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Unilateral Carbon Pricing and Heterogeneous Firms*

Robin Sogalla§

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Abstract

Several empirical studies document the relevance of firm heterogeneity to assess the effect of trade and environmental policy. This paper develops a multi-country and -sector general equilibrium trade model with heterogeneous firms and analyzes the effect of domestic carbon pricing as well as carbon border adjustments. With heterogeneous firms, these unilateral carbon pricing tools affect the emission intensity both via within- and across-firm adjustments. I show that the across-firm reallocation of market shares can be quantified *ex-ante* using publicly available data on the share of exporting firms. Applying the model to EU climate policy, I find that emission reductions arise mainly through a lower emission intensity of production within firms, while the reallocation channel is negligible. Scale economies aggravate the output loss of emission-intensive manufacturing and the reduction of real income due to more stringent climate policy, but increase the effectiveness of border adjustments to counter carbon leakage. The selection of heterogeneous firms plays a more limited role for aggregate effects.

JEL codes: F12, F13, F18, Q54, Q56

Keywords: International trade; Firm heterogeneity; Unilateral climate policy; Carbon Border Adjustment; GHG emissions

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1 Introduction

In order to combat climate change, greenhouse gas (GHG) emissions must be drastically reduced. Globally coordinated action is deemed to be the most effective solution. However, the stringency of climate policy varies across regions. While 195 countries agreed on reduction targets in the Paris Agreement in 2015, the level of ambition differs considerably across countries (Larch and Wanner 2022). Consequently, only 23% of global GHG emissions are, as of 2023, taxed or covered by an emissions trading scheme (ETS) and the effective price varies substantially (World Bank 2023). These unilateral climate policies pose the risk of so-called carbon leakage, i.e., the increase of emissions in countries with less stringent carbon pricing schemes. A prominent tool to prevent carbon leakage are carbon border adjustments that charge the domestic carbon price on the emissions embodied in imports.

Several *ex-ante* simulation studies assessing the effects of unilateral climate policies point out that these border adjustments are effective at reducing the extent of carbon leakage (see Böhringer et al. (2012), Branger and Quirion (2014) or Cosbey et al. (2019) for overviews). However, they mostly abstract from an important fact: firms are heterogeneous along several dimensions. Since the seminal work of Melitz (2003), many studies illustrate the relevance of productivity dispersion across firms in the context of trade liberalization. More recently, scholars have shown that, even within narrowly defined industries, producers are heterogeneous in their emission intensity (Lyubich et al. 2018). Furthermore, there is convincing evidence that factor productivity and emission intensity are negatively correlated (Copeland et al. 2022). This has key implications for the impact of trade policy on emissions. As shown theoretically by Kreickemeier and Richter (2014), trade liberalization can affect the emission intensity of a sector by reallocating resources toward more productive firms, while this effect is absent in frameworks with homogeneous firms. Thus, by limiting the extent of international competition a border adjustment could have adverse effects on the emission intensity of the economy.

On the other hand, tariffs affect the entry decision of heterogeneous firms (Caliendo et al. 2015). By forcing the least productive firms to exit, endogenous entry generates economies of scale that lead to productivity gains in industries a country specializes in and losses in contracting industries (Kucheryavyy et al. 2023). These specialization effects imply lower or higher effects of domestic and border carbon pricing on the scale of production, real income, and emissions depending on which industries expand. Furthermore, import protection can foster exports in the presence of scale economies (Breinlich et al. 2022). Therefore, even a one-sided carbon border adjustment, which only targets imports, could be effective at promoting a level playing field for exporters.

In this paper, I analyze the general equilibrium implications of firm heterogeneity for unilateral climate policies. For this, I develop a quantitative general equilibrium trade model with multiple countries and sectors, emissions linked to fossil fuels and monopolistic competition of heterogeneous firms. The modelling framework combines several important aspects that are only partly addressed in the existing literature. First, the assumption of monopolistic competition generates external economies of scale that are not present in the standard perfectly competitive frameworks with constant returns to scale. Second, unilateral carbon pricing leads to lower demand for fossil fuels. Consequently, fossil fuel prices fall, which induces producers in other regions to use more fossil fuels, and thus increasing their emissions. These repercussions on the fossil fuel market are known as energy market leakage. By linking emissions to the combustion of fossil fuels, the model allows me to quantify this energy market leakage. Finally, the presence of heterogeneous firms allows for a more detailed decomposition of the emission effects than the previous literature.

Using publicly available data on the share of exporters to a certain destination, I can decompose the effect of unilateral climate policy on the emission intensity into a reallocation of market shares across firms, as opposed to within-firm adjustments. Previous quantitative studies on the general equilibrium effects of unilateral climate policies have acknowledged different combinations of these aspects. This papers' contribution is to include all of them and to quantify the reallocation channel of a counterfactual climate and trade policy change *ex-ante*. Because the reallocation effect is directly linked to the average productivity, this approach allows for the quantification of average productivity changes in a multi-sector and country trade model with heterogeneous firms.

I apply my model to analyze the Fit-for-55 package of the European Union. Besides the emission reduction target of 55% by 2030, a central pillar of this legislative package is the introduction of a Carbon Border Adjustment Mechanism (CBAM). I quantify the effects of varying emission reduction targets combined with different CBAM design options that vary in terms of the sectoral coverage and how embodied emissions are calculated. In the base scenario, I assume that the CBAM is applied on the imports of all sectors that are part of the European Emission Trading System (ETS) and the tax base is a sector-level benchmark. In the first alternative design, the CBAM covers only those ETS industries that are part of the regulation introduced in 2023 (Regulation (EU) 2023/956 of the European Parliament and of the Council (2023)). Finally, I compare the CBAM based on sector-level benchmarks to a design targeted at the emission intensity of the individual firm. In the presence of producers with heterogeneous emission intensity, a firm-level CBAM has the advantage that it might incentivize abatement at the individual firm-level. On the other hand, it might induce reshuffling, if the least emission intensive producers procure the European markets while the most emission intensive ones produce for the domestic market and other export destinations (Fontagné and Schubert (2023)). This paper contributes to the literature by studying this trade-off in a general equilibrium trade model with heterogeneous firms.

The results of the simulation show that a lower emission intensity is the main driver for the decline in EU manufacturing emissions following the introduction of a lower emission cap. However, the composition of economic activity across sectors plays a larger role the more stringent the reduction target. Further decomposing the emission intensity shows that the reductions are mostly driven by within-firm adjustments, while the reallocation effect is almost absent. In line with the previous literature, I find that the CBAM is effective at reducing carbon leakage. While the CBAM mainly targets competitiveness market leakage, my results show that it also induces lower fossil prices. Thus, the CBAM leads to additional leakage in the sectors that it does not cover. Similar to the leakage results, the CBAM reduces the output loss of carbon pricing in emission intensive manufacturing by promoting higher domestic sales and intra-EU trade. However, the CBAM can only partially offset the negative effect of carbon pricing on exports.

Concerning the alternative CBAM designs, I find that a CBAM to the sectors according to the CBAM regulation in 2023, achieves around 60% of the leakage reduction of a CBAM on all ETS sectors. Although the firm-level design induces a larger emission intensity reduction of exports to the EU compared to a design targeted at the industry-level, resource reshuffling of emission intensive production toward non-EU destinations leads to a higher leakage rate. The Fit-for-55 emission target reduces real income in the EU by around 0.3%. While the CBAM shifts part of the burden to other countries, the EU still faces the largest real income loss.

Finally, I quantify the aggregate implications of scale economies and firm heterogeneity. I find that scale economies amplify the negative competitiveness effect of unilateral carbon pricing, as reflected in a higher output loss in ETS industries and a larger leakage rate. On the other hand, the CBAM is more effective at reducing these adverse competitiveness effects compared to a perfect competition constant returns to scale model. Due to a shift of entry into sectors with lower scale elasticity, the presence of scale economies leads to around 25% higher real income loss in the EU due to the Fit-for-55 reduction target compared to a perfectly competitive model. Although the selection of heterogeneous firms reinforce these scale economies effects, they seem quantitatively less important.

The rest of this paper is structured as follows. Section 2 provides an overview of the literature. Section 3 develops the theoretical model and derives the decomposition of emission changes. In 4, I discuss the data, the counterfactual scenario and the solution algorithm. Finally, section 5 shows the quantitative results before section 6 concludes.

2 Literature

This study relates to several different strands of literature. First, it speaks to studies on the role of heterogeneous firms when analyzing the effect of trade and environmental policy. Empirically, several scholars show that firms differ in their emission intensity and that more productive firms produce with a lower emission intensity. (see Copeland et al. (2022) and Cherniwchan et al. (2017) for overviews). Relatedly, exporters seem to be cleaner than domestic firms (Holladay (2016),Richter and Schiersch (2017), Forslid et al. (2018)). This heterogeneity inspired theoretical work on the relationship between trade and emissions that accounts for the reallocation of market shares across firms. Kreickemeier and Richter (2014) show, in a model with two countries and one sector, that trade liberalization can decrease aggregate emissions by reallocating market shares toward more productive firms. LaPlue (2019) extends the framework to a two sector model to study the interaction of the across-firms within-sector reallocation effects with those across sectors due to comparative advantage. He finds that within-sector adjustments dampen the compositional changes across sectors. Calibrating the model to the values of the decomposition of Levinson (2009), he finds that trade liberalization leads to relatively small composition effects, but through reallocation of market shares has a substantial effect on the scale of production and the sector-level emission intensity. Egger et al. (2021), focusing on the effect of unilateral environmental taxes, derive similar reallocation effects as for trade liberalization. In a comparable model, Kurz (2022) studies the effect of incomplete regulation. She finds that if small and unproductive firms are exempted from environmental regulation, an increase in carbon prices limits the reallocation toward more productive firms.

The magnitude of the reallocation effect is still an open question and depends on the context. Shapiro and Walker (2018) attribute most of the emission reductions in US manufacturing between 1990 and 2008 to within-firm changes. Martin (2011) obtains similar results for India and Rottner and Graevenitz (2021) for Germany. On the other hand, Najjar and Cherniwchan (2021), Barrows and Ollivier (2018), Holladay and LaPlue III (2021) find large reallocation effects. All these studies quantify the reallocation effect *ex-post*. In contrast to this, this paper investigates the reallocation effect of different counterfactual policy changes *ex-ante*.

Second, I contribute to studies that analyze environmental outcomes in quantitative trade models. Despite the micro-level evidence, firm heterogeneity is less prominent in the evaluation of trade and climate policy in general equilibrium. Most studies apply perfectly competitive Ricardian or Armington trade models (Egger and Nigai (2015), Shapiro (2016), Larch and Wanner (2017), Larch and Wanner (2022), Shapiro (2021), Duan et al. (2021), Caron and Fally (2022)). An early exception is Balistreri and Rutherford (2012), who allow for heterogeneous firms in one aggregated emission intensive manufacturing sector to analyze the impact of emission reduction targets combined with carbon tariffs in a Computable General Equilibrium model (CGE). They find that heterogeneous firms lead to higher carbon leakage rates and render carbon tariffs more effective compared to an Armington trade model. In a similar model, Balistreri et al. (2018) analyze the role of heterogeneous firms for the effect of sub-global carbon pricing. They find that heterogeneous firms lead to higher competitiveness gains of emission-intensive manufacturing production in countries that do not implement the policy. These competitiveness gains can increase welfare in these regions, while non-abating regions lose welfare in Armington models. Compared to my structural gravity model, these CGE studies have the advantage of capturing input-output linkages and detailing differences in substitution between inputs. In contrast, my modelling framework allows me to decompose the mechanisms through which emissions change in more detail. Moreover, they consider heterogeneous firms only in one sector, while my model features several manufacturing industries and firm heterogeneity in all sectors.

More closely related to my framework, Shapiro and Walker (2018) develop a model with heterogeneous firms and endogenous abatement to analyze the main driver behind the emission reductions in US manufacturing. While the general structure of my model follows their approach, I extend it in several dimensions. First, I link the emissions to the use of fossil fuels instead of treating them as a byproduct of production. This modelling choice does not just reflect reality more closely (Richter and Schiersch (2017)), but it allows me to quantify the repercussion on the fossil fuel market. Hence, I can quantify carbon leakage via the energy market channel on top of the competitiveness channel. Furthermore, I do not assume a Cobb-Douglas production function, but rather allow the elasticity of substitution between emissions and other inputs to be different from one. Another related study is Farrokhi and Lashkaripour (2021), who develop a model with scale economies and derive optimal carbon taxes and tariffs. Like Shapiro and Walker (2018), they do not quantify the energy market channel. Moreover, firms are assumed to be homogeneous in their framework.

Third, this study advances the literature on the effect of carbon border adjustments and, in particular, those focusing on the EU CBAM. Since the EU CBAM will be the first nationwide border adjustment, most studies analyzing this policy tool rely on *ex-ante* simulation models. They find that carbon border adjustments are in general effective at reducing carbon leakage, but face practical implementation issues (see Böhringer et al. (2022), Böhringer et al. (2012), Cosbey et al. (2019) for overviews). Some studies analyze the specific design of the EU CBAM.

Bellora and Fontagné (2023) compare different options for the tax base of the CBAM as well as an addition of export rebates to a baseline where firms in the EU-ETS continue to receive free allowances. They find that the introduction of the CBAM is more effective at reducing carbon leakage than the free allocation of emission allowances. However, the CBAM leads to higher carbon prices in the EU ETS and a drop in value-added in downstream sectors.
Mörsdorf (2022) find that free allocations are as effective as the CBAM on imports, but less effective when the CBAM covers indirect emissions and rebates exports. Both studies apply homogeneous firms frameworks, thus abstracting from the reallocation introduced by heterogeneous firms. Furthermore, these studies use more aggregated data sets for the simulation of counterfactual policies. Thus, I cover each individual EU country instead of an aggregated region, which allows for changes in intra-EU trade in response to the CBAM. Moreover, I distinguish between 54 different sectors, compared to 23 in Bellora and Fontagné (2023) and 10 in Mörsdorf (2022).

Korpar et al. (2022) apply the perfectly competitive model of Larch and Wanner (2017) to quantify the impact of different CBAM designs. Similar to my results, they find that the CBAM has a limited effect on global emissions. One qualitative difference is that their model implies a negative effect of the CBAM on EU exports. In contrast to that, accounting for economies of scale in my model leads to an export promoting effect of the CBAM.
Campolmi et al. (2023) introduce a Leakage Border Adjustment Mechanim (LBAM) as an alternative that does not require the administrative burden of collecting emission intensities of foreign producers. Instead, the main idea is to combine carbon pricing with import tariffs (and export rebates) that hold trade at the level without carbon pricing. The calibration of this policy instrument substitutes added structure and estimated elasticities for the need of detailed emission intensity data. Quantitatively, they find that a LBAM would be more effective at reducing carbon leakage compared to the CBAM limited to the sectors of the EU regulation in 2023.

Considering the firm-level CBAM design, this paper relates to studies that quantify the difference between targeted carbon border adjustments as opposed to designs relying on benchmark values. Böhringer et al. (2017) and Winchester (2012) find that, in models with homogeneous firms, targeted border adjustments are more effective at leakage reduction. On the other hand, the results of Fowlie et al. (2021) indicate substantial resource reshuffling for electricity trade in the case of the Californian border adjustment. Applying a detailed power market model with varying emission intensity across power plants, they show that a border adjustment that targets the emission intensity of individual producers is completely ineffective at reducing leakage. I contribute to this literature by considering a firm-level targeted CBAM on manufacturing products, when producers are heterogeneous.

More generally, my study is linked to the literature on quantitative trade models that account for external economies of scale. In their overview paper, Costinot and Rodríguez-Clare (2014) find distinct welfare effects of tariff increases for models with monopolistic competition compared to perfectly competitive models due to economies of scale. Kucheryavyy et al. (2023) provide the micro-foundation for these scale economies in different modelling frameworks. They include external economies of scale into a canonical Armington model and derive conditions for which this model is isomorphic to models with monopolistic competition. They further show that standard monopolistic competition models as in Costinot and Rodríguez-Clare (2014), implicitly assume that the trade elasticity is equal to the inverse of the scale elasticity. However, estimates of Lashkaripour and Lugovskyy (2023) and Bartelme et al. (2019) suggest that these two elasticities differ. Moreover, Kucheryavyy et al. (2023) provide analytical and numerical evidence for multiple equilibria in case the product of the scale and trade elasticity is not lower than one. Quantitatively, they present evidence that the real income gains from trade liberalization in models with scale economies are larger. This scale economies premium is heterogeneous across countries and depends on whether the reduction of tariffs leads to specialization in industries with low or high scale elasticity. The application of differing scale and trade elasticities in quantitative trade models is still limited. Lashkaripour and Lugovskyy (2023) and Bartelme et al. (2019) study the optimal industrial and trade policy, while Breinlich et al. (2022) quantify the effects of increased US imports from China on exports. To the best of my knowledge, the only study applying this framework to the environmental context is Farrokhi and Lashkaripour (2021). As mentioned above, compared to their model, I allow for heterogeneous firms and model the fossil fuel market.

All-in-all, my model combines several important features for the analysis of unilateral climate policy. Most importantly, as I show below, including heterogeneous firms allows for a detailed decomposition of the channels through which domestic/border carbon pricing affects emissions.

3 Model

This section develops a multi-sector quantitative trade model with heterogeneous firms, scale economies, and emissions linked to the usage of fossil fuels. The main structure of the model follows Lashkaripour and Lugovskyy (2023) and Kucheryavyy et al. (2023), extended by heterogeneous firms as in Melitz (2003) and Chaney (2008). The inclusion of the fossil fuel sector is based on the modelling framework for commodities of Fally and Sayre (2018). There are M countries and K sectors that consist of one fossil fuel sector denoted by f (e.g., extraction of coal or fossil natural gas) and a set of other sectors $s \in S$, which comprise manufacturing, services, and secondary energy sectors such as electricity generation.

3.1 Equilibrium in levels

3.1.1 Demand

Demand for final goods and intermediate goods are given by a three-tier CES-Cobb-Douglas nest.

Tier 1: Cobb Douglas across industries:

$$U_i = \prod_{s \in S} Q_{is}^{\alpha_{is}} \Delta_i(Z) \tag{3.1}$$

where α_{is} is the spending share in country i on industry s.

Tier 2: CES within industries across origins:

$$Q_{is} = \left(\sum_{j \in N} Q_{jis}^{\sigma_s/(\sigma_s - 1)} \right)^{\sigma_s/(\sigma_s-1)}$$

Tier 3: CES within countries and industries across firms:

$$Q_{jis} = \left(\int_{\omega \in \Omega_{jis}} q_{jis}(\omega)^{(\eta_s - 1)/(\eta_s)} d\omega \right)^{\eta_s/(\eta_s-1)}$$

Demand for variety ω in sector s shipped from j to i, $q_{jis}(\omega)$, is given by:

$$q_{jis}(\omega) = p_{jis}^{-\eta_s} P_{jis}^{\eta_s-\sigma_s} P_{is}^{\sigma_s-1} \alpha_{is} Y_i \tag{3.2}$$

where $Y_i = w_i L_i + T_i + r_{if} R_{if} + D_i$ is the total expenditure, which consists of labor income, $w_i L_i$, fossil fuel resource income, $r_{if} R_{if}$, collected taxes and tariffs, T_i, and an exogenous trade deficit D_i. The corresponding price indices are given by:

$$P_{is} = \left(\sum_{j \in M} P_{jis}^{1-\sigma_s} \right)^{1/(1-\sigma_s)}$$

$$P_{jis} = \left(\int_{\omega \in \Omega_{jis}} p_{jis}(\omega)^{1-\eta_s} d\omega \right)^{1/(1-\eta_s)}$$

For simplicity, I abstract from fossil fuel usage and emissions that arise from consumption (e.g., heating with fossil natural gas). Finally, $\Delta_i(Z)$ measures the disutility from global GHG emissions, Z. I follow Shapiro (2016) and assume the functional form of pollution damages:

$$\Delta_i(Z) = \frac{1}{1 + \left(\frac{Z}{\upsilon_i}\right)^2}$$

3.1.2 Fossil fuel sector

Fossil fuel producers have the following production technology:

$$q_{if} = a_{if}(\omega_f) \left[\mu_{if} L_{if}^{\frac{\zeta_f - 1}{\zeta_f}} + (1 - \mu_{if}) R_{if}^{\frac{\zeta_f - 1}{\zeta_f}} \right]^{\frac{\zeta_f}{\zeta_f - 1}}$$

where L_{if} is labor and R_{if} are fossil fuel resources. Following Eaton and Kortum (2002), $a_i^f(\omega^f)$ is a country specific productivity parameter that is drawn from a Fréchet distribution with cumulative density function $H_i^f(a) = exp(-A_{if} a^{-\epsilon_f})$. The unit cost of producing fossil fuels is $c_{if} = a_{if}(\omega)\tilde{c}_{if}$ with:

$$\tilde{c}_{if} = \left[\mu_{if}^{\zeta_f} r_{if}^{1-\zeta_f} + (1 - \mu_{if})^{\zeta_f} w_i^{1-\zeta_f} \right]^{1/(1-\zeta_f} \tag{3.3}$$

Perfect competition in the fossil fuel sector implies that prices equal marginal costs and that the lowest cost producer serves a certain destination. Hence, the price for fossil fuels in country i is given by:

$$P_{if} = \tilde{\Gamma}\left[\sum_{j\in M} A_{jf}(\tilde{c}_{jf}\tau_{jif})^{-\epsilon_f}\right]^{-1/\epsilon_f} \tag{3.4}$$

where $\tilde{\Gamma} = \left[\Gamma\left(\frac{\epsilon_f+1-\zeta_s}{\epsilon_f}\right)\right]^{1/(1-\zeta_s)}$ is a constant. The share of country i's fossil fuel expenditure on fossil fuels from country j is:

$$\lambda_{jif} = \frac{A_{jf}(\tilde{c}_{jf}\tau_{jif})^{-\epsilon_f}}{\sum_{k\in M} A_{kf}(\tilde{c}_{kf}\tau_{kif})^{-\epsilon_f}} \tag{3.5}$$

Thus, the fossil fuel price differs across countries depending on the costs of sourcing them. These sourcing costs are a function of the trade and production costs in the host country. Countries that are closer in terms of trade costs to fossil fuel producing countries or have low fossil fuel production costs themselves benefit from lower fossil fuel prices. As pointed out by Mahlkow and Wanner (2022), this introduces a Heckscher-Ohlin force into the model, since the endowment of fossil fuels matters for their relative costs.

3.1.3 Manufacturing sectors

A continuum of firms produces each a distinct variety ω in every sector s. Firms are heterogeneous in their productivity φ. Production for market j from country i is given by:

$$q_{ijs}(\varphi) = \varphi\left[\mu_{is} l_{ijs}^{\frac{\zeta_s-1}{\zeta_s}} + (1-\mu_{is}) e_{ijs}^{\frac{\zeta_s-1}{\zeta_s}}\right]^{\frac{\zeta_s}{\zeta_s-1}}$$

where $l_{ijs}(\varphi)$ is the labor used for the production of variety φ and $e_{ijs}(\varphi)$ are fossil fuels. GHG emissions are proportional to the usage of fossil fuels, i.e $z_{ijs}(\varphi) = \iota e_{ijs}(\varphi)$. Hence, one can express production in terms of emissions instead of fossil fuels.

Carbon taxes and border adjustment Similar to Larch and Wanner (2022), the government can charge an *ad-valorem* carbon tax, ν_{is}, on the usage of fossil fuels. Furthermore, a levy on the emissions embodied in trade flows from i to j in sector s can be applied. This carbon border adjustment can take two different designs. In the first design, the government implements the CBAM as an *ad-valorem* tariff rate, t_{ijs}^{cadv}. Modelling carbon border adjustments as an additional tariff is the predominant approach in the literature. Because the tariff rate is the same for all firms exporting from i to j in s, this approach implicitly assumes that the CBAM proxies the emissions embodied in the imports of an individual firm with a sector-level reference value. Alternatively, the government implementing the CBAM could gather data on the emissions released in the production process of the individual firm and apply the CBAM based on the actual firm-level emissions. When the firm-specific CBAM design, t^{cf}_{ijs}, is introduced, the effective carbon price of a firm is destination specific, i.e. $\kappa_{ijs} = (1 + \nu_{is} + t^{cf}_{ijs})\frac{P_{if}}{\iota}$. Modelling a border adjustment targeted at the firm-level in this way is similar to Winchester (2012) and Böhringer et al. (2017).

Unit costs and emissions The unit costs of production are then given by $c_{ijs} = \varphi^{-1}\tilde{c}_{ijs}$ with:

$$\tilde{c}_{ijs} = \left[\mu_{is}^{\zeta_s} w_i^{1-\zeta_s} + (1-\mu_{is})^{\zeta_s}\kappa_{ijs}^{1-\zeta_s}\right]^{\frac{1}{1-\zeta_s}} \tag{3.6}$$

Hence, firms with higher productivity have lower production costs. Emissions associated with the production for destination j can be expressed as:

$$z_{ijs}(\varphi) = \gamma_{ijfs}\frac{\tilde{c}_{is}}{\kappa_{ijs}}\frac{\tau_{ijs}q_{ijs}(\varphi)}{\varphi} \tag{3.7}$$

where

$$\gamma_{ijfs} = \iota((1-\mu_{is})^{\zeta_s}\left(\frac{\kappa_{ijs}}{\tilde{c}_{ijs}}\right)^{1-\zeta_s} \tag{3.8}$$

is the fossil fuel cost share multiplied by the emission factor. The firm-level emission intensity is then given by:

$$i_{is}(\varphi) = \frac{1}{\varphi}\frac{z_{is}(\varphi)}{q_{is}(\varphi)} = \sum_{j\in M}\gamma_{ijfs}\frac{\tilde{c}_{ijs}}{\kappa_{ijs}} \tag{3.9}$$

Thus, more productive firms produce with a lower emission intensity.

Profits and pricing Firms must pay two different types of fixed costs. First, when entering the market, they pay $\tilde{c}_{is}f^e_{is}$ to draw a productivity. Moreover, for each market served, there is an additional fixed cost of $\tilde{c}_{ijs}f_{ijs}$. Both types of fixed costs are paid in terms of all inputs to production. Total profits of a firm in country i and sector s with productivity φ are provided by:

$$\pi_{is}(\varphi) = \sum_{j\in M}\pi_{ijs}(\varphi) - \tilde{c}_{is}f^e_{is} \tag{3.10}$$

where π_{ijs} are the profits of serving market j from country i and sector s, which are equal to

$$\pi_{ijs} = \frac{p_{ijs}q_{ijs}(\varphi)}{1+t_{ijs}} - \frac{\tilde{c}_{ijs}}{\varphi}\tau_{ijs}q_{ijs}(\varphi) - \tilde{c}_{ijs}f_{ijs}$$

where $t_{ijs} = t^{b}_{ijs} + t^{cadv}_{ijs}$ are the sum of baseline *ad-valorem* tariffs, t^{b}_{ijs} and the *ad-valorem* CBAM design. τ_{ijs} are iceberg trade costs. To ease notation, define $\phi_{ijs} = \tau_{ijs}(1+t_{ijs})$ as total trade costs. The first order condition leads to the following constant mark-up pricing rule:

$$p_{ijs} = \frac{\phi_{ijs}\tilde{c}_{ijs}}{\varphi}\frac{\eta_s}{\eta_s - 1} \tag{3.11}$$

and from (3.2) the quantity supplied can be written as:

$$q_{ijs}(\varphi) = \left(\frac{\phi_{ijs}\tilde{c}_{ijs}}{\varphi}\frac{\eta_s}{\eta_s - 1}\right)^{-\eta_s} P_{ijs}^{\eta_s-\sigma_s} P_{js}^{\sigma_s-1} Y_{js} \tag{3.12}$$

where $Y_{js} = \alpha_{js}Y_j$ is the sector level spending. Define the aggregate market level for a firm exporting from i to j in sector s as:

$$B_{ijs} = P_{ijs}^{\eta_s-\sigma_s} P_{js}^{\sigma_s-1} Y_{js} \tag{3.13}$$

Then revenues are given by:

$$r_{ijs}(\varphi) = p_{ijs}(\varphi)q_{ijs}(\varphi) = p_{ijs}^{1-\eta_s} B_{ijs} \tag{3.14}$$

Profits can thus be written as:

$$\pi_{ijs} = \frac{x_{ijs}(\varphi)}{\eta_s} - \tilde{c}_{ijs}f_{ijs} \tag{3.15}$$

where $x_{ijs}(\varphi) = \frac{r_{ijs}(\varphi)}{1+t_{ijs}}$ are the sales after accounting for tariffs.

Market entry and cut-off productivities Firm-level productivity follows a pareto distribution with cumulative density function $G_{is} = 1 - \left(\frac{b_{is}}{\varphi}\right)^{\theta_s}$. Firms in sector s in country i enter market j as long as they earn positive profits. Due to the fixed costs of serving a market, there exists a unique productivity for each i, j, s triple such that firms with productivity lower than this productivity do not supply to market j from country i in sector s. This zero profit cut-off productivity (ZCP) is obtained by solving (3.15) for φ, which leads to:

$$\varphi^*_{ijs} = \frac{\eta_s}{\eta_s - 1}\phi_{ijs}\tilde{c}_{ijs}\left(\frac{\eta_s \tilde{c}_{ijs} f_{ijs}(1+t_{ijs})}{B_{ijs}}\right)^{\frac{1}{\eta_s - 1}} \tag{ZCP}$$

Firms will enter as long as $\sum_{j\in M} Pr\left\{\varphi \geq \varphi^*_{ijs}\right\} E\left[\pi_{ijs}|\varphi \geq \varphi^*_{ijs}\right] \geq \tilde{c}_{is} f^e_{is}$. As shown in Appendix A.1, this can be simplified to:

$$\sum_{j\in M} b_{is}^{\theta_s}(\varphi^*_{ijs})^{-\theta_s}\frac{\eta_s - 1}{1-\eta_s+\theta_s}\tilde{c}_{ijs} f_{ijs} = \tilde{c}_{is} f^e_{is} \tag{FE}$$

3.1.4 Equilibrium

In the following, I present the aggregate equilibrium outcomes. All derivations are deferred to Appendix A.1. The price index for goods shipped from i to j in sector s is given by:

$$P_{ijs} = (N_{is})^{\frac{\delta_s}{(1-\sigma_s)}}\left(\phi_{ijs}\tilde{c}_{ijs}\right)^{\frac{-\epsilon_s}{(1-\sigma_s)}}\left[\left(\frac{Y_{js}}{(1+t_{ijs})\tilde{c}_{ijs}}\right)\right]^{\frac{\psi_s\delta_s}{(1-\sigma_s)}}(P_{js})^{(-\psi_s\delta_s)}\xi_{ijs} \tag{3.16}$$

where ξ_{ijs} is a constant depending on fixed costs and parameters. $\delta_s = \frac{\epsilon_s}{\theta_s}$ is the product of the scale elasticity, $\frac{1}{\theta_s}$, and the trade elasticity, $\epsilon_s = \frac{\theta_s}{1+\theta_s\left(\left(\frac{1}{\sigma_s-1} - \frac{1}{\eta_s-1}\right)\right.}$. $\psi_s = \frac{1-\eta_s+\theta_s}{\eta_s-1}$ captures the extent of firm heterogeneity. As shown by Costinot and Rodríguez-Clare (2014), one obtains the price index in a model with monopolistic competition without firm heterogeneity by setting $\psi_s = 0$. In addition to the formula obtained by Costinot and Rodríguez-Clare (2014), the additional parameter δ_s captures the difference between the scale elasticity and the trade elasticity. In the standard Armington model $\delta_s = 0$ and in a standard Melitz/Chaney or Krugman model $\delta_s = 1$. The aggregate price index for products from sector s in country i is then given by:

$$P_{is} = \left[\sum_{j\in M}(N_{js})^{\delta_s}\left(\phi_{jis}\tilde{c}_{jis}\right)^{-\epsilon_s}\left(\frac{Y_{is}}{(1+t_{jis})\tilde{c}_{ijs}}\right)^{\psi_s\delta_s}\right]^{\frac{-1}{\epsilon_s}} \tag{3.17}$$

Consumers in country i spend the following share of their expenditure on goods from country j, sector s:

$$\lambda_{ijs} = \frac{P_{ijs}^{1-\sigma_s}}{\sum_{l\in M} P_{ljs}^{1-\sigma_s}}$$

which can be rewritten as

$$\lambda_{ijs} = \frac{(N_{is})^{\delta_s} \left(\tilde{c}_{ijs}\phi_{ijs}\right)^{-\epsilon_s} \left((1+t_{ijs})\tilde{c}_{ijs}\right)^{-\delta_s\psi_s} \xi_{ijs}}{\sum_{l\in M}(N_{ls})^{\delta_s} \left(\tilde{c}_{ljs}\phi_{ljs}\right)^{-\epsilon_s} \left((1+t_{ljs})\tilde{c}_{ljs}\right)^{-\delta_s\psi_s} \xi_{ljs}} \tag{3.18}$$

The expenditure of consumers in j on varieties from country i and sector s is thus $\lambda_{ijs}Y_{js}$. However, due to imports tariffs, producers in i receive only part of this expenditure and total exports must be adjusted for tariffs. Total exports from i to j in sector s are equal to:

$$X_{ijs} = \frac{\lambda_{ijs}}{1+t_{ijs}} Y_{js} \tag{3.19}$$

The emissions embodied in these trade flows are given by:

$$Z_{ijs} = \frac{\gamma_{ijfs}}{\kappa_{ijs}} X_{ijs} \tag{3.20}$$

The government collects tariffs and taxes of:

$$T_i = \sum_{s\in S} \nu_{is} \sum_{j\in M} \frac{\gamma_{ijfs}}{1+\nu_{ijs}} Y_{js} + \sum_{s\in S} Y_{is} \sum_{j\in M} \frac{\lambda_{jis}}{1+t_{jis}} \left(t_{jis} + t^{cf}_{jis} \frac{\gamma_{jifs}}{1+\nu_{jis}} \right) \tag{3.21}$$

Hence, consumers in i spend on products from sector s:

$$Y_{is} = \alpha_{is} \left(w_i L_i + r_{if} R_{if} + T_i \right) \tag{3.22}$$

The expenditure on fossil fuels is provided by:

$$Y_{if} = \sum_{s,j} \frac{\kappa_{ijs}}{\iota} \gamma_{ijfs} X_{ijs} \tag{3.23}$$

and revenues from fossil fuels are equal to: $X_{if} = \sum_{j\in M} \lambda_{ijf} Y_{jf}$. Labor demand in country i and sector s implies:

$$w_i L_{is} = \sum_{s,j} \gamma_{ijls} \frac{\lambda_{ijs}}{1+t_{ijs}} Y_{js} \tag{3.24}$$

The labor market clearing condition in country i can be expressed as:

$$w_i L_i = \sum_{s,j} \gamma_{ijls} \frac{\lambda_{ijs}}{1+t_{ijs}} Y_{js} + \gamma_{ilf} \sum_{j\in M} \lambda_{ijf} Y_{jf} \tag{3.25}$$

and the fossil fuel resource clearing is given by:

$$r_{if} R_{if} = \gamma_{irf} \sum_{j \in M} \lambda_{ijf} Y_{jf} \tag{3.26}$$

where $\gamma_{irf} = \mu_{if}^{\zeta_f} \left(\frac{r_{if}}{\tilde{c}_{if}} \right)^{1-\zeta_f}$. Finally, the number of entering firms is obtained by summing over the revenues from all markets, namely:

$$N_{is} = \frac{X_{is}}{\tilde{c}_{is} f_{is}^{e}} \frac{\eta_s - 1}{\theta_s \eta_s} \tag{3.27}$$

Definition 3.1 (Equilibrium in levels)**.** An equilibrium under the tax structure $\{\nu_{is}, t_{ijs},\}$ is a vector of wages, $\{w_i\}$, labor allocations $\{L_{ik}\}$, and fossil rental rates $\{r_{if}\}$ such that given the fundamentals $\{L_i, R_{if}, D_i, A_{if}, \tau_{ik},\ f_{ijs}, \mu_{ik}, \zeta_k, \epsilon_k, \eta_s, \sigma_s, \theta_s, \alpha_{is}, \iota, \phi_{ijs}, b_{is}\}$ the equilibrium conditions (3.3), (3.4), (3.6), (3.8), (3.18), (3.19), (3.20), (3.21), (3.22), (3.23) hold and the market clearing conditions (3.24), (3.25) and (3.26) are satisfied.

To quantify the equilibrium after a policy, I follow the hat-algebra approach of Eaton et al. (2008) and express the equilibrium in changes. Let x be the outcome of variable x in the baseline and x' the outcome after the policy change. Appendix A.6 shows how to express the equilibrium in changes, $\hat{x} = \frac{x'}{x}$.

3.2 Comparative statics of different CBAM designs

This paper compares the difference between a firm-specific CBAM design and an *ad-valorem* equivalent based on sector-level emission intensities. The following proposition summarizes how the two design options affect firm-level trade flows and embodied emissions:

Proposition 3.1. *Suppose country j imposes a CBAM on exports from country i in sector s, where the CBAM is either an* ad-valorem *tariff, t_{ijs}^{cadv}, or firm specific, t_{ijs}^{cf}. Holding the market level, B_{ijs},constant:*

(i) Both CBAM types locally affect the emissions embodied in the exports of firm φ from i to j in sector s. The firm-level CBAM, t_{ijs}^{cf}, additionally impacts the emission intensity of this export flow.

(ii) Both CBAM types locally reduce firm level exports to the destination imposing it and the firm-level emissions embodied in exports to this destination.

(iii) The embodied emissions locally decline more for the firm-level CBAM iff:

$$\left[\frac{\zeta_s}{\eta_s} + \frac{\gamma_{ifs}}{\iota}\left(1 - \frac{\zeta_s}{\eta_s}\right)\right] > \frac{1+\nu_{is}}{1+t_{ijs}} \tag{3.28}$$

Proof. See A.2. □

Because the CBAM increases the cost of exporting to the destination implementing it, it reduces the firm-level exports. Moreover, the firm-level design incentivizes an adjustment in the production factors leading to a reduction in the emission intensity of exports, while a CBAM based on sector-level default values does not alter the production decisions of firms. Therefore, it is tempting to conclude that the firm-specific CBAM incentivizes larger firm-level emission reductions. However, the two CBAM designs affect firm-level exports differently. Part (iii) of proposition 3.1 shows that the firm-specific CBAM reduces emissions more whenever:

- The carbon cost share, γ_{ifs}, is relatively large and hence the cost increase of the firm-specific CBAM design is relatively large;
- Firms can switch relatively easily to non-fossil inputs (large ζ_s);
- The baseline carbon price of the origin country relative to the baseline *ad-valorem* tariff is relatively low and hence an additional price on carbon via the firm specific CBAM has a larger effect compared to and additional *ad-valorem* tariff.

These results only showed the local changes, holding the market level fixed. However, the CBAM designs impact the market level via the price index and total demand differently. Moreover, the proposition only summarizes the effect on firm-level embodied emissions. One of the key disadvantages of the CBAM targeted at the individual firm is the reshuffling of the least emission intensive producers toward the region implementing the CBAM and the more polluting firms toward other markets (Böhringer et al. (2022)). These general equilibrium effects are addressed in the results of the quantitative model in section 5.

3.3 Decomposition of production emission changes

Research on the relationship between international trade and emissions is guided by a simple decomposition framework initially proposed by Grossman and Krueger (1991). It is based on the following accounting identity:

$$Z = Q \sum_{s \in S} \Xi_s I_s$$

where Q is total output, $I_s = \frac{Z_s}{Q_s}$ the emission intensity of a sector s and $\Xi_s = \frac{Q_s}{Q}$ the share of sector s in total output. Totally differentiating leads to the decomposition of the change in emissions into a scale, composition, and technique effect:

$$d \ln Z = \underbrace{d \ln Q}_{\text{Scale Effect}} + \underbrace{\sum_{s \in S} \rho_s d \ln \Xi_s}_{\text{Composition Effect}} + \underbrace{\sum_{s \in S} \rho_s d \ln I_s}_{\text{Technique Effect}} \tag{3.29}$$

where $\rho_s = \frac{Z_s}{Z}$ is the baseline emission share of sector s. The *Scale effect* measures changes in emissions due to a change in the level of total output. The *Composition effect* accounts for changes in emissions that occur due to a shift in production patterns across sectors. Finally, the *Technique effect* captures changes in the emission intensity of production. Following Cherniwchan et al. (2017), the emission intensity can be decomposed into:

$$I_s = \frac{Z_s}{Q_s} = \int_0^{n_s} i_s(\varphi) \xi_s(\varphi) dG(\varphi)$$

where $i_s(\varphi) = \frac{z_s(\varphi)}{q_s(\varphi)}$ is the emission intensity of firm φ in sector s and $\xi_s(\varphi) = \frac{q_s(\varphi)}{Q_s}$ the output share of firm φ. Totally differentiating yields a decomposition into the following three effects:

$$d \ln I_s = \int_0^{n_s} d \ln i_s(\varphi) \varrho_s(\varphi) dG(\varphi) + \int_0^{n_s} d \ln \xi_s(\varphi) \varrho_s(\varphi) dG(\varphi) + d \ln n_s \theta_s(n_s) n_s \tag{3.30}$$

where $\varrho_s(\varphi) = \frac{z_s(\varphi)}{Z_s}$ is the share of emissions of firm φ in sector s. The first term relates to emission intensity changes within a firm, the second to a reallocation of market shares within a sector across firms, and the last captures changes in the emission intensity due to entry and exit. The entry and reallocation effects are only operative when firms are heterogeneous.

Model based decomposition One of the key insights of my heterogeneous firms framework is the ability to quantify the within- and across-firm channel for different emission targets with and without a CBAM. In the following, I derive a model based decomposition of the emission intensity. I focus solely on the emissions that arise due to the production and not on those that are released for the fixed cost payments. For this purpose, I follow Egger et al. (2021) and define the average productivity of sector s in country i as the output weighted harmonic mean of firm-level productivity:

$$\bar{\varphi}_{is} = \left[\sum_{j \in M} (\varphi^*_{ijs})^{-\theta_s} b_{is}^{\theta_s} \int_{\varphi^*_{ijs}} \varphi^{-1} \frac{\tau_{ijs} q_{ijs}}{\bar{q}_{is}} \frac{dG(\varphi)}{1 - G(\varphi^*_{ijs})} \right]^{-1} \tag{3.31}$$

Similarly, I define the sector level emission intensity as the output weighted emission intensity of individual firms:

$$I_{is} = \sum_{j \in M} (\varphi^*_{ijs})^{-\theta_s} b_{is}^{\theta_s} \int_{\varphi^*_{ijs}} i_{ijs}(\varphi) \frac{\tau_{ijs} q_{ijs}}{\bar{q}_{is}} \frac{dG(\varphi)}{G(\varphi^*_{ijs})} \tag{3.32}$$

where $i_{ijs}(\varphi) = \frac{z_{ijs}}{\tau_{ijs} q_{ijs}} = \gamma_{ifs} \frac{\tilde{c}_{is}}{\kappa_{is}} \frac{1}{\varphi}$ is the emission intensity of a good produced by a firm with productivity φ in sector s in country i that is shipped to j. Since the decomposition focuses on the producers in the country implementing the carbon border adjustment (and not those exporting to it), the carbon prices, unit costs, and fossil shares are not destination specific. Hence, the sector-level emission intensity can be written as:

$$I_{is} = \gamma_{ifs} \frac{\tilde{c}_{is}}{\kappa_{ifs}} (\bar{\varphi}_{is})^{-1} \tag{3.33}$$

Thus, the change in the emission intensity can thus be decomposed as follows:

$$d \ln I_{is} = d \ln \gamma_{ifs} + d \ln \tilde{c}_{is} - d \ln \kappa_{is} - d \ln \bar{\varphi}_{is} \tag{3.34}$$

As shown in Appendix A.3, the first three terms capture the within firm effect, while the change in the average productivity summarizes the entry effect as well as the reallocation of market shares. Because both of these latter effects correspond to a reallocation across firms, I label this effect *Reallocation*. The *Within* effect consists of a change in the cost share of fossil fuels and the relative factor prices. Hence, there is no within firm productivity effect, because firm-level productivity is assumed to be exogenous and, thus, not affected by any policy change. Plugging in (A.41) the within-firm effect simplifies to:

$$Within = \zeta_s \left(d\ln \kappa_{is} - d\ln \tilde{c}_{is} \right) \tag{3.35}$$

Therefore, the within firm-effect is entirely driven by relative factor prices. If the effective price of carbon increases, either because of a rise in the emission tax or an increase in the price of fossil fuels, firms will switch to other factors of production and the emission intensity will fall. The magnitude of this effect is governed by the elasticity of substitution between fossil fuels and other inputs. The higher ζ_s, the easier firms can substitute inputs. Consequently, the within-firm effect is larger in absolute value for a higher ζ_s. The last term in (3.34) captures the reallocation and selection effect, which is summarized in the change of the average productivity. Integrating the different parts over a discrete shock, a change in the emission intensity can be decomposed as follows:

$$\hat{I}_{is} = \underbrace{\left(\frac{\hat{\kappa}_{is}}{\hat{\tilde{c}}_{is}} \right)^{-\zeta_s}}_{Within} - \underbrace{\hat{\tilde{\varphi}}_{is}}_{Reallocation} \tag{3.36}$$

where $\hat{x} = \frac{x'}{x}$ and x' is the value of variable x after a policy changes.

Proposition 3.2. *Given a change in carbon prices ν'_{is} or trade policy, t'_{ijs}, the change in the average productivity is given by:*

$$\hat{\tilde{\varphi}}_{is} = \widehat{\varphi^*_{iis}} \quad * \quad H(\hat{n}_{ijs}) \tag{3.37}$$

where $H(\hat{n}_{ijs})$ is a non-linear function of the change in the share of exporters.

Proof. See A.4 □

This formula is the exact hat-algebra equivalent in a multi-country and -sector environment of the log-linearized result in Egger et al. (2021). Similar to their finding, the average productivity rises in the domestic productivity cut-off. If the domestic productivity cut-off increases, the least productive firms are forced to exit the market, thus leading to higher average productivity. In Egger et al. (2021), the change in the domestic productivity cut-off is a sufficient statistic for the change of the average productivity. However, this result hinges both on the log-linear approximation and the restriction to a two-country economy. In the more general case considered here, a change in carbon prices or trade policy has an additional effect through the adjustment in the share of exporting firms. Intuitively, a higher share of exporting firms has two opposing effects on average productivity. On the one hand, if the pool of more productive exporters compared to domestic firms is larger, average productivity increases. On the other hand, a higher exporting share implies that less productive domestic firms start exporting, hence expanding their production. Therefore, the average exporting firm is less productive, which reduces average productivity. In the multi-industry and country economy, the relative magnitude of these two effects depends on the parameters. As evident from Appendix A.4, the function $H(\cdot)$ can be fully characterized by the baseline exporter share, the relative fixed costs of the respective destination and the domestic market, the pareto shape parameters, θ_s, as well as the equilibrium change in the exporting share. In section 4, I describe how to obtain these variables from publicly available sources. To complete the decomposition analysis, the scale and composition effect are given by the following equations (see Appendix A.5):

$$\hat{Q}_i = \sum_{s \in S} \xi_{is} \left(\frac{\hat{X}_{is} \hat{\bar{\varphi}}_{is}}{\hat{\bar{c}}_{is}} \right) \tag{3.38}$$

$$Composition = \sum_{s \in S} (\rho_{is} \left(\frac{1}{\hat{Q}_i} \frac{\hat{X}_{is} \hat{\bar{\varphi}}_{is}}{\hat{\bar{c}}_{is}} \right) \tag{3.39}$$

A problem is that I do not observe physical quantities. Therefore, I proxy $\xi_{is} = \frac{Q_{is}}{Q_i}$ with the corresponding revenue share.

3.4 Decomposition of carbon leakage

To analyze the relevance of fossil fuel market leakage, I decompose emission changes outside the EU. Recalling that the change in emissions abroad in a particular sector is given by $\hat{Z}_{ijs} = \frac{\hat{\gamma}_{ijfs}}{\hat{\kappa}_{ijs}} \hat{X}_{ijs}$, one can decompose the change in emissions outside the EU into three distinct effects:

$$\rho^z_{ijs} \hat{Z}_{ijs} = \underbrace{\sum_{i \notin EU, s \in S, j \in M} \rho^z_{ijs} \hat{\gamma}_{ijfs}}_{\text{Fossil share}} - \underbrace{\sum_{i \notin EU, s \in S, j \in M} \rho^z_{ijs} \hat{\kappa}_{ijs}}_{\text{Fossil price}} + \underbrace{\sum_{i \notin EU, s \in S, j \in M} \rho^z_{ijs} \hat{X}_{ijs}}_{\text{Output}} \tag{3.40}$$

where $\rho^z_{ijs} = \frac{Z_{ijs}}{Z_{noneu}}$. The endogenous changes in the spending share on fossil fuels are due to the CES-production function. Because fossil fuels and labor are complements ($\zeta_s<1$), this share increases if fossil prices rise more than wages. The second term captures the change in the fossil fuel price. Because carbon pricing is assumed to be constant outside the EU, $\hat{\kappa}_{ijs}$ solely depends on changes in the fossil fuel prices and the carbon border adjustment set by the EU. Finally, the last term summarizes emission changes due to output adjustments holding factor inputs constant.

3.5 Decomposition of welfare

Finally, I follow Caliendo et al. (2023) and decompose the change in utility following a change in carbon prices and tariffs. To see the additional insights from this model, recall from Arkolakis et al. (2012) that the real income changes due to a change in iceberg costs in a multi-sector perfectly competitive model only depend on changes in the domestic expenditure share. From (3.1) a change in utility comprises three parts:

$$d \ln U_i = d \ln Y_i - \sum_{s \in S} \alpha_{is} d \ln P_{is} - d \ln \Delta_i(Z) \tag{3.41}$$

The first term relates to a change in nominal income, the second measures the change in the price index, and the last term is the social cost of carbon emissions. Appendix A.7 shows that these three parts can be decomposed as follows:

$$\begin{aligned} d \ln U_i = & \underbrace{\frac{T_i}{Y_i} d \ln T_i}_{\text{Taxes/Tariffs}} + \underbrace{\frac{r_{if} R_{if} d \ln r_{if} + w_i L_i d \ln w_i}{Y_i}}_{\text{Factor income}} \\ & - \sum_{s \in S} \alpha_{is} \left[\underbrace{\frac{1}{\theta_s} d \ln \lambda_{iis}}_{\text{Domestic share}} - \underbrace{\frac{1}{\theta_s} d \ln N_{is}}_{\text{Entry}} + \underbrace{d \ln \tilde{c}_{is}}_{\text{Unit Costs}} + \underbrace{\delta_s \left(\frac{1}{\sigma_s - 1} - \frac{1}{\eta_s - 1} \right) d \ln \hat{\lambda}_{iis}}_{\text{Armington}} \right] \\ & + \sum_{s \in S} \alpha_{is} \underbrace{\frac{\psi_s}{\theta_s} \left(d \ln Y_{is} - d \ln \tilde{c}_{is} \right)}_{\text{Selection}} \\ & - \underbrace{d \ln \Delta_i(Z)}_{\text{Social Costs of Carbon}} \end{aligned} \tag{3.42}$$

The first line measures the change in nominal income. This change is comprised of the direct effect of changing carbon prices and tariffs on tax revenue and a change in factor income due to changing demand for labor and fossil resources. The second and third line refer to changes in the price index. The first and second term in line two are the standard real income change in the multi-sector and monopolistic competition extension of Arkolakis et al. (2012). In a perfectly competitive model, without accounting for tariff revenues, the change in the domestic expenditure share would be a sufficient statistic for real income. In the context of monopolistic competition, the domestic expenditure is adjusted for the endogenous entry of firms. In the Melitz Model, this firm entry is the source for scale economies. As pointed out by Kucheryavyy et al. (2023), a percentage increase in the number of firms entering increases the domestic productivity cutoff, which reduces the price index by $\frac{1}{\theta_s}$ percentage, the scale elasticity. The second term is a change in the unit costs that occurs due to the presence of the upstream fossil fuel sector and wage effects. Finally, the last term in the second line captures the different elasticity of substitution between domestic and foreign varieties. Since $\sigma_s < \eta_s$, this term is positive. Hence, an increase in the domestic expenditure increases the price index even more compared to a non-nested structure. The terms in the first two lines are also present in a monopolistic competition model with homogeneous firms. In contrast, the third line summarizes the selection effect, which only occurs if firms are heterogeneous; i.e. $\psi_s > 0$. The selection effect consists of the market size relative to the fixed costs. As noted by Caliendo et al. (2023), a larger market size allows for a higher number of firms to select into serving this market, which will reduce the price index in turn. Finally, the last line corresponds to a change in the social costs of carbon.

4 Counterfactual scenario and data

4.1 Counterfactual scenario

I use the model to simulate the effect of different emission reduction targets and the introduction of a CBAM by the EU. Specifically, I suppose that the EU introduces a binding emission target on the entire economy. I assume that the emission target is implemented through a European wide carbon price that is equal across countries and sectors. Given the emission target $\bar{Z} = \frac{\sum_{s,i \in EU} Z'_{is}}{\sum_{s,i \in EU} Z_{is}}$, the corresponding carbon price is endogenously determined by solving the change in emissions, i.e.:

$$\left(\widehat{(1+\nu)}\right)^{\zeta_s} = \frac{1}{\hat{\hat{Z}}} \sum_{s \in S, i \in EU} \frac{Z_{is}}{\sum_{s \in S, i \in EU} Z_{is}} \hat{X}_{is} \left(\hat{P}_i^f\right)^{-\zeta_s} \left(\hat{\hat{c}}_{is}\right)^{\zeta_s - 1} \tag{4.1}$$

To analyze how the effect varies in the stringency of the emission target I investigate emission reduction targets of 20, 30, 40, 45, 50 and 60 percent compared to the baseline. A particular emphasis is on the results for the 42% reduction target, which mimics the Fit-for-55 target.[1] I complement each of these reduction scenarios with the implementation of the CBAM, which is applied to all sectors that are part of the EU-ETS. In the base scenarios, I model the CBAM as an *ad-valorem* import duty based on the emission intensity of the exporting country, i.e. :

$$t_{ijs}^{cadv} = \begin{cases} \frac{Z'_{is}}{X'_{is}} \iota \nu' & \text{if } i \notin EU \;\&\; j \in EU \;\&\; s \in ETS \\ 0 & \text{otherwise} \end{cases}$$

Thus, the tariff rate in the CBAM scenarios is the sum of the existing duty in a certain sector and the CBAM rate, i.e. $t'_{ijs} = t_{ijs} + t_{ijs}^{cadv}$. I compare this CBAM design, with a CBAM that only covers those sectors according to the regulation implemented in 2023, i.e. Cement, Iron and Steel, Aluminum, Fertilizers, Electricity and Hydrogen (summarized as energy in this model). Finally, I conduct a scenario of a firm-level CBAM as described before.

4.2 Data and parameters

The main data source for my analysis is Exiobase (Stadler et al. 2018), which provides data on production international trade flows and GHG emissions. I use the year 2015, since this is the latest available year for which detailed emission and energy data are based on real data points.[2] Compared to other databases that are more frequently used in quantitative trade models, such as WIOD or GTAP, Exiobase provides, with 163 industries, a more detailed sector disaggregation. Most important for this analysis, Exiobase features 59 distinct manufacturing industries, compared to 27 (GTAP) and 19 (WIOD). I aggregate the original 163 industries to 53 sectors which comprise 43 manufacturing sectors, 21 ETS sectors, and a fossil fuel sector (for a list of all sectors see Appendix B).

1. Because emissions have declined by 22% between 2015 and 1990, an emission reduction of 42% from 2015 is equivalent to a 55% reduction of the emission level in 1990.

2. The database is updated until 2022. However, these data are produced by now-casting methods

Carbon prices and tariffs I obtain effective carbon prices by country in 2015 from Dolphin et al. (2019). I source tariff rates from the World Integrated Trade Solution (WITS) database.

Share of exporters and average exports The quantification of the reallocation channel requires data on the share of firms exporting, n_{ijs}. I obtain the number of exporters from country i to j in sector s from the OECD Trade by Enterprise Characteristics Database. One limitation is that this database only provides the aggregate number of exporters in each country/sector, N_{is}, and the aggregate number of exporters to a certain destination, N_{ij}. To obtain N_{ijs}, I multiply the number of firms in each sector with the share of exporters to certain destination, i.e.

$$N_{ijs} = \frac{N_{ij}}{\sum_{j' \in M} N_{ij'}} N_{is}$$

I calculate the share of exporting firms by dividing by the number of active firms, which I source from Eurostat. Because, for some origin-destination-sector triples with non-zero trade flows the number of exporting firms is missing, I impute these values using the methodology of Sogalla et al. (2023). In particular, I regress the share of exporting firms on the share of export value to domestic sales and destination fixed effects. Finally, I exploit the (ZCP) condition to obtain a measure of the relative fixed costs:

$$\frac{f_{ijs}}{f_{iis}} = \frac{\bar{x}_{ijs}}{\bar{x}_{iis}}$$

Hence, the relative fixed costs are determined by the share of average exports to a destination to average domestic sales. I obtain these average exports and sales by dividing the corresponding value by the number of exports and active firms respectively.

Elasticities and additional parameters I source estimates for σ_s and η_s from Lashkaripour and Lugovskyy (2023). For the pareto shape parameter θ_s, I use the median value of the estimates in di Giovanni et al. (2011), Hsieh and Ossa (2016), and Shapiro and Walker (2018). From this set of parameters, I can calculate the trade elasticity with respect to iceberg-costs, ϵ_s, as well as δ_s and ψ_s. The list of these parameters by sector are provided in Appendix B. For the elasticity of substitution in production, I use $\zeta_f = 0.75$ from Caron and Fally (2022) and $\zeta_s = 0.624$ from Farrokhi and Lashkaripour (2021). For the fossil fuel trade elasticity, I use the estimate of Fontagné et al. (2022) for oil and gas of $\epsilon_f = 10.892274$. The remaining parameters to calibrate are the cost share of value added, γ_{ils}, and fossil fuels, γ_{ifs}, as well as the share of resources in the production of fossil fuels, γ_{irf}. To calibrate γ_{ifs}, I sum the spending on coal, crude oil natural gas, coke oven products, and refined petroleum, then divide it by gross output. Since fossil fuels are the only intermediate product in my model, I calculate the value added share, γ_{ils}, as the ratio of the difference between gross output and fossil fuel spending to gross output. For the primary fossil fuel sector, the value added is calculated as the difference of gross output and the spending on resources. I obtain the spending of fossil fuels from the Adjusted Net Savings database of the World Bank. This database provides oil, natural gas, and coal rents, by country. The total spending on fossil fuel resources in my model is the sum of these three rents. I follow Shapiro (2016) to calibrate the pollution damage parameter υ_i. In particular, I differentiate the indirect utility with respect to Z and solve for υ_i such that the derivative equals the social costs of carbon. In contrast to their paper, I use country-specific estimates for the social costs of carbon from Ricke et al. (2018). To compare my results to the existing literature, I rescale their estimates to a social cost of carbon of 185€, which is close to the preferred mean estimate of a 2022 overview study (Rennert et al. 2022).

5 Results

5.1 Baseline scenarios

Emissions and carbon leakage Table 5.1 shows the change in emissions, the leakage rates and the implicit carbon price for different emission reduction targets. As expected, a tighter cap on emissions requires a higher carbon price. Since, the value of the carbon price depends on the numéraire,[3] the magnitude of the price should be interpreted cautiously. Qualitatively, the carbon price is higher in the presence of the CBAM. The reason is that the CBAM leads to more emissions in the protected industries, which, in turn, requires a higher carbon price to induce the necessary emission reductions in other sectors. Around 17-20% of the emission reductions in the EU are offset by emission increases in other regions. This leakage rate is in the range between 10% and 30% of previous studies (Carbone and Rivers 2017). Surprisingly, the leakage rate is relatively constant in the stringency of the emission target. In contrast, the effectiveness of the CBAM at reducing carbon leakage declines in the emission cap. While the CBAM reduces

3. I choose the average wage as the numéraire.

the leakage rate by almost half for an emission reduction target of 20%, the CBAM prevents only 31% of the leakage when emissions in the EU decline by 60%. This leakage rate reduction is in line with previous studies, which find that border adjustments reduce leakage by around one third (Böhringer et al. 2012). By limiting the extent of leakage, the CBAM increases the effect of unilateral European climate policy on global emissions. However, even a 60% emission reduction target in the EU, leads only to a decline of less than 5% of global GHG emissions. This small effect on global emissions is in line with previous findings of the limited effect of unilateral climate policy on curbing global emissions (Farrokhi and Lashkaripour 2021).

	No CBAM			CBAM		
Target	CO2 price	Leakage rate	Global	CO2 price	Leakage rate	Global
20%	42€	17.01%	-1.48 %	42€	8.97%	-1.63 %
30%	74€	17.25%	-2.22 %	75€	10.06%	-2.41 %
40%	121€	17.68%	-2.94 %	122€	11.00%	-3.18 %
Fit-for-55	132€	17.79%	-3.09 %	134€	11.20%	-3.33 %
50%	191€	18.35%	-3.65 %	194€	12.01%	-3.93 %
60%	308€	19.39%	-4.32 %	314€	13.25%	-4.65 %

Table 5.1: Changes in emissions and leakage rate

To gain a better understanding of the drivers of emission reductions, Figure 5.1 shows the emission savings by sector for different targets without a CBAM. Around one third of the decline occurs in the energy sector, while the manufacturing sector is responsible for almost one fifth of the emission reductions. Comparing ETS to non-ETS industries illustrates that more than 70% of the decline in manufacturing emissions is achieved in industries that are covered by the ETS.

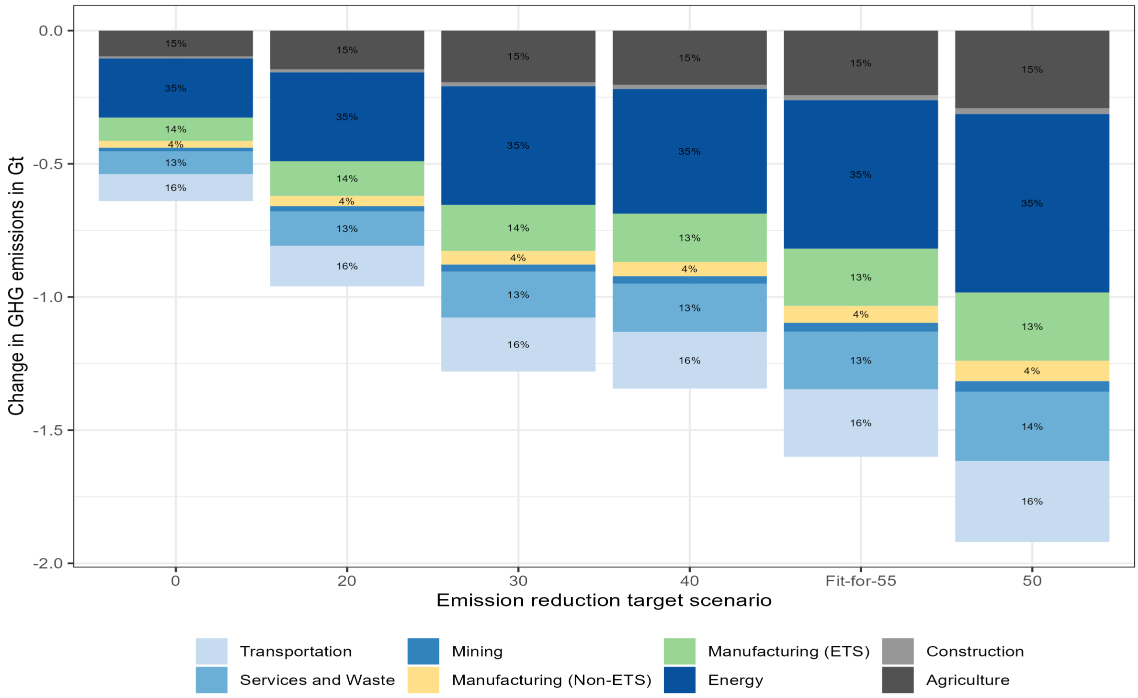

Figure 5.1: Emission changes by aggregated sector

Note: Emission changes in the EU by emission target scenario without a CBAM and aggregated sector. Numbers inside the bars indicate the contribution to overall emission reductions of the particular sector in percent.

Figure 5.2 plots the decomposition of the emission effects in manufacturing sectors. The black upper line shows the scale effect, the dark gray line the combination of the scale and composition effect, and the bottom line the aggregate emissions. Therefore, the difference between the dark gray and the black line is the composition effect and the difference between the light and dark gray line captures the technique effect. The technique effect is responsible for around 90% of the decline in emissions. The shift of production toward less emission intensive sectors reduces emissions by 1% to 7%. This composition effect becomes more important, the tighter the emission target. Hence, more ambitious emission reductions have a larger effect on the comparative advantage forces that redistribute economic activity toward less emission intensive sectors. By shielding the emission intensive industries from competition, the introduction of the CBAM limits their contraction, thus almost halving the composition effect. The effect on the scale of production is rather limited, and, even for a 60% emission reduction target below 1%. As shown by figure B.1, the technique effect drives the bulk of the emission reductions, including for most individual European countries.

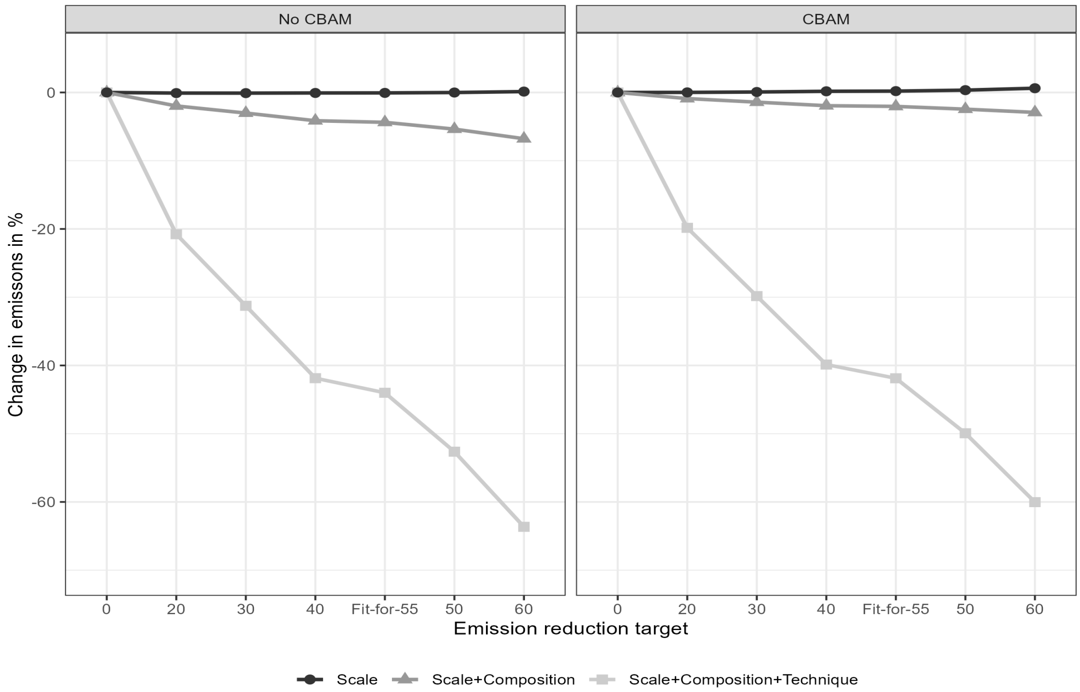

Figure 5.2: Decomposition of CO_2 emissions

Note: The figure plots the sector-level decomposition for different emission targets without a CBAM (left panel) and with the baseline CBAM design (right panel).

A key novelty of this study is the ability to decompose the sector-level technique effect into a within-firm changes and an across-firm reallocation effect. Figure 5.3 plots the decomposition of the emission intensity according to equation (3.36). Different to the theoretical finding of Egger et al. (2021), carbon pricing has almost no impact on the average productivity; hence, the reallocation effect is close to zero (upper light gray line). Thus, emission reductions are entirely driven by within-firm emission intensity reductions (lower gray line). The CBAM does not alter this result and the reallocation effect remains negligible.

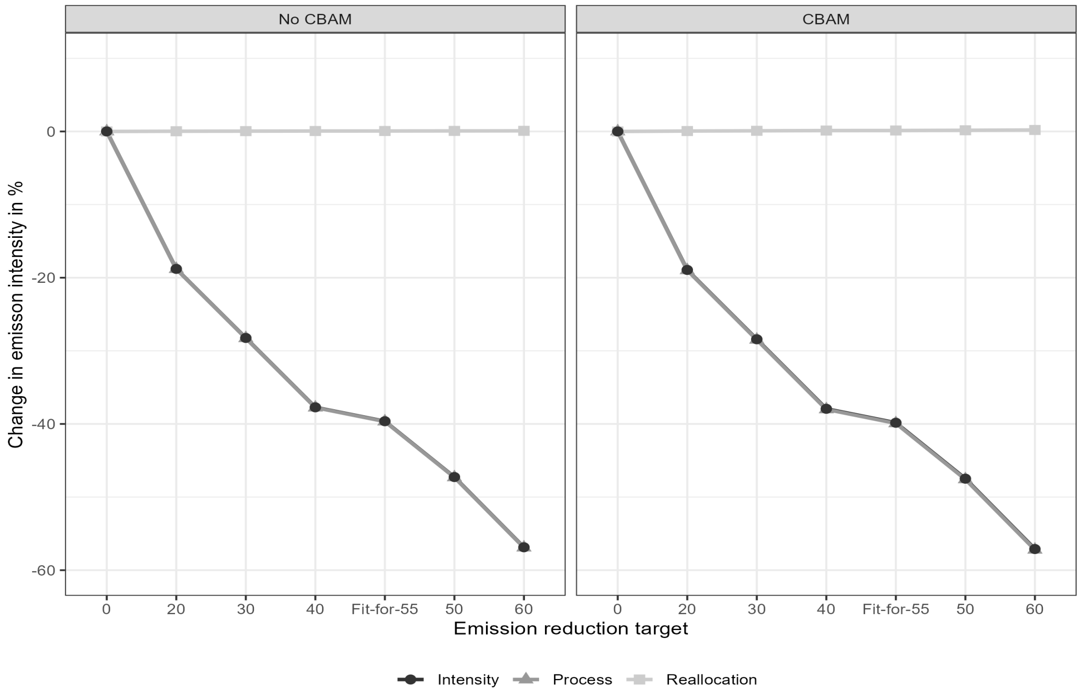

Figure 5.3: Decomposition of emission intensity

Note: The figure shows the decomposition of the sector-level emission intensity into within- and across-firms adjustments for different emission targets without a CBAM (left panel) and with the baseline CBAM design (right panel).

Since the figure shows a weighted average across manufacturing industries and EU-countries, it might hide heterogeneity in the reallocation effect. Table B.2 illustrates that the reallocation effect is small and positive for most ETS industries. Figure 5.4 presents the distribution of the average productivity effects. The graph confirms the small effect of carbon pricing on the average productivity. However, the graph also shows a substantial heterogeneity across sectors. For ETS industries, around half of the country-sector pairs experience an increase in the average productivity following carbon pricing without a CBAM. On the other hand, for a quarter of them, productivity declines by more than 0.18%. In non-ETS industries, carbon pricing has a more positive effect on the average productivity with more than 70% of country-industry pairs experiencing an increase. However, the effect is small and even the 95th percentile less than 0.5%. The CBAM shifts the distribution downwards, especially for ETS industries where the average productivity effect is now negative for more than 65% of the country-industry tuples.

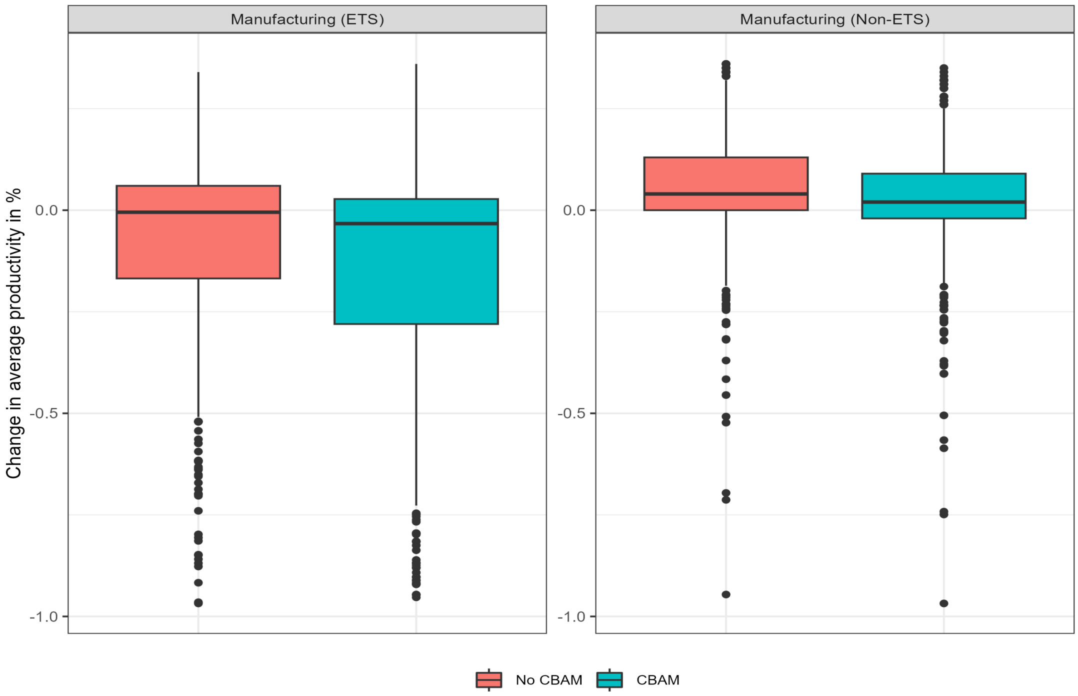

Figure 5.4: Productivity effects

Note: Figure plots the distribution of the percentage change in $\bar{\varphi}_{is}$ for the Fit-for-55 emission reduction target. The figure is trimmed at the 5^{th} and 95^{th} percentile

The limited, even negative, average productivity effect of carbon pricing is surprising in light of the theoretical findings in Egger et al. (2021). A potential reason for this deviation in the more general setting considered here is that the presence of multiple sectors and countries induces additional general equilibrium effects, which reduce the change on the average productivity. First, the key mechanism behind the average productivity rise in Egger et al. (2021) is the increase in the relative size abroad compared to the domestic market potential. Considering more than one additional country, the effect on the foreign market might be more limited. Moreover, the scenario of an EU-wide tightening of the emission target does not provide a pure unilateral environmental policy, because, for inner-EU trade, the carbon price in the destination country also increases. Finally, the presence of multiple sectors potentially dampens the productivity response, as Egger et al. (2021) note that the average productivity response would be smaller and might even turn negative in a two sector economy extension of their framework. Figure 5.5 decomposes the average productivity changes into three distinct effects. The first relates to the productivity affect via the adjustment in the exporter share, captured by the function

$H(\cdot)$ in (3.37). The other two relate to the change in the domestic productivity cut-off. From (A.54), the domestic productivity cut-off rises in the unit cost of production and declines in the domestic market potential. The figure shows that the main reason for the small average productivity effect is the increase in the domestic market potential that completely offsets the positive effect of higher production costs on the domestic productivity cut-off.

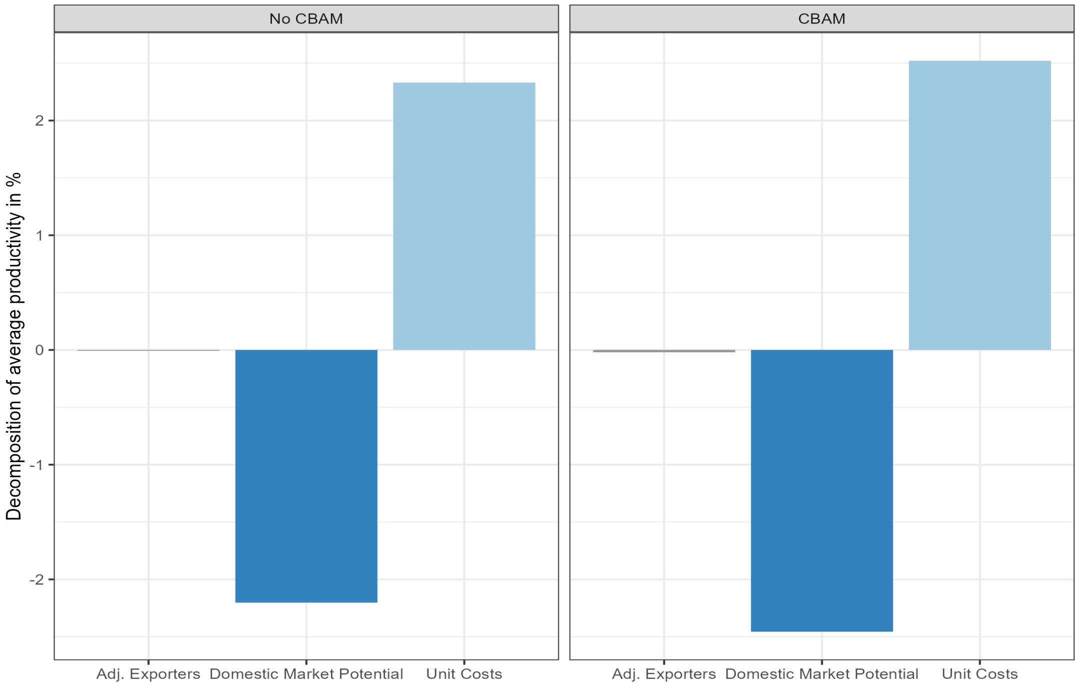

Figure 5.5: Decomposition of average productivity

Note: The Figure plots the percentage change of the different parts of $\bar{\varphi}_{is}$ for the Fit-for-55 emission reduction target. *Adj. Exporters* refers to the change in $H(\hat{n}_{ijs})$ in (3.37). The sum of *Unit costs*,$\hat{c}_{is}^{\frac{\eta_s}{\eta_s-1}}$, and *Domestic Market Potential*, $\hat{B}_{iis}^{\frac{-1}{\eta_s-1}}$, captures the change in the domestic productivity cut-off $\widehat{\varphi^*_{iis}}$. The changes are aggregated as the weighted sum over all manufacturing sectors and EU countries with the weight equal to the baseline share in emissions.

Apart from emission reductions in the EU, an important question is how much are these reductions offset by emission increases in other regions. Table 5.1 shows that carbon leakage occurs and that the CBAM reduces it considerably. Figure 5.6 illustrates which sectors drive the leakage reductions for the Fit-for-55 emission reduction target. The leakage rate varies considerably across sectors. This difference is particularly pronounced for manufacturing industries. Without a CBAM, the leakage rate is almost 30% for industries covered by the ETS and only 14% for non-ETS industries. This result changes drastically when the CBAM on ETS-industries is introduced. For those sectors, the leakage rate even turns negative. Hence, the emission target combined with the CBAM incentivizes emission reductions abroad for these sectors compared to the baseline. Thus, the CBAM reverses the comparative disadvantage these sectors experience due to the emission cap. As shown in Table B.4, there is also considerable heterogeneity across ETS industries in the leakage rate and the effectiveness of the CBAM. The bulk of leakage in ETS industries without a CBAM is driven by the basic iron and steel industry, and chemicals, which jointly comprise more than 60% of the emission increases in ETS manufacturing abroad. For these two industries, the CBAM induces emission reductions abroad compared to the baseline, while for other industries such as casting of metals, the leakage reduction of the CBAM is more limited. Figure B.2 shows that both the emission increases and the effectiveness in countering leakage in ETS industries varies across European trading partners. The largest emission increases in non-EU ETS industries without a CBAM occur in Russia and China. While the CBAM induces negative leakage in ETS industries in Russia, it only partially reduces the leakage of ETS emissions to China.

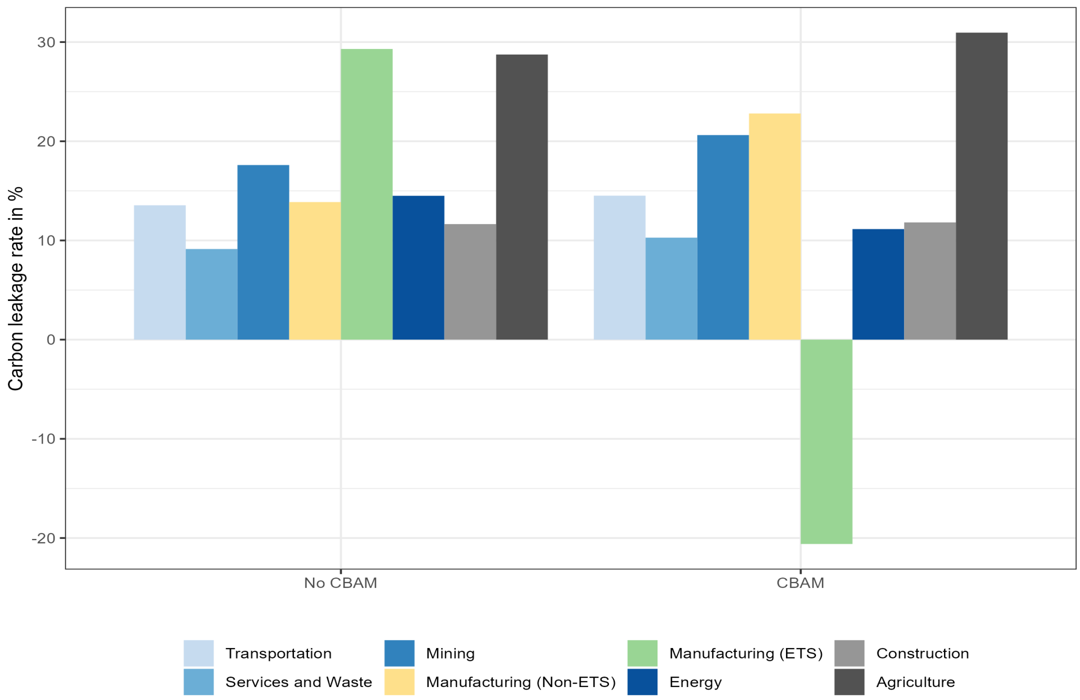

Figure 5.6: Emission leakage by aggregated sector for the Fit-for-55 emission reduction target

Note: The carbon leakage rate is defined as the negative of the emission change outside the EU divided by the emission change in the EU. Because emissions in the EU fall by definition of the scenario, a negative leakage rate implies that emissions fall also outside the EU. Results shown for the Fit-for-55 target and the baseline CBAM.

The CBAM also affects non-ETS industries and induces a higher leakage rate for those sectors that it does not cover. In particular, in non-covered manufacturing sectors, the leakage rate increases by almost 50% due to the CBAM. To understand the drivers underlying these different leakage effects across sectors, Figure 5.7 presents the decomposition of carbon leakage according to (3.40). Leakage occurs predominately via increased output outside the EU. For ETS industries, the increase of competitiveness in emission intensive production is more important than in the aggregate. As expected, the CBAM reduces carbon leakage via the competitiveness channel and limits the increase of emission intensive production outside the EU. Yet, similar to the finding in Larch and Wanner (2017), the CBAM has repercussions on the fossil fuel market. Although the CBAM does not target the use of fossil fuels, it lowers emissions abroad, thus indirectly reducing the demand for fossil fuels. Therefore, the fossil price abroad is even lower in the CBAM scenario compared to the pure domestic carbon pricing scenario. Thus, neglecting the fossil fuel market channel would overestimate the effectiveness of the CBAM to reduce leakage. Zooming into the emission effects in manufacturing shows that the CBAM reduces the production value in ETS industries outside the EU. As a consequence, the CBAM induces emission reductions abroad by limiting the size of emission intensive sectors instead of a switch toward low-carbon production factors. For the uncovered sectors, the lower fossil fuel price is the main driver for the higher leakage rate when the CBAM is introduced. Moreover, the CBAM induces a shift of production activity toward the emission intensive industries abroad, which it does not cover.

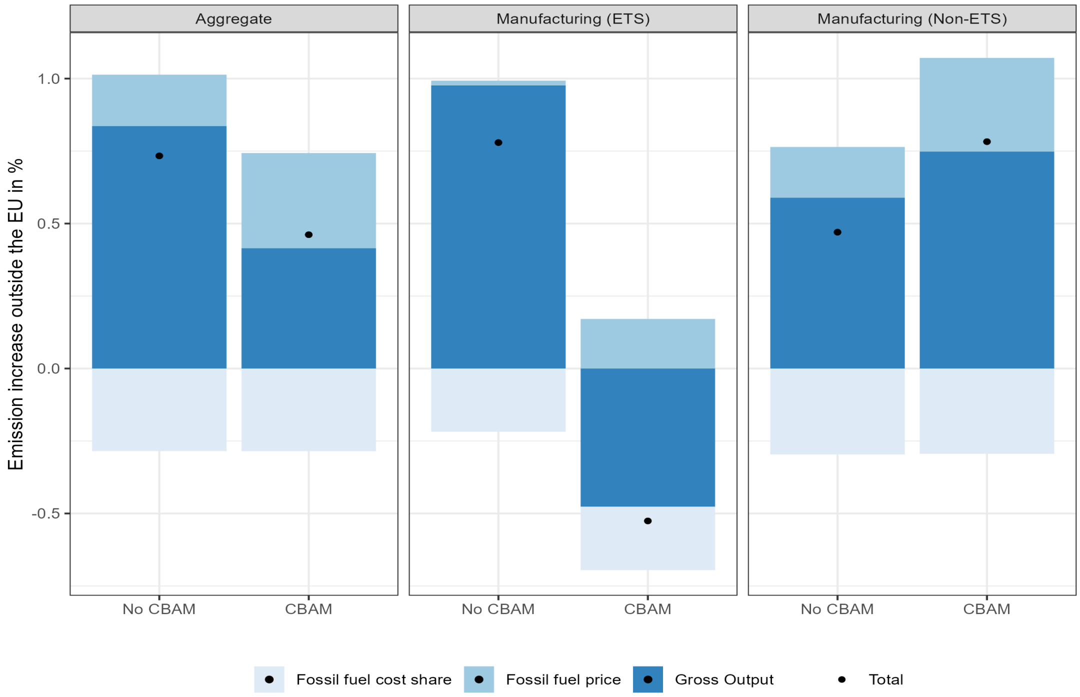

Figure 5.7: Decomposition of leakage

Note: The figure shows the decomposition of leakage according to equation (3.40) for the Fit-for-55 emission target and the baseline CBAM design.

Entry effects, trade flows and gross output Table 5.2 presents the trade and gross output response in EU-ETS industries. Tightening the emission cap according to the Fit-for-55-Target increases imports from outside the EU in ETS industries by almost 8%. Because the CBAM raises their costs, it reduces the imports of ETS products. The higher imports from outside the EU without a CBAM substitute for EU-ETS production, which leads to a decline of around 2% in the value of output following higher carbon prices without a CBAM. While the output of ETS-industries declines both on the domestic market and when selling to other EU countries, exports to regions outside the EU face the largest decline (more than 8%). The introduction of the CBAM limits the negative effect on exporting. However, ETS exports are still more than 7% below their baseline level. On the other hand, the CBAM promotes Intra-EU trade as well as domestic sales, which are even higher than in the baseline without a carbon price increase.

	No CBAM	CBAM
Extra EU Imports	7.89	-6.00
Gross Output	-2.13	0.39
Extra EU Exports	-8.11	-7.11
Intra EU Trade	-2.05	2.92
Domestic Sales	-0.96	1.22

Note: All values in percentage change to baseline. Values shown for the Fit-for-55 target and the baseline CBAM design.

Table 5.2: Changes in tradeflows gross output of ETS manufacturing sectors

Apart from the effect on gross output, carbon pricing and the CBAM affect firm entry. Figure 5.8 shows that the entry margin of carbon pricing in EU-ETS manufacturing is very active and heterogeneous across industries and countries. In line with theory, the CBAM shifts the entry distribution to the right, thus increasing the entry of firms in those sectors that it protects.

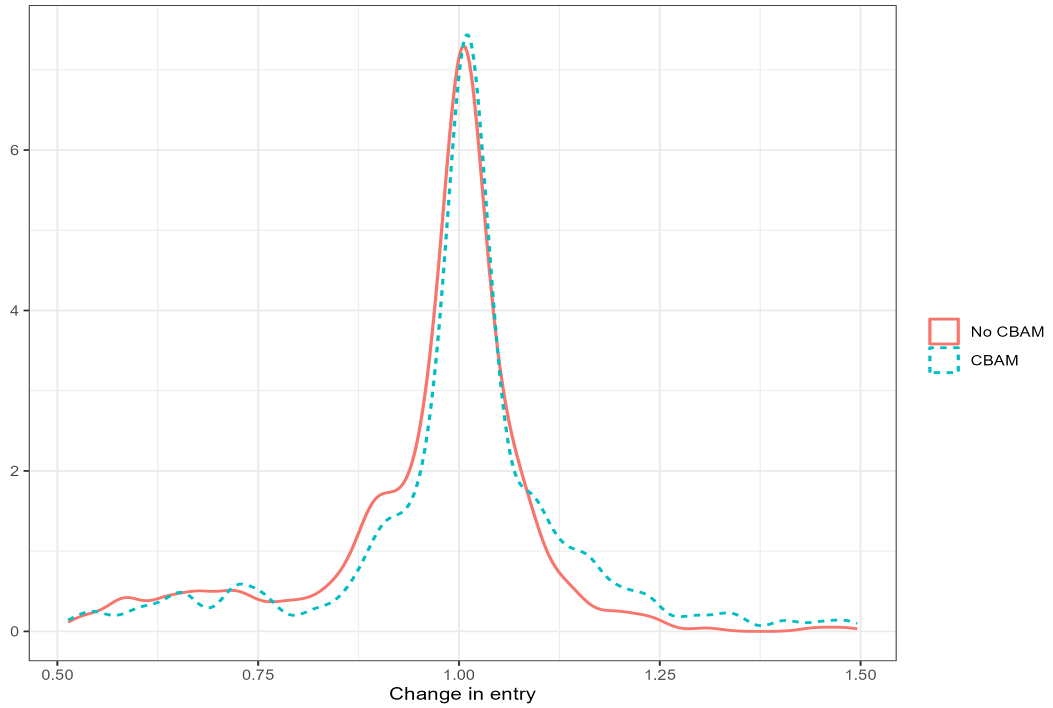

Figure 5.8: Entry effects

Note: Figure plots the distribution of $\hat{N}_{is}$ for EU-ETS manufacturing industries for the Fit-for-55 emission reduction target. The figure is trimmed between 0.5 and 1.5

Real income and welfare effects The Fit-for-55 emission target reduces the real income in the EU by approximately 0.3% (Table 5.3). In contrast, almost all non-EU countries gain in real income when the EU carbon pricing is not accompanied by a CBAM. The only exceptions are Russia and Norway, who export fossil fuels to the EU and, hence, are adversely impacted by the reduced European demand (Table B.5). The climate benefits of lower emissions outweigh the real income losses outside the EU, but do not do so for EU countries. However, the relative magnitude of climate benefits and real income losses must be treated with caution, because the former depend on the assumed functional form of climate damages and the social costs of carbon. The introduction of the CBAM shifts part of the burden of emission reductions from the EU to other countries. Thus, on average the real income gain outside the EU is almost zero and for some countries it even turns negative. However, these negative effects are small and the EU still absorbs most of the real income losses. On a global level, the real income is 0.005 percentage points lower with the CBAM compared to solely domestic carbon pricing in the EU.

	No CBAM	CBAM
Global		
Real Income	-0.049	-0.054
Climate Benefits	0.056	0.060
Social Welfare	0.007	0.007
EU		
Real Income	-0.307	-0.304
Climate Benefits	0.008	0.008
Social Welfare	-0.299	-0.296
Non EU		
Real Income	0.007	0.001
Climate Benefits	0.067	0.072
Social Welfare	0.073	0.072

Note: The values are the weighted average of country-level changes, where the weight is the baseline nominal income. Values shown for the Fit-for-55 target and baseline CBAM design.

Table 5.3: Changes in real income and climate benefits

Table 5.4 decomposes the real income changes in the EU. As expected, the emission cap increases the nominal income due to additional revenue from collected carbon prices. The remaining rows show the different channels how the emission target affects the price level. First, the emission cap reduces the domestic trade share, because more products are imported from abroad. The lower domestic trade share has a direct negative effect on the price level, as well as through the love-of-variety effect captured in the Armington term. On the other hand, the emission cap fosters entry in sectors with low scale elasticity, which increases the price index. Moreover, the higher unit costs lead to higher fixed-costs relative to the market size within the EU, which induces a negative selection effect. More importantly, the cost of production increases within the EU, which is the main driver for the real income decline in the EU. The introduction of the CBAM raises the unit costs even further, because it increases the wage rate in the EU. However, the additional tariff revenue leads to a higher real income compared to the pure emission reduction target scenario.

	No CBAM	CBAM
Nominal Income	0.49	0.65
Trade Share	0.10	0.07
Entry	-0.13	-0.13
Unit Costs	-0.81	-0.92
Armington	0.04	0.03
Selection	-0.01	-0.01

Note: Results for the decomposition according to equation (3.42). The values are the weighted average of country-level changes, where the weight is the baseline nominal income. Values shown for the Fit-for-55 target and baseline CBAM design.

Table 5.4: Decomposition of real income changes

5.2 Different CBAM Designs

This subsection compares the effects of different CBAM designs. Table 5.5 summarizes the economic and emission effects of the design options compared to the base scenario without a CBAM. The effect of the designs on global emissions and real income are small. However, the design affects the leakage rate and ETS manufacturing output. A CBAM on the six industries, as implemented in the 2023 regulation, achieves around 60% of the leakage reduction that a coverage of all ETS manufacturing industries would achieve. Yet, its design cannot completely mitigate the output loss in ETS manufacturing. In contrast to Böhringer et al. (2017), I find that the firm-level CBAM leads to a larger leakage rate than the other two options based on industry-level benchmarks.

	Base (No CBAM)	CBAM (all ETS)	CBAM (current)	CBAM (firm)
GO (ETS Manuf.)	-2.13	0.39	-1.41	0.83
Global Emissions	-3.09	-3.33	-3.24	-3.30
Leakage rate	17.79	11.20	13.73	12.09
Real Income (EU)	-0.31	-0.30	-0.31	-0.31
Real Income (Global)	-0.05	-0.05	-0.05	-0.06
Social Welfare (Global)	0.01	0.01	0.01	0.00

Note: All values in percentage change to baseline. Values shown for the Fit-for-55 target.

Table 5.5: Different CBAM design options

The higher leakage rate of the firm-level CBAM points to the presence of resource shuffling. A firm-level CBAM might induce the cleanest firms in a sector to export to the EU, whereas the more emission intensive producers export to other destinations instead. Hence, the emissions embodied in exports to non-EU countries would increase more in the firm-level CBAM. Because all firms in a sector are subject to the same adjustment when the CBAM is introduced based on industry benchmarks, there is no differential incentive across firms to select into their destination. Figure 5.9 shows that the firm-level CBAM indeed induces more emissions for non-EU market production compared to the industry-level CBAM. On the other hand, it reduces the emissions embodied in exports to the EU by more compared to the industry-level CBAM due to a lower emission intensity of exports. In total, the increase in emissions embodied in domestic sales and non-EU exports relative to the industry-level CBAM, outweigh the larger emission reducing effect on exports to the EU of the firm-level CBAM.

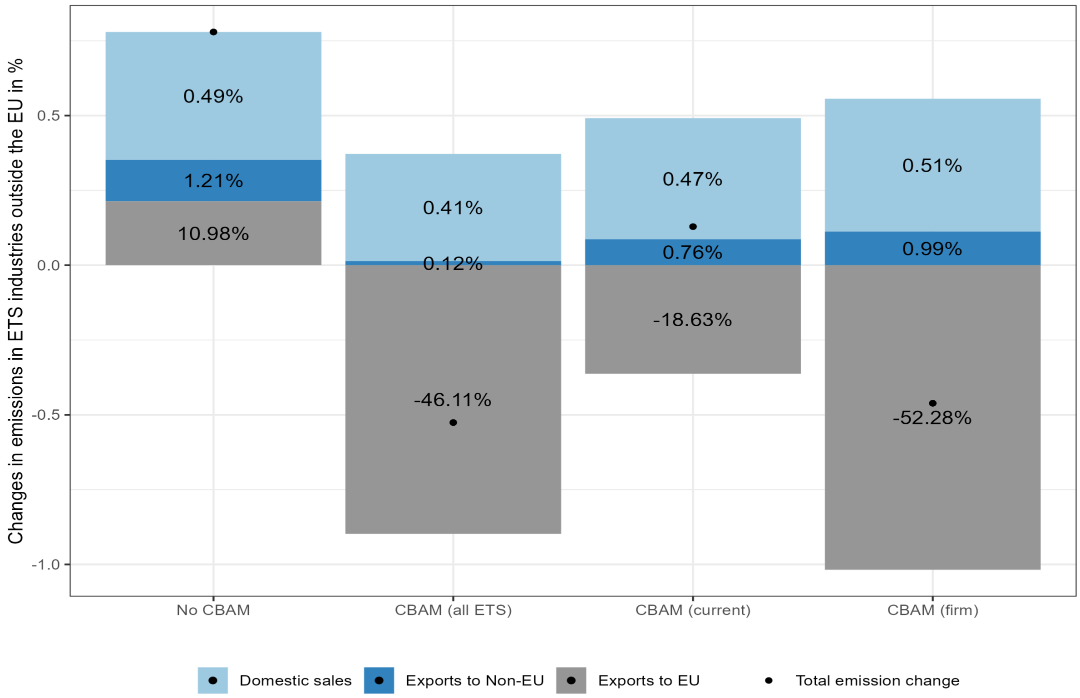

Figure 5.9: Embodied emissions by CBAM design

Note: The figure plots the change in emissions outside the EU in ETS industries. The graph differentiates between emissions embodied in exports to the EU, exports to other destinations, and in sales that occur within non-EU countries. The numbers inside the bars show the percent change in the corresponding variable compared to the baseline. Values shown for the Fit-for-55 emission reduction target.

5.3 The role of scale economies and firm heterogeneity

Finally, I quantify the aggregate consequences of economies of scale and firm heterogeneity. As shown by Kucheryavyy et al. (2023) and Costinot and Rodríguez-Clare (2014), the model becomes a standard perfectly competitive model if $\psi_s = 0$ and $\delta_s = 0$, where the role of firm heterogeneity is governed by the parameter ψ_s. Table 5.6 presents the effects of a model without scale economies (columns 3 and 4) and with scale economies but without firm heterogeneity (columns 5 and 6). For comparison, the first two columns restate the baseline results. The inclusion of firm heterogeneity and scale economies does not change the results qualitatively, but there are quantitative differences. The output loss in ETS manufacturing and the leakage rate is lower without scale economies and firm heterogeneity. However, the CBAM is more effective in countering leakage when scale economies and firm heterogeneity are operative. Similarly, Böhringer et al. (2012) find that carbon tariffs are more effective when firm heterogeneity is accounted for compared to a perfectly competitive model. However, the evidence here suggests that this advantage is rather driven by scale economies that would also be present in a homogeneous firms framework with monopolistic competition. Moreover, scale economies and firm heterogeneity aggravate the real income loss due to carbon pricing. Thus, a perfectly competitive model would underestimate the real income loss in the EU due to the Fit-for-55 target by almost 20%. Recalling the decomposition in Table 5.4, the larger real income decline in the presence of scale economies seem to be due to a shift in entry toward sectors with low scale elasticity following carbon pricing. Quantitatively, the inclusion of scale economies seems to be more important than the selection effects of heterogeneous firms in the aggregate.

	Base		No Scale		No Heterogeneity	
variable	No CBAM	CBAM	No CBAM	CBAM	No CBAM	CBAM
GO (ETS Manuf.)	-2.13	0.39	-1.18	0.60	-1.96	0.43
Global Emissions	-3.09	-3.33	-3.14	-3.34	-3.09	-3.33
Leakage rate	17.79	11.20	16.25	10.92	17.65	11.20
Real Income (EU)	-0.31	-0.30	-0.25	-0.24	-0.30	-0.29
Social Welfare (Global)	0.01	0.01	0.01	0.01	0.01	0.01
Real Income (Global)	-0.05	-0.05	-0.04	-0.05	-0.05	-0.05

Note: All values in percentage change. Values shown for the Fit-for-55 target and baseline CBAM design. The constant returns to scale scenario is calibrated by setting $\psi_s = 0$ and $\delta_s = 0$ for all sectors. The no firm heterogeneity scenario sets $\psi_s = 0$ for all sectors.

Table 5.6: Scale economies and firm heterogeneity

6 Conclusion

In this paper, I develop a multi-country and -sector quantitative general equilibrium with heterogeneous firms to analyze the relevance of firm heterogeneity for unilateral carbon pricing. I show how emission intensity changes can be decomposed into a reallocation of market shares across firms as well as within-firm changes. The reallocation channel is related to the average productivity, which can be quantified using publicly available data on the share of exporting firms. Hence, this paper provides a methodology to trace productivity changes following trade and climate policy changes in general equilibrium trade models.

Applying my model to the climate policy of the EU, I find that a tighter emission target reduces emissions in manufacturing mainly through a reduction of the emission intensity within firms, whereas reallocation of market shares toward more productive firms play a limited role. A CBAM on imports of sectors covered by the EU-ETS effectively reduces carbon leakage in these sectors. It even induces emission reductions abroad for some sectors, mostly by reshoring economic activity of emission intensive industries to the EU. On the other hand, the CBAM depresses fossil fuel prices, thus inducing leakage via the energy market channel. The CBAM is also effective at reducing output loss due to carbon pricing. Accounting for scale economies leads to an export promoting effect of the CBAM. Yet, this effect does not offset the negative effect of carbon pricing on exports. Hence, a one-sided CBAM on imports is not enough to provide a level playing field for exporters, even if scale economies are operative. The real income effects of carbon pricing and the CBAM outside the EU are small, while higher production costs decrease the real income in the EU.

Concerning different CBAM designs, I find that a CBAM targeted at the firm-level would lead to a larger leakage rate compared to a CBAM on the industry level due to resource reshuffling. Scale economies and firm heterogeneity have a limited effect on the global level. Yet, accounting for scale economies leads to a larger output decline and leakage in EU-ETS manufacturing and real income loss in the EU, while the CBAM becomes more effective in countering the adverse competitiveness effect. This paper quantified the role of firm heterogeneity for unilateral domestic and border carbon pricing in the canonical Melitz-Chaney model of firm heterogeneity. A fruitful area for future research would be to allow for more dimensions of heterogeneity, such as varying emission intensity apart from productivity differences.

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A Appendix

A.1 Derivation of Key Equations of the Model

Derivation of the free entry condition (FE) Note that:

$$E[\pi_{ijs}] = (1-G_{is}(\varphi^*_{ijs}))E[\pi_{ijs}|\varphi > \varphi^*_{ijs}] = \left(\frac{b_{is}}{\varphi^*_{ijs}}\right)^{\theta_s}\left(\frac{1}{\eta_s(1+t_{ijs})}E[r_{ijs}(\varphi)|\varphi > \varphi^*_{ijs}] - \tilde{c}_{ijs}f_{ijs}\right)$$

Define average revenues in sector s from serving market j from country i:

$$\bar{r}_{ijs} \equiv E[r_{ijs}(\varphi)|\varphi > \varphi^*_{ijs}]$$

To solve for $\bar{r}_{ijs}$ one needs the conditional density which is given by:

$$g_{is}(\varphi|\varphi > \varphi^*_{ijs}) = \begin{cases} \frac{g_{is}(\varphi)}{1-G_{is}(\varphi_{ijs})} = b_{is}^{-\theta_s}(\varphi^*_{ijs})^{\theta_s}\theta_s b_{is}^{\theta_s}\varphi^{-\theta_s-1} & \text{if } \varphi \geq \varphi^*_{ijs} \\ 0 & \text{if } \varphi < \varphi^*_{ijs} \end{cases}$$

Define the average productivity across firms in a particular market as:

$$(\bar{\varphi}_{ijs})^{\eta_s-1} = E[\varphi^{\eta_s-1}|\varphi > \varphi_{ijs}] = (\varphi^*_{ijs})^{\theta_s}\int_{\varphi^*_{ijs}}^{\infty}\varphi_{ijs}^{\eta_s-1}\theta_s\varphi^{-\theta_s-1}d\varphi$$

which simplifies to:

$$\bar{\varphi}_{ijs}^{\eta_s-1} = \frac{\theta_s}{1-\eta_s+\theta_s}(\varphi^*_{ijs})^{\eta_s-1}$$

With this definition the average revenues are:

$$\bar{r}_{ijs} = \left[\phi_{ijs}\tilde{c}_{is}\frac{\eta_s}{\eta_s-1}\right]^{1-\eta_s}P_{ijs}^{\eta_s-\sigma_s}P_{js}^{\sigma_s-1}Y_{js}\bar{\varphi}_{ijs}^{\eta_s-1} = \frac{\theta_s}{1-\eta_s+\theta_s}(1+t_{ijs})w_i\eta_s f_{ijs} \tag{A.1}$$

Plugging in (3.1.3) and the pareto distribution we get the following equation for the free entry condition:

$$\sum_{j\in M} b_{is}^{\theta_s}(\varphi^*_{ijs})^{-\theta_s}\left(\frac{\bar{r}_{ijs}}{(1+t_{ijs})\eta_s} - \tilde{c}_{ijs}f_{ijs}\right) \geq \tilde{c}_{is}f^e_{is} \tag{A.2}$$

with the definition of the average revenues this equation becomes:

$$\sum_{j \in M} b_{is}^{\theta_s} (\varphi_{ijs}^*)^{-\theta_s} \left(\frac{\theta_s}{1 - \eta_s + \theta_s} \tilde{c}_{ijs} f_{ijs} - \tilde{c}_{ijs} f_{ijs} \right) = \tilde{c}_{is} f_{is}^e \tag{A.3}$$

Rearranging leads to (FE).

Derivation of the price index P_{ijs} Now recall that P_{ijs} is given by:

$$P_{ijs}^{1-\eta_s} = \left[N_{is} b_{is}^{\theta_s} \theta_s \int_{\varphi_{ijs}^*} \left(\phi_{ijs} \tilde{c}_{ijs} \frac{\eta_s}{\eta_s - 1} \right)^{1-\eta_s} \varphi^{\eta_s - 1 - \theta_s} \right]$$

Solving the integral yields:

$$P_{ijs}^{1-\eta_s} = \left[N_{is} b_{is}^{\theta_s} \theta_s \frac{1}{1 + \theta_s - \eta_s} \left(\phi_{ijs} \tilde{c}_{ijs} \frac{\eta_s}{\eta_s - 1} \right)^{1-\eta_s} (\varphi_{ijs}^*)^{\eta_s - 1 - \theta_s} \right]$$

With (ZCP) this becomes:

$$P_{ijs}^{1-\eta_s} = \left[N_{is} b_{is}^{\theta_s} \frac{\theta_s \tilde{\eta}_s}{1 + \theta_s - \eta_s} (\phi_{ijs} \tilde{c}_{ijs})^{1-\eta_s} \left(\left(\frac{\eta_s}{\tilde{\eta}_s} \frac{(1 + t_{ijs}) \tilde{c}_{ijs} f_{ijs}}{Y_{js}} \right)^{\frac{1}{(\eta_s - 1)}} \frac{\tilde{c}_{ijs} \phi_{ijs}}{P_{js}^{(\sigma_s - 1)/(\eta_s - 1)}} P_{ijs}^{\frac{\eta_s - \sigma_s}{1 - \eta_s}} \right)^{\eta_s - 1 - \theta_s} \right]$$

where $\tilde{\eta}_s = \left(\frac{\eta_s}{\eta_s - 1} \right)^{1-\eta_s}$ Defining $\psi_s = \frac{1 - \eta_s + \theta_s}{\eta_s - 1}$ this equation can be rewritten as:

$$P_{ijs}^{(1-\eta_s) - \psi_s(\eta_s - \sigma_s)} = N_{is} b_{is}^{\theta_s} \frac{\theta_s \tilde{\eta}_s}{1 + \theta_s - \eta_s} (\phi_{ijs} \tilde{c}_{ijs})^{1-\eta_s} \left(\left(\frac{\eta_s}{\tilde{\eta}_s} \frac{(1 + t_{ijs}) \tilde{c}_{ijs} f_{ijs}}{Y_{js}} \right)^{\frac{1}{(\eta_s - 1)}} \frac{\tilde{c}_{ijs} \phi_{ijs}}{(P_{js})^{\frac{(\sigma_s - 1)}{(\eta_s - 1)}}} \right)^{\eta_s - 1 - \theta_s}$$

Now note that:

$$\begin{aligned} 1 - \eta_s - \psi(\eta_s - \sigma_s) &= 1 - \eta_s + \eta_s - \sigma_s - \frac{\theta_s(\eta_s - \sigma_s)}{1 - \eta_s} = 1 - \sigma_s + \theta_s \left(\frac{(\sigma_s - 1)}{1 - \eta_s} - 1 \right) \\ &= (1 - \sigma_s)(1 + \theta_s \left(\frac{1}{\sigma_s - 1} - \frac{1}{\eta_s - 1} \right) \end{aligned}$$

This leads to:

$$P_{ijs} = (N_{is})^{\frac{\delta_s}{(1-\sigma_s)}} (\phi_{ijs} \tilde{c}_{ijs})^{\frac{-\theta_s \delta_s}{(1-\sigma_s)}} \left[\left(\frac{Y_{js}}{(1 + t_{ijs}) \tilde{c}_{ijs}} \right) (P_{js})^{(\sigma_s - 1)} \right]^{\frac{\psi_s \delta_s}{(1-\sigma_s)}} \xi_{ijs}$$

where $\delta_s = \frac{1}{1+\theta_s\left(\left(\frac{1}{\sigma_s-1}-\frac{1}{\eta_s-1}\right)\right.}$ is the product of scale and trade elasticity and

$$\xi_{ijs} = \left(b_{is}^{\theta_s} \frac{\theta_s \tilde{\eta}_s}{1+\theta_s-\eta_s} \left(\frac{\eta_s}{\tilde{\eta}_s} f_{ijs} \right)^{\frac{\psi_s}{(\eta_s-1)}} \right)^{\frac{\delta_s}{1-\sigma_s}}.$$

Rearranging and noting that $\epsilon_s = \delta_s\theta_s$ is the trade elasticity yields (3.16). Summing over all source countries and noting that $1+\psi\delta_s = \frac{\epsilon_s}{\sigma_s-1}$ leads to (3.17).

Derivation of the expenditure share Total expenditure of country j on products from country i in sector s is given by: $Y_{ijs} = N_{is} b_{is}^{\theta_s} (\varphi_{ijs}^*)^{-\theta_s} \bar{r}_{ijs}$. From (A.1) this can be rewritten as:

$$Y_{ijs} = N_{is} b_{is}^{\theta_s} (\varphi_{ijs}^*)^{-\theta_s} \left[\phi_{ijs} \tilde{c}_{is} \frac{\eta_s}{\eta_s-1} \right]^{1-\eta_s} P_{ijs}^{\eta_s-1} \left(\frac{P_{ijs}}{P_{js}} \right)^{1-\sigma_s} Y_{js} \frac{\theta_s}{1-\eta_s+\theta_s} (\varphi_{ijs}^*)^{\eta_s-1}$$

which is equivalent to:

$$Y_{ijs} = N_{is} b_{is}^{\theta_s} (\varphi_{ijs}^*)^{-\theta_s} \frac{\theta_s}{1-\eta_s+\theta_s} \left(\frac{p_{ijs}(\varphi_{ijs}^*)}{P_{ijs}} \right)^{1-\eta_s} \left(\frac{P_{ijs}}{P_{js}} \right)^{1-\sigma_s} Y_{js} \tag{A.4}$$

Note that one can rewrite the price index to:

$$P_{ijs} = p_{ijs}(\varphi_{ijs}^*) \left[N_{is} b_{is}^{\theta_s} (\varphi_{ijs}^*)^{-\theta_s} \frac{1}{1+\theta_s-\eta_s} \right]^{1/(1-\eta_s)}$$

Hence (A.4) simplifies to:

$$Y_{ijs} = \left(\frac{P_{ijs}}{P_{js}} \right)^{1-\sigma_s} Y_{js}$$

Thus, the expenditure share λ_{ijs} is given by:

$$\lambda_{ijs} = \frac{P_{ijs}^{1-\sigma_s}}{\sum_{l\in M} P_{ljs}^{1-\sigma_s}} \tag{A.5}$$

Plugging in the trade in P_{ijs} this is equivalent to:

$$\lambda_{ijs} = \frac{(N_{is})^{\delta_s} (\tilde{c}_{ijs}\phi_{ijs})^{-\epsilon_s} ((1+t_{ijs})\tilde{c}_{ijs})^{-\delta_s\psi_s} \xi_{ijs}}{\sum_{l\in M} (N_{ls})^{\delta_s} (\tilde{c}_{ljs}\phi_{ljs})^{-\epsilon_s} ((1+t_{ljs})\tilde{c}_{ljs})^{-\delta_s\psi_s} \xi_{ijs}}$$

Sector level emissions From the individual factor demands the emissions generated in the production process by a firm with productivity φ in sector s exporting from country i to j is given by:

$$z_{ijs}(\varphi) = \frac{\gamma_{ifs}\tilde{c}_{is}}{\kappa_{is}} \frac{\tau_{ijs} q_{ijs}(\varphi)}{\varphi} \tag{A.6}$$

or in terms of revenues

$$z_{ijs}(\varphi) = \frac{\eta_s - 1}{\eta_s} \frac{\gamma_{ifs}}{\kappa_{is}} \frac{r_{ijs}(\varphi)}{1 + t_{ijs}} \tag{A.7}$$

Aggregate emissions for serving market j in sector s from country i are thus given by:

$$Z_{ijs} = \frac{\eta_s - 1}{\eta_s} \frac{\gamma_{ifs}}{\kappa_{is}} N_{is} b_{is}^{\theta_s} (\varphi^*_{ijs})^{-\theta_s} \bar{x}_{ijs}$$

Hence the (direct) emissions embodied in trade flows are given by:

$$Z_{ijs} = \frac{\eta_s - 1}{\eta_s} \frac{\gamma_{ifs}}{\kappa_{is}} X_{ijs} \tag{A.8}$$

where X_{ijs} are the exports from country i to country j in sector s. Summing over all destination countries leads to the total production related emissions in sector s in country i.

A.2 Proof of proposition 3.1

Proof (i) The result follows directly by differentiating (A.7) with respect to t^{cadv}_{ijs}

$$\frac{\partial z_{ijs}(\varphi)}{\partial t^{cadv}_{ijs}} = \frac{z_{ijs}(\varphi)}{x_{ijs}(\varphi)} \frac{\partial x_{ijs}}{\partial t^{cadv}_{ijs}} \tag{A.9}$$

and with respect to t^{cf}_{ijs}:

$$\frac{\partial z_{ijs}(\varphi)}{\partial t^{cf}_{ijs}} = \frac{z_{ijs}(\varphi)}{x_{ijs}(\varphi)} \frac{\partial x_{ijs}}{\partial t^{cf}_{ijs}} + \frac{\partial i^x_{ijs}}{\partial t^{cf}_{ijs}} \frac{z_{ijs}(\varphi)}{i^r_{ijs}} \tag{A.10}$$

where

$$i^x_{ijs} = \frac{\gamma_{ijfs}}{\kappa_{ijs}} = \kappa_{ijs}^{-\zeta_s} (\tilde{c}_{ijs})^{\zeta_s - 1} \iota (1 - \mu_{is})^{\zeta_s} \tag{A.11}$$

is the emission intensity of sales in terms of sales.

Proof (ii) Differentiating $x_{ijs}(\varphi)$ with respect to t^{cadv}_{ijs} yields:

$$\frac{\partial x_{ijs}(\varphi)}{\partial t^{cadv}_{ijs}} = \frac{\partial r_{ijs}(\varphi)}{\partial t^{cadv}_{ijs}} \frac{1}{1+t_{ijs}} - \frac{r_{ijs}(\varphi)}{(1+t_{ijs})^2} \tag{A.12}$$

With (3.14) this yields:

$$\frac{\partial x_{ijs}(\varphi)}{\partial t^{cadv}_{ijs}} = (1-\eta_s)\frac{r_{ijs}}{1+t_{ijs}} \frac{1}{1+t_{ijs}} - \frac{r_{ijs}(\varphi)}{(1+t_{ijs})^2}$$

which simplifies to

$$\frac{\partial x_{ijs}(\varphi)}{\partial t^{cadv}_{ijs}} = -\eta_s \frac{x_{ijs}(\varphi)}{1+t_{ijs}} < 0 \tag{A.13}$$

which ends the first part of the proof. Differentiating $x_{ijs}(\varphi)$ with respect to t^{cf}_{ijs} yields:

$$\frac{\partial x_{ijs}(\varphi)}{\partial t^{cf}_{ijs}} = -(\eta_s - 1)\frac{x_{ijs}(\varphi)}{\tilde{c}_{ijs}} \frac{\partial \tilde{c}_{ijs}}{\partial t^{cf}_{ijs}} \tag{A.14}$$

Hence, the firm-level variant affects firm level exports exclusively via a change in the costs of production. From (3.6), the change in unit cost is given by:

$$\frac{\partial \tilde{c}_{ijs}}{\partial t^{cf}_{ijs}} = \frac{\kappa_{ijs}^{-\zeta_s}(1-\mu_{is})^{\zeta_s}\frac{\partial \kappa_{ijs}}{\partial t^{cf}_{ijs}}}{\mu_{is}^{\zeta_s} w_i^{1-\zeta_s} + (1-\mu_{is})^{\zeta_s}\kappa_{ijs}^{1-\zeta_s}} \tilde{c}_{ijs}$$

By noting that the change in the emissions price is given by $\frac{\partial \kappa_{ijs}}{\partial t^{cf}_{ijs}} = \frac{P_{if}}{\iota}$ and with the definition of the carbon cost share γ_{ijfs} the change in unit costs simplifies to:

$$\frac{\partial \tilde{c}_{ijs}}{\partial t^{cf}_{ijs}} = \tilde{c}_{ijs} \frac{\gamma_{ijfs}}{(1+\nu_{ijs})\iota} \tag{A.15}$$

Hence, (A.14) simplifies to:

$$\frac{\partial x_{ijs}(\varphi)}{\partial t^{cf}_{ijs}} = -(\eta_s - 1)\frac{x_{ijs}(\varphi)}{(1+\nu_{ijs})} \frac{\gamma_{ifs}}{\iota} < 0 \tag{A.16}$$

Now, we turn to the emissions embodied in trade flows. From (i) the change in exports of firm φ in s from i to j is a sufficient statistic for the change in emissions embodied in this trade flow for the ad-valorem CBAM. From the first part of (ii) this change is negative. The sign of the effect of the firm-level CBAM depends additionally on the change in the emission intensity.

Differentiating (A.11) yields:

$$\frac{\partial i^x_{ijs}}{\partial t^{cf}_{ijs}} = \frac{\gamma_{ijfs}}{\kappa_{ijs}} \left[-\zeta_s \frac{\partial \kappa_{ijs}}{\partial t^{cf}_{ijs}} \frac{1}{\kappa_{ijs}} + (\zeta_s - 1) \frac{1}{\tilde{c}_{ijs}} \frac{\partial \tilde{c}_{ijs}}{\partial t^{cf}_{ijs}} \right] \tag{A.17}$$

Plugging in the change in κ_{ijs} and (A.15), yields

$$\frac{\partial i^x_{ijs}}{\partial t^{cf}_{ijs}} = \frac{\gamma_{ijfs}}{\kappa_{ijs}} \frac{1}{1+\nu_{is}} \left(-\zeta_s + (\zeta_s - 1) \frac{\gamma_{ifs}}{\iota} \right) \tag{A.18}$$

Then, (A.10) simplifies to:

$$\frac{\partial z_{ijs}(\varphi)}{\partial t^{cf}_{ijs}} = \frac{z_{ijs}(\varphi)}{(1+\nu_{is})} \left[\zeta_s (\frac{\gamma_{ifs}}{\iota} - 1) - \eta_s \frac{\gamma_{ifs}}{\iota} \right] \tag{A.19}$$

which is smaller than zero, because $\frac{\gamma_{ifs}}{\iota} < 1$

Proof (iii) Define $\Delta^{tcf+}_z \equiv -\frac{\partial z_{ijs}(\varphi)}{\partial t^{cf}_{ijs}}$ and $\Delta^{cadv+}_z \equiv -\frac{\partial x_{ijs}(\varphi)}{\partial t^{cadv}_{ijs}}$ as the absolute value of the change in emissions embodied in tradeflows from i to j for firm φ. If the difference between Δ^{tcf+}_z and Δ^{cadv+}_z is positive, the effect on firm-level embodied emission changes is larger for the firm-level CBAM. With (A.9), (A.13) and (A.19) the difference between the two embodied emission changes becomes:

$$\Delta^{tcf+}_z - \Delta^{cadv+}_z = \frac{z_{ijs}(\varphi)}{(1+\nu_{is})} \left[\zeta_s (1 - \frac{\gamma_{ifs}}{\iota}) + \eta_s \frac{\gamma_{ifs}}{\iota} \right] - \eta_s \frac{z_{ijs}(\varphi)}{1+t_{ijs}}$$

which is positive as long as

$$(1+t_{ijs}) \left[\zeta_s (1 - \frac{\gamma_{ifs}}{\iota}) + \eta_s \frac{\gamma_{ifs}}{\iota} \right] > \eta_s (1+\nu_{is})$$

$$\left[\frac{\zeta_s}{\eta_s} (1 - \frac{\gamma_{ifs}}{\iota}) + \frac{\gamma_{ifs}}{\iota} \right] > \frac{(1+\nu_{is})}{1+t_{ijs}}$$

which can be rearranged to

$$\left[\frac{\zeta_s}{\eta_s} + \frac{\gamma_{ifs}}{\iota} \left(1 - \frac{\zeta_s}{\eta_s} \right) \right] > \frac{(1+\nu_{is})}{1+t_{ijs}} \tag{A.20}$$

A.3 Decomposition of emission changes in physical quantity

Technique effect The technique effect is the sum of the change in sector-level emission intensities weighted by the baseline emission share. From (3.32), the emission intensity can be expressed as:

$$I_{is}(\varphi) = \sum_{j \in M} N_{ijs} \int_{\varphi^*_{ijs}} i_{ijs}(\varphi)\xi_{ijs}(\varphi)(\varphi^*_{ijs})^{-\theta_s}\theta_s\varphi^{-\theta_s-1}d\varphi \tag{A.21}$$

Applying the Leibniz rule a change in the emission intensity can be decomposed to:

$$\begin{aligned}\hat{I}_{is} = \sum_{j \in M} \Bigg[& d\ln N_{ijs} N_{ijs} \int_{\varphi^*_{ijs}} \varrho_{ijs}(\varphi^*_{ijs})^{\theta_s}\theta_s\varphi^{-\theta_s-1}d\varphi + \\ & N_{ijs}\Bigg(\int_{\varphi^*_{ijs}} d\ln i_{ijs}\varrho_{ijs}(\varphi^*_{ijs})^{\theta_s}\theta_s\varphi^{-\theta_s-1}d\varphi + \\ & \int_{\varphi^*_{ijs}} d\ln \xi_{ijs}\varrho_{ijs}(\varphi^*_{ijs})^{\theta_s}\theta_s\varphi^{-\theta_s-1}d\varphi + \\ & \theta_s d\ln\varphi^*_{ijs}\int_{\varphi^*_{ijs}} \varrho_{ijs}(\varphi^*_{ijs})^{\theta_s}\theta_s\varphi^{-\theta_s-1}d\varphi - \\ & d\ln\varphi^*_{ijs}\theta_s\varrho_{ijs}(\varphi^*_{ijs})\Bigg)\Bigg]\end{aligned} \tag{A.22}$$

The second and third line are the within-firm and reallocation effect. The other three lines correspond to the change in entry and exit. As I will show below, neither the change in the firm level emission intensity $d\ln i_{ijs}$ nor the change in relative market shares, $d\ln\xi_{ijs}$ depend on φ. Noting that:

$$N_{ijs}\int_{\varphi^*_{ijs}} \varrho_{ijs}(\varphi^*_{ijs})^{\theta_s}\theta_s\varphi^{-\theta_s-1}d\varphi = \frac{Z_{ijs}}{Z_{is}}$$

one gets:

$$d\ln I_{is} = \sum_{j \in M}\left[\frac{Z_{ijs}}{Z_{is}}\left(d\ln N_{ijs} + d\ln i_{ijs} + d\ln\xi_{ijs} + \theta_s d\ln\varphi^*_{ijs}\right) - d\ln\varphi^*_{ijs}\theta_s\frac{N_{ijs}z_{ijs}(\varphi^*_{ijs})}{Z_{is}}\right]$$

Because $N_{ijs}z_{ijs}(\varphi^*_{ijs}) = \frac{1-\eta_s+\theta_s}{\theta_s}Z_{ijs}$, the expression can be simplified to:

$$d\ln I_{is} = \sum_{j \in M}\frac{Z_{ijs}}{Z_{is}}\left[d\ln i_{ijs} + d\ln\xi_{ijs} + \theta_s d\ln\varphi^*_{ijs} - (1-\eta_s+\theta_s)\ln\varphi^*_{ijs} + d\ln N_{ijs}\right]$$

From the definition of the emission intensity in (3.9) the within firm effect is given by:

$$d \ln i_{ijs} = d \ln \gamma_{ifs} + d \ln \tilde{c}_{is} - d \ln \kappa_{is} \tag{A.23}$$

The change in the market share of a firm is given by:

$$d \ln \xi_{ijs} = d \ln q_{ijs}(\varphi) - d \ln Q_{is} = d \ln x_{ijs}(\varphi) - d \ln \tilde{c}_{is} - d \ln Q_{is} \tag{A.24}$$

From (A.35) the change in aggregate output can be expressed as:

$$d \ln Q_{is} = d \ln \bar{\varphi}_{is} + d \ln X_{is} - d \ln \tilde{c}_{is} \tag{A.25}$$

Thus

$$d \ln \xi_{ijs} = d \ln x_{ijs}(\varphi) - d \ln \bar{\varphi}_{is} - d \ln X_{is} \tag{A.26}$$

With the definition of average sales to a certain destination, the change in firm level sales is given by:

$$d \ln x_{ijs}(\varphi) = d \ln \bar{x}_{ijs} - (\eta_s - 1) d \ln \varphi^*_{ijs}$$

and the aggregate sales in a sector are given by:

$$d \ln X_{is} = \sum_{j \in M} \frac{X_{ijs}}{X_{is}} \left(d \ln N_{ijs} + d \ln \bar{x}_{ijs} \right)$$

From (A.8), $\frac{X_{ijs}}{X_{is}} = \frac{Z_{ijs}}{Z_{is}}$, hence the change in the emission intensity is given by:

$$\begin{aligned} d \ln I_{is} = & \underbrace{d \ln \gamma_{ifs} + d \ln \tilde{c}_{is} - d \ln \kappa_{is}}_{Within} + \\ & \underbrace{\sum_{j \in M} \frac{Z_{ijs}}{Z_{is}} \left[d \ln N_{ijs} - d \ln \bar{\varphi}_{is} - (\eta_s - 1) d \ln \varphi^*_{ijs} \right]}_{Across} + \\ - & \underbrace{\sum_{j \in M} \frac{Z_{ijs}}{Z_{is}} \left[(\eta_s - 1) \ln \varphi^*_{ijs} + d \ln N_{ijs} \right]}_{Entry/Exit} \end{aligned}$$

Summing the second and third line yields (3.34).

A.4 Proof of proposition 3.2

I start by rewriting the average productivity:

$$\bar{\varphi}_{is} = \left[\sum_{j \in M} \frac{\eta_s}{\eta_s - 1} \frac{1}{\tilde{c}_{is}} (\varphi^*_{ijs})^{-\theta_s} b_{is}^{\theta_s} \bar{x}_{ijs}\right]^{-1} \bar{q}_{is}$$

Now, note that

$$\bar{q}_{is} = \sum_{j \in M} (\varphi^*_{ijs})^{-\theta_s} b_{is}^{\theta_s} \int_{\varphi^*_{ijs}} \tau_{ijs} q_{ijs}(\varphi) \frac{dG(\varphi)}{1 - G(\varphi^*_{ijs})} = \sum_{j \in M} \frac{\theta_s + 1 - \eta_s}{\theta_s - \eta_s} \frac{\eta_s - 1}{\eta_s} \frac{1}{\tilde{c}_{is}} b_{is}^{\theta_s} (\varphi^*_{ijs})^{-\theta_s} \varphi^*_{ijs} \bar{x}_{ijs}$$

Thus, the average productivity is given by:

$$\bar{\varphi}_{is} = \frac{\theta_s + 1 - \eta_s}{\theta_s - \eta_s} \sum_{j \in M} \frac{(\varphi^*_{ijs})^{1-\theta_s} \bar{x}_{ijs}}{\sum_{l \in M} (\varphi^*_{ils})^{-\theta_s} \bar{x}_{ils}}$$

Plugging in (FE) this simplifies to:

$$\bar{\varphi}_{is} = \frac{\eta_s - 1}{(\theta_s - \eta_s) b_{is}^{-\theta_s} f_{is}^e} \sum_{j \in M} (\varphi^*_{ijs})^{1-\theta_s} \bar{x}_{ijs}$$

Applying the hat algebra approach yields:

$$\hat{\bar{\varphi}}_{is} = \sum_{j \in M} \frac{\widehat{(\varphi^*_{ijs})}^{1-\theta_s} (\varphi^*_{ijs})^{1-\theta_s} \bar{x}_{ijs}}{\sum_{j' \in M} (\varphi^*_{ij's})^{1-\theta_s} \bar{x}_{ij's}}$$

In order to match this expression to observable data I exploit the following relationship between the cut-off productivities and the share of exporting firms among the active firms:

$$n_{ijs} = \frac{1 - G(\varphi^*_{ijs})}{1 - G(\varphi^*_{iis})} = \left(\frac{\varphi^*_{ijs}}{\varphi^*_{iis}}\right)^{-\theta_s}$$

Hence, changes in the average productivity can be equivalently expressed as:

$$\hat{\bar{\varphi}}_{is} = \frac{\sum_{j \in M} \widehat{(\varphi^*_{ijs})}^{1-\theta_s} (n_{ijs})^{(\theta_s - 1)/\theta_s} \bar{x}_{ijs}}{\sum_{j' \in M} (n_{ij's})^{(\theta_s - 1)/\theta_s} \bar{x}_{ij's}} \tag{A.27}$$

which can be written as:

$$\hat{\tilde{\varphi}}_{is} = \widehat{\varphi^*_{iis}} \left[(\widehat{\varphi^*_{iis}})^{-\theta_s} \sum_{j \in M} \hat{n}_{ijs}^{(\theta_s - 1)/\theta_s} h_1(n_{ijs}) \right] \tag{A.28}$$

where

$$h_1(n_{ijs}) = \frac{n_{ijs}^{(\theta_s-1)/\theta_s} \frac{f_{ijs}}{f_{iis}}}{\sum_{j' \in M} n_{ij's}^{(\theta_s-1)/(\theta_s)} \frac{f_{ij's}}{f_{iis}}} \tag{A.29}$$

Expressing (FE) in changes yields:

$$\sum_{j \in M} \widehat{(\varphi^*_{ijs})}^{-\theta_s} h_2(n_{ijs}) = 1 \tag{A.30}$$

where

$$h_2(n_{ijs}) = \frac{n_{ijs} \frac{f_{ijs}}{f_{iis}}}{\sum_{j' \in M} n_{ij's} \frac{f_{ij's}}{f_{iis}}} \tag{A.31}$$

which can be rearranged to

$$(\widehat{\varphi^*_{iis}})^{-\theta_s} = \frac{1}{\sum_{j \in M} \hat{n}_{ijs} h_2(n_{ijs})} \tag{A.32}$$

Plugging into (A.28) yields:

$$\hat{\tilde{\varphi}}_{is} = \widehat{\varphi^*_{iis}} \left[\frac{\sum_{j \in M} h_1(n_{ijs}) \hat{n}_{ijs}^{(\theta_s-1)/\theta_s}}{\sum_{j \in M} h_2(n_{ijs}) \hat{n}_{ijs}} \right] \tag{A.33}$$

Defining

$$H(\hat{n}_{ijs}) = \frac{\sum_{j \in M} h_1(n_{ijs}) \hat{n}_{ijs}^{(\theta_s-1)/\theta_s}}{\sum_{j \in M} h_2(n_{ijs}) \hat{n}_{ijs}} \tag{A.34}$$

yields (3.37).

A.5 Scale and composition effect

Aggregate physical sales are the product of the number of firms and the average quantity supplied by these firms, i.e. $Q_{is} = N_{is}\bar{q}_{is}$. where the average quantity is defined as:

$$\bar{q}_{is} = \sum_{j \in M} (\varphi^*_{ijs})^{-\theta_s} b_{is}^{\theta_s} \int_{\varphi^*_{ijs}} \tau_{ijs} q_{ijs}(\varphi) \frac{dG(\varphi)}{1 - G(\varphi^*_{ijs})}$$

From the definition of the average productivity the average physical quantity can be expressed as:

$$\bar{q}_{is} = \bar{\varphi}_{is} \left[\sum_{j \in M} (\varphi^*_{ijs})^{-\theta_s} b_{is}^{\theta_s} \int_{\varphi^*_{ijs}} \varphi^{-1} \tau_{ijs} q_{ijs} \frac{dG(\varphi)}{1 - G(\varphi^*_{ijs})} \right]$$

Noting that $\tau_{ijs} q_{ijs}(\varphi) = \frac{\eta_s - 1}{\eta_s} \varphi \frac{x_{ijs}(\varphi)}{\tilde{c}_{is}}$ this can be rewritten as:

$$\bar{q}_{is} = \bar{\varphi}_{is} \left[\sum_{j \in M} \frac{\eta_s}{\eta_s - 1} \frac{1}{\tilde{c}_{is}} (\varphi^*_{ijs})^{-\theta_s} b_{is}^{\theta_s} \bar{x}_{ijs} \right]$$

Since $X_{is} = \sum_{j \in M} (\varphi^*_{ijs})^{-\theta_s} b_{is}^{\theta_s} \bar{x}_{ijs}$, the aggregate physical quantity is given by:

$$Q_{is} = \frac{\eta_s}{\eta_s - 1} \bar{\varphi}_{is} \frac{X_{is}}{\tilde{c}_{is}} \tag{A.35}$$

Expressing this equation in changes yields:

$$\hat{Q}_{is} = \hat{\bar{\varphi}}_{is} \frac{\hat{X}_{is}}{\hat{\tilde{c}}_{is}} \tag{A.36}$$

From the definition of the scale and composition effect this directly yields (3.38) and (3.39).

A.6 Equilibrium in changes

To limit the number of parameters to be solved for, I express the equilibrium in changes following the hat algebra approach of Eaton et al. (2008):

$$\hat{\kappa}_{is} = \widehat{(1 + \nu_{ijs})} \hat{P}_{if} \tag{A.37}$$

$$\hat{\tilde{c}}_{ijs} = \left[\gamma_{ils} \hat{w}_i^{1-\zeta_s} + \gamma_{ifs} \hat{\kappa}_{ijs}^{1-\zeta_s} \right]^{\frac{1}{1-\zeta_s}} \tag{A.38}$$

$$\hat{\tilde{c}}_{if} = \left[\gamma_{ilf} \hat{w}_i^{1-\zeta_f} + \gamma_{irf} \hat{r}_{if}^{1-\zeta_f} \right]^{\frac{1}{1-\zeta_f}} \tag{A.39}$$

$$\hat{P}_{if} = \left[\sum_{j \in M} \lambda_{ijf} \left(\hat{\tilde{c}}_{if} \hat{\tau}_{ijf} \right)^{-\epsilon_f} \right]^{-1/\epsilon_f} \tag{A.40}$$

$$\hat{\gamma}_{ijls}=\left(\frac{\hat{w}_i}{\hat{\tilde{c}}_{ijs}}\right)^{1-\zeta_k} \quad \text{for k= s, f} \tag{A.41}$$

$$\hat{\gamma}_{ijfs}=\left(\frac{\hat{\kappa}_{ijs}}{\hat{\tilde{c}}_{ijs}}\right)^{1-\zeta_s} \tag{A.42}$$

$$\hat{\gamma}_{irf}=\left(\frac{\hat{r}_{if}}{\hat{\tilde{c}}_{if}}\right)^{1-\zeta_f} \tag{A.43}$$

$$\hat{N}_{is}=\left(\frac{\hat{w}_i}{\hat{\tilde{c}}_{is}}\right)^{\zeta_s}\hat{L}_{is} \tag{A.44}$$

$$\hat{\lambda}_{ijs}=\frac{\hat{N}_{is}^{\delta_s}\left(\hat{\tilde{c}}_{ijs}\phi_{ijs}\right)^{-\epsilon_s}\left((\widehat{1+t_{ijs}})\hat{\tilde{c}}_{ijs}\right)^{-\delta_s\psi_s}}{\sum_{l\in M}\lambda_{ljs}\hat{N}_{ls}^{\delta_s}\left(\hat{\tilde{c}}_{ljs}\phi_{ljs}\right)^{-\epsilon_s}\left((\widehat{1+t_{ljs}})\hat{\tilde{c}}_{ljs}\right)^{-\delta_s\psi_s}} \tag{A.45}$$

$$\begin{aligned}Y'_{ik}=&\alpha_{ik}\left[\hat{w}_i w_i L_i+\hat{r}_{if}r_{if}R_{if}+\sum_{s\in S}\nu'_{is}\sum_{j\in M}\frac{\gamma'_{ijfs}}{1+\nu'_{ijs}}\frac{\lambda'_{jis}}{1+t'_{jis}}Y_{js}\right]+\\&\alpha_{ik}\left[\sum_{s\in S}\sum_{j\in M}\frac{\lambda'_{jis}}{1+t'_{jis}}\left(t'_{jis}+(t^{cf}_{jis})'\frac{\gamma'_{jifs}}{1+\nu'_{jis}}Y'_{is}\right)\right]\end{aligned} \tag{A.46}$$

$$\hat{L}_{is}=\frac{\hat{\gamma}_{ils}\gamma_{ils}}{\hat{w}_i w_i L_{is}}\sum_{j\in M}\frac{\hat{\lambda}_{ijs}}{(\widehat{1+t_{ijs}})}\hat{Y}_{js}\frac{\lambda_{ijs}}{1+t_{ijs}}Y_{js} \tag{A.47}$$

$$\hat{r}_{if}=\frac{1}{r_{if}R_{if}}\hat{\gamma}_{irf}\gamma_{irf}\sum_{j\in M}\hat{\lambda}_{ijf}\hat{Y}_{jf}\lambda_{ijf}Y_{jf} \tag{A.48}$$

$$\hat{w}_i=\frac{1}{w_i L_i}\sum_{s\in S}\hat{\gamma}_{ils}\gamma_{ils}\sum_{j\in M}\frac{\hat{\lambda}_{ijs}}{(\widehat{1+t_{ijs}})}\hat{Y}_{js}\frac{\lambda_{ijs}}{1+t_{ijs}}Y_{js}+\frac{1}{w_i L_i}\hat{\gamma}_{ilf}\gamma_{ilf}\sum_{j\in M}\hat{\lambda}_{ijf}\hat{Y}_{jf}\lambda_{ijf}Y_{jf} \tag{A.49}$$

Next, I solve the equilibrium in changes following the strategy of Kucheryavyy et al. (2023). First, note that (A.37) to (A.44) can be simplified to 2M+M*(S+1) equations in the 2M+M*(S+1) unknowns $\left\{\hat{L}_{ik}\right\}_{s,f}$,$\{\hat{w}_i\}_i$ and $\{\hat{r}_{if}\}_i$. The solution algorithm works as follows: Given an initial guess of these variables and a starting point for the novel carbon tax, ν'_{is}, one can solve equations (A.37) to (A.45). To solve for, Y'_{is}, I follow Caliendo and Parro (2014) and express (A.46) in

Matrix form:

$$\mathbf{\Omega}(\hat{w},\hat{r}_f,\hat{L})\mathbf{Y'} = \mathbf{\Delta}(\hat{\mathbf{w}},\hat{\mathbf{r}}_\mathbf{f}),\hat{\mathbf{L}} \tag{A.50}$$

with the two M*Sx1 vectors:

$$\mathbf{Y'} = \begin{bmatrix} Y'_{11} \\ \vdots \\ Y'_{1S} \\ \vdots \\ Y'_{i1} \\ \vdots \\ Y'_{is} \\ \vdots \\ Y'_{Ms} \\ \vdots \\ Y'_{MS} \end{bmatrix} \quad ; \quad \mathbf{\Delta}(\hat{\mathbf{w}},\hat{\mathbf{r}}_\mathbf{f},\hat{\mathbf{L}}) = \begin{bmatrix} \alpha_{11}(\hat{w}_1 w_1 L_1 + \hat{r}_{1f} R_{1f} \\ \vdots \\ \alpha_{1S}(\hat{w}_1 w_1 L_1 + \hat{r}_{1f} R_{1f} \\ \vdots \\ \alpha_{i1}(\hat{w}_i w_i L_i + \hat{r}_{if} R_{if} \\ \vdots \\ \alpha_{is}(\hat{w}_i w_i L_i + \hat{r}_{if} R_{if} \\ \vdots \\ \alpha_{Ms}(\hat{w}_M w_M L_M + \hat{r}_{Mf} R_{Mf} \\ \vdots \\ \alpha_{MS}(\hat{w}_M w_M L_M + \hat{r}_{Mf} R_{Mf} \end{bmatrix}$$

The M*SxM*S matrix $\mathbf{\Omega}(\hat{\mathbf{w}},\hat{\mathbf{r}}_\mathbf{f},\hat{\mathbf{L}})$ is constructed as follows. First, define the two Mx1 vectors:

$$\mathbf{A_i}' = \begin{bmatrix} \alpha_{i1} \\ \vdots \\ \alpha_{iS} \end{bmatrix} \quad ; \quad \tilde{\mathbf{F}}_\mathbf{i}(\hat{\mathbf{w}},\hat{\mathbf{r}}_\mathbf{f},\hat{\mathbf{L}}) = \begin{bmatrix} \tilde{F}_{i1}(\hat{w},\hat{r}_f,\hat{L}) \\ \vdots \\ \tilde{F}_{iS}(\hat{w},\hat{r}_f,\hat{L}) \end{bmatrix}$$

where

$$\tilde{F}_{is} = \sum_{j\in M} \frac{\lambda'_{jis}}{1+t'_{jis}} (t'_{jis} + (t^c_{jis})' \frac{\gamma'_{jifs}}{1+\nu'_{jis}}$$

Hence, one can define the M*SxM*S matrix:

$$\mathbf{F}(\hat{\mathbf{w}},\hat{\mathbf{r}}_\mathbf{f},\hat{\mathbf{L}}) = \begin{bmatrix} \mathbf{A_1} \otimes \tilde{\mathbf{F}}_\mathbf{1}(\hat{\mathbf{w}},\hat{\mathbf{r}}_\mathbf{f},\hat{\mathbf{L}}) & \dots & 0_{MxM} \\ \vdots & \ddots & \vdots \\ 0_{MxM} & \dots & A_M \otimes \tilde{\mathbf{F}}_\mathbf{M}(\hat{\mathbf{w}},\hat{\mathbf{r}}_\mathbf{f},\hat{\mathbf{L}}) \end{bmatrix}$$

Finally, I define the M*SxM*S T matrix, as

$$\mathbf{T}(\hat{\mathbf{w}}, \hat{\mathbf{r}}_\mathbf{f}, \hat{\mathbf{L}}) = \begin{bmatrix} \alpha_{11}\tilde{\lambda}_{111} & \dots & \alpha_{11}\tilde{\lambda}_{11S} & \dots & \alpha_{11}\tilde{\lambda}_{1M1} & \dots & \alpha_{11}\tilde{\lambda}_{1MS} \\ \vdots & \ddots & \vdots & \ddots & \vdots & \ddots & \vdots \\ \alpha_{1S}\tilde{\lambda}_{111} & \dots & \alpha_{1S}\tilde{\lambda}_{11S} & \dots & \alpha_{1S}\tilde{\lambda}_{1M1} & \dots & \alpha_{1S}\tilde{\lambda}_{1MS} \\ \vdots & \ddots & \vdots & \ddots & \vdots & \ddots & \vdots \\ \alpha_{i1}\tilde{\lambda}_{i11} & \dots & \alpha_{i1}\tilde{\lambda}_{i1S} & \dots & \alpha_{i1}\tilde{\lambda}_{iM1} & \dots & \alpha_{i1}\tilde{\lambda}_{iMS} \\ \vdots & \ddots & \vdots & \ddots & \vdots & \ddots & \vdots \\ \alpha_{iS}\tilde{\lambda}_{i11} & \dots & \alpha_{iS}\tilde{\lambda}_{i1S} & \dots & \alpha_{iS}\tilde{\lambda}_{iM1} & \dots & \alpha_{iS}\tilde{\lambda}_{iMS} \\ \vdots & \ddots & \vdots & \ddots & \vdots & \ddots & \vdots \\ \alpha_{M1}\tilde{\lambda}_{M11} & \dots & \alpha_{M1}\tilde{\lambda}_{M1S} & \dots & \alpha_{M1}\tilde{\lambda}_{MM1} & \dots & \alpha_{M1}\tilde{\lambda}_{MMS} \\ \vdots & \ddots & \vdots & \ddots & \vdots & \ddots & \vdots \\ \alpha_{MS}\tilde{\lambda}_{M11} & \dots & \alpha_{MS}\tilde{\lambda}_{M1S} & \dots & \alpha_{MS}\tilde{\lambda}_{MM1} & \dots & \alpha_{MS}\tilde{\lambda}_{MMS} \end{bmatrix}$$

where $\tilde{\lambda}_{ijs} = \nu'_{is} \frac{\gamma'_{ijfs}}{1+\nu'_{ijs}} \frac{\lambda'_{jis}}{1+t'_{jis}}$. Then, the matrix $\mathbf{\Omega}(\hat{\mathbf{w}}, \hat{\mathbf{r}}_\mathbf{f}, \hat{\mathbf{L}})$ is defined as

$$\mathbf{\Omega}(\hat{\mathbf{w}}, \hat{\mathbf{r}}_\mathbf{f}, \hat{\mathbf{L}}) = I - \mathbf{T}(\hat{\mathbf{w}}, \hat{\mathbf{r}}_\mathbf{f}, \hat{\mathbf{L}}) - \mathbf{F}(\hat{\mathbf{w}}, \hat{\mathbf{r}}_\mathbf{f}, \hat{\mathbf{L}})$$

and the vector of expenditure is

$$\mathbf{Y}' = (\mathbf{\Omega}(\hat{\mathbf{w}}, \hat{\mathbf{r}}_\mathbf{f}, \hat{\mathbf{L}}))^{-1} \mathbf{\Delta}(\hat{\mathbf{w}}, \hat{\mathbf{r}}_\mathbf{f}), \hat{\mathbf{L}} \tag{A.51}$$

With the solution for Y'_{is}, the initial guess is updated using (A.47) to (A.49). Finally, the change in emissions embodied in trade flows is given by:

$$\hat{Z}_{ijs} = \hat{\gamma}_{ijfs} \frac{\hat{X}_{ijs}}{\hat{\kappa}_{ijs}} \tag{A.52}$$

from which I update the carbon price according to (4.1).

Changes in share of exporters and cut-off productivity In the following, I show how to calculate the change in the share of exporters. From the definition of the share of exporters, it directly follows:

$$\hat{n}_{ijs} = \left(\frac{\widehat{\varphi^*_{ijs}}}{\widehat{\varphi^*_{iis}}} \right)^{-\theta_s} \tag{A.53}$$

Hence, the change in the exporter share depends only on changes in the productivity cut-offs:

$$\widehat{\varphi^*_{ijs}} = \hat{\phi}_{ijs}\hat{\tilde{c}}_{ijs} \left(\frac{\widehat{(1+t_{ijs})}\tilde{c}_{ijs}}{\hat{B}_{ijs}} \right)^{1/(\eta_s-1)} \tag{A.54}$$

with

$$\hat{B}_{ijs} = (\hat{P}_{ijs})^{\eta_s-\sigma_s}(\hat{P}_{js})^{\sigma_s-1}\hat{Y}_{js} \tag{A.55}$$

where the changes in the price indices can be calculated as

$$\hat{P}_{ijs} = (\hat{N}_{is})^{\frac{\delta_s}{(1-\sigma_s)}} \left(\hat{\phi}_{ijs}\hat{\tilde{c}}_{is}\right)^{\frac{-\epsilon_s}{(1-\sigma_s)}} \left(\frac{\hat{Y}_{js}}{\widehat{(1+t_{ijs})}\hat{\tilde{c}}_{ijs}} \right)^{\frac{\psi_s\delta_s}{1-\sigma_s}} \left(\hat{P}_{js}\right)^{-\psi_s\delta_s} \tag{A.56}$$

$$\hat{P}_{is} = \left[\sum_{j\in M} \lambda_{jis} N_{js}^{\delta_s} \left(\hat{\phi}_{jis}\hat{\tilde{c}}_{jis}\right)^{-\epsilon_s} \left(\frac{\hat{Y}_{is}}{\widehat{(1+t_{jis})}\hat{\tilde{c}}_{jis}} \right)^{\psi_s\delta_s} \right]^{\frac{-1}{\epsilon_s}} \tag{A.57}$$

A.7 Decomposition of real income changes

The change in nominal income follows directly from the definition of Y_i. In order to derive the change in the price index, recall from (A.5) changes in the domestic expenditure share can be expressed as:

$$\hat{\lambda}_{iis} = \left(\frac{\hat{P}_{iis}}{\hat{P}_{is}} \right)^{1-\sigma_s}$$

Plugging in (A.56) and rearranging yields:

$$\left(\hat{P}_{is}\right)^{(1-\sigma_s)(1+\psi_s\delta_s)} = \hat{\lambda}_{iis}^{-1}(\hat{N}_{is})^{(1-\sigma_s)} \left(\hat{\tilde{c}}_{is}\right)^{-\theta_s\delta_s} \left(\frac{\hat{Y}_{is}}{\hat{\tilde{c}}_{is}} \right)^{\psi_s\delta_s}$$

Now note that:

$$(1+\psi_s\delta_s) = \frac{1-\eta_s+\theta_s+(\eta_s-1)(1+\theta_s\left(\frac{1}{\sigma_s-1}-\frac{1}{\eta_s-1}\right)}{(\eta_s-1)(1+\theta_s\left(\frac{1}{\sigma_s-1}-\frac{1}{\eta_s-1}\right)}$$
$$= \frac{(\eta_s-1)\frac{\theta_s}{\sigma_s-1}}{(\eta_s-1)(1+\theta_s\left(\frac{1}{\sigma_s-1}-\frac{1}{\eta_s-1}\right)}$$
$$= \frac{\epsilon_s}{\sigma_s-1}$$

With this definition, the price index can be expressed as:

$$\hat{P}_{is} = \hat{\lambda}_{iis}^{1/\epsilon_s}(\hat{N}_{is})^{-1/\theta_s}\hat{\tilde{c}}_{is}\left(\frac{\hat{Y}_{is}}{\hat{w}_i}\right)^{-\psi_s/\theta_s} \tag{A.58}$$

Finally, noting that:

$$\varepsilon_s = 1/\theta_s - 1/\theta_s(1-\delta_s) = 1/\theta_s + \delta_s\left(\frac{1}{\sigma_s-1}-\frac{1}{\eta_s-1}\right)$$

the change in the price index due to the change in the domestic expenditure share can be further decomposed:

$$\hat{P}_{is} = \hat{\lambda}_{iis}^{1/\theta_s}(\hat{N}_{is})^{-1/\theta_s}\hat{\tilde{c}}_{is}\hat{\lambda}_{iis}^{\delta_s\left(\frac{1}{\sigma_s-1}-\frac{1}{\eta_s-1}\right)}\left(\frac{\hat{Y}_{is}}{\hat{\tilde{c}}_{is}}\right)^{-\psi_s/\theta_s} \tag{A.59}$$

Hence,

$$d\ln P_{is} = -\frac{1}{\theta_s}d\ln N_{is}+\frac{1}{\theta_s}d\ln\lambda_{iis}+d\ln\tilde{c}_{is}+\delta_s\left(\frac{1}{\sigma_s-1}-\frac{1}{\eta_s-1}\right)d\ln\lambda_{iis}-\frac{\psi_s}{\theta_s}\left(d\ln Y_{is}-d\ln\tilde{c}_{is}\right)$$

Noting that $d\ln P_i = \sum_{s\in S}\alpha_{is}d\ln P_{is}$ leads to (3.42).

B Appendix

Table B.1: List of sectors and parameters

	Sector Name	$1/\theta_s$	ϵ_s	η_s	σ_s	δ_s	ψ_s
1	Agriculture	0.09	8.05	9.11	7.23	0.70	0.42
2	Fossil fuels	0.00	10.89			0.00	0.00
3	Mining	0.09	7.94	9.11	7.23	0.70	0.39
4	Meat processing	0.15	3.20	4.65	3.30	0.49	0.81
5	Vegetable processing	0.15	3.20	4.65	3.30	0.49	0.81
6	Dairy Products	0.15	3.20	4.65	3.30	0.49	0.81
7	Rice proccesing	0.15	3.20	4.65	3.30	0.49	0.81
8	Sugar refining	0.15	3.20	4.65	3.30	0.49	0.81
9	Processing of other food products	0.15	3.20	4.65	3.30	0.49	0.81
10	Manufacture of beverages	0.15	3.20	4.65	3.30	0.49	0.81
11	Manufacture of fish products	0.15	3.20	4.65	3.30	0.49	0.81
12	Manufacture of tobacco products	0.15	3.20	4.65	3.30	0.49	0.81
13	Manufacture of textiles	0.13	3.86	6.79	4.36	0.52	0.29
14	Wearing apparel	0.13	3.86	6.79	4.36	0.52	0.29
15	Leather, footwear, luggage	0.13	3.86	6.79	4.36	0.52	0.29
16	Wood and cork	0.14	4.56	6.49	4.90	0.66	0.26
17	Pulp	0.17	3.18	5.30	3.65	0.54	0.37
18	Paper	0.17	3.18	5.30	3.65	0.54	0.37
19	Publishing, printing	0.17	3.18	5.30	3.65	0.54	0.37
20	Processing of nuclear fuel	0.32	0.71	3.11	1.64	0.23	0.46
21	Plastics, basic	0.07	7.21	6.39	4.97	0.52	1.57
22	Fertilizer	0.07	7.21	6.39	4.97	0.52	1.57
23	Chemicals nec	0.07	7.21	6.39	4.97	0.52	1.57
24	Rubber and plastic products	0.07	6.92	9.54	6.16	0.47	0.73

Table B.1: List of sectors and parameters *(continued)*

	Sector Name	$1/\theta_s$	ϵ_s	η_s	σ_s	δ_s	ψ_s
25	Glass and glass products	0.07	8.63	8.13	6.28	0.58	1.10
26	Ceramic goods	0.07	8.63	8.13	6.28	0.58	1.10
27	Bricks, tiles and construction products	0.07	8.63	8.13	6.28	0.58	1.10
28	Cement, lime and plaster	0.07	8.63	8.13	6.28	0.58	1.10
29	Re-processing of ash into clinker	0.07	8.63	8.13	6.28	0.58	1.10
30	Other non-metallic mineral products	0.07	8.63	8.13	6.28	0.58	1.10
31	Basic iron, steel, ferro-alloys	0.12	3.34	7.39	4.00	0.41	0.27
32	Precious metals	0.12	3.34	7.39	4.00	0.41	0.27
33	Aluminium	0.12	3.34	7.39	4.00	0.41	0.27
34	Lead, zinc, tin	0.12	3.34	7.39	4.00	0.41	0.27
35	Copper	0.12	3.34	7.39	4.00	0.41	0.27
36	Other non-ferrous metals	0.12	3.34	7.39	4.00	0.41	0.27
37	Casting of metals	0.12	3.34	7.39	4.00	0.41	0.27
38	Fabricated metal products	0.12	3.34	7.39	4.00	0.41	0.27
39	Machinery and equipment	0.08	10.06	10.44	8.75	0.77	0.39
40	Office machinery and computers	0.23	1.36	4.28	2.24	0.32	0.30
41	Electrical machinery and apparatus	0.23	1.36	4.28	2.24	0.32	0.30
42	Communication equipment and apparatus	0.23	1.36	4.28	2.24	0.32	0.30
43	Medical, precision and optical instruments	0.23	1.36	4.28	2.24	0.32	0.30
44	Motor vehicles	0.08	1.39	7.16	2.24	0.11	1.12
45	Other transport equipment	0.08	1.39	7.16	2.24	0.11	1.12
46	Furniture; other manufacturing	0.09	7.98	8.64	7.17	0.75	0.39
47	Recycling of waste	0.09	7.98	8.64	7.17	0.75	0.39
48	Energy (non-primary fossil fuels)	0.12	4.74	7.16	4.90	0.55	0.39
49	Construction	0.12	4.74	7.16	4.90	0.55	0.39
50	Retail Wholesale	0.12	4.74	7.16	4.90	0.55	0.39

Table B.1: List of sectors and parameters *(continued)*

	Sector Name	$1/\theta_s$	ϵ_s	η_s	σ_s	δ_s	ψ_s
51	Transportation	0.16	3.93	7.16	4.90	0.63	0.01
52	Other Services	0.13	4.51	7.16	4.90	0.58	0.27

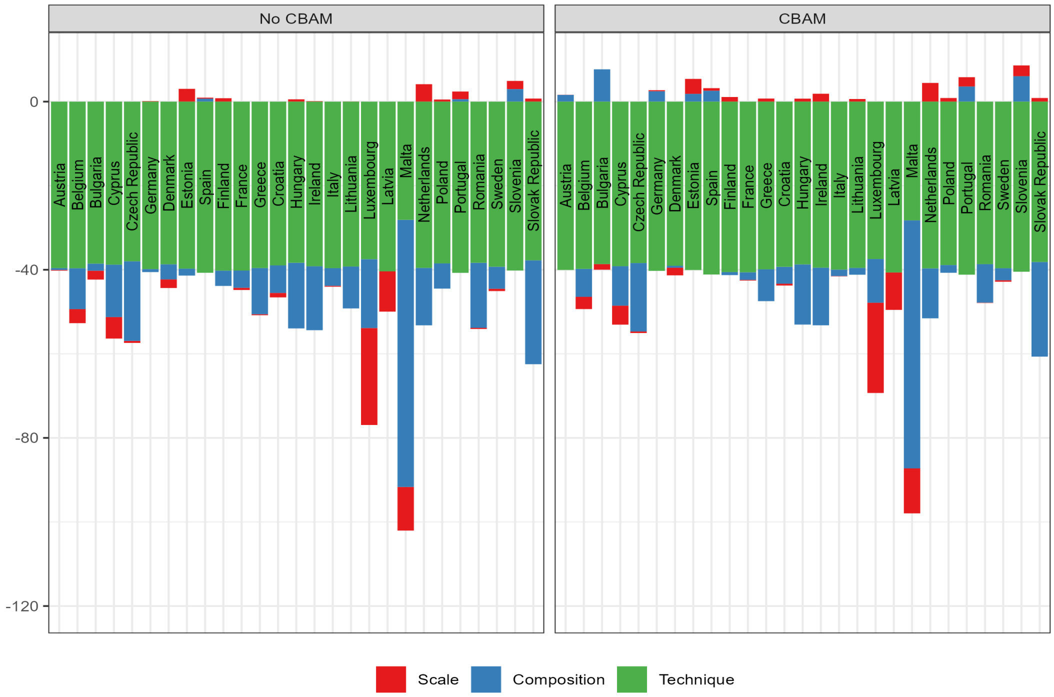

Figure B.1: Decomposition by country for the Fit-for-55 target

Sector	Process		Reallocation	
	No CBAM	CBAM	No CBAM	CBAM
Aluminium	-39.40	-39.66	0.17	0.21
Basic iron, steel, ferro-alloys	-38.86	-39.11	0.19	0.30
Bricks, tiles and construction products	-39.56	-39.81	0.03	0.04
Casting of metals	-39.66	-39.92	0.01	0.01
Cement, lime and plaster	-39.90	-40.15	0.01	0.01
Ceramic goods	-39.15	-39.39	0.17	0.23
Chemicals nec	-38.61	-38.85	0.32	0.99
Copper	-39.77	-40.02	0.01	0.11
Fertilizer	-37.54	-37.78	0.18	0.67
Glass and glass products	-39.79	-40.04	0.09	0.14
Lead, zinc, tin	-39.26	-39.50	0.09	0.14
Other non-ferrous metals	-39.22	-39.47	0.13	0.37
Other non-metallic mineral products	-40.00	-40.25	0.03	0.07
Paper	-40.34	-40.60	-0.04	0.01
Plastics, basic	-39.19	-39.44	0.12	0.13
Precious metals	-39.73	-39.98	0.09	0.19
Processing of nuclear fuel	-37.61	-37.84	-0.41	-0.37
Publishing, printing	-40.30	-40.56	-0.02	-0.01
Pulp	-39.95	-40.20	0.08	0.13
Re-processing of ash into clinker	-40.01	-40.26	0.04	0.04
Rubber and plastic products	-40.10	-40.35	-0.02	0.01

Note: All values in percentage change to baseline. Values shown for the Fit-for-55 target and the baseline CBAM design.

Table B.2: Decomposition of the sector-level emission intensity by ETS sector

	Process	Reallocation
No CBAM	-39.50	0.09
CBAM (all ETS)	-39.75	0.17
CBAM (current)	-39.69	0.12
CBAM (firm)	-39.65	0.19

Note: All values in percentage change to baseline. Values shown for the Fit-for-55 target.

Table B.3: Decomposition of the sector-level emission intensity by CBAM design

	Gross output		Leakage rate		Share in leakage
Sector	No CBAM	CBAM	No CBAM	CBAM	No CBAM
Aluminium	-1.44	3.96	28.97	-67.40	3.33
Basic iron, steel, ferro-alloys	-1.78	2.63	36.17	-25.22	21.92
Bricks, tiles and construction products	-0.01	1.02	6.70	1.07	0.36
Casting of metals	0.39	0.69	10.14	7.68	1.17
Cement, lime and plaster	0.29	2.09	20.90	-12.48	17.63
Ceramic goods	-8.69	-0.59	29.85	-7.72	3.02
Chemicals nec	-22.05	-9.80	114.12	-88.60	34.18
Copper	0.47	1.11	10.37	-0.20	0.43
Fertilizer	-25.82	2.10	111.70	-211.32	4.55
Glass and glass products	-3.31	2.86	15.28	-4.49	1.76
Lead, zinc, tin	-0.71	1.77	15.49	-53.86	0.29
Other non-ferrous metals	-3.70	-0.64	61.69	-2.97	0.69
Other non-metallic mineral products	-2.10	6.40	24.75	-43.29	4.32
Paper	0.98	1.46	10.88	4.10	0.77
Plastics, basic	-1.15	-0.28	9.57	3.13	3.71
Precious metals	-0.21	-0.11	24.45	5.50	0.32
Processing of nuclear fuel	-4.93	-4.99	26.25	12.44	0.10
Publishing, printing	0.65	0.85	3.30	2.74	0.32
Pulp	0.27	0.98	8.49	-4.60	0.48
Re-processing of ash into clinker	0.28	0.61	1.28	1.08	0.28
Rubber and plastic products	1.11	1.30	12.86	9.50	0.39

Note: All values in percentage change to baseline. Values shown for the Fit-for-55 target and the baseline CBAM design.

Table B.4: Gross output changes and leakage by ETS sector

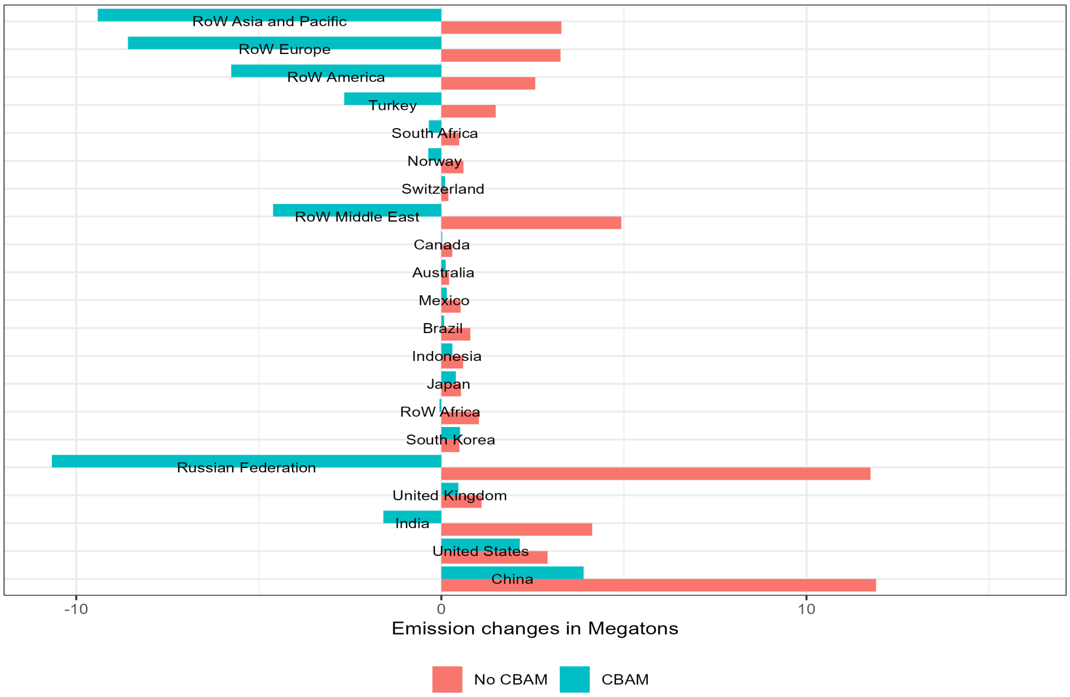

Figure B.2: Emission leakage in ETS industries by country for the Fit-for-55 target

<table>
<tr><th></th><th colspan="3">No CBAM</th><th colspan="3">CBAM</th></tr>
<tr><th>Country</th><th>Real Inc.</th><th>Nominal Inc.</th><th>Price</th><th>Real Inc.</th><th>Nominal Inc.</th><th>Price</th></tr>
<tr><td>Australia</td><td><|0.005|%</td><td>0.61%</td><td>0.61%</td><td><|0.005|%</td><td>0.50%</td><td>0.51%</td></tr>
<tr><td>Brazil</td><td>0.01%</td><td>0.64%</td><td>0.63%</td><td>0.01%</td><td>0.52%</td><td>0.51%</td></tr>
<tr><td>Canada</td><td>0.01%</td><td>0.59%</td><td>0.59%</td><td><|0.005|%</td><td>0.49%</td><td>0.49%</td></tr>
<tr><td>China</td><td>0.01%</td><td>0.57%</td><td>0.57%</td><td><|0.005|%</td><td>0.44%</td><td>0.44%</td></tr>
<tr><td>India</td><td><|0.005|%</td><td>0.57%</td><td>0.57%</td><td><|0.005|%</td><td>0.43%</td><td>0.43%</td></tr>
<tr><td>Indonesia</td><td>0.01%</td><td>0.62%</td><td>0.61%</td><td><|0.005|%</td><td>0.48%</td><td>0.48%</td></tr>
<tr><td>Japan</td><td><|0.005|%</td><td>0.57%</td><td>0.56%</td><td><|0.005|%</td><td>0.46%</td><td>0.46%</td></tr>
<tr><td>Mexico</td><td>0.01%</td><td>0.59%</td><td>0.58%</td><td><|0.005|%</td><td>0.48%</td><td>0.48%</td></tr>
<tr><td>Norway</td><td>-0.12%</td><td>0.60%</td><td>0.72%</td><td>-0.14%</td><td>0.47%</td><td>0.61%</td></tr>
<tr><td>RoW Africa</td><td>0.04%</td><td>0.77%</td><td>0.73%</td><td>0.04%</td><td>0.68%</td><td>0.64%</td></tr>
<tr><td>RoW America</td><td>0.02%</td><td>0.68%</td><td>0.67%</td><td><|0.005|%</td><td>0.48%</td><td>0.48%</td></tr>
<tr><td>RoW Asia and Pacific</td><td>0.03%</td><td>0.67%</td><td>0.63%</td><td>0.04%</td><td>0.56%</td><td>0.52%</td></tr>
<tr><td>RoW Europe</td><td>0.06%</td><td>0.75%</td><td>0.69%</td><td><|0.005|%</td><td>0.36%</td><td>0.37%</td></tr>
<tr><td>RoW Middle East</td><td><|0.005|%</td><td>0.64%</td><td>0.64%</td><td>-0.03%</td><td>0.37%</td><td>0.40%</td></tr>
<tr><td>Russian Federation</td><td>-0.07%</td><td>0.63%</td><td>0.69%</td><td>-0.11%</td><td>0.10%</td><td>0.22%</td></tr>
<tr><td>South Africa</td><td><|0.005|%</td><td>0.55%</td><td>0.55%</td><td>-0.01%</td><td>0.42%</td><td>0.43%</td></tr>
<tr><td>South Korea</td><td>0.01%</td><td>0.54%</td><td>0.53%</td><td>0.01%</td><td>0.45%</td><td>0.44%</td></tr>
<tr><td>Switzerland</td><td>0.02%</td><td>0.64%</td><td>0.62%</td><td>0.02%</td><td>0.72%</td><td>0.70%</td></tr>
<tr><td>Turkey</td><td>0.03%</td><td>0.64%</td><td>0.61%</td><td>0.01%</td><td>0.45%</td><td>0.44%</td></tr>
<tr><td>United Kingdom</td><td>0.02%</td><td>0.56%</td><td>0.54%</td><td>0.01%</td><td>0.50%</td><td>0.49%</td></tr>
<tr><td>United States</td><td><|0.005|%</td><td>0.58%</td><td>0.58%</td><td><|0.005|%</td><td>0.47%</td><td>0.47%</td></tr>
</table>

Note: All values in percentage change to baseline. Values shown for the Fit-for-55 target and the baseline CBAM design.

Table B.5: Real income changes for Non-EU coutnries