\text{Entry or exit effect}}.\end{aligned} \tag{33}$$

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 (33). 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 (33). 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 (33) 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 (33) 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:

$$\begin{aligned}\frac{d\mathcal{W}}{d\tau} = & \underbrace{[qG(\tilde\theta) - D(p_h) - \delta\gamma D'(p_h)]\frac{dp_h}{d\tau}}_{\text{Price effect}} \\ & + \underbrace{q\int_{\underline{\theta}}^{\tilde\theta}[\delta-\tau]\frac{da^*(\theta)}{d\tau}dG(\theta)}_{\text{Abatement effect}} \\ & + \underbrace{q[\tau(1-a^*(\tilde\theta)) - \alpha - \delta(1-a^*(\tilde\theta)-\gamma)]g(\tilde\theta)\frac{d\tilde\theta}{d\tau}}_{\text{Entry or exit effect}}.\end{aligned} \tag{34}$$

Compared to the case with territorial emissions in (33), 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 (34). An increase of p_h with a marginally higher τ decreases demand by $-D'(p_h)$ in cases (a) (with

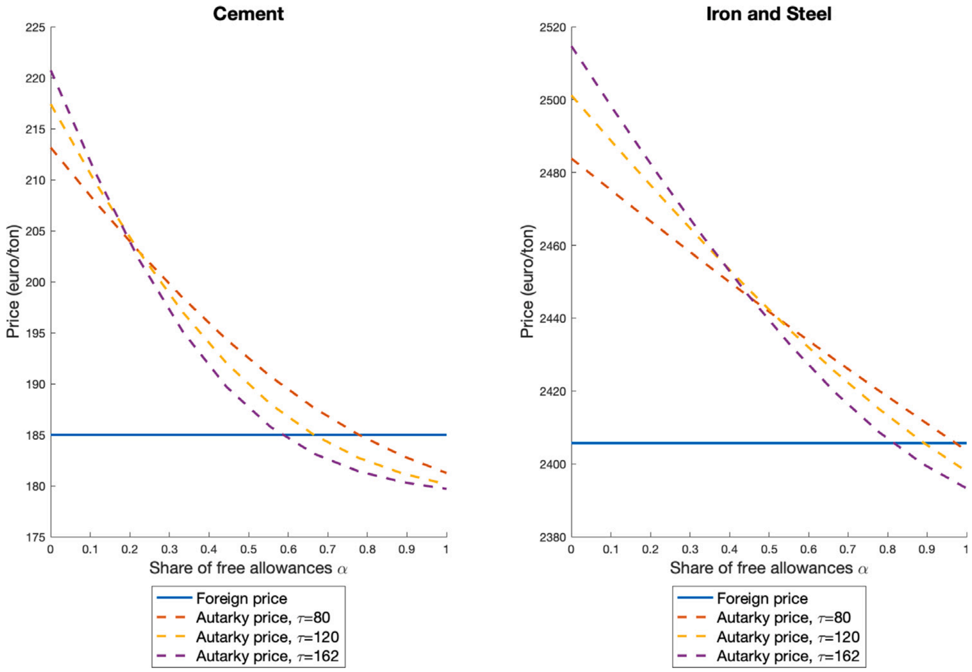

Fig. 9. Equilibrium prices with CBAM.

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 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.7. Additional figures

See Figs. 9–11.

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 $\hat{\beta} = 0.77$ for 2017 (using the average τ of 5).[35] In Fig. 12 we plot the welfare under CBAM in each sector (as in Fig. 7) 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.

In Fig. 13, 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.

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[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.

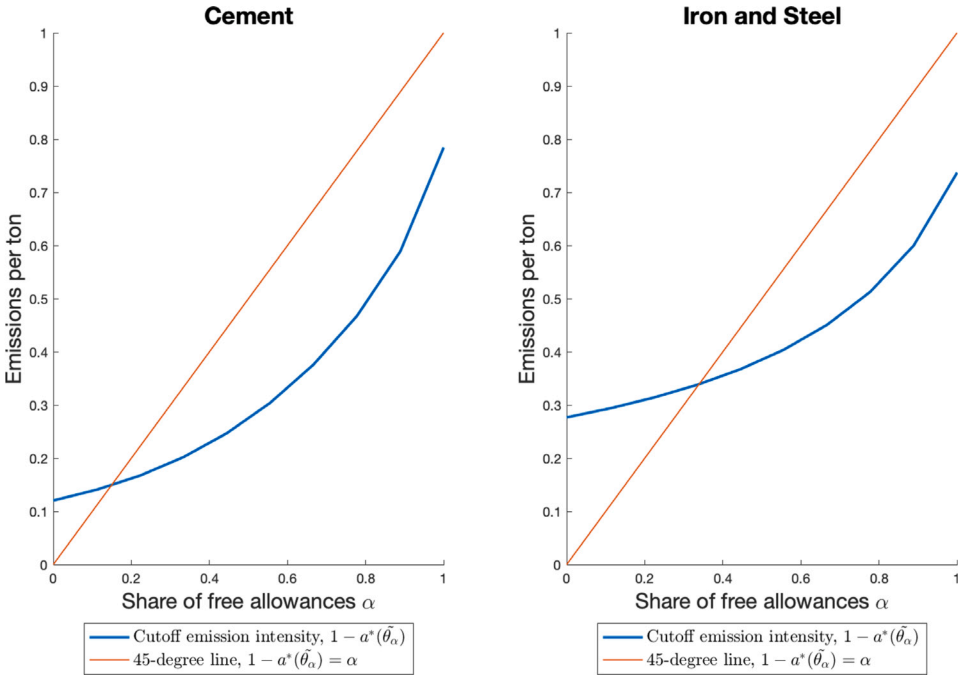

Fig. 10. Cutoff emission intensity, $\tau = 162$.

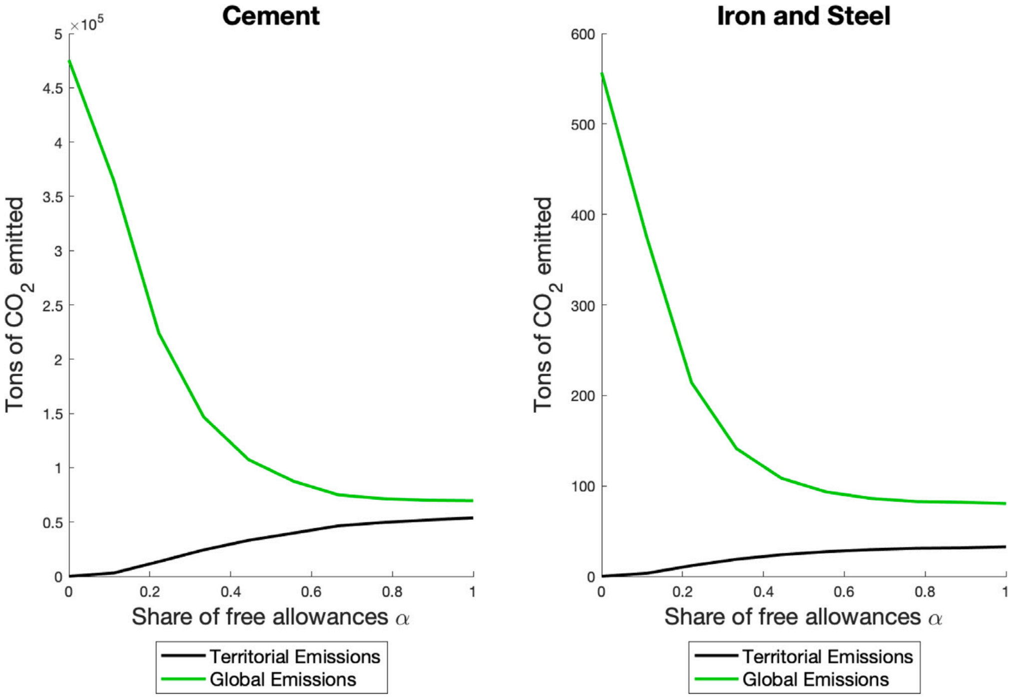

Fig. 11. Emissions without CBAM, with $\tau = 162$.

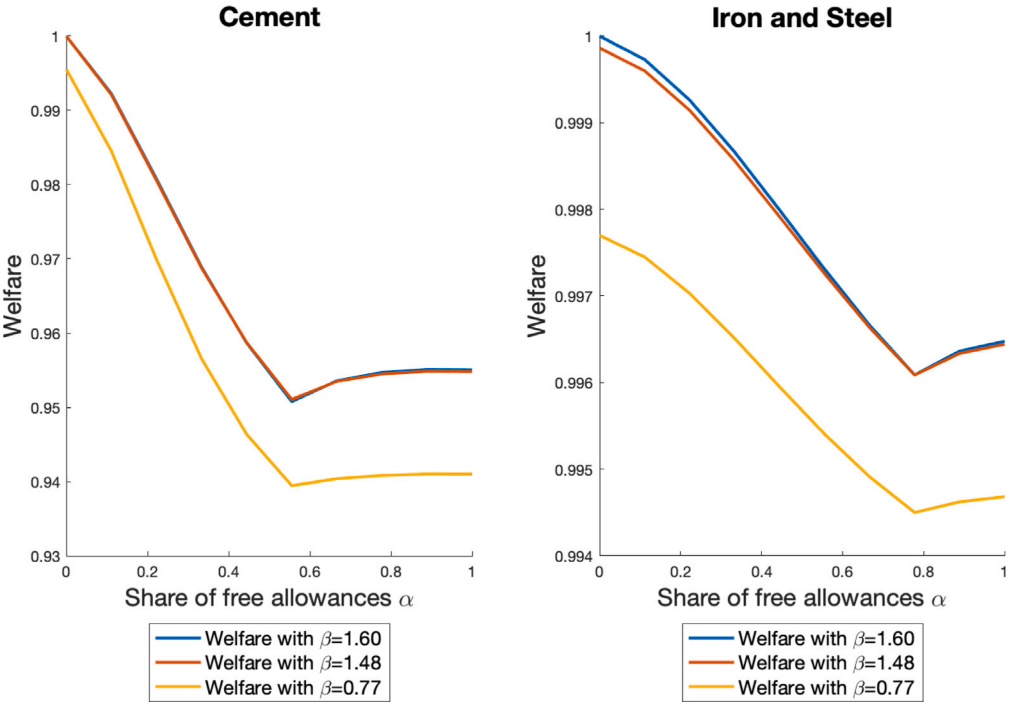

Fig. 12. Welfare with CBAM with β calibrated in different years.

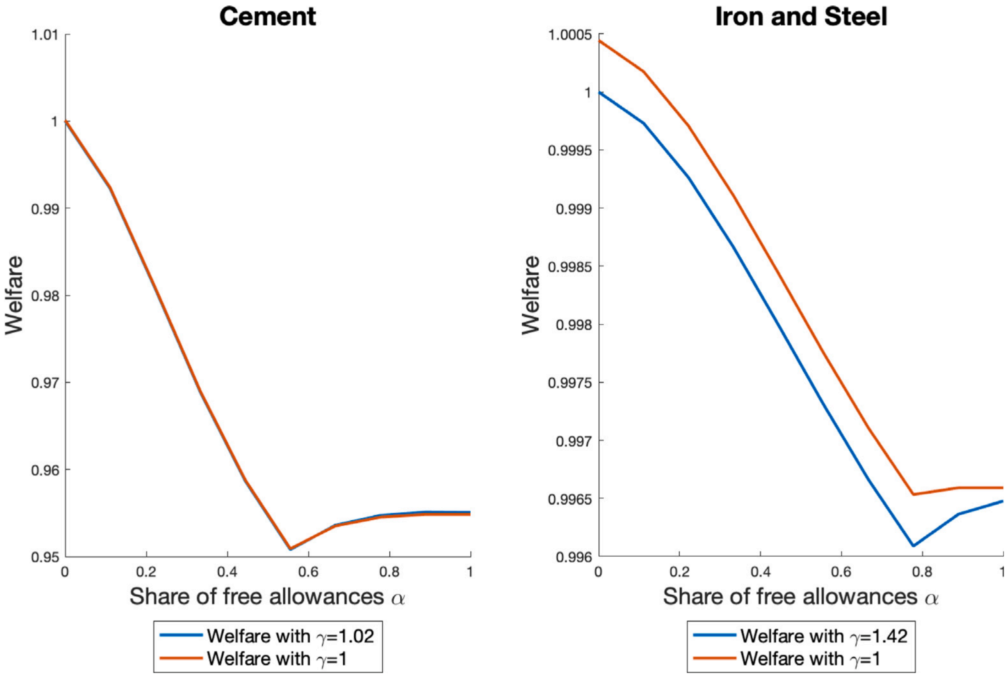

Fig. 13. Welfare with CBAM with $\gamma = 1$.

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