The network effects of carbon pricing*

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Abstract

We develop a macroeconomic model to study how carbon pricing initiatives could affect the global economy via international production networks. Using sector- and country-specific data, we estimate the impact of three policies: (i) a global uniform tax; (ii) an EU-only tax; and (iii) an EU-only tax combined with a carbon border adjustment mechanism. Our results show that the distribution of tax-induced socioeconomic losses across sectors and countries critically depends on their relative position within global value chains. Negative impacts triggered by demand shocks in downstream sectors (and propagating upstream) appear to be stronger than that of direct taxation. We also find carbon pricing policies to reconfigure the structure of the international production network, with some countries/sectors becoming more marginal and others more central. Marginalisation on the intermediate input market is salient for countries imposing unilateral carbon policies.

Keywords: low-carbon transition; carbon pricing; production networks; global value chains
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1 Introduction

Macroeconomic costs and competitive drawbacks are prominent obstacles to the introduction of carbon pricing. Emission-intensive industries (electricity, heat, steel, cement, chemicals and others) are typically at the core of most economies, providing precious intermediate inputs to other sectors, and employing a large share of labour world-wide. Large-scale taxation of the emission content of goods and services, although widely advocated by economists, has the potential for creating disruptions that affect economic output and social welfare through passed-forward input price increases and recomposition of value chains (Whalley and Wigle, 1991).

A carbon tax can trigger a loss in competitiveness for both (i) emission-intensive industries, and (ii) industries supplying high-carbon value chains. In the first case, the tax-related price increase directly affects the industry. In the second case, the decline in demand from downstream industries is reducing market opportunities for their suppliers. In both cases, domestic buyers might choose to import relatively less tax-affected products, while the industry loses its exports opportunities as foreign buyers recompose their (final or intermediate) optimal goods and services bundles. The global production network therefore has a twofold effect that might magnify (or mitigate) carbon pricing disruptions: (i) an upstream propagation of demand shocks from emission-intensive industries, and (ii) a recomposition of value chains and final demand. When aggregated at the national level, these industry-specific impacts are prominent in shaping political support for carbon pricing (Carattini et al., 2018, 2017).

This paper studies the distribution of costs of implementing a carbon price across productive sectors and countries. We develop a model with multiple countries producing, exchanging and consuming multiple differentiated goods. We study the impact of three types of carbon pricing policies: (i) a global uniform tax, (ii) an EU-only tax on production, and (iii) an EU-only tax with an additional carbon border adjustment mechanism (CBAM). The change in relative prices reverberates internationally via the global production network and modifies the purchasing choices of both firms (intermediate goods) and households (final goods). We run numerical simulations based on the country- and sector-specific data provided by the World Input-Output Database (WIOD), compute the distribution of output and employment losses, and study the features of the new equilibrium the system reaches.

The main message arising from our numerical results is that the structure of the international production network matters in defining winners and losers from low-carbon transition policies. First, in all the scenarios we consider, the distribution of transition-related losses (output and employment losses) crucially depends on the relative position of countries and sectors within the global production network. Losses appear to be driven more by the indirect economic impacts triggered by an upstream propagation of (downstream) demand shocks than by the direct economic impacts of taxation. We also show how the tax-induced prices modify the configuration of global value chains, with some countries/sectors becoming more marginal and others more central. Losses in competitiveness (or marginalisation) on the intermediate input market appears salient for countries imposing unilateral carbon policies. Carbon tariffs, even though they push towards an emission-based distribution of costs, do not compensate fully for the losses suffered by the country imposing the policy.

Our paper is related to the literature studying the macroeconomic impacts of carbon pricing.[1] Given the limited empirical evidence offered by existing carbon initiatives, a most favoured approach in the literature consists in implementing numerical simulations of carbon pricing schemes, either with computable general equilibrium (CGE) models or input-output (IO) models, leading to mixed and methodologically-driven results.[2] CGE-based contributions (e.g. Goulder et al., 2019; Mckibbin et al., 2018) often develop a single-economy model, either at the national or global level, thereby excluding from the analysis sector- or country-differentiated impacts of carbon pricing. These long-run and equilibrium-based analyses generally find modest adverse effects of carbon pricing on economic output. Conversely, IO-based models (e.g. Hebbink et al., 2018; Choi et al., 2010; Metcalf, 2007) tend to portrait more sizeable economic losses borne by carbon-intensive industries. We are for instance similar in spirit to the work developed by Cahen-Fourot et al. (2021), Espagne et al. (2021) and Godin and Hadji-Lazaro (2020), who investigate the impact of the low-carbon transition, either from the supply- or demand-side, via an IO framework. These analyses are however carried out in a static setting, agnostic about agents' behaviour and recompositions of the industry landscapes, hence with limited relevance for the investigation of medium- to long-run dynamics. The methodology we present in this paper offers a useful middle ground between these two extremes, incorporating flexible adaptive behaviours by firms and households in the form of input substitution and demand adjustment mechanisms, while allowing for sectoral-level disaggregation of carbon pricing impacts. Flexibility in the model also allows us to consider a large array of policy scenarios (different policy schemes implemented by different countries), to keep track of realistic short- to medium-run adjustments of the global production network, and to highlight their direct and indirect (network-related) economic impacts.

Our analysis also speaks to the literature on the competitiveness impacts of carbon pricing. While the perspective of competitive downgrading likely undermines political willingness for pricing carbon at the national level (Aldy, 2017), several policy options are available. Unilateral domestic carbon taxes are generally found to impair competitiveness of carbon-intensive domestic industries through export losses and domestic substitution of carbon-intensive goods (see for instance Aldy and Pizer, 2015; Coxhead et al., 2013). However, the extent to which carbon tariffs - imposing the tax burden on high-emitting and unregulated countries through imports - would achieve desirable

[1] See Timilsina (2018) for an extensive review of the literature.

[2] Most papers estimating empirically the adverse effects of carbon pricing find limited (if any) impacts of existing carbon pricing schemes on aggregate economic output and social welfare (see for instance Metcalf and Stock, 2020; Bernard et al., 2018; Parry and Mylonas, 2017; Meng et al., 2013)

carbon emission abatement while preserving the competitiveness of the implementing country is still unclear (Böhringer et al., 2018, 2016). We propose a direct comparison between several policy schemes, with aims to illustrate the trade-offs faced by countries when designing carbon policies. Among our studied scenarios are two distinct policies - a unilateral tax on domestic emissions and a border tax on imported emissions - implemented at the EU level. Our discussion of the non-trivial impacts the global production network architecture has on winners and losers of large-scale carbon pricing directly contributes to this debate.

Finally, we relate to the limited literature assessing carbon pricing through the prism of the production network literature. To that extent, our paper is most closely connected to the recent work of Sager (2021) and Devulder and Lisack (2020). Although their studies differ from ours in terms of coverage and purpose, both build on a production network framework (in particular from Baqaee and Farhi, 2019) to study an economy with heterogeneous agents and nested production structures with intermediate inputs and labour.[3] Both these contributions also emphasise the contagion and adaptation mechanisms arising from firms and consumers substitution to cleaner goods, which our model also allows for.

The remainder of the paper is structured as follows. Section 2 presents the model. Section 3 explains our data and calibration strategy. Section 4 presents and discusses our numerical results. Section 5 concludes.

2 The model

We consider an economy producing a finite number of goods used for both intermediate and final consumption. Each good is produced by a distinct productive sector $s \in \mathcal{S}$. Each sector exists in a finite number of countries trading among themselves, where countries supplying (final or intermediate) goods are indexed by $i \in \mathcal{C}$, and countries importing goods for final consumption are indexed by $n \in \mathcal{C}$.

In the market for intermediate goods (firms only), we also define a sector-country index for buyers $\omega \in \Omega = \mathcal{S} \times \mathcal{C}$. For ease of notation, we suppress subscripts for representative firms and consumers as buyers. When useful for clarity, subscripts n and ω are displayed in parenthesis.

2.1 Market structure

There is a finite number of producers, denoted by a double $\{s, i\}$ where $s \in \mathcal{S}$ are sectors and $i \in \mathcal{C}$ are (producer) countries (or equivalently in full notation, $\omega \in \Omega$). Each country-sector producer

[3]Sager (2021) studies the distributional impacts of global-scale carbon pricing on consumer welfare, and finds a globally net progressive effect of carbon pricing when revenues are recycled as national carbon dividends. Devulder and Lisack (2020) also investigate the effect of carbon pricing on the global production network, but restrict the scope of the analysis only to its effect on France, and otherwise consider aggregated regions (EU and the rest of the world.

provides a differentiated good in perfect competition, supplying an amount X of intermediate goods to other suppliers and final goods to households.[4] Firms produce goods with a CES combination of factors (labour) and intermediate inputs, the latter being composed of sector-specific nests of goods from other country-sector suppliers. Households in each country inelastically supply sector-specific endowments of labour at wage w.

The technology of a firm ω is defined as

$$X = \left(\alpha_L^{\frac{1}{\xi}} L^{\frac{\xi-1}{\xi}} + \alpha_M^{\frac{1}{\xi}} M^{\frac{\xi-1}{\xi}}\right)^{\frac{\xi}{\xi-1}}, \tag{1}$$

where α_{L} and α_{M} are the respective technology requirement coefficients of labour and intermediate inputs in the production of X quantity of the good ω, and ξ is the elasticity of substitution.[5] The representative firm's intermediate input bundle is jointly defined by a double-nested CES structure such that

$$M = \left(\sum_{s\in S} \alpha_s^{\frac{1}{\theta}} N_s^{\frac{\theta-1}{\theta}}\right)^{\frac{\theta}{\theta-1}} \tag{2}$$

and

$$N_s = \left(\sum_{i\in C} \alpha_{si}^{\frac{1}{\sigma}} f_{si}^{\frac{\sigma-1}{\sigma}}\right)^{\frac{\sigma}{\sigma-1}}, \tag{3}$$

where θ is the elasticity of substitution between sectoral nests, and σ the elasticity of substitution between countries, within a given sectoral nest.

The optimal consumption of intermediate input $\{s, i\}$ by firm ω is given by

$$f_{si} = \alpha_M \alpha_s \alpha_{si} X \left(\frac{P}{P_M}\right)^{\xi} \left(\frac{P_M}{P_{Ns}}\right)^{\theta} \left(\frac{P_{Ns}}{p_{si}}\right)^{\sigma}, \tag{4}$$

where $P = (\alpha_L w^{1-\xi} + \alpha_M P_M^{1-\xi})^{\frac{1}{1-\xi}}$ is the price index of good ω, $P_M = \left(\sum_{s\in\mathcal{S}} \alpha_s P_{Ns}^{1-\theta}\right)^{\frac{1}{1-\theta}}$ is the price index of the combination of sectoral nests used by ω, $P_{Ns} = \left(\sum_{i\in\mathcal{C}} \alpha_{si} p_{si}^{1-\sigma}\right)^{\frac{1}{1-\sigma}}$ is the price index of sectoral nest s, and p_{si} is the price of intermediate good f_{si}.

In addition, the optimal use of labour by firm ω is given by

$$L = \alpha_L X \left(\frac{P}{w}\right)^{\xi}. \tag{5}$$

We can now characterise the market structure of this economy, summarised by the $(\mathcal{S} \times \mathcal{C})^2$ input-output coefficient matrix $\mathbf{A}$, whose elements are the share of expenses that firm ω dedicates

[4] In full notation, the market clearing condition for goods is $X_{si} = \sum_{\omega\in\Omega} f_{si(\omega)} + \sum_{n\in\mathcal{C}} c_{si(n)}$, where $f_{si(\omega)}$ is the intermediate input supplied by firm $\{s, i\}$ and used by firm ω, and $c_{si(n)}$ is the final good supplied by firm $\{s, i\}$ to households in country n. We also impose a zero-profit condition for firms.

[5] Technology requirement coefficients embody the respective values (in *real* terms) of labour or of the input bundle that is used in the production of one US$ of output for firm ω (expressed also in real terms).

to intermediate good from supplier $\{s, i\}$ (over all its expenses) $a_{si} = \frac{p_{si} f_{si}}{PX}$. In addition, the share of labour expenses used in the production process of firm ω constitutes the value-added component κ, such that $\kappa = \frac{wL}{PX}$.[6] As it will be useful for future results, we normalise all baseline prices to one, such that $a_{si(\omega)} = \alpha_{M(\omega)}\alpha_{s(\omega)}\alpha_{si(\omega)}$ are the elements of $\mathbf{A}$ expressed in *real* terms, while the value-added components are given by $\kappa_{(\omega)} = \alpha_{L(\omega)}$.

2.2 Consumption

Each country is populated with a representative household, inelastically supplying labour. A representative household in (consumer) country $n \in \mathcal{C}$ derives utility directly from consuming a bundle of sector-specific nests of goods

$$C = \left(\sum_{s \in \mathcal{S}} \gamma_s^{\frac{1}{\rho}} C_s^{\frac{\rho-1}{\rho}} \right)^{\frac{\rho}{\rho-1}}, \tag{6}$$

where C_s is consumption of the nest of goods from sector s. Each nest is composed of final goods c_{si} purchased at price p_{si} from different countries within a given sector, such that $C_s = \left(\sum_{i \in \mathcal{C}} \gamma_{si}^{\frac{1}{\varepsilon}} c_{si}^{\frac{\varepsilon-1}{\varepsilon}} \right)^{\frac{\varepsilon}{\varepsilon-1}}$. In such a functional form assumption, the elasticity of substitution between sector-specific goods ρ is clearly distinguished from the elasticity of substitution between country-specific goods ε.

Households earn revenues from labour and taxes. Tax revenues collected on carbon emissions are evenly distributed among domestic households in a lump-sum fashion.[7] Households in country n therefore maximise utility subject to the budget constraint $P_C C = w \sum_{s \in \mathcal{S}} L_s + T$, where, P_C is the price index of goods consumed by the representative household and T is the sum of carbon taxes collected in the respective country.

Given the utility, consumption and budget constraint functional form assumptions, the representative household's demand in country n can be expressed as

$$G_{si} = \frac{c_{si}}{C} = \gamma_s \gamma_{si} \left(\frac{P_C}{P_{Cs}} \right)^{\rho} \left(\frac{P_{Cs}}{p_{si}} \right)^{\varepsilon}, \tag{7}$$

where $P_C = \left(\sum_{s \in \mathcal{S}} \gamma_s P_{Cs}^{1-\rho} \right)^{\frac{1}{1-\rho}}$ and $P_{Cs} = \left(\sum_{i \in \mathcal{C}} \gamma_{si} p_{si}^{1-\varepsilon} \right)^{\frac{1}{1-\varepsilon}}$ are the respective price indices of the final bundle of goods and of each sector-specific nest, and p_{si} is the price of final good c_{si}.

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[6] Input-output and value-added components coefficients are often referred to in the literature as d*irect requirement coefficients*. They embody the respective values (in *nominal* terms) of labour and of the input bundle that is used in the production of one US$ of output for firm ω. They differ from the technology requirement coefficients α in that they incorporate all price changes arising from carbon pricing.

[7] Tax revenues are scenario-dependent and explained in details further. Note that the zero-profit condition for firms implies that firms profits do not enter the budget constraint of households.

2.3 Carbon tax and pricing dynamics

2.3.1 Price model

Consider now the introduction of a carbon tax τ on the direct carbon content of goods produced in a given country-sector. Tax revenues are collected by the imposing country. Two distinct policies are to be highlighted in this setting. A *production tax* is a tax $\tau_{si(\omega)}$ (i) faced by *all* countries i' hosting sector-country buyers $\omega = \{s', i'\}$ of goods $\{s, i\}$ (origin-specific), and (ii) whose revenues are collected by country i. On the contrary, a *border tax* is a tax $\tau_{si(\omega)}$ (i) imposed on all goods $\{s, i\}$ by country $i' \neq i$ hosting sector-country buyers $\omega = \{s', i'\}$ and (ii) whose revenues are collected by country i'. In the first case, carbon emissions are taxed when a good is produced (then sold). In the second case, carbon emissions are taxed when a good crosses a border. It is to be noted that only direct emissions are observed by imposing countries, and therefore taxed. Indirect emissions - all emissions that are emitted further up the value chain and implicitly embedded into the total carbon content of a product - are not taxed by the imposing country, although they cumulatively affect the input prices if they were taxed by the respective upstream producers or buyers.

Therefore, the new price p^{new}_{si} of intermediate good f_{si} faced by a buyer ω should reflect (i) the direct price increase resulting from the tax imposed on the direct emissions of sector $\{s, i\}$, and (ii) the indirect price increases resulting from the taxes imposed on the suppliers of $\{s, i\}$, further up the value chain. With initial prices normalised to 1, the $(\mathcal{S} \times \mathcal{C})^2$ matrix $\mathbf{P}^{new}$ of new seller-buyer-specific prices faced by producers in this economy is given by

$$\mathbf{P}^{new} = \mathbf{J} + \hat{\mathbf{d}}\mathbf{T} + ((\mathbf{T} \odot \mathbf{A})\mathbf{L})^T\mathbf{D} \; , \tag{8}$$

where $\mathbf{J}$ is a $(\mathcal{S} \times \mathcal{C})^2$ matrix of ones, $\mathbf{T} = \{\tau_{si(\omega)}\}$ is a $(\mathcal{S} \times \mathcal{C})^2$ matrix of bilateral carbon taxes, $\mathbf{D}$ is a $(\mathcal{S} \times \mathcal{C})^2$ matrix repeating the direct emission intensity vector $\mathbf{d}$ times along the columns, $\hat{\mathbf{d}}$ is a $(\mathcal{S} \times \mathcal{C})^2$ diagonalised matrix of vector $\mathbf{d}$, and the operator $\odot$ is the element-wise (or Hadamard) product of two matrices. Equation (3) implies that, after all taxes have been collected, the new price $p^{new}_{si(\omega)}$ faced by buyer ω for good $\{s, i\}$ can be expressed as $p^{new}_{si(\omega)} = 1 + \delta_{si}\tau_{si(\omega)} + \sum_j \sum_k \tau_{j(k)} a_{j(k)} l_{k(si)} \delta_j$. The term $\delta_{si}\tau_{si(\omega)}$ represents the bilateral tax markup levied on the direct emissions of producer $\{s, i\}$ and faced by ω. The term $\sum_j \sum_k \tau_{j(k)} a_{j(k)} l_{k(si)} \delta_j$ is composed of the successive markups faced by each buyer $k \in (\mathcal{S} \times \mathcal{C})$ for the direct emissions δ_j from intermediate inputs $j \in (\mathcal{S} \times \mathcal{C})$ in the upstream value chain of producer $\{s, i\}$.[8]

It is instructive to focus on a simplified case with two single-industry countries, such that

[8] Recall that, for $\{s, i\} \neq k \in (\mathcal{S} \times \mathcal{C})$, the elements of the transposed Leontief inverse $\mathbf{L}^T$ are given by $l_{k(si)} = a_{k(si)} + \sum_k a_{k(r)} a_{r(si)} + ...$ and represent the weight of supplier $\{s, i\}$ as a buyer of intermediate input k in the economy, and across all value chains.

$(\mathcal{S} \times \mathcal{C}) = \{1, 2\}$. After emissions are taxed, the 2×2 matrix $\mathbf{P}^{new}$ of new prices is of the form

$$\mathbf{P}^{new} = \begin{pmatrix} 1 & 1 \\ 1 & 1 \end{pmatrix} + \begin{pmatrix} \delta_1 & 0 \\ 0 & \delta_2 \end{pmatrix} \cdot \begin{pmatrix} \tau_{1,1} & \tau_{1,2} \\ \tau_{2,1} & \tau_{2,2} \end{pmatrix}$$
$$+ \left\{ \left[\begin{pmatrix} \tau_{1,1} & \tau_{1,2} \\ \tau_{2,1} & \tau_{2,2} \end{pmatrix} \odot \begin{pmatrix} a_{1,1} & a_{1,2} \\ a_{2,1} & a_{2,2} \end{pmatrix} \right] \cdot \begin{pmatrix} l_{1,1} & l_{1,2} \\ l_{2,1} & l_{2,2} \end{pmatrix} \right\}^T \cdot \begin{pmatrix} \delta_1 & \delta_1 \\ \delta_2 & \delta_2 \end{pmatrix}.$$

This implies that the price of good 2 faced by sector 1 is given by

$$p^{new}_{2,1} = 1 + \delta_2\tau_{2,1} + (\tau_{1,1}a_{1,1}l_{1,2} + \tau_{1,2}a_{1,2}l_{2,2})\delta_1 + (\tau_{2,1}a_{2,1}l_{1,2} + \tau_{2,2}a_{2,2}l_{2,2})\delta_2 \ .$$

The term $\delta_2\tau_{2,1}$ accounts for the *direct* emissions embodied in good 2 that are taxed with the tax rate of the direct (and ultimate) buyer sector 1. The middle term $(\tau_{1,1}a_{1,1}l_{1,2}+\tau_{1,2}a_{1,2}l_{2,2})\delta_1$ accounts for the *indirect* emissions of sector 1 embodied in one unit of good 2. A part of those emissions was first (i.e. directly) used - and therefore taxed - by country 1 before flowing into good 2 further downstream $(\tau_{1,1}a_{1,1}l_{1,2}\delta_1)$, and another part was first used (and taxed) by country 2 $(\tau_{1,2}a_{1,2}l_{2,2}\delta_1)$. The last term $(\tau_{2,1}a_{2,1}l_{1,2} + \tau_{2,2}a_{2,2}l_{2,2})\delta_2$ accounts for the *indirect* emissions of sector 2 embodied in one unit of good 2. Again, a part of those was originally taxed by country 1 $(\tau_{2,1}a_{2,1}l_{1,2}\delta_2)$, and another part by country 2 $(\tau_{2,2}a_{2,2}l_{2,2}\delta_2)$.

The 2×2 simplified case also allows for a better understanding of the several taxation policies which will be presented in this paper. First, consider a *border tax* imposed by country 1 on goods from country 2 ($\tau_{1,1} = 0$ and $\tau_{2,1} > 0$), while country 2 does not take policy action ($\tau_{1,2} = 0$ and $\tau_{2,2} = 0$). In such case, the price of goods 2 faced by country 1 becomes

$$p^{new}_{2,1} = 1 + \delta_2\tau_{2,1} + \tau_{2,1}a_{2,1}l_{1,2}\delta_2 \ .$$

As the tax is imposed at the border of country 1 on incoming goods, tax revenues are entirely collected by country 1, such that $T_1 = \delta_2\tau_{2,1}(f_{2,1}+c_{2,1})$. Extrapolating to larger sets of countries and sectors, border tax revenues for country i' are computed as $T_{i'} = \sum_{s,i,s'} \delta_{si}\tau_{si(s'i')}(f_{si(s'i')} + c_{si(i')})$.[9]

Consider next a *production tax* imposed by country 2 on the emissions of its own industries. This is equivalent to country 1 facing a tax on good 2 solely ($\tau_{1,1} = 0$ and $\tau_{2,1} > 0$) and country 2 imposing a tax on its own goods ($\tau_{1,2} = 0$ and $\tau_{2,2} > 0$). The price of good 2 faced by country 1 is therefore given by

$$p^{new}_{2,1} = 1 + \delta_2\tau_{2,1} + (\tau_{2,1}a_{2,1}l_{1,2} + \tau_{2,2}a_{2,2}l_{2,2})\delta_2 \ .$$

However, in this case, all tax revenues are collected by producing country 2, such that $T_2 = \delta_2(\tau_{2,1}(f_{2,1} + c_{2,1}) + \tau_{2,2}(f_{2,2} + c_{2,2}))$. A general expression for production tax revenues of country i is $T_i = \sum_{s,s',i'} \delta_{si}\tau_{si(s'i')}(f_{si(s'i')} + c_{si(i')})$.

[9] Note that in the latter expression, we have that $i' = n$ for harmonisation purposes.

2.3.2 Adjustments to tax-induced price changes

The introduction of carbon price distortions affects the structure of the intermediate goods market. In particular, after all producers simultaneously adjust their price (1-1 after the imposition of the tax and a consequence of prefect competition), the new input-output structure of the economy in *real* terms is defined by $\mathbf{A}^{new}$ with elements

$$a_{si}^{new} = a_{si} \left(\frac{P^{new}}{P_M^{new}} \right)^{\xi} \left(\frac{P_M^{new}}{P_{Ns}^{new}} \right)^{\theta} \left(\frac{P_{Ns}^{new}}{p_{si}^{new}} \right)^{\sigma} \tag{9}$$

for firm ω using intermediate good $\{s, i\}$. Furthermore, the new value-added share in country-sector ω is given by

$$\kappa^{new} = \kappa \left(P^{new} \right)^{\xi}. \tag{10}$$

We can also specify changes in consumption behaviour of households resulting from price changes. Note that Equation (7) is the consumption share (in real terms) of good c_{si} in consumption bundle C of country n. After prices changes, the new consumption share of good c_{si} in the real consumption bundle of country n is given by

$$G_{si}^{new} = \frac{c_{si}^{new}}{C^{new}} = \gamma_s \gamma_{si} \left(\frac{P_C^{new}}{P_{Cs}^{new}} \right)^{\rho} \left(\frac{P_{Cs}^{new}}{p_{si}^{new}} \right)^{\varepsilon}. \tag{11}$$

We obtain C^{new} from updating the budget constraint with new price index P_C^{new} and new income generated from capital ownership $r \sum_s u_s^{new} K_s$ and tax revenues T^{new}.

We can finally characterise the effect of carbon pricing on sector-countries real production. Summing households' demand for final goods $c_{si(n)}$ across importing countries, we to obtain an aggregate global demand value for each country-sector $\hat{c}_{si}^{new} = \sum_{n \in C} c_{si(n)}^{new}$. Using the vector $\mathbf{c}^{new} = \{\hat{c}_{si}^{new}\}$ of global demand for all country-sectors and the new input-output structure $\mathbf{A}^{new}$, the vector of demand-adjusted production level is given by $\mathbf{x}^{new} = (\mathbf{I} - \mathbf{A}^{new})^{-1} \mathbf{c}^{new}$. After the market for intermediate inputs and final goods converge to an equilibrium, we obtain the vector of changes in real production $\Delta \mathbf{x}$, with elements $\Delta X_{(\omega)} = \frac{X_{(\omega)}^{new}}{X_{(\omega)}}$.

We simulate the introduction of each carbon pricing scenario and the movement of the economy to a new equilibrium via an iterative procedure illustrated in figure 1. The equilibrium is approximated numerically, as described in detail in Appendix A.3.

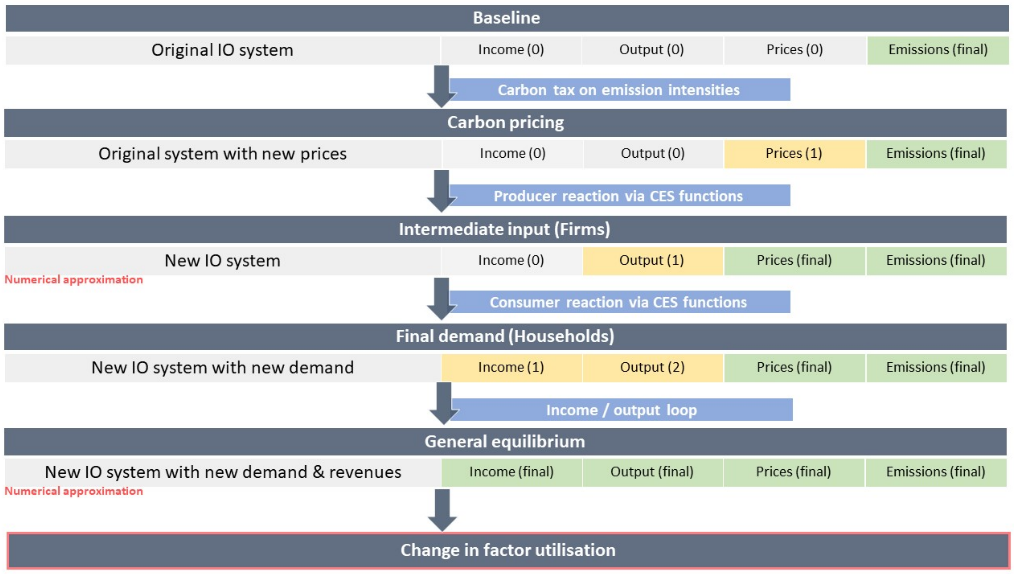

Figure 1: Steps of the modelling procedure

3 Data and calibration

3.1 Data

Our main source of data is the World Input-Output Database (WIOD, Timmer et al., 2015).[10] WIOD is a multi-regional input-output database comprising 44 regions and 56 productive sectors. Table 1 and Table A1 provide a list of all countries and sectors included in the database, respectively.[11] The WIOD tables depict the structure of the world economy, describing the industrial interrelations between the different producing sectors and final consumers. As such, they provide the baseline information for the calibration of technology requirement coefficients (α) on the supply side as well as consumption shares (γ) on the demand side.[12] Data on sectoral carbon emissions (in kilotons) is taken from the WIOD Environmental Accounts and transformed into the vector $\mathbf{d}$ of sectoral emission intensities (in tons per dollar of output). Our model is calibrated to the WIOD tables for the year 2014, the most recent year available in the database.

[10]The WIOD database is available at http://www.wiod.org.

[11]Productive sectors present in WIOD are classified using NACE level 2 categories (Eurostat, 2008) We create new sector codes to make our results easier to understand. The first three upper-case letters of each sector code reflect the NACE level 1 category (e.g. MAN for manufacturing), while the following three lower-case letters reflect the NACE level 2 category (e.g. MANche for manufactured chemical products). When discussing a NACE level 1 sector, or in the case of NACE level 1 sectors for which no further disaggregation is available, we use a + sign at the end of the code, to signify that several sub-activities are included there (e.g. MAN+ is the equivalent of the entire NACE C level 1 sector).

[12]The calibration of the technology requirement coefficients is described in Appendix A.4.

Table 1: WIOD regions

Income group	**Country**
High-income	Australia (AUS); Austria (AUT); Belgium (BEL), Canada (CAN), Switzerland (CHE), Cyprus (CYP), Czechia (CZE), Germany (DEU), Denmark (DNK), Spain (ESP), Estonia (EST), Finland (FIN), France (FRA), Great Britain (GBR), Greece (GRC), Croatia (HRV), Hungary (HUN), Ireland (IRL), Italy (ITA), Japan (JPN), South Korea (KOR), Lithuania (LTU), Luxembourg (LUX), Latvia (LVA), Malta (MLT), Netherlands (NLD), Norway (NOR), Poland (POL), Portugal (PRT), Slovakia (SVK), Slovenia (SVN), Sweden (SWE), Taiwan (TWN), United States of America (USA)
Upper-middle	Bulgaria (BGR), Brazil (BRA), China (CHN), Mexico (MEX), Romania (ROU), Russia (RUS), Turkey (TUR)
Lower-middle	Indonesia (IDN), India (IND)

3.2 Elasticities

We calibrate the model so that numerical simulations picture the short-run impacts of carbon pricing. Two main reasons motivate this choice. First, we view short-run macroeconomic impacts as prominent concerns underlying political support to environmental policies. Second, such a modelling choice allows us to claim that our results approach the lower bound of carbon pricing disruptions. We specify 5 structural parameters in our model, all being symmetric across country-sectors or consumers.[13] With regards to the upper nest of our CES specification, we implement the Leontief limit of the elasticity of substitution between labour L and intermediate inputs M, such that $\xi \to 0$. This reflects the increasing evidence that labour does not easily reallocate across country-sectors in the short run (Acemoglu et al., 2016). For the remaining elasticity parameters, we set $(\theta, \varepsilon, \rho, \sigma) = (0.001, 0.9, 0.9, 0.9)$. Following Baqaee and Farhi (2019), we set the (firm) elasticity of substitution between sector-specific intermediate inputs as $\theta = 0.001$, and the (consumer) elasticity of substitution between the consumption of different sector-specific final goods as $\rho = 0.9$.[14] In line with the short-run trade elasticities of Boehm et al. (2020), we set the firm and consumer elasticity of substitution between country-specific (intermediate and final) goods within each sector-nest as $\varepsilon = \sigma = 0.9$.

[13]This is a strong assumption. However, our purpose here tends more towards illustrating key mechanisms and trends than providing accurate estimates of macroeconomic impacts.

[14]Firms' and consumers' elasticity of substitution between sectoral goods match the estimates of Atalay (2017).

3.3 Carbon tax policy experiments

We investigate three different carbon pricing settings: i) a global uniform production tax covering the emissions of all sectors; ii) a production tax of the same level levied only within the EU and iii) a border tax on EU imports (CBAM: carbon border adjustment mechanism), complementing the tax within the EU as a tool to counteract adverse effects on competitiveness. For all scenarios, we set the price per ton of CO_2 to a conservative value of 40$, representing the lower bound of the range suggested by the High-Level Commission on Carbon Prices (Stiglitz et al., 2017).[15] The global tax scenario covers the direct emissions occurring in the production processes of all sectors in the global economy. Representing an ideal scenario in terms of economic efficiency, the global tax serves as a benchmark for the two EU-specific scenarios. The EU production tax applied in scenario 2 covers all economic sectors within the EU, thus extending the coverage of existing European industrial carbon pricing policies.[16] In scenario 3, a CBAM in the form of an import tax on all goods and services entering the EU is implemented in combination with the production tax of scenario 2. Such policies have been widely proposed in order to balance the negative effect of unilateral taxation on countries' competitiveness and consequently reduce carbon leakage (Monjon and Quirion, 2011; Felbermayr et al., 2020).

In all scenarios, tax revenues are fully reimbursed to consumers in the country where the tax is collected. The production taxes of scenarios 1 and 2 are collected in the countries where the taxed emissions occur, while the border tax is collected in the EU country that imports the respective good.[17] We do not consider emissions that occur at the stage of final consumption, e.g. in the combustion of heating oil in private households.

4 Results

This section presents the results of our numerical simulations. We start by discussing the results in terms of emission reduction and changes in both country/sector output and employment. We then decompose them to understand their drivers, and finally, we study the implications in terms of network structure and global value chains.

[15] We recognise that the true cost of carbon may be well above this value. However, we are mainly interested in the structural patterns of transmission of pricing shocks through the global industrial network. Therefore, we choose a conservative value within the range of currently implemented policies. Future versions of this work will aim to investigate the effects of various price levels.

[16] In absence of data on sector-specific effective tax rates at the global level, the simulated prices are implemented on top of policies already in place (such as the EU ETS or national carbon taxation schemes). Thus, the policies introduced in our scenarios represent an *introduction* of taxes for sectors so far not covered by any carbon price, and an *increase* for those already subject to a tax. In future versions of this work, we aim to take existing policies into account more accurately.

[17] Note that border taxes can lead to different outcomes than production taxes (a) because price increases passed on through the economic system are buyer-seller-specific and (b) because revenues are reimbursed differently. While the border tax needs to be understood as a tariff on embodied direct emissions in goods passing a border, the production tax can be understood both as a price to be paid per unit of emissions or as a proportional tax levied on fossil fuels.

Table 2: Emission reduction (MtCO2)

	GLOBAL		EU		EU+CBAM	
Total change (% of total)	-1459	4.5%	-88	0.27%	-129	0.40%
Largest absolute reductions - countries (% of global)	CHN	29.8%	RUS	22.7%	RUS	22.0%
	ROW	19.2%	DEU	14.4%	CHN	13.0%
	USA	15.9%	POL	9.1%	RoW	11.3%
	IND	11.5%	GBR	5.6%	DEU	9.3%
	RUS	6.4%	CHN	4.5%	POL	6.1%
Largest absolute reductions - sectors (% of global)	PWR	58.2%	PWR+	46.0%	PWR+	45.3%
	MANmin	8.3%	WATwst	22.8%	WATwst	17.0%
	MANmet	7.0%	MANmin	4.0%	MANmin	6.1%
	MIN+	4.2%	TRAair	3.4%	MANmet	5.4%
	MANche	3.2%	MANmet	3.1%	TRAair	3.4%
Largest relative reductions - countries (% of emissions)	LUX	12.4%	LUX	12.5%	LUX	12.1%
	EST	10.0%	EST	9.9%	EST	9.6%
	CHE	10.0%	MLT	9.2%	CHE	8.9%
	MLT	9.7%	CHE	9.0%	MLT	8.8%
	IND	8.2%	HRV	7.7%	HRV	7.5%
Largest relative reductions - sectors (% of emissions)	WATwst	15.0%	WATwst	11.8%	WATwst	11.9%
	AGRfis	6.9%	AGRfis	6.0%	AGRfis	6.0%
	PWR+	5.9%	MANpha	2.4%	MANpha	2.3%
	MIN+	5.1%	COMvid	1.4%	COMvid	1.3%
	MANpla	4.9%	COMpub	1.3%	COMpub	1.2%

4.1 Reduction in CO_2 emissions

The three policy scenarios, unsurprisingly, lead to different outcomes in terms of reduction of CO_2 emissions. Total emission reduction amounts to 1459MtCO_2 (4.5% of total industrial emissions worldwide) when a global uniform tax is introduced, but only to 88MtCO_2 (0.27% of total) when the EU alone applies a tax. Implementing a CBAM in the EU increases emission reduction to 129MtCO_2 (0.40% of total). These results stress the importance of a coordinated climate mitigation policy effort at the international level.

The emission reduction burden is distributed very differently across countries, as shown in Table 2. In the case of a global uniform tax, almost 30% of absolute emission reduction comes from China, followed by the Rest of the World (ROW) aggregate region, the United States, India and Russia. When only the EU implements a tax, most emission reduction takes place in Russia instead. The presence of Russia at the top of this ranking highlights the key role the country plays in providing upstream carbon-intensive inputs to Europe, whose trade is likely to be affected if European firms and consumers adjust their purchase choices following the change in relative prices brought by the tax. Within Europe, the largest emission reductions take place in Germany, Poland and Great Britain. An EU tax together with a CBAM shifts part of the emission reduction burden outside of Europe, with China and ROW rising to the second and third spot of the ranking. When we consider the initial level of emissions and hence their relative reduction within a country, the countries experiencing the largest drops in emissions are mainly European (Luxembourg, Estonia, Switzerland and Malta; all close or higher than 10%), followed by India. Implementing the tax only in the EU, with or without the border tax, generally reduces the relative sectoral drop in emissions but reinforces the concentration of European countries at the top of the ranking.[18]

The sectoral distribution of emission reduction is relatively more stable across scenarios. The electricity and gas sector (PWR+) is always the one where most of the emission reductions take place. The non-metallic mineral manufacturing sector (MANmin) and the basic metal sector (MANmet) also appear in the top 5 sectors ranked by emission reduction across the three policy scenarios. At the global level, the mining (MIN+) and chemical sector also experience significant reductions, while in the EU tax and EU tax+CBAM scenarios the waste and air transport sectors are relatively more important, highlighting their stronger carbon weights within the European economic system. The prominence of the power sector emission reduction is drastically reduced if one looks at the sectoral drop rates. In this case, it is the waste sector that experiences the largest reduction in all scenarios, followed by the fishing sector. In the case of a global tax these two are followed by power, mining and rubber and plastic products; while if the tax is implemented only in the EU, the pharmaceutical, video&sound industry and publishing are more relevant in terms of relative sectoral emission cuts.

4.2 The economic impact of carbon pricing

We now study how the implementation of a carbon price could affect production and employment in sectors and countries. We start by presenting average output loss values for all countries in Figure 2, where they are plotted against the country's average initial emission intensity. We also distinguish between EU and non-EU countries by using different colours.

The first thing that stands out from the simulation is that almost all countries suffer an overall loss of output in all scenarios, except for rare exceptions (Denmark in both the EU and EU+CBAM scenarios; Spain only in the EU+CBAM one). While some less carbon-intensive countries might benefit from the process of input substitution by firms, the general drop in demand following the price increase tends to create negative net effects for all regions (see section 4.3 on drivers of output losses).

However, the distribution of costs is quite different depending on the type of policy implemented. In the case of a global carbon tax, the most affected countries (India, China, Russia) all experience a loss of output close to or higher than 3%. At the other extreme, a number of (mostly European) countries have losses of less than 1% of their output. An evident correlation exists between the

[18] A summary of emission changes in each country, alongside changes in output and employment can be found in Appendix A.5.

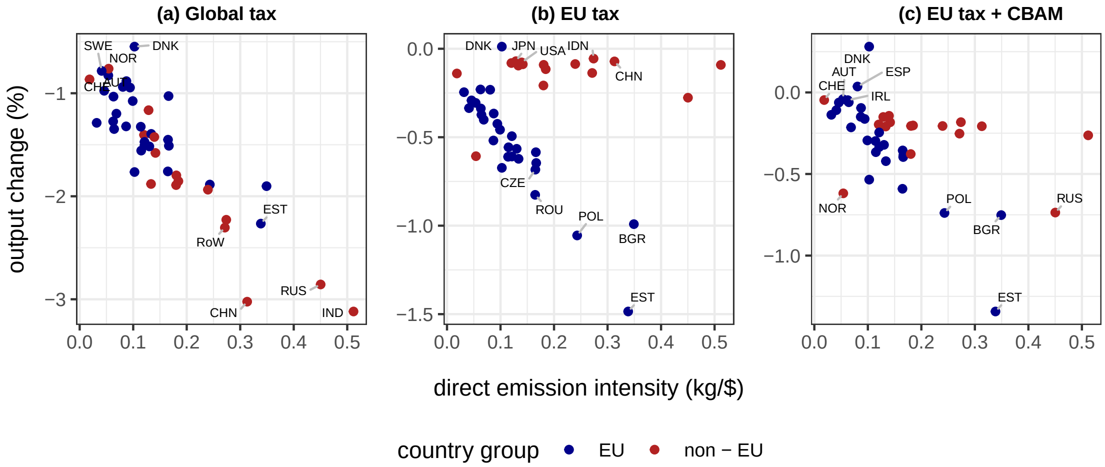

Figure 2: Direct emission intensity and output loss

initial direct emission intensity of a country's economy and the proportional loss of output. At the global level, the loss is approximately equal to \$3 trillion, corresponding to 1.9% of total output.

When the tax is applied only by European Union countries, unsurprisingly, most of the output loss is concentrated among them, especially in Eastern Europe (Estonia, Poland, Bulgaria, Romania and Czechia). Most non-EU countries experience losses smaller than 0.25%. However, the impact on EU countries is smaller than in the global tax case, suggesting that a significant part of EU disruption in that scenario would reach Europe via external supply chains. The loss at the global level is much lower than in the global tax case, averaging 0.16% (approximately \$267 billion).

When a CBAM is added to the EU carbon tax, output losses go back to a more balanced distribution between EU and non-EU countries, although EU ones still tend to be more affected. Russia and Norway, leading exporters of fossil fuels, appear as the ones suffering the largest impact from the CBAM. The correlation between emission intensity and national output losses remain strong also in the EU tax scenarios.

Figure 3 offers a more granular view of the sector-specific impacts for the top 5 most affected countries per scenario. In both India and China the construction sector is the one suffering the most from the introduction of a global tax, followed at a distance by the metal industry. The effect is different in Russia, where mining, wholesale trade and the power sectors are the ones with the largest losses. The power sector is also at the top of the loss ranking for ROW and Estonia. The power sector is always the sector suffering the most also in the top 5 countries affected by an EU-only tax. The ranking partly changes when a CBAM is added, which leads to higher losses for Russia and Norway, from which EU countries import a significant amount of fossil fuels.

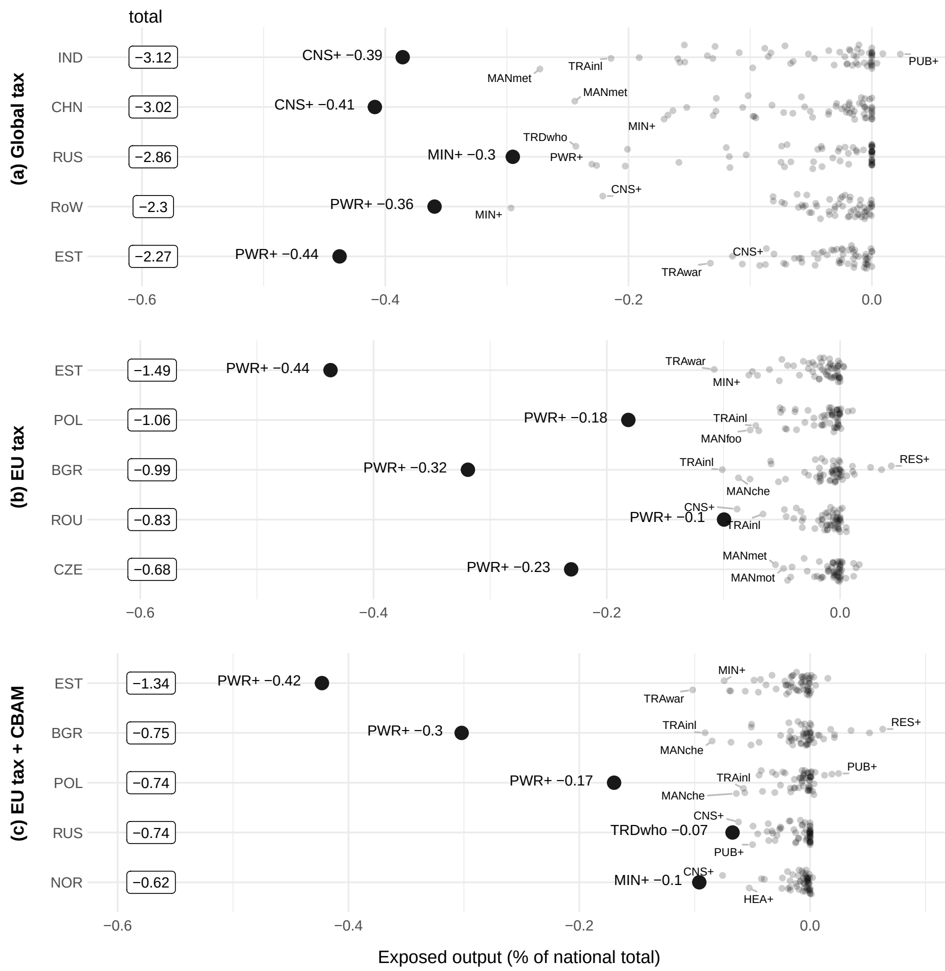

Figure 3: Relative changes in output - Most exposed countries

Finally, we can also report some data concerning the employment that would be at risk following the tax-induced output changes.[19] Employment at risk in the case of a global carbon tax is around 1.9% of the global labour force (47 million people in total). The most affected countries are Russia, China and India, who would all lose more than 2% of their employed workforce. The most affected sectors are power (6.5% loss), followed by mining (4.9%) and non-metallic manufacturing (4.8%). When the tax is implemented only in the EU, the workforce at risk is 2.8 million people (0.11%),

[19]We use employment data (number of employed workers in each country-sector) from the WIOD Socioeconomic Satellite Accounts. Employment at risks corresponds to the percent change in total employed workers resulting from the total change in output.

with Estonia, Poland and Norway the most affected (1%, 0.78% and 0.66%, respectively). Most affected sectors are power (0.49%), refining (0.37%) and waste (0.35%). Finally an EU tax plus a CBAM would put around 5.5 million people at risk of losing their employment (0.22%), with most affected countries Estonia (0.9%), Russia (0.8%) and Norway (0.7%); and most affected sectors power (0.6%), refining (0.4%) and non-metallic products (0.3%).[20]

4.3 Value chain disruptions and network effects

While the results in the previous section have highlighted how a carbon tax implemented at the global or regional level has the potential to create significant disruptions, they do not explain what are the inner drivers of such effects. In this section we disaggregate the determinants of country-level output losses and trade disruptions by distinguishing three main effects: (i) a *direct final demand* effect, caused by the direct change in final demand of a sector due to its tax-induced price increase; (ii) a *downstream final demand* effect, representing the change in intermediate demand for a sector's products triggered by changes in final demand of downstream sectors; and (iii) an *input substitution* effect, driven solely by changes in the relative input composition of downstream producers (i.e. supply-side adjustments of "production recipes"), holding real final demand constant at the original (pre-tax) level. The latter two can be jointly understood as *network* effects: disruptions in the intermediate input market and the position of the country-sector within the global value chain magnify or mitigate the sole effect of direct taxation on the emissions of imported final goods.[21] A sector can have low direct emissions, but it can still be involved in emission-intensive value chains, inducing indirect repercussions that propagate through the production network. Investigating these different effects can shed light on the dimensions of exposure experienced by individual country-sectors. Figure 4 displays the decomposition of (relative) losses in output for the most affected economies in each scenario.[22]

In the global tax scenario, demand effects are preponderant compared to input substitution.[23] With the carbon tax being imposed globally, all prices are affected and the demand effect is negative for all countries. This result stands even though tax revenues are recycled in the form of lump-

[20] A full listing of employment effects in all countries can be found in Appendix A.5.

[21] What we capture with those two effects are essentially network effects originating from *downstream* sectors: the indirect network effects propagating upwards along the value chain and eventually reaching a sector via its inter-sectoral linkages. While the *input substitution* effect is provoked by behavioural reactions on the supply side, the *downstream final demand* effect is a result of final consumer reactions and income changes *in other downstream country-sectors*. It is important to note that there are also *upstream* network effects, i.e. price increases passed on from emissions further upstream in the value chain, but these effects are hard to disentangle in an equilibrium framework and are therefore embodied in all three effects mentioned here.

[22] We compute these three effects along our numerical simulations. Using the usual notation for the Leontief inverse $\mathbf{L} = (\mathbf{I} - \mathbf{A})^{-1}$ and $\mathbf{L}^{new} = (\mathbf{I} - \mathbf{A}^{new})^{-1}$, the input substitution effect is computed as $\mathbf{L}^{new}\mathbf{c} - \mathbf{x} = \mathbf{L}^{new}\mathbf{c} - \mathbf{L}\mathbf{c} = (\mathbf{L}^{new} - \mathbf{L})\mathbf{c}$. The direct final demand effect is computed as $\mathbf{A}^{new}(\mathbf{c}^{new} - \mathbf{c})$ (so that it represents the first-round effect of final demand on production). The downstream effect is computed as $\mathbf{L}^{new} - (\mathbf{c}^{new} - \mathbf{c})\mathbf{A}^{new}(\mathbf{c}^{new} - \mathbf{c})$ (the subsequent rounds of final demand effect in the power series $\mathbf{L}^{new}$).

[23] Demand effects include the direct final demand and the downstream final demand effects.

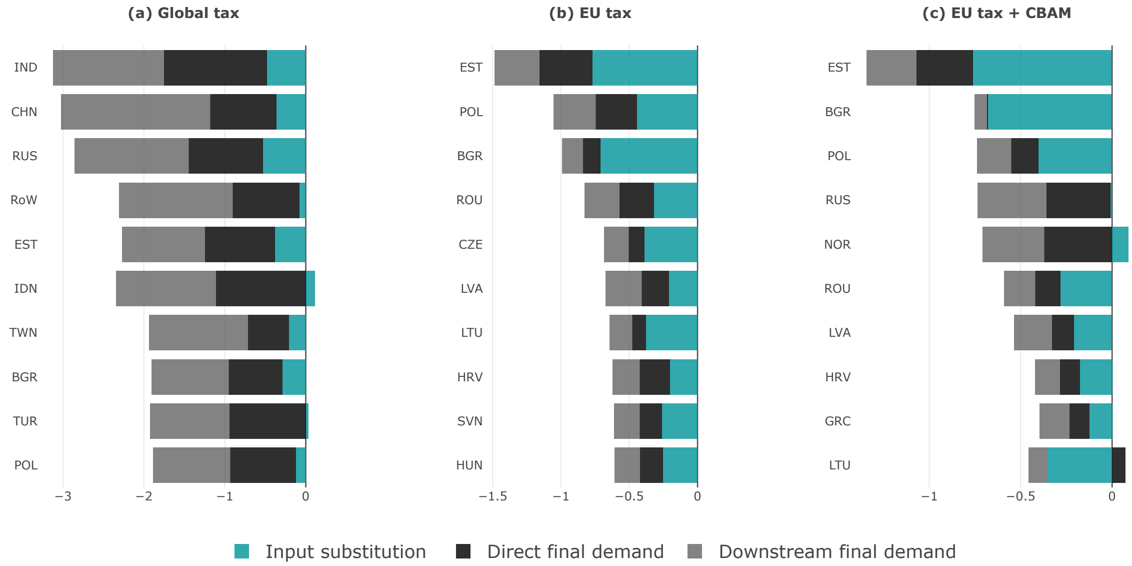

Figure 4: Drivers of output loss - Most exposed countries

sum transfers to domestic consumers. The global negative demand effects therefore indicate that countries that generate the most tax revenues (the heaviest polluters) are not the ones whose consumers contribute the most to shaping demand on the global market. In some cases, input substitution effects are positive (see Indonesia, but also most of the least-affected countries), but they are more than compensated by a drop in demand.

The relative importance of input substitution is stronger in the case of EU-only and EU-CBAM taxes. In fact, when taxation is not implemented globally, the final demand effects (both downstream and direct) are generally dominated by recompositions of the global value chains (the intermediate input market).[24] In the case of an EU tax, global intermediate input trade diverts from the EU to non-EU countries. All EU countries suffer from decreased demand for their intermediate inputs (the average input substitution effect amounts to −0.23% of relative decrease in output across EU countries) while non-EU countries all experience an increase in intermediate input demand (+0.05% on average). The EU tax+CBAM scenario does not substantially correct the losses in competitiveness borne by the EU. Intermediate input originating from the EU are still relatively less used by global trade partners (−0.21% average input substitution effect).

[24]Figures A1, A2 and A3 (displayed in appendix section A.5 for brevity) present a more complete picture of trade disruption on the intermediate input market, by representing changes in the direct requirement coefficients of the input-output matrix **A**. It is immediate to retrieve some of our earlier results: the baseline scenario shows substantially larger trade disruptions than other scenarios, while clearly displaying a "polluters pay" effect. The other EU-centred policy scenarios show results with larger consequences for EU countries in terms of intermediate input trade intensities with main partners.

The results from the previous section nonetheless established that adding a CBAM to the EU carbon tax balances the distribution of output losses. Looking at the determinants at play, we find that the demand effects (both direct and downstream) are the main drivers behind the CBAM correction (relative to the EU-only tax). In fact, in the EU-only tax scenario, the demand effect (combination of direct and downstream) averages to -0.3% of change in relative output for EU countries, relatively larger than those of non-EU countries (-0.19% average). This fact is drastically reversed when a CBAM is added to the policy scheme: the average demand effect of EU countries only amounts to -0.09%, while it reaches -0.3% for non-EU countries. Both the downstream and direct effects are at play here. Part of the correction for non-EU countries is due to the direct final demand effect (taxation on imported goods from non-EU countries due to the CBAM, -0.15% average), given that EU countries are particularly import-oriented. The other part involves the downstream final demand effect. In fact, when a CBAM is introduced, global consumers divert away from non-EU countries, as they produce with relatively more carbon-intensive value chains (-0.15% of average downstream effect for non-EU countries).

We now move to some implications of the previous results. We identified that: (i) for unilateral policy schemes (either production tax or carbon tariffs), the relative importance of the intermediate input market increases; and (ii) the downstream final demand effect is of the same magnitude as the direct final demand effect. These joint *network* effects suggest that the position of a given country within the global value chains matters to understand the macroeconomic impacts of carbon pricing. To investigate further these results, we use two well-known indicators of global value chain positioning, the downstreamness and upstreamness indices.[25] Following Antràs and Chor (2013), we interpret the indices as follows: a high (low) upstreamness index and low (high) downstreamness index indicates a relatively *upstream* (*downstream*) economy, closer to (away from) primary inputs and away from (closer to) final goods. An economy with both high upstreamness and downstreamness indices is positioned deep within long and complex value chains.

In light of these measures, we explore the impact of carbon pricing on the positioning of countries within global value chains. Figure 5 displays the relative change in downstreamness and upstreamness for all economies across our scenarios. Motivated by empirical evidence that participation in complex global value chains generates productivity gains and income growth through long-term firm-to-firm relationships and increased specialisation in specific goods and tasks (surveyed for instance in World Bank, 2020; Gereffi, 2019), we identify *winners* and *losers* from carbon pricing along the value chain positioning dimension. We first observe that each scenario generates countries with drops in both upstreamness and downstreamness indices, indicating a marginalisation from global value chains (these countries are moving towards simpler and shorter value chains), while some others benefit from integration into longer and deeper value chains. Most interestingly - and key for

[25]We compute these indices as in Miller and Temurshoev (2017). They show that these measures are exactly the industries' *total forward linkages* (for the upstreamness index) and *total backward linkages* (for the downstreamness index) which are widely used measures in input-output analysis.

our policy design discussion - the countries affected by such a global value chain marginalisation are different across scenarios. In the baseline global tax, the downstream-upstream changes are driven by the emission intensities. Most highly-emitting countries drop in both indices and move towards shorter value chains, while relatively cleaner countries tend to have a more upstream position (closer to primary inputs) since they have a lesser impact on upstream demand shock propagation - or possibly on downstream price propagation. Conversely, the two EU-centred policy scenarios affect primarily EU countries, which experience a clear relative marginalisation from value chains (all EU countries have negative changes in downstreamness and upstreamness indices).

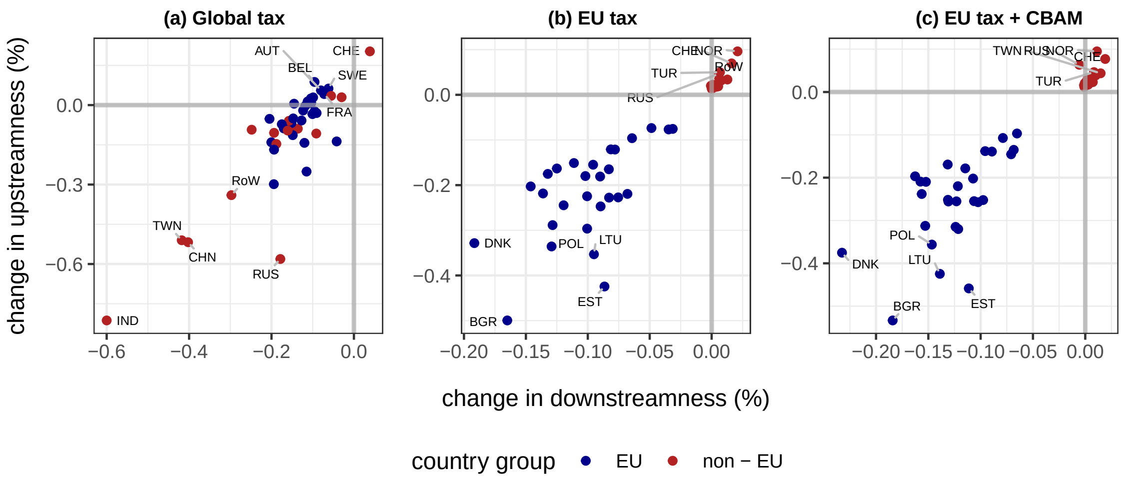

Figure 5: Recomposition of global value chains

5 Conclusions

This paper investigates how the strong interconnectedness of the global economic system and its dependence on fossil-intensive inputs might have significant effects on the structure and composition of the global production network if large-scale mitigation policies were implemented. We develop a novel model through which, following a change in relative prices brought by a tax on direct carbon emissions, we are able to compute its international network repercussions triggered by: (i) the substitution between inputs by firms; and (ii) the readjustment of demand patterns across final products. Using a multi-regional input-output database, we run numerical simulations of the impact of introducing a tax of 40$ per ton of CO_2 (i) at the global level; (ii) at the EU level; (iii) at the EU level, together with a carbon border adjustment mechanism.

Our simulations unsurprisingly show that mitigation policies, while effective in reducing emissions if implemented globally, come at a cost in terms of sectoral output loss and a drop in employment in the short run. In addition to the existing literature on macroeconomic impacts of carbon pricing, we document the fact that the distribution of transition losses across sectors and countries depends not only on their emission intensity, but also on their relative position within global value chains.

Economic consequences of being positioned deep along carbon-intensive value chains often outweigh those of being taxed upon own emissions. Also, the tax-induced price changes modify the configuration of the international production network, with some countries/sectors becoming more marginal and others more central. We find this impact to be mainly driven by demand shocks originating from downstream industries, rather than by the process of input substitution, although for unilateral policy schemes (either production tax or carbon tariffs), the relative importance of the intermediate input market increases. This last finding indicates that, while unilateral policy schemes are detrimental to the competitiveness of the implementing country on the intermediate input market, carbon tariffs tend to reallocate the burden to highly-emitting countries - although still far from a "polluter pays" perspective.

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A Appendix

A.1 Sector codes and descriptions

Table A1: NACE level 2 sectors [26]

NACE	Code	Sector description
A	AGR+	Agriculture, forestry and fishing
A01	AGRagr	Crop and animal production, hunting and related service activities
A02	AGRfor	Forestry and logging
A03	AGRfis	Fishing and aquaculture
B	MIN+	Mining and quarrying
B05-06	MINfos	Mining and extraction of energy producing products
B07-08	MINoth	Mining and quarrying of non-energy producing products
B09	MINsup	Mining support service activities
C	MAN+	Manufacturing
C10-12	MANfoo	Food, beverages and tobacco products
C13-15	MANtex	Textiles, wearing apparel, leather and related products
C16	MANwoo	Wood and products of wood and cork, except furniture
C17	MANpap	Paper and paper products
C18	MANpri	Printing and reproduction of recorded media
C19	MANref	Coke and refined petroleum products
C20	MANche	Chemicals and chemical products
C21	MANpha	Basic pharmaceutical products and pharmaceutical preparations
C22	MANpla	Rubber and plastic products
C23	MANmin	Other non-metallic mineral products
C24	MANmet	Basic metals
C25	MANfmp	Fabricated metal products, except machinery and equipment
C26	MANcom	Computer, electronic and optical products
C27	MANele	Electrical equipment
C28	MANmac	Machinery and equipment n.e.c.
C29	MANmot	Motor vehicles, trailers and semi-trailers
C30	MANtra	Other transport equipment
C31_32	MANfur	Furniture and other manufactured goods
C33	MANrep	Repair and installation services of machinery and equipment
D	PWR+	Electricity, gas, steam and air conditioning
E	WAT+	Water supply; sewerage; waste management and remediation
E36	WATwat	Natural water; water treatment and supply services
E37-39	WATwst	Sewerage services; sewage sludge; waste collection, treatment and disposal services
F	CNS+	Constructions and construction works
G	TRD+	Wholesale and retail trade; repair of motor vehicles and motorcycles
G45	TRDmot	Wholesale and retail trade and repair services of motor vehicles and motorcycles
G46	TRDwho	Wholesale trade, except of motor vehicles and motorcycles

Continued on next page

Table A1: Sector codes and descriptions (continued)

NACE	Code	Sector description
G47	TRDret	Retail trade services, except of motor vehicles and motorcycles
H	TRA+	Transportation and storage
H49	TRAinl	Land transport and transport via pipelines
H50	TRAwat	Water transport
H51	TRAair	Air transport
H52	TRAwar	Warehousing and support activities for transportation
H53	TRApos	Postal and courier activities
I	FD+	Accommodation and food service activities
J	COM+	Information and communication
J58	COMpub	Publishing activities
J59_60	COMvid	Motion picture, video and television production, sound recording, broadcasting
J61	COMtel	Telecommunications
J62_63	COMcom	Computer programming, consultancy; Information service activities
K	FIN+	Financial and insurance activities
K64	FINser	Financial services, except insurance and pension funding
K65	FINins	Insurance, reinsurance and pension funding services, except compulsory social security
K66	FINaux	Activities auxiliary to financial services and insurance services
L	RES+	Real estate activities
M	PRO+	Professional, scientific and technical activities
M69_70	PROleg	Legal and accounting services; Activities of head offices; management consultancy activities
M71	PROeng	Architectural and engineering activities; technical testing and analysis
M72	PROsci	Scientific research and development
M73	PROadv	Advertising and market research
M74_75	PROoth	Other professional, scientific and technical activities; Veterinary activities
N	ADM+	Administrative and support service activities
O	PUB+	Public administration and defence; compulsory social security
P	EDU+	Education
Q	HEA+	Human health and social work activities
R_S	ART+	Arts, entertainment and recreation
U	HOU+	Activities of households as employers

A.2 Proofs of main results

Proof of Equations (4) and (5)

Consider a representative firm ω, with technology

$$X_{(\omega)} = \left(\alpha_{L(\omega)}^{\frac{1}{\xi}} L_{(\omega)}^{\frac{\xi-1}{\xi}} + \alpha_{M(\omega)}^{\frac{1}{\xi}} M_{(\omega)}^{\frac{\xi-1}{\xi}}\right)^{\frac{\xi}{\xi-1}}, \tag{A.1}$$

[26]See Eurostat (2008) for a more detailed description of NACE codes.

maximising profits

$$\pi_\omega = P_{(\omega)} X_{(\omega)} - wL_{(\omega)} - \sum_{s\in\mathcal{S}, i\in\mathcal{C}} p_{si(\omega)} f_{si(\omega)}. \tag{A.2}$$

On the intermediate input market, firm ω minimises costs

$$\min \Gamma_{(\omega)} = \sum_{s\in\mathcal{S}, i\in\mathcal{C}} p_{si(\omega)} f_{si(\omega)}, \tag{A.3}$$

while being subject to the two-level CES technology constraint defined by

$$M_{(\omega)} = \left(\sum_{s\in\mathcal{S}} \alpha_{s(\omega)}^{\frac{1}{\theta}} N_{s(\omega)}^{\frac{\theta-1}{\theta}} \right)^{\frac{\theta}{\theta-1}}, \text{ and } \; N_{s(\omega)} = \left(\sum_{i\in\mathcal{C}} \alpha_{si(\omega)}^{\frac{1}{\sigma}} f_{si(\omega)}^{\frac{\sigma-1}{\sigma}} \right)^{\frac{\sigma}{\sigma-1}}. \tag{A.4}$$

The first order conditions of firm ω with respect to the intermediate input bundle, to sectoral nests and intermediate inputs are given by

$$M_{(\omega)} = \alpha_{M(\omega)} X_{(\omega)} P_{(\omega)}^{\xi} P_{M(\omega)}^{1-\xi}, \tag{A.5}$$

$$N_{s(\omega)} = \alpha_{s(\omega)} \alpha_{M(\omega)}^{\frac{\theta}{\xi}} X_{(\omega)}^{\frac{\theta}{\xi}} M_{(\omega)}^{1-\frac{\theta}{\xi}} P_{M(\omega)}^{\theta} P_{Ns(\omega)}^{-\theta}, \tag{A.6}$$

and

$$f_{si(\omega)} = \alpha_{si(\omega)} \alpha_{s(\omega)}^{\frac{\sigma}{\theta}} \alpha_{M(\omega)}^{\frac{\sigma}{\xi}} X_{(\omega)}^{\frac{\sigma}{\xi}} M_{(\omega)}^{\frac{\sigma}{\theta}-\frac{\sigma}{\xi}} N_{s(\omega)}^{1-\frac{\sigma}{\theta}} P_{(\omega)}^{\sigma} p_{si(\omega)}^{-\sigma}, \tag{A.7}$$

where $P_{(\omega)}$, $P_{M(\omega)}$ and $P_{Ns(\omega)}$ are price indices defined as

$$P_{(\omega)} = \left(\alpha_{L(\omega)} w^{1-\xi} + \alpha_{M(\omega)} P_{M(\omega)}^{1-\xi} \right)^{\frac{1}{1-\xi}}, \tag{A.8}$$

$$P_{M(\omega)} = \left(\sum_{s\in\mathcal{S}} \alpha_{s(\omega)} P_{Ns(\omega)}^{1-\theta} \right)^{\frac{1}{1-\theta}}, \tag{A.9}$$

and

$$P_{Ns(\omega)} = \left(\sum_{i\in\mathcal{C}} \alpha_{si(\omega)} p_{si(\omega)}^{1-\sigma} \right)^{\frac{1}{1-\sigma}}. \tag{A.10}$$

Combining the first-order conditions (A.5), (A.6), and (A.7) gives Equation (4):

$$f_{si(\omega)} = \alpha_{M(\omega)} \alpha_{s(\omega)} \alpha_{si(\omega)} X_{(\omega)} \left(\frac{P_{(\omega)}}{P_{M(\omega)}} \right)^{\xi} \left(\frac{P_{M(\omega)}}{P_{Ns(\omega)}} \right)^{\theta} \left(\frac{P_{Ns(\omega)}}{p_{si(\omega)}} \right)^{\sigma}.$$

From the maximisation problem detailed above, taking the first order condition with respect to $L_{(\omega)}$ directly gives Equation (5):

$$L_{(\omega)} = \alpha_{L(\omega)} X_{(\omega)} \left(\frac{P_{(\omega)}}{w_{(\omega)}} \right)^{\xi} .$$

Proof of Equation (7)
Consider a representative household in country $n \in \mathcal{C}$, deriving utility from a consumption bundle $C_{(n)}$ defined jointly by

$$C_{(n)} = \left(\sum_{s \in \mathcal{S}} \gamma_{s(n)}^{\frac{1}{\rho}} C_{s(n)}^{\frac{\rho-1}{\rho}} \right)^{\frac{\rho}{\rho-1}} , \text{ and } C_{s(n)} = \left(\sum_{i \in \mathcal{C}} \gamma_{si(n)}^{\frac{1}{\varepsilon}} c_{si(n)}^{\frac{\varepsilon-1}{\varepsilon}} \right)^{\frac{\varepsilon}{\varepsilon-1}} . \tag{A.11}$$

Households' revenues are composed of labour revenues, with labour $L_{(n)}$ being supplied inelastically to home firms at a wage $w_{(n)}$, and of tax revenues collected on home firms' carbon emission and redistributed to households in a lump-sum fashion. It follows that households maximise utility

$$U_{(n)} = C_{(n)} , \tag{A.12}$$

subject to budget constraint

$$P_{C(n)} C_{(n)} = w \sum_{s} L_{s(n)} + T_{(n)} . \tag{A.13}$$

Setting up the Lagrangian (with Lagrange multiplier $\mu_{(n)}$) and taking the first order conditions with respect to consumption $C_{(n)}$, final good nests $C_{s(n)}$ and sector-specific final goods $c_{si(n)}$ imply

$$\mu_{(n)} = P_{C(n)}^{-1} , \tag{A.14}$$

$$C_{s(n)} = C_{(n)} \gamma_{s(n)} P_{Cs(n)}^{-\rho} \mu_{(n)}^{-\rho} , \tag{A.15}$$

and

$$c_{si(n)} = \gamma_{si(n)} \gamma_{s(n)}^{\frac{\varepsilon}{\rho}} C_{s(n)}^{1-\frac{\varepsilon}{\rho}} C_{(n)}^{\frac{\varepsilon}{\rho}} p_{si(n)}^{-\varepsilon} \mu_{(n)}^{-\varepsilon} , \tag{A.16}$$

where price indices are defined by

$$P_{C(n)} = \left(\sum_{s \in \mathcal{S}} \gamma_{s(n)} P_{Cs(n)}^{1-\rho} \right)^{\frac{1}{1-\rho}} , \tag{A.17}$$

and

$$P_{Cs(n)} = \left(\sum_{i \in \mathcal{C}} \gamma_{si(n)} p_{si(n)}^{1-\varepsilon} \right)^{\frac{1}{1-\varepsilon}} . \tag{A.18}$$

Combining optimality conditions (A.14), (A.15) and (A.16) gives Equation (7):

$$G_{si(n)} = \frac{c_{si(n)}}{C_{s(n)}} = \gamma_{si(n)}\gamma_{s(n)} \left(\frac{P_{C(n)}}{P_{Cs(n)}}\right)^{\rho} \left(\frac{P_{Cs(n)}}{p_{si(n)}}\right)^{\varepsilon}.$$

Note that Equation (7) allows for substitution between sectoral goods. Strict complementarity in consumption of sectoral goods ($\rho = 0$) implies $G_{si(n)} = \gamma_{si(n)}\gamma_{s(n)} \left(\frac{P_{Cs(n)}}{p_{si(n)}}\right)^{\varepsilon}$.

Proof of Equations (9) and (10)

For a representative firm ω, the share of the value of input $\{s, i\}$ over all expenses is

$$a_{si(\omega)} = \frac{p_{si(\omega)} f_{si(\omega)}}{P_{(\omega)} X_{(\omega)}} = \alpha_{M(\omega)}\alpha_{s(\omega)}\alpha_{si(\omega)} P_{(\omega)}^{\xi-1} P_{M(\omega)}^{\theta-\xi} P_{Ns(\omega)}^{\sigma-\theta} p_{si(\omega)}^{1-\sigma}, \tag{A.19}$$

while the value-added component is given by

$$\kappa_{(\omega)} = \frac{w_{(\omega)} L_{(\omega)}}{P_{(\omega)} X_{(\omega)}} = \alpha_{L(\omega)} P_{(\omega)}^{\xi-1} w_{(\omega)}^{1-\xi}. \tag{A.20}$$

The $(\mathcal{S} \times \mathcal{C})^2$ matrix of origin-destination specific new prices induced by carbon taxes is given by

$$\mathbf{P}^{new} = \mathbf{J} + \hat{\mathbf{d}}\mathbf{T} + ((\mathbf{T} \odot \mathbf{A})\mathbf{L})^T \mathbf{D} \; . \tag{A.21}$$

After price changes, the new market structure in *nominal terms*, denoted jointly by $\tilde{a}_{si(\omega)}^{new}$ and $\tilde{\kappa}_{(\omega)}^{new}$, is given by updating (A.18) and (A.19) with new prices and price indices. We further seek to express the new input-output architecture as a function of intermediate input price changes, but keeping the variable in *real terms*. To do so, we deflate both the numerator and denominator of $\tilde{a}_{si(\omega)}^{new}$ and $\tilde{\kappa}_{(\omega)}^{new}$ by their respective prices. That is, we deflate (i) the value-added coefficient by the price of good ω and wages, and (ii) the intermediate input coefficient by the new input price and the price of good ω. We obtain:

$$a_{si(\omega)}^{new} = \tilde{a}_{si(\omega)}^{new} \frac{P_{(\omega)}^{new}}{p_{si(\omega)}^{new}} = a_{si(\omega)} \left(\frac{P_{(\omega)}^{new}}{P_{M(\omega)}^{new}}\right)^{\xi} \left(\frac{P_{M(\omega)}^{new}}{P_{Ns(\omega)}^{new}}\right)^{\theta} \left(\frac{P_{Ns(\omega)}^{new}}{p_{si(\omega)}^{new}}\right)^{\sigma}, \tag{A.22}$$

and

$$\kappa_{(\omega)}^{new} = \tilde{\kappa}_{(\omega)}^{new} \frac{P_{(\omega)}^{new}}{w_{(\omega)}} = \kappa_{(\omega)} \left(P_{(\omega)}^{new}\right)^{\xi}, \tag{A.23}$$

where we used the fact that all factor and input prices are normalised to one in the baseline equilibrium, and that wages are constant.

A.3 Carbon pricing equilibrium

A.3.1 Definition

An equilibrium in the model is jointly defined by:

- a set of quantities

$$\{X_{(\omega)}\}_{\omega\in(\mathcal{S}\times\mathcal{C})}\ ,\quad \{L_{(\omega)}\}_{\omega\in(\mathcal{S}\times\mathcal{C})}\ ,\quad \{\{c_{\omega(n)}\}_{\omega\in(\mathcal{S}\times\mathcal{C})}\}_{n\in\mathcal{C}}\ ,\quad \{f_{si(\omega)}\}_{\{s,i\},\omega\in(\mathcal{S}\times\mathcal{C})}\ ,$$

- and a set of prices

$$\{P_{(\omega)}, P_{M(\omega)}\}_{\omega\in(\mathcal{S}\times\mathcal{C})},\ \{p_{si(\omega)}\}_{\{s,i\},\omega\in(\mathcal{S}\times\mathcal{C})},\ \{\{p_{\omega(n)}\}_{\omega\in(\mathcal{S}\times\mathcal{C})}\}_{n\in\mathcal{C}},$$

$$\{\{P_{Ns(\omega)}\}_{\omega\in(\mathcal{S}\times\mathcal{C})}\}_{s\in\mathcal{S}},\ \{\{P_{Cs(n)}\}_{s\in\mathcal{S}}\}_{n\in\mathcal{C}},\ \{\{P_{C(n)}\}_{n\in\mathcal{C}},$$

such that:

- *(Cost minimization)* For each $\omega\in\mathcal{S}\times\mathcal{C}$, firms minimize input costs (A.3) subject to the technology constraints (A.4) given a matrix of destination-origin specific price p, while L satisfy (A.1), maximising profits (A.2),
- *(Consumer maximisation)* For each $n\in\mathcal{C}$, households maximise utility (A.12), given the budget constraint (A.13) and a matrix of destination-origin specific prices p,
- *(Carbon pricing)* The set of origin-destination specific prices is given by (A.21).

For completeness, we specify the functional form of the new equilibrium reached after the introduction of new prices. We explicit hereafter the numerical procedure implemented to approximate this new equilibrium.

Given a set of direct emission intensities $\{\delta_{si}\}$, carbon taxes $\{\tau_{si(\omega)}\}$, new destination-origin specific prices $\{p_{si(\omega)}\}$, and initial technology and consumption requirements $\{\alpha_s, \alpha_{si}, \alpha_L, \gamma_s, \gamma_{si}\}$, the new equilibrium is jointly defined by

$$\mathbf{P}^{new} = \mathbf{J} + \hat{\mathbf{d}}\mathbf{T} + ((\mathbf{T}\odot\mathbf{A})\mathbf{L})^T\mathbf{D}\ . \tag{A.24}$$

$$a^{new}_{si(\omega)} = a_{si(\omega)}\left(\frac{P^{new}_{(\omega)}}{P^{new}_{M(\omega)}}\right)^{\xi}\left(\frac{P^{new}_{M(\omega)}}{P^{new}_{Ns(\omega)}}\right)^{\theta}\left(\frac{P^{new}_{Ns(\omega)}}{p^{new}_{si(\omega)}}\right)^{\sigma}, \tag{A.25}$$

$$\kappa^{new}_{(\omega)} = \tilde{\kappa}^{new}_{(\omega)}\frac{P^{new}_{(\omega)}}{w_{(\omega)}} = \kappa_{(\omega)}\left(P^{new}_{(\omega)}\right)^{\xi}, \tag{A.26}$$

$$\frac{c_{si(n)}^{new}}{C_{s(n)}^{new}} = \gamma_{si(n)}\gamma_{s(n)} \left(\frac{P_{C(n)}^{new}}{P_{Cs(n)}^{new}}\right)^{\rho} \left(\frac{P_{Cs(n)}^{new}}{p_{si(n)}^{new}}\right)^{\varepsilon}, \tag{A.27}$$

$$P_{C(n)}^{new} C_{(n)}^{new} = w \sum_{s} L_{s(n)}^{new} + T_{(n)}^{new}, \tag{A.28}$$

$$\mathbf{x}^{new} = (\mathbf{I} - \mathbf{A}^{new})^{-1} \mathbf{c}^{new}. \tag{A.29}$$

A.3.2 Numerical approximation

1. The new supply-side production structure is determined as sectors react to changing input prices and adapt the composition of their input bundle as captured by the technical coefficient matrix $\mathbf{A}^{new}$.

2. Households change the composition of their consumption bundle $C_{(n)}^{new}$.

3. Once the composition of intermediate input and final consumption bundles are defined, the market is cleared and a new general equilibrium state is approximated.

The numerical solution for each step is described below in detail. Step 1 and 3 are based on an iterative process that approximates the equilibrium and stops once a convergence criterion is fulfilled. To ease the notation, we consider a process with T iterations, were $t = 1, ..., T$ indicates an iteration.

Step 1: Supply-side production structure

The sub-equilibrium of the supply-side production structure is defined jointly by the technical coefficient matrix $\mathbf{A}^{new}$ with elements $a_{si(\omega)}^{new} = a_{si(\omega)} \left(\frac{P_{M(\omega)}^{new}}{P_{Ns(\omega)}^{new}}\right)^{\theta} \left(\frac{P_{Ns(\omega)}^{new}}{p_{si(\omega)}^{new}}\right)^{\sigma_s}$ and the matrix $\mathbf{P}^{new}$ with origin-destination specific prices $p_{si(\omega)}^{new} = 1 + \delta_{si}\tau_{si(\omega)} + \sum_j \sum_k \tau_{j(k)} a_{j(k)}^{new} l_{k(si)}^{new} \delta_j$. In equilibrium, producers do not change their input structure any more and prices remain at a given level. Numerically, this state is approximated with the following steps:[27]

1. The introduction of carbon prices in the global production system defined by a system of origin-destination specific carbon tax rates $\mathbf{T} = \{\tau_{si(\omega)}\}$ yields in combination with direct emission intensities δ_{si} and the baseline input output structure $\mathbf{A}$ an initial price change $p_{si(\omega)}^{new_1} = 1 + \delta_{si}\tau_{si(\omega)} + \sum_j \sum_k \tau_{j(k)} a_{j(k)} l_{k(si)} \delta_j$.

2. These price changes determine an initial adjustment of the input output structure according to $a_{si(\omega)}^{new_1} = a_{si(\omega)} \left(\frac{P_{M(\omega)}^{new_1}}{P_{Ns(\omega)}^{new_1}}\right)^{\theta} \left(\frac{P_{Ns(\omega)}^{new_1}}{p_{si(\omega)}^{new_1}}\right)^{\sigma_s}$.

3. In the second iteration, the adjusted technical input structure $\mathbf{A}^{new_1}$ in turn yields an updated price structure p^{new_2}.

[27] This procedure is similar to the one described in Sager (2021)

4. Subsequently, producers again adjust their input bundle according to price changes relative to the previous iteration, yielding updated input coefficients given by

$$a^{new_2}_{si(\omega)} = a^{new_1}_{si(\omega)} \left(\frac{P^{new_2}_{M(\omega)}/P^{new_1}_{M(\omega)}}{P^{new_2}_{Ns(\omega)}/P^{new_1}_{Ns(\omega)}}\right)^{\theta} \left(\frac{P^{new_2}_{Ns(\omega)}/P^{new_1}_{Ns(\omega)}}{p^{new_2}_{si(\omega)}/p^{new_1}_{si(\omega)}}\right)^{\sigma_s}.$$

5. Steps 2-3 are then repeated until additional changes from iteration t to $t+1$ become sufficiently small. As a convergence criterion, we use the 1-norm of coefficient differences between one iteration and the next, defined as $\sum_s \sum_i \sum_\omega |\frac{a^{new_{t+1}}_{si(\omega)} - a^{new_t}_{si(\omega)}}{a^{new_t}_{si(\omega)}}|$. Typically, this state is reached after less then ten iterations.

Step 2: Demand-side consumption structure

Once the new input output structure has reached an equilibrium, prices do not change anymore due to the assumptions of perfect competition and constant returns to scale. Taking these prices as given, consumers change the composition of their consumption bundle according to their CES preferences described in section 2.2. Accordingly, new expenditure shares are given by

$$G^{new}_{si(n)} = \frac{c^{new}_{si(n)}}{C^{new}_{(n)}} = \gamma_{s(n)}\gamma_{si(n)} \left(\frac{P^{new}_{C(n)}}{P^{new}_{Cs(n)}}\right)^{\rho} \left(\frac{P^{new}_{Cs(n)}}{p^{new}_{si(n)}}\right)^{\varepsilon}. \tag{A.30}$$

This determines the expenditure shares of good $\{s, i\}$ within the consumption bundle $C_{(n)}$ of households n. To determine absolute expenditure levels, national income levels are required, which in turn depend on sectoral production and the reimbursement of carbon pricing revenues. This final step is obtained in via the general equilibrium closure.

Step 3: General equilibrium

The model is closed by market clearing condition $X_{si} = \sum_\omega f_{si(\omega)} + \sum_{n\in\mathcal{C}} c_{si(n)}$, which can be denoted in matrix notation as $\mathbf{x} = \mathbf{Ax} + \mathbf{c} = (\mathbf{I} - \mathbf{A})^{-1}\mathbf{c}$, and the budget constraint $P_{C(n)}C_{(n)} = r_{(n)} \sum_s u_{s(n)}K_{s(n)} + w_{(n)} \sum_s L_{s(n)} + \Pi_{(n)} + T_{(n)}$ [define this as a function of X, as all variable on the RHS are functions of X], which can also be denoted as [TBA in matrix notation]. In equilibrium, both equations hold simultaneously. To approximate this state, we again use an iterative numerical procedure of the following steps:

1. We start the procedure by computing the new vector $\mathbf{c^{new_1}}$ of world demand for each sector-country, (i) resulting only from price changes, and (ii) keeping original national income as a baseline. The vector $\mathbf{c^{new_1}}$ has elements $\hat{c}^{new_1}_{si} = \sum_{n\in C} c^{new_1}_{si(n)}$ where $c^{new_1}_{si(n)} = G^{new}_{si(n)} C^{new_1}_{(n)}$. The new real consumption $C^{new_1}_{(n)}$ is computed with original national income as a baseline. That is, we take $P_{C(n)}C_{(n)} = P^{new}_{C(n)} C^{new_1}_{(n)}$ where $P_{C(n)}C_{(n)}$ is the original national expenditure of

country n in WIOD, and $P^{new}_{C(n)}$ is the price index of consumers after price changes, as in A.14 and A.15.

2. Plugging the updated global final demand vector $\mathbf{c}^{new_1}$ into the new input-output structure yields an updated total output vector $\mathbf{x}^{new_1} = (\mathbf{I} - \mathbf{A}^{new})^{-1}\mathbf{c}^{new_1}$.

3. From $\mathbf{x}^{new_1}$, derive updated national real income $C^{new_2}_{(n)}$ and apply expenditure shares $G^{new}_{si(n)}$ to obtain updated real final demand $c^{new_2}_{si(n)}$, and the corresponding world vector $\mathbf{c^{new_2}}$.

4. Repeat steps 2-3 until changes in total output from iteration t to $t+1$ become negligible, as defined by the 1-norm of the relative output changes $\sum_s \sum_i |\frac{X^{new_{t+1}}_{si} - X^{new_t}_{si}}{X^{new_t}_{si}}|$.

A.4 Calibration of technology requirement coefficients.

If the $\Omega \times \Omega$ matrix $\mathbf{Z}$ denotes the monetary exchanges of intermediate inputs $z_{si(\omega)}$ between selling (row) sectors si and buying (column) sectors ω, and $\bar{\mathbf{x}}$ is the $1 \times \Omega$ vector of total output by sector then the technology requirement coefficient for the intermediate input bundle in the CES production function are given by

$$\alpha_{M(\omega)} = \frac{\sum_{s,i} z_{si(\omega)}}{\bar{x}_{(\omega)}} \qquad \alpha_{s(\omega)} = \frac{\sum_i z_{si(\omega)}}{\sum_{s,i} z_{si(\omega)}} \qquad \alpha_{si(\omega)} = \frac{z_{si(\omega)}}{\sum_i z_{si(\omega)}} \; .$$

These technology requirement coefficients can also be interpreted as the respective cost shares under uniform and normalised (to 1) input prices. The technology requirement coefficient for primary inputs (the counterpart of the intermediate input bundle M in the top level of the CES function) is derived using sectoral value-added data from the WIOD. As labour is the only primary input in our model, value-added can be understood as nominal labour compensation. Denoting the $\Omega \times 1$ vector of sectoral value-added by $\mathbf{l}$, the corresponding technology requirement coefficient is given by

$$\alpha_{L(\omega)} = \frac{l_{(\omega)}}{\bar{x}_{(\omega)}} \; .$$

Equivalently, if the matrix $\Omega \times \mathcal{C}$ matrix $\mathbf{Y}$ denotes the purchases $y_{si(n)}$ of goods from sector si by consumers in country n, then the baseline consumption shares (representing consumer taste under uniform prices), are defined as

$$\gamma_{s(n)} = \frac{\sum_i y_{si(n)}}{\sum_{s,i} y_{si(n)}} \qquad \gamma_{si(n)} = \frac{y_{si(n)}}{\sum_i y_{si(n)}} \; .$$

A.5 Summary results

Table A2: Change in main variables per country

Country	**Emissions** - megatons (% of total)			**Output** - billion USD (% of total)			**Employment** - thousands of heads (% of toal)		
	Global tax	EU tax	EU tax + CBAM	Global tax	EU tax	EU tax + CBAM	Global tax	EU tax	EU tax + CBAM
AUS	-16.5 (-4.5%)	-0.2 (-0.1%)	-0.6 (-0.2%)	-51.5268 (-1.9%)	-2.6092 (-0.1%)	-5.7234 (-0.2%)	-200 (-1.8%)	0 (-0.1%)	0 (-0.2%)
AUT	-0.5 (-1.1%)	-0.5 (-1.1%)	-0.3 (-0.7%)	-6.7247 (-0.8%)	-2.4878 (-0.3%)	-0.336 (0%)	0 (-0.8%)	0 (-0.2%)	0 (0.1%)
BEL	-1 (-1.5%)	-0.9 (-1.3%)	-0.7 (-0.9%)	-15.045 (-1.4%)	-4.1656 (-0.4%)	-0.6713 (-0.1%)	-100 (-1.3%)	0 (-0.2%)	0 (0.2%)
BGR	-2.9 (-6.8%)	-2.7 (-6.3%)	-2.5 (-5.9%)	-2.3489 (-1.9%)	-1.2243 (-1%)	-0.9287 (-0.8%)	-100 (-1.5%)	0 (-0.5%)	0 (-0.3%)
BRA	-11.4 (-2.3%)	-0.1 (0%)	-0.9 (-0.2%)	-57.718 (-1.4%)	-3.3196 (-0.1%)	-8.0745 (-0.2%)	-1400 (-1.3%)	-100 (-0.1%)	-200 (-0.2%)
CAN	-13.1 (-2.8%)	-0.2 (0%)	-0.7 (-0.1%)	-52.0323 (-1.6%)	-2.8962 (-0.1%)	-6.0309 (-0.2%)	-300 (-1.4%)	0 (-0.1%)	0 (-0.2%)
CHE	-0.3 (-1%)	0 (0%)	0 (0%)	-12.1808 (-0.9%)	-1.9676 (-0.1%)	-0.6565 (0%)	0 (-1%)	0 (-0.2%)	0 (-0.1%)
CHN	-435.6 (-4.4%)	-5.4 (0%)	-20.7 (-0.2%)	-960.7147 (-3%)	-22.7239 (-0.1%)	-65.8156 (-0.2%)	-20100 (-2.3%)	-700 (-0.1%)	-1900 (-0.2%)
CYP	-0.3 (-6.2%)	-0.3 (-5.7%)	-0.3 (-5.5%)	-0.6328 (-1.5%)	-0.236 (-0.6%)	-0.1342 (-0.3%)	0 (-1.4%)	0 (-0.4%)	0 (-0.1%)
CZE	-3.7 (-4.5%)	-3.5 (-4.3%)	-3.1 (-3.8%)	-7.2 (-1.4%)	-3.39 (-0.7%)	-1.7647 (-0.4%)	-100 (-1.2%)	0 (-0.3%)	0 (0%)
DEU	-18.1 (-2.7%)	-17 (-2.5%)	-14.7 (-2.2%)	-67.918 (-0.9%)	-30.498 (-0.4%)	-11.6783 (-0.2%)	-400 (-0.8%)	-100 (-0.2%)	0 (0%)
DNK	-1.2 (-1.9%)	-1.3 (-2.1%)	-1.2 (-2%)	-3.3883 (-0.6%)	0.0749 (0%)	1.739 (0.3%)	0 (-0.3%)	0 (0.4%)	0 (0.7%)
ESP	-3.5 (-1.7%)	-2.5 (-1.2%)	-2 (-1%)	-24.144 (-0.9%)	-5.9597 (-0.2%)	0.9332 (0%)	-100 (-0.8%)	0 (0%)	0 (0.2%)
EST	-1.9 (-10%)	-1.9 (-9.9%)	-1.8 (-9.6%)	-1.2455 (-2.3%)	-0.8164 (-1.5%)	-0.7382 (-1.3%)	0 (-1.9%)	0 (-1%)	0 (-0.9%)
FIN	-0.6 (-1.4%)	-0.6 (-1.3%)	-0.4 (-1%)	-4.5445 (-0.9%)	-1.8863 (-0.4%)	-0.4905 (-0.1%)	0 (-0.8%)	0 (-0.2%)	0 (0.1%)
FRA	-2.5 (-1.1%)	-1.8 (-0.8%)	-1.2 (-0.5%)	-49.1228 (-1%)	-14.6928 (-0.3%)	-3.1165 (-0.1%)	-300 (-1%)	-100 (-0.2%)	0 (0%)
GBR	-8.3 (-2.3%)	-6.6 (-1.8%)	-5.9 (-1.6%)	-63.5079 (-1.2%)	-21.2616 (-0.4%)	-11.3464 (-0.2%)	-300 (-1.1%)	-100 (-0.3%)	0 (-0.1%)
GRC	-4.9 (-7.7%)	-4.9 (-7.6%)	-4.6 (-7.2%)	-3.9758 (-1%)	-2.2634 (-0.6%)	-1.5326 (-0.4%)	0 (-0.8%)	0 (-0.3%)	0 (-0.1%)
HRV	-1.1 (-8.1%)	-1 (-7.7%)	-1 (-7.5%)	-1.3736 (-1.4%)	-0.6128 (-0.6%)	-0.4149 (-0.4%)	0 (-1.4%)	0 (-0.6%)	0 (-0.4%)
HUN	-0.8 (-2.4%)	-0.7 (-2%)	-0.6 (-1.6%)	-4.3028 (-1.5%)	-1.7422 (-0.6%)	-0.9572 (-0.3%)	-100 (-1.4%)	0 (-0.4%)	0 (-0.1%)
IDN	-26.5 (-5.6%)	-0.2 (0%)	-0.8 (-0.2%)	-38.2313 (-2.2%)	-0.955 (-0.1%)	-3.1262 (-0.2%)	-2800 (-1.6%)	-100 (-0.1%)	-300 (-0.2%)
IND	-165.2 (-8.1%)	-1.4 (-0.1%)	-5.6 (-0.3%)	-124.4084 (-3.1%)	-3.6422 (-0.1%)	-10.4942 (-0.3%)	-14100 (-2.1%)	-600 (-0.1%)	-1800 (-0.3%)
IRL	-0.8 (-2.5%)	-0.6 (-1.9%)	-0.5 (-1.6%)	-6.5955 (-1.3%)	-1.1916 (-0.2%)	-0.2451 (0%)	0 (-1.3%)	0 (-0.1%)	0 (0.2%)
ITA	-4.2 (-1.6%)	-3.1 (-1.2%)	-2.2 (-0.9%)	-42.3689 (-1%)	-13.8502 (-0.3%)	-2.265 (-0.1%)	-200 (-0.9%)	0 (-0.2%)	0 (0.1%)
JPN	-30.9 (-2.8%)	-0.4 (0%)	-1.4 (-0.1%)	-101.4857 (-1.2%)	-6.1169 (-0.1%)	-13.1134 (-0.1%)	-600 (-1%)	0 (-0.1%)	-100 (-0.2%)
KOR	-20.4 (-3.3%)	-0.2 (0%)	-1 (-0.2%)	-61.4688 (-1.8%)	-3.1118 (-0.1%)	-7.0233 (-0.2%)	-400 (-1.6%)	0 (-0.1%)	-100 (-0.2%)
LTU	-0.5 (-3.5%)	-0.5 (-3.1%)	-0.4 (-2.9%)	-1.375 (-1.5%)	-0.588 (-0.7%)	-0.3489 (-0.4%)	0 (-1.2%)	0 (-0.3%)	0 (0%)
LUX	-0.8 (-12.4%)	-0.8 (-12.5%)	-0.8 (-12.1%)	-2.7412 (-1.3%)	-0.5227 (-0.2%)	-0.2923 (-0.1%)	0 (-1.3%)	0 (-0.2%)	0 (0.1%)
LVA	-0.2 (-2.3%)	-0.1 (-1.5%)	-0.1 (-1.4%)	-1.1648 (-1.8%)	-0.4443 (-0.7%)	-0.3528 (-0.5%)	0 (-1.7%)	0 (-0.5%)	0 (-0.4%)
MEX	-15.2 (-3.8%)	-0.3 (-0.1%)	-0.7 (-0.2%)	-40.0923 (-1.9%)	-2.4995 (-0.1%)	-4.382 (-0.2%)	-700 (-1.7%)	0 (-0.1%)	-100 (-0.2%)
MLT	-0.3 (-9.8%)	-0.3 (-9.2%)	-0.3 (-8.8%)	-0.4605 (-1.6%)	-0.1647 (-0.6%)	-0.1083 (-0.4%)	0 (-1.5%)	0 (-0.4%)	0 (-0.2%)
NLD	-3.7 (-2.5%)	-3.5 (-2.4%)	-2.9 (-2%)	-22.1983 (-1.3%)	-8.7119 (-0.5%)	-2.5124 (-0.1%)	-100 (-1.2%)	0 (-0.3%)	0 (0.1%)
NOR	-0.4 (-0.8%)	-0.2 (-0.3%)	-0.2 (-0.4%)	-6.5092 (-0.8%)	-5.1922 (-0.6%)	-5.2887 (-0.6%)	0 (-0.7%)	0 (-0.7%)	0 (-0.7%)
POL	-12.5 (-4.6%)	-10.7 (-4%)	-9.7 (-3.6%)	-20.9461 (-1.9%)	-11.7184 (-1.1%)	-8.2059 (-0.7%)	-300 (-1.7%)	-100 (-0.8%)	-100 (-0.4%)
PRT	-0.8 (-2%)	-0.7 (-1.6%)	-0.6 (-1.4%)	-4.4723 (-1.1%)	-1.9034 (-0.5%)	-1.2234 (-0.3%)	0 (-1%)	0 (-0.3%)	0 (-0.2%)
ROU	-1.9 (-2.8%)	-1.4 (-2.1%)	-1.2 (-1.8%)	-7.025 (-1.8%)	-3.2979 (-0.8%)	-2.3591 (-0.6%)	-100 (-1.6%)	0 (-0.6%)	0 (-0.4%)
RUS	-69.4 (-4.6%)	-2.9 (-0.2%)	-11.1 (-0.7%)	-96.7577 (-2.9%)	-9.3725 (-0.3%)	-24.9434 (-0.7%)	-1800 (-2.4%)	-200 (-0.3%)	-600 (-0.8%)
SVK	-0.8 (-2.7%)	-0.6 (-2.1%)	-0.5 (-1.8%)	-3.4492 (-1.5%)	-1.1575 (-0.5%)	-0.5746 (-0.2%)	0 (-1.2%)	0 (-0.2%)	0 (0.1%)
SVN	-0.4 (-3.3%)	-0.4 (-3.4%)	-0.3 (-2.8%)	-1.3333 (-1.3%)	-0.6145 (-0.6%)	-0.2998 (-0.3%)	0 (-1.3%)	0 (-0.5%)	0 (-0.1%)
SWE	-0.4 (-1.1%)	-0.5 (-1.2%)	-0.4 (-0.9%)	-8.0166 (-0.8%)	-3.4347 (-0.3%)	-1.1111 (-0.1%)	0 (-0.8%)	0 (-0.3%)	0 (0%)
TUR	-13.8 (-5.1%)	-0.1 (0%)	-1.4 (-0.5%)	-28.429 (-1.9%)	-3.1206 (-0.2%)	-5.6759 (-0.4%)	-600 (-1.7%)	-100 (-0.2%)	-100 (-0.4%)
TWN	-20.7 (-7%)	0 (0%)	-0.5 (-0.2%)	-23.7719 (-1.9%)	-1.0607 (-0.1%)	-2.5262 (-0.2%)	-300 (-1.4%)	0 (-0.1%)	0 (-0.2%)
USA	-231.8 (-5.3%)	-2.1 (0%)	-5.8 (-0.1%)	-443.5298 (-1.4%)	-24.0451 (-0.1%)	-44.574 (-0.1%)	-2000 (-1.3%)	-100 (-0.1%)	-200 (-0.1%)
RoW	-280.5 (-4%)	-5.2 (-0.1%)	-17.9 (-0.3%)	-592.6588 (-2.3%)	-35.1941 (-0.1%)	-64.9584 (-0.2%)	0 (0%)	0 (0%)	0 (0%)

Table A3: Decomposition of output effect by country (in % of total output).
sub = subsitution, direct = direct final demand, downstr = downstream final demand

Country	Global tax				EU tax				EU tax + CBAM			
	sub	direct	downstr	total	sub	downstr	indirect	total	sub	direct	downstr	total
AUS	0.17	-0.89	-1.17	-1.88	0.03	-0.06	-0.07	-0.10	0.03	-0.11	-0.13	-0.21
AUT	0.31	-0.45	-0.69	-0.83	-0.07	-0.09	-0.15	-0.31	-0.03	0.05	-0.06	-0.04
BEL	0.26	-0.69	-0.91	-1.35	-0.15	-0.08	-0.15	-0.37	-0.14	0.12	-0.04	-0.06
BGR	-0.29	-0.66	-0.95	-1.90	-0.71	-0.13	-0.15	-0.99	-0.68	-0.00	-0.07	-0.75
BRA	0.10	-0.75	-0.76	-1.40	0.03	-0.06	-0.06	-0.08	0.02	-0.12	-0.10	-0.20
CAN	0.02	-0.74	-0.86	-1.58	0.03	-0.06	-0.06	-0.09	0.03	-0.11	-0.10	-0.18
CHE	0.47	-0.55	-0.78	-0.87	0.11	-0.12	-0.13	-0.14	0.13	-0.08	-0.10	-0.05
CHN	-0.36	-0.82	-1.84	-3.02	0.03	-0.03	-0.07	-0.07	0.03	-0.08	-0.16	-0.21
CYP	0.15	-0.85	-0.82	-1.52	-0.16	-0.21	-0.20	-0.57	-0.13	-0.06	-0.13	-0.32
CZE	0.01	-0.57	-0.89	-1.45	-0.39	-0.12	-0.18	-0.68	-0.34	0.03	-0.05	-0.36
DEU	0.27	-0.50	-0.72	-0.94	-0.13	-0.13	-0.16	-0.42	-0.10	0.01	-0.08	-0.16
DNK	0.23	-0.23	-0.54	-0.55	-0.19	0.20	0.00	0.01	-0.17	0.36	0.08	0.28
ESP	0.15	-0.46	-0.62	-0.94	-0.13	-0.00	-0.10	-0.23	-0.11	0.15	-0.00	0.04
EST	-0.38	-0.86	-1.02	-2.27	-0.77	-0.39	-0.33	-1.49	-0.76	-0.31	-0.27	-1.34
FIN	0.23	-0.42	-0.68	-0.88	-0.20	-0.05	-0.11	-0.37	-0.17	0.09	-0.02	-0.10
FRA	0.20	-0.56	-0.62	-0.98	-0.06	-0.11	-0.13	-0.29	-0.03	0.02	-0.05	-0.06
GBR	0.13	-0.63	-0.70	-1.20	-0.10	-0.14	-0.16	-0.40	-0.08	-0.04	-0.09	-0.21
GRC	0.23	-0.58	-0.67	-1.03	-0.15	-0.23	-0.21	-0.58	-0.12	-0.11	-0.16	-0.40
HRV	0.17	-0.75	-0.82	-1.39	-0.20	-0.22	-0.20	-0.62	-0.18	-0.11	-0.14	-0.42
HUN	0.08	-0.76	-0.83	-1.50	-0.25	-0.17	-0.19	-0.61	-0.22	-0.02	-0.09	-0.33
IDN	0.11	-1.11	-1.23	-2.23	0.03	-0.04	-0.05	-0.06	0.03	-0.10	-0.11	-0.18
IND	-0.48	-1.27	-1.37	-3.12	0.03	-0.06	-0.06	-0.09	0.02	-0.15	-0.13	-0.26
IRL	0.17	-0.65	-0.79	-1.27	-0.07	-0.06	-0.10	-0.23	-0.07	0.07	-0.05	-0.05
ITA	0.21	-0.53	-0.71	-1.03	-0.09	-0.09	-0.16	-0.34	-0.06	0.06	-0.06	-0.06
JPN	0.12	-0.58	-0.70	-1.16	0.03	-0.05	-0.05	-0.07	0.03	-0.09	-0.09	-0.15
KOR	0.08	-0.68	-1.19	-1.80	0.05	-0.05	-0.09	-0.09	0.05	-0.10	-0.15	-0.21
LTU	0.04	-0.69	-0.85	-1.51	-0.38	-0.10	-0.17	-0.65	-0.36	0.07	-0.10	-0.38
LUX	0.14	-0.37	-1.06	-1.29	-0.07	-0.04	-0.14	-0.25	-0.09	0.04	-0.09	-0.14
LVA	0.11	-0.80	-1.08	-1.76	-0.21	-0.20	-0.27	-0.67	-0.21	-0.12	-0.21	-0.53
MEX	0.03	-1.09	-0.79	-1.85	0.02	-0.08	-0.06	-0.12	0.02	-0.14	-0.09	-0.20
MLT	-0.09	-0.66	-0.81	-1.56	-0.25	-0.13	-0.18	-0.56	-0.24	-0.02	-0.10	-0.37
NLD	0.23	-0.57	-0.98	-1.32	-0.22	-0.07	-0.23	-0.52	-0.17	0.13	-0.11	-0.15
NOR	0.48	-0.41	-0.83	-0.76	0.09	-0.36	-0.34	-0.61	0.09	-0.37	-0.34	-0.62
POL	-0.12	-0.81	-0.95	-1.89	-0.44	-0.30	-0.31	-1.06	-0.40	-0.15	-0.19	-0.74
PRT	0.17	-0.54	-0.71	-1.08	-0.15	-0.12	-0.18	-0.46	-0.12	-0.04	-0.13	-0.29
ROU	-0.00	-0.81	-0.94	-1.76	-0.32	-0.25	-0.26	-0.83	-0.28	-0.14	-0.17	-0.59
RUS	-0.53	-0.91	-1.41	-2.86	0.08	-0.15	-0.21	-0.28	-0.01	-0.35	-0.38	-0.74
SVK	-0.01	-0.64	-0.83	-1.47	-0.28	-0.06	-0.15	-0.49	-0.25	0.06	-0.05	-0.25
SVN	0.15	-0.64	-0.83	-1.32	-0.26	-0.16	-0.19	-0.61	-0.22	0.00	-0.08	-0.30
SWE	0.33	-0.45	-0.67	-0.78	-0.05	-0.13	-0.15	-0.34	-0.02	-0.01	-0.08	-0.11
TUR	0.03	-0.94	-0.98	-1.89	0.06	-0.14	-0.13	-0.21	0.04	-0.23	-0.19	-0.38
TWN	-0.21	-0.51	-1.22	-1.94	0.06	-0.05	-0.09	-0.09	0.05	-0.11	-0.15	-0.21
USA	0.09	-0.84	-0.68	-1.42	0.02	-0.05	-0.05	-0.08	0.02	-0.09	-0.07	-0.14
RoW	-0.08	-0.82	-1.40	-2.30	0.06	-0.08	-0.12	-0.14	0.04	-0.13	-0.17	-0.25

A.6 Input substitution effects - Heatmaps

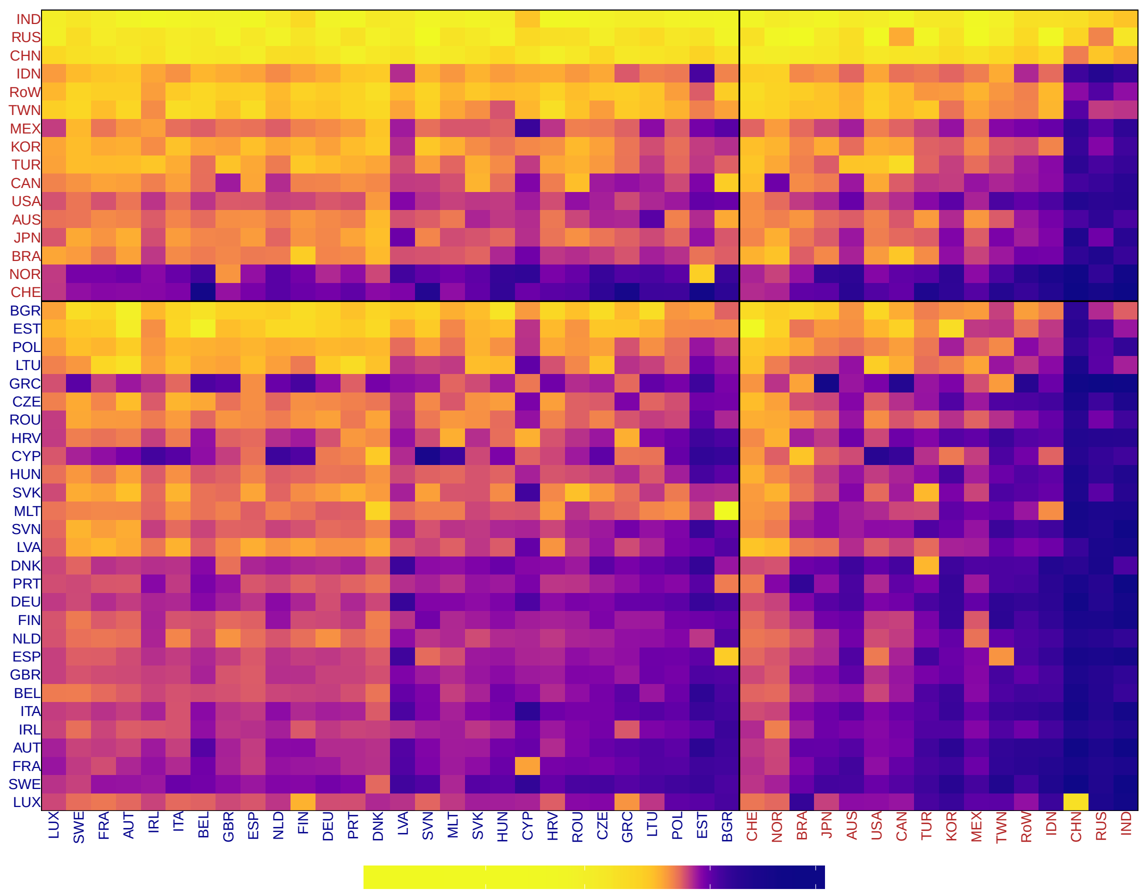

Figure A1: Percent change in direct requirement coefficients (Global tax). Rows are supplying countries, columns are buying countries. Countries are separated by EU membership, then ordered by emission intensity (bottom to top).

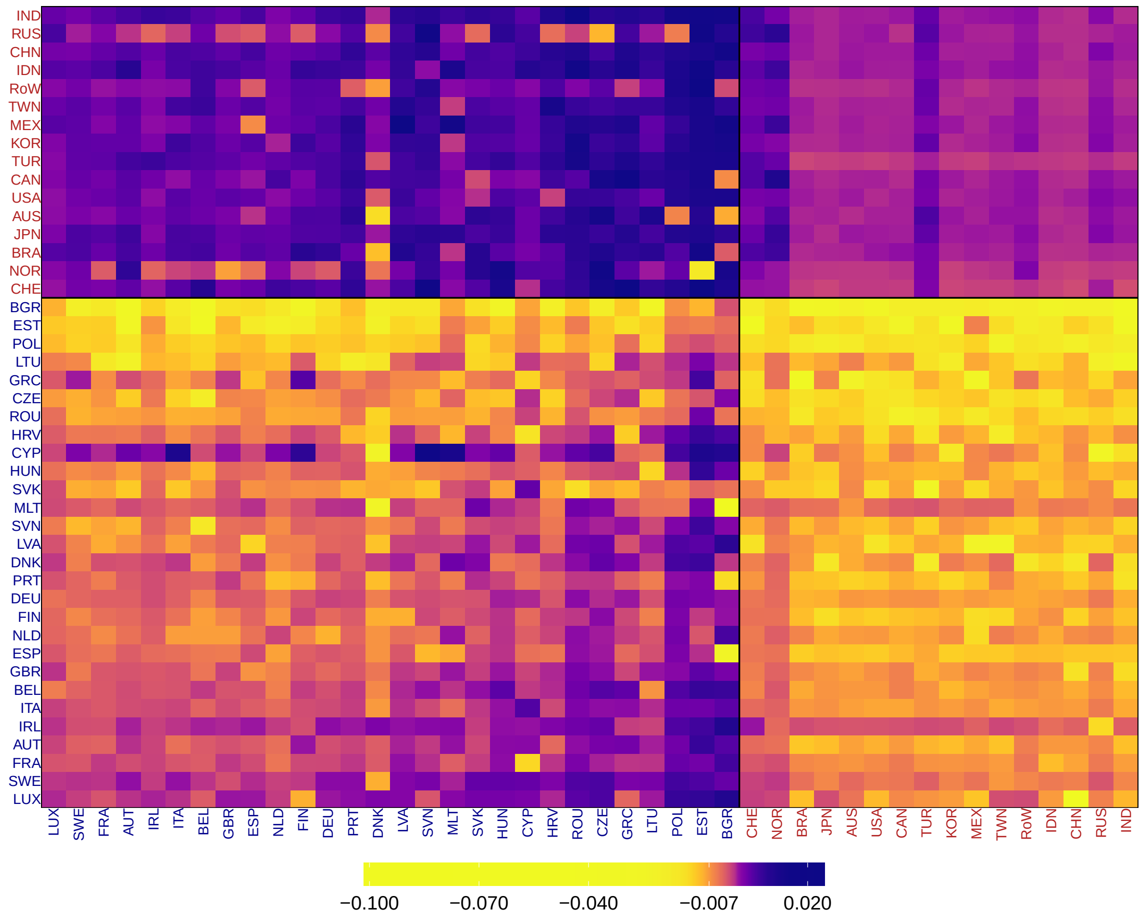

Figure A2: Percent change in direct requirement coefficients (EU tax). Rows are supplying countries, columns are buying countries. Countries are separated by EU membership, then ordered by emission intensity (bottom to top).

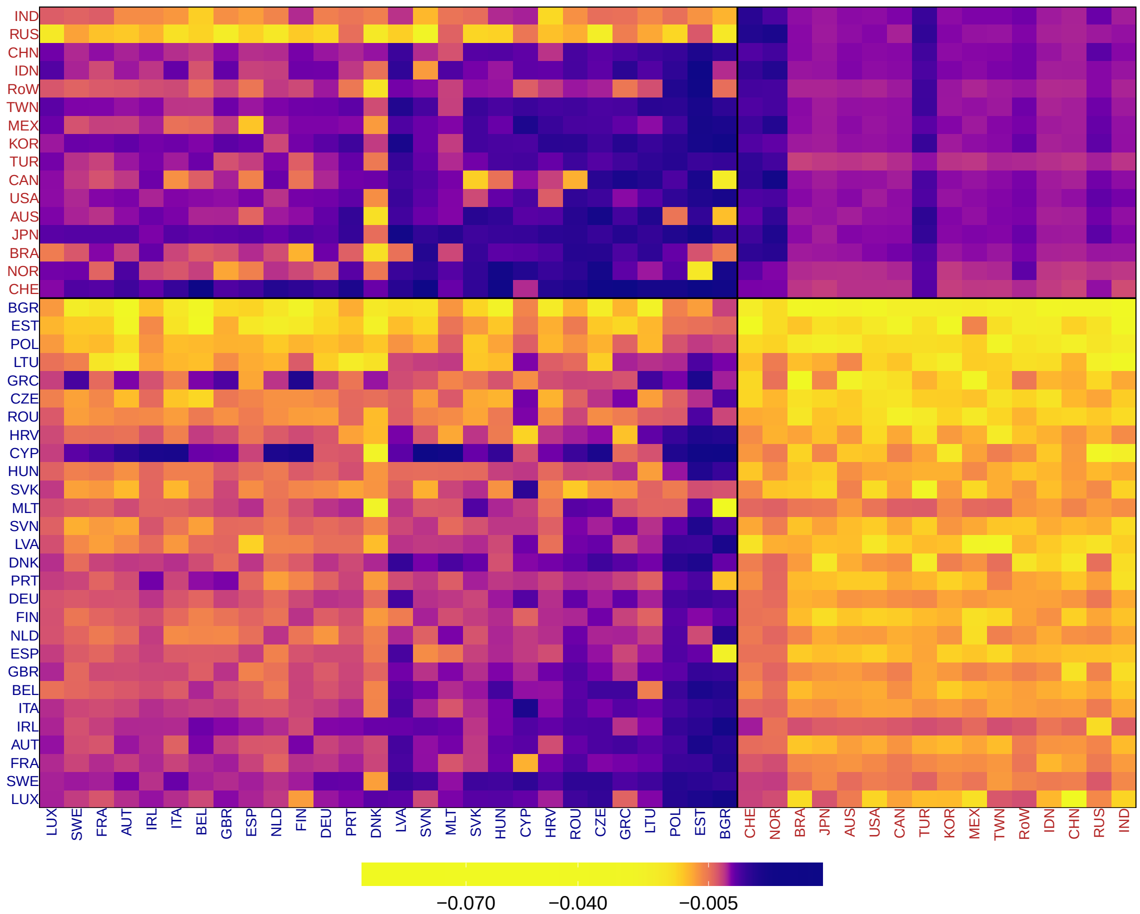

Figure A3: Percent change in direct requirement coefficients (EU tax + CBAM). Rows are supplying countries, columns are buying countries. Countries are separated by EU membership, then ordered by emission intensity (bottom to top).