# The impact of border carbon adjustment on global emissions shifting*
## – Model Sketch –

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**Note:** This manuscript is an excerpt from the ongoing research project: Richter and Wanner, 2024, "The Impact of Border Carbon Adjustments on Global Emissions Shifting". It presents the quantitative trade and environment model we develop, in the version used for the EconPol Policy Report "EU Climate Policy in a Globalized World". For updates and revisions, please refer to the latest version of the paper.

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# 1 A Quantitative Trade and Environment Model

## 1.1 General model description

The model is part of a recent strand of new quantitative trade models that integrate environmental components (see e.g. Caron and Fally, 2022; Egger and Nigai, 2015; Shapiro, 2016; Shapiro and Walker, 2018). Specifically, it extends the model by Larch and Wanner (2024), which in turn builds on Larch and Wanner (2017). Larch and Wanner (2017)'s framework is a multi-sector, multi-factor structural gravity model with emissions that is applied to study the effects of carbon tariffs on sectoral shifts in trade and production patterns, and hence, on emissions. Larch and Wanner (2024) additionally incorporate a constant elasticity of fossil fuel supply function as in Boeters and Bollen (2012). This addition allows to consider carbon leakage through both the goods trade/competitiveness channel and the international energy market. We extend their framework in the following five dimensions:

- We allow goods production functions combine energy and other factors in a constant elasticity of substitution (CES) rather than Cobb-Douglas. This way, we can take into account that energy is an input that is hard to substitute which is important in quantifying climate policy costs and carbon leakage patterns.

- We allow the energy production function to be a CES rather than Cobb-Douglas aggregate of fossil fuels and other production inputs, hence taking into account that fossil fuels are potentially particularly difficult to substitute.

- We allow joint emission reduction targets for a group of countries. This way, we can mimic supranational emission trading schemes in our counterfactual analyses and hence implement scenarios that are very close to the real-life policy setups.

- We incorporate import tariffs into the model. Specifically, we include the possibility to charge tariffs based on the embodied $CO_2$ emissions that vary by country of origin and sector, allowing us to also investigate policy scenarios including a carbon border adjustment mechanism (CBAM).

- We include the possibility for a global climate coalition to introduce a tax on fossil fuel extraction tax as supply-side climate policy instrument. This way, we can complement the standard consideration of demand-side climate policy that taxes the use of fossil fuels and see how this affects the incidence of climate policy costs across countries.

In the following, we lay out the components of the extended model formally and show how it can be solved for an equilibrium after a counterfactual policy shock. There is a set of countries $\mathcal{N}$, indexed by $i$, $j$, and $k$, and a set of sectors $\mathcal{L}$, index by $l$. Products in all sectors are differentiated by the country of origin. Each country is endowed with a fixed supply $V_f^i$ of each factor $f$ of a set of factors

$\mathcal{F}$. Factors are internationally immobile. For factor mobility across sectors, we distinguish two cases: full mobility and no mobility at all.

## 1.2 Supply

### 1.2.1 Goods Production

Production functions are constant elasticity of substitution (CES:)

$$q_l^i = A_l^i \left( \nu_l^i (E_l^i)^{\frac{\rho-1}{\rho}} + (1-\nu_l^i) \left( \prod_{f\in\mathcal{F}} (V_{lf}^i)^{\bar{\alpha}_{lf}^i} \right)^{\frac{\rho-1}{\rho}} \right)^{\frac{\rho}{\rho-1}},$$

where $A_l^i$ denotes productivity, $E_l^i$ the amount of energy used in production, $V_{lf}^i$ the used amounts of a production factor $f \in \mathcal{F}$, $\nu_l^i$ is a CES share parameter, $\rho$ the elasticity of substitution between energy and the production factor bundle, while $\bar{\alpha}_{lf}^i$ denote the Cobb-Douglas shares within the factor bundle (with $\sum_f \bar{\alpha}_{lf}^i = 1$). Production cost shares $\alpha_{lE}^i$ and $\alpha_{lf}^i$ are endogenously determined by cost minimization as

$$\alpha_{lE}^i = \frac{(\nu_l^i)^\rho (e^i)^{1-\rho}}{(\nu_l^i)^\rho (e^i)^{1-\rho} + (1-\nu_l^i)^\rho \left( \prod_{f\in\mathcal{F}} (w_{lf}^i)^{\bar{\alpha}_{lf}^i} \right)^{1-\rho}},$$
$$\alpha_{lf}^i = (1-\alpha_{lE}^i)\bar{\alpha}_{lf}^i,$$

where $e^i$ is the energy price and $w_{lf}^i$ are factor prices in country $i$ and sector $l$ (with $\alpha_{lE}^i + \sum_f \alpha_{lf}^i = 1$).

Markets are perfectly competitive and goods therefore sold at marginal costs:

$$p_l^i = \frac{1}{A_l^i} \left( (\nu_l^i)^\rho (e^i)^{1-\rho} + (1-\nu_l^i)^\rho \left( \prod_{f\in\mathcal{F}} (w_{lf}^i)^{\bar{\alpha}_{lf}^i} \right)^{1-\rho} \right)^{\frac{1}{1-\rho}}. \tag{1}$$

### 1.2.2 Energy Production

The energy production function is CES, too:

$$E^i = A_E^i \left( \nu_E^i (R^i)^{\frac{\rho_E-1}{\rho_E}} + (1-\nu_E^i) \left( \prod_{f\in\mathcal{F}} (V_{Ef}^i)^{\bar{\xi}_f^i} \right)^{\frac{\rho_E-1}{\rho_E}} \right)^{\frac{\rho_E}{\rho_E-1}},$$

where $A_E^i$ denotes productivity, $R^i$ is the amount of an internationally tradable fossil fuel resource used in energy production, $\nu_E^i$ is a CES share parameter, $\rho_E$ the elasticity of substitution between the fossil fuel resource and the production factor input bundle, while $\bar{\xi}_f^i$ are Cobb-Douglas shares of the factor bundle (with $\sum_f \bar{\xi}_f^i = 1$). $CO_2$ emissions are directly proportional to fossil fuel use and, based on the chosen scaling, are equal to $R^i$ in country $i$.

From cost minimization, the endogenous cost shares in energy production of the fossil fuel resource $\xi_R^i$ and other factors $\xi_f^i$ are determined as:

$$\xi_R^i = \frac{(\nu_E^i)^{\rho_E}((1+\lambda^i)(1+\lambda_s)r)^{1-\rho_E}}{(\nu_E^i)^{\rho_E}((1+\lambda^i)(1+\lambda_s)r)^{1-\rho_E} + (1-\nu_E^i)^{\rho_E}\left(\prod_{f\in\mathcal{F}}(w_{Ef}^i)^{\bar{\xi}_f^i}\right)^{1-\rho_E}},$$
$$\xi_f^i = (1-\xi_R^i)\bar{\xi}_f^i,$$

where $\lambda^i$ and $\lambda_s$ represent ad-valorem carbon taxes on fossil fuel use and extraction, respectively, $r$ is the world price of the fossil fuel resource, and $w_{Ef}^i$ denotes the factors prices incurred in energy production in country $i$ (with $\xi_R^i + \sum_f \xi_f^i = 1$).

The energy market is also assumed to be competitive, and as a result, the energy price is given by:

$$e^i = \frac{1}{A_E^i}\left((\nu_E^i)^{\rho_E}\left((1+\lambda^i)(1+\lambda_s)r\right)^{1-\rho_E} + (1-\nu_E^i)^{\rho_E}\left(\prod_{f\in\mathcal{F}}(w_{Ef}^i)^{\bar{\xi}_f^i}\right)^{1-\rho_E}\right)^{\frac{1}{1-\rho_E}}. \tag{2}$$

#### 1.2.3 Fossil Fuel Supply

The fossil fuel market is modeled as perfectly globally integrated. To model how the global supply of the fossil resource $R^W$ reacts to changes in the world market price for fossil fuels, we follow Boeters and Bollen (2012) and use a constant elasticity of fossil fuel supply (CEFS) function:

$$R^W = \zeta\left(\frac{r}{P}\right)^{\eta}, \tag{3}$$

where $\zeta$ is a supply parameter, $P \equiv \prod_{i\in\mathcal{N}}(P^i/\omega^i)^{\omega^i}$, with $P^i \equiv \prod_{l\in\mathcal{L}}(P_l^i/\gamma_l^i)^{\gamma_l^i}$. $\gamma_l^j$ are Cobb-Douglas expenditure shares of country $j$ for sector $l$. The endowment shares $\omega^i$ (with $\sum_{i\in\mathcal{N}}\omega^i = 1$) pin down the distribution of which countries provide which share of the global supply. Finally, $\eta$ is the key parameter of the CEFS function, namely the supply elasticity.

## 1.3 Demand

#### 1.3.1 Utility

Consumers in country $j$ have a two-tier utility function that puts together CES utility across the nationally differentiated varieties within a sector and Cobb-Douglas utility across sectors:

$$U^j = \prod_{l\in\mathcal{L}}\left(\left(\sum_{i\in\mathcal{N}}(\beta_l^i)^{\frac{1-\sigma_l}{\sigma_l}}(q_l^{ij})^{\frac{\sigma_l-1}{\sigma_l}}\right)^{\frac{\sigma_l}{\sigma_l-1}}\right)^{\gamma_l^j},$$

where $\beta_l^i$ is a preference shifter, $q_l^{ij}$ is the amount of good in sector $l$ from country $i$ bought in country $j$, $\sigma_l$ denotes the elasticity of substitution across varieties within a sector, and $\gamma_l^j$ the Cobb-Douglas expenditure share parameter.

### 1.3.2 Gravity

Trade costs $T_l^{ij}$ (with $T_l^{ij} = T_l^{ji} \geq 1$ and $T_l^{ii} = 1$) are assumed to be of the usual iceberg-type. Additionally, international purchases may be subject to (carbon) tariffs $\tau_l^{ij}$, where $\tau_l^{ij} - 1$ is the ad-valorem tariff rate. With these two types of bilateral trade frictions, sectoral bilateral trade shares can be written as an Eaton and Kortum (2002)-type gravity equation:

$$\pi_l^{ij} = \frac{\left(\beta_l^i p_l^i T_l^{ij} \tau_l^{ij}\right)^{1-\sigma_l}}{\sum_{k \in \mathcal{N}} \left(\beta_l^k p_l^k T_l^{kj} \tau_l^{kj}\right)^{1-\sigma_l}} = \left(\frac{\beta_l^i p_l^i T_l^{ij} \tau_l^{ij}}{P_l^j}\right)^{1-\sigma_l}. \tag{4}$$

## 1.4 Climate Policy

### 1.4.1 National Reduction Targets

As mentioned above, countries can levy a tax $\lambda^i$ on the use of fossil fuels. We let countries formulate their climate policy targets in terms of quantity targets $\overline{R}^i$. The tax is then endogenously determined at the level necessary to exactly meet the emission target:

$$\lambda^i = \begin{cases} 0 \quad \text{if } i \notin cop, \\ \frac{\xi_R^i \sum_{l \in \mathcal{L}} \alpha_{lE}^i Y_l^i}{\overline{R}^i r} - 1 \quad \text{if } i \in cop, \end{cases} \tag{5}$$

where $cop \subseteq \mathcal{N}$ denotes the set of committed countries (i.e. countries that are part of the climate coalition). Countries outside of the coalition don't charge a (new) carbon tax.[1]

### 1.4.2 Joint Reduction Targets

With a joint carbon market across countries, instead of national targeted emission levels, $\overline{R}^i$, there is a joint targeted level for the cooperating countries, $\overline{R}^{cop}$ with $R^{cop} \equiv \sum_{i \in cop} R^i$:

$$\lambda^i = \begin{cases} 0 \quad \text{if } i \notin cop, \\ \frac{\sum_{j \in cop} \xi_R^j \sum_{l \in \mathcal{L}} \alpha_{lE}^j Y_l^j}{\overline{R}^{cop} r} - 1 \quad \forall \quad i \in cop. \end{cases} \tag{6}$$

This implies that all countries that are part of the joint carbon market charge the same ad-valorem fossil fuel use tax. Income from the tax is assumed to be distributed to the countries in which the

[1] In all policy scenarios, we will focus on the introduction of new, additional climate policy and abstract from modeling initial climate policy differences explicitly.

respective emissions occur.

### 1.4.3 CBAM

Countries with emission reduction targets may choose to implement a border carbon adjustment, applying their domestic carbon price (increase) as a tariff on all or selected imports from countries without such targets. The carbon tariff imposed by country $j$ on imports from country $i$ is defined as:

$$\tau_l^{ij} = \begin{cases} 1 + \lambda^j \xi_R^i \alpha_{lE}^i & \text{if} \quad i \notin \text{cop} \wedge j \in cop \wedge l \in cbam, \\ 1 & \text{if} \quad i \in \text{cop} \vee j \notin cop \vee l \notin cbam, \end{cases} \tag{7}$$

where $cbam \subseteq \mathcal{L}$ denotes the set of sectors covered by the CBAM.

### 1.4.4 Global Supply-side Climate Policy

In the case of a global climate coalition (i.e. $cop = \mathcal{N}$), we also consider the implementation of climate policy via an alternative, supply-side policy. Specifically, we let the global coalition achieve its global emission target by introducing a joint fossil fuel extraction tax $\lambda_s$. It is determined according to the following expression:

$$\lambda_s = \frac{\sum_j \xi_R^j \sum_{l \in \mathcal{L}} \alpha_{lE}^j Y_l^j}{\overline{R}_s^W r} - 1. \tag{8}$$

In the supply-side policy case, we assume that there is no parallel demand-side policy effort (i.e. $\lambda_i = 0$ $\forall\ i$). Tax revenues from the extraction tax are assumed to remain in the extracting countries.

## 1.5 Income

In each country, income is generated from (i) the expenditure on their domestic production factors, (ii) their share of the global supply of fossil fuels, (iii) the carbon tax charged on its fossil fuel use, (iv) tariffs:

$$Y^i = I_{\mathcal{F}}^i + I_R^i + \left(\frac{\lambda^i}{1+\lambda^i}\right) \xi_R^i \sum_{l \in \mathcal{L}} \alpha_{lE}^i Y_l^i + \sum_{l \in \mathcal{L}} \sum_{j \in \mathcal{N}} (\tau_l^{ji} - 1) \frac{\pi_l^{ji}}{\tau_l^{ji}} \gamma_l^i Y^i, \tag{9}$$

where $I_{\mathcal{F}}^i \equiv \sum_{f \in \mathcal{F}} I_f^i$ denotes total income across all factors, $I_R^i \equiv \omega^i R^W (1+\lambda_s) r$ the fossil resource income (including from extraction taxes in case of global supply-side climate policy), and $Y_l^i \equiv q_l^i p_l^i$ are the sectoral values of production.

Each factor can generate income from all sectors (goods and energy) represented by $I_f^i = I_{Ef}^i + \sum_l I_{lf}^i$, where $I_{lf}^i \equiv w_{lf}^i V_{lf}^i = \alpha_{lf}^i Y_l^i$ denotes income of factor $f$ from goods production within sector $l$, while $I_{Ef}^i \equiv w_{Ef}^i V_{Ef}^i = \xi_f^i \sum_l \alpha_{lE}^i Y_l^i$ is the income of factor $f$ generated in the energy sector $E$. It is also useful to decompose total factor income at the sector-level: In sector $l$, factor income is generated as $I_l^i = \sum_f I_{lf}^i = (1-\alpha_{lE}^i)Y_l^i$, and in the energy sector as $I_E^i = \sum_f I_{Ef}^i = (1-\xi_R^i)\sum_l \alpha_{lE}^i Y_l^i$.

## 1.6 Trade Balance, Market Clearing and Equilibrium

Trade is assumed to be balanced, and both the national energy and factor markets, as well as the international goods and fossil fuel markets, are all assumed to clear. While there are case-specific adjustments for mobile and immobile factors to complete the equilibrium conditions, the following generally hold:

$$\sum_{i\in\mathcal{N}}\sum_{l\in\mathcal{L}} \frac{\pi_l^{ij}}{\tau_l^{ij}}\gamma_l^j Y^j = \sum_{j\in\mathcal{N}}\sum_{l\in\mathcal{L}} \frac{\pi_l^{ji}}{\tau_l^{ji}}\gamma_l^i Y^i \tag{10}$$

$$E^i = \sum_{l\in\mathcal{L}} E_l^i \tag{11}$$

$$V_f^i = \sum_{l\in\mathcal{L}} V_{lf}^i + V_{Ef}^i, \tag{12}$$

$$Y_l^i = \sum_{j\in\mathcal{N}} \frac{\pi_l^{ij}}{\tau_l^{ij}}\gamma_l^j Y^j, \tag{13}$$

$$R^W r = \frac{1}{1+\lambda_s}\sum_{i\in\mathcal{N}}\left(\frac{1}{1+\lambda^i}\right)\xi_R^i \sum_{l\in\mathcal{L}}\alpha_{lE}^i Y_l^i. \tag{14}$$

This gives a general definition of an equilibrium:

**Definition 1** *For given factor endowments $V_f^i$, productivity parameters $A_l^i$, $A_E^i$, and $\theta_l$, preference parameters $\beta_l^i$ and $\sigma_l$, production function parameters $\nu_l^i$, $\nu_E^i$, $\bar{\alpha}_{lf}^i$, $\bar{\xi}_f^i$, $\rho$, and $\rho_E$, fossil fuel supply parameters $\zeta$ and $\eta$, and trade costs $T_l^{ij}$, an equilibrium under climate policy structure $\{cop, \overline{R}^i, \overline{R}^{cop}, \overline{R}_s^W\}$ is a set of factor prices $w_{lf}^i$ and $w_{Ef}^i$, energy prices $e^i$, carbon taxes $\lambda^i$, carbon tariffs $\tau_l^{ij}$, extraction taxes $\lambda_s$, a world fossil fuel price $r$, a global fossil fuel supply $R^W$, and costs shares $\alpha_{lE}^i$, $\alpha_{lf}^i$, $\xi_R^i$ and $\xi_f^i$ that satisfy equilibrium conditions (1)-(14).*

Following the "exact hat notation" of Dekle, Eaton, and Kortum (2007, 2008), we can re-express the equilibrium in terms of changes, where $\hat{x} \equiv x'/x$ denotes the change from the baseline value of the variable $x$ to its counterfactual value $x'$. This approach allows us to conduct counterfactual analyses without needing to identify the levels of e.g. the factor endowments $V_f^i$, productivities $A_l^i$ and $A_E^i$, or preference shifters $\beta_l^i$.[2]

### 1.6.1 Case I: Mobile Factors Across Sectors

In the mobile factor case, factor prices are equalized across all goods sectors and energy production, i.e. $w_{lf}^i = w_{Ef}^i = w_f^i \;\forall\, l$. This implies that total income of factor $f$ collapses to $I_f^i = w_f^i V_f^i$. Accordingly,

[2] For simplification, we focus on the *changes* in climate policy and hence assume $(1+\lambda^i) = \tau_l^{ij} = (1+\lambda_s) = 1 \;\forall\, i,j,l$.

building on Definition 1, we define both a baseline and counterfactual equilibrium for the case of mobile factors, and express variables in terms of changes:

**Definition 2** *Let* $\{w_f^i, e^i, r, R^W, \alpha_{lE}^i, \alpha_{lf}^i, \xi_R^i, \xi_f^i\}$ *be a baseline equilibrium under climate policy structure* $\{\lambda^i, \tau_l^{ij}, \lambda_s\}$ *and* $\{w_f^{i'}, e^{i'}, \lambda^{i'}, \tau_l^{ij'}, \lambda_s', r', R^{W'}, \alpha_{lE}^{i'}, \alpha_{lf}^{i'}, \xi_R^{i'}, \xi_f^{i'}\}$ *be a counterfactual equilibrium under climate policy structure* $\{cop, \overline{R}^{i'}, \overline{R}^{cop'}, \overline{R}_s^{W'}\}$*. Then,* $\{\hat{w}_f^i, \hat{e}^i, \widehat{1+\lambda^i}, \hat{\tau}_l^{ij}, \widehat{1+\lambda_s}, \hat{r}, \hat{R}^W, \hat{\alpha}_{lE}^i, \hat{\alpha}_{lf}^i, \hat{\xi}_R^i, \hat{\xi}_f^i\}$ *satisfy the following equilibrium conditions (15)-(29):*

*Carbon tax change (national targets case):*

$$\widehat{1+\lambda^i} = \begin{cases} 1 \quad \text{if } i \notin cop, \\ \frac{\hat{\xi}_R^i \xi_R^i \sum_l \hat{\alpha}_{lE}^i \alpha_{lE}^i \sum_j (\hat{\pi}_l^{ij}\pi_l^{ij}/(\hat{\tau}_l^{ij}\tau_l^{ij}))\gamma_l^j Y^{j'}}{\xi_R^i \sum_l \alpha_{lE}^i \sum_j (\pi_l^{ij}/\tau_l^{ij})\gamma_l^j Y^j} \left(\frac{\overline{R}^{i'}}{R^i}\hat{r}\right)^{-1} \text{if } i \in cop. \end{cases} \tag{15}$$

*Carbon tax change (joint target case):*

$$\widehat{1+\lambda^i} = \begin{cases} 1 \quad \text{if } i \notin cop, \\ \frac{\sum_{k\in cop} \hat{\xi}_R^k \xi_R^k \sum_l \hat{\alpha}_{E,l}^k \alpha_{lE}^k \sum_j (\hat{\pi}_l^{kj}\pi_l^{kj}/\hat{\tau}_l^{kj}\tau_l^{kj})\gamma_l^j Y^{j'}}{\sum_{k\in cop} \xi_R^k \sum_l \alpha_{lE}^k \sum_j (\pi_l^{kj}/\tau_l^{kj})\gamma_l^j Y^j} \left(\frac{\overline{R}^{cop'}}{R^{cop}}\hat{r}\right)^{-1} \quad \forall \quad i \in cop. \end{cases} \tag{16}$$

*Tariff change (CBAM case):*

$$\hat{\tau}_l^{ij} = \begin{cases} 1 + \lambda^{j'} \hat{\xi}_R^i \xi_R^i \hat{\alpha}_{lE}^i \alpha_{lE}^i & \text{if} \quad i \notin \text{cop} \wedge j \in cop, \\ 1 & \text{if} \quad i \in \text{cop} \vee j \notin cop. \end{cases} \tag{17}$$

*Extraction tax change:*

$$\widehat{1+\lambda_s} = \frac{\sum_i \hat{\xi}_R^i \xi_R^i \sum_l \hat{\alpha}_{E,l}^i \alpha_{lE}^i \sum_j (\hat{\pi}_l^{ij}\pi_l^{ij}/(\hat{\tau}_l^{ij}\tau_l^{ij}))\gamma_l^j Y^{j'}}{\sum_i \xi_R^i \sum_l \alpha_{lE}^i \sum_j (\pi_l^{ij}/\tau_l^{ij})\gamma_l^j Y^j} \left(\frac{\overline{R}_s^{W'}}{R^W}\hat{r}\right)^{-1}. \tag{18}$$

*Production cost change:*

$$\hat{c}_l^i = \left(\alpha_{lE}^i (\hat{e}^i)^{1-\rho} + (1-\alpha_{lE}^i)\left(\prod_f (\hat{w}_f^i)^{\bar{\alpha}_{lf}^i}\right)^{1-\rho}\right)^{\frac{1}{1-\rho}}. \tag{19}$$

*Cost share changes:*

$$\hat{\alpha}_{lE}^i = \left(\frac{\hat{e}^i}{\hat{c}_l^i}\right)^{1-\rho} \qquad \text{and} \qquad \hat{\alpha}_{lf}^i = \frac{1-\hat{\alpha}_{lE}^i \alpha_{lE}^i}{1-\alpha_{lE}^i}. \tag{20}$$

*Trade share change:*

$$\hat{\pi}_l^{ij} = \frac{\left(\hat{\tau}_l^{ij}\hat{c}_l^i\right)^{1-\sigma_l}}{\sum_k \pi_l^{kj}\left(\hat{\tau}_l^{kj}\hat{c}_l^k\right)^{1-\sigma_l}}. \tag{21}$$

*Price index change:*

$$\hat{P}_l^j = \left( \sum_i \pi_l^{ij} \left( \hat{\tau}_l^{ij} \hat{c}_l^i \right)^{1-\sigma_l} \right)^{1/(1-\sigma_l)}. \tag{22}$$

*Fossil fuel supply change:*

$$\hat{R}^W = \left( \frac{\hat{r}}{\prod_i \left( \prod_l \left( \hat{P}_l^i \right)^{\gamma_l^i} \right)^{\omega^i}} \right)^{\eta}. \tag{23}$$

*Counterfactual income:*

$$Y^{j'} = \sum_f \hat{w}_f^j I_f^j + \hat{R}^W \widehat{(1+\lambda_s)} \hat{r} I_R^j + \left( \frac{\lambda^{j'}}{1+\lambda^{j'}} \right) \hat{\xi}_R^j \xi_R^j \sum_l \hat{\alpha}_{E,l}^j \alpha_{E,l}^j \sum_i \frac{\hat{\pi}_l^{ji} \pi_l^{ji}}{\hat{\tau}_l^{ij} \tau_l^{ij}} \gamma_l^i Y^{i'} \tag{24}$$

$$+ \sum_l \sum_i (\hat{\tau}_l^{ij} \tau_l^{ij} - 1) \frac{\hat{\pi}_l^{ij} \pi_l^{ij}}{\hat{\tau}_l^{ij} \tau_l^{ij}} \gamma_l^j Y^{j'}. \tag{25}$$

*Factor price change:*

$$\hat{w}_f^i = \frac{1}{I_f^i} \sum_l \left( \left( \hat{\alpha}_{lf}^i \alpha_{lf}^i + \hat{\xi}_f^i \xi_f^i \hat{\alpha}_{lE}^i \alpha_{lE}^i \right) \sum_j \frac{\hat{\pi}_l^{ij} \pi_l^{ij}}{\hat{\tau}_l^{ij} \tau_l^{ij}} \gamma_l^j Y^{j'} \right). \tag{26}$$

*Energy price change:*

$$\hat{e}^i = \left( \xi_R^i \left( \widehat{(1+\lambda^i)} \widehat{(1+\lambda_s)} \hat{r} \right)^{1-\rho_E} + (1-\xi_R^i) \left( \prod_f \left( \hat{w}_f^i \right)^{\bar{\xi}_f^i} \right)^{1-\rho_E} \right)^{\frac{1}{1-\rho_E}}. \tag{27}$$

*Cost share – energy production – changes:*

$$\hat{\xi}_R^i = \left( \frac{\widehat{(1+\lambda^i)} \widehat{(1+\lambda_s)} \hat{r}}{\hat{e}^i} \right)^{1-\rho_E} \qquad \text{and} \qquad \hat{\xi}_f^i = \frac{1-\hat{\xi}_R^i \xi_R^i}{1-\xi_R^i}. \tag{28}$$

*Fossil fuel price change:*

$$\hat{r} = \frac{\sum_i \left( \frac{1}{1+\lambda^{i'}} \right) \hat{\xi}_R^i \xi_R^i \sum_l \hat{\alpha}_{lE}^i \alpha_{lE}^i \sum_j \frac{\hat{\pi}_l^{ij} \pi_l^{ij}}{\hat{\tau}_l^{ij} \tau_l^{ij}} \gamma_l^j Y^{j'}}{\sum_i \left( \frac{1}{1+\lambda^i} \right) \xi_R^i \sum_l \alpha_{lE}^i \sum_j \frac{\pi_l^{ij}}{\tau_l^{ij}} \gamma_l^j Y_j} \left( \widehat{(1+\lambda_s)} \hat{R}^W \right)^{-1}. \tag{29}$$

### 1.6.2 Case II: Immobile Factors Across Sectors

In the immobile factor case, the factor market clearing condition in Eq. (12) is complemented by sector specific factor inputs, i.e. $V_{lf}^i$ and $V_{Ef}^i$ are exogenous and cannot adjust. As a result, factor prices are determined, and adjust to climate policy shocks, at the factor-sector level. However, due to our assumed Cobb-Douglas factor nests in the production functions of goods and energy, factor prices change proportionally within each sector, i.e. $\hat{w}^i_{lf} = \hat{w}^i_l \ \forall \ f$ and $\hat{w}^i_{Ef} = \hat{w}^i_E$. Accordingly, building on Definition 1, we define both a baseline and counterfactual equilibrium for the case of immobile factors, and express variables in terms of changes:

**Definition 3** *Let* $\{w^i_{lf}, w^i_{Ef}, e^i, r, R^W, \alpha^i_{lE}, \alpha^i_{lf}, \xi^i_R, \xi^i_f\}$ *be a baseline equilibrium under climate policy structure* $\{\lambda^i, \tau^{ij}_l, \lambda_s\}$ *and* $\{w^{i'}_{lf}, w^{i'}_{Ef}, e^{i'}, \lambda^{i'}, r', R^{W'}, \alpha^{i'}_{lE}, \alpha^{i'}_{lf}, \xi^{i'}_R, \xi^{i'}_f\}$ *be a counterfactual equilibrium under climate policy structure* $\{cop, \overline{R}^{i'}, \overline{R}^{cop'}, \overline{R}^{W'}_s\}$*. Then,* $\{\hat{w}^i_l, \hat{w}^i_E, \hat{e}^i, \widehat{1+\lambda^i}, \hat{\tau}^{ij}_l, \widehat{1+\lambda_s}, \hat{r}, \hat{R}^W, \hat{\alpha}^i_{lE}, \hat{\alpha}^i_{lf}, \hat{\xi}^i_R, \hat{\xi}^i_f\}$ *satisfy the following equilibrium conditions* (30)-(44)*:*

*Carbon tax change (national targets case):*

$$\widehat{1+\lambda^i} = \begin{cases} 1 \quad \text{if } i \notin cop, \\ \frac{\hat{\xi}^i_R \xi^i_R \sum_l \hat{\alpha}^i_{E,l} \alpha^i_{lE} \sum_j (\hat{\pi}^{ij}_l \pi^{ij}_l / (\hat{\tau}^{ij}_l \tau^{ij}_l)) \gamma^j_l Y^{j'}}{\xi^i_R \sum_l \alpha^i_{lE} \sum_j (\pi^{ij}_l / \tau^{ij}_l) \gamma^j_l Y^j} \left( \frac{\overline{R}^{i'}}{R^i} \hat{r} \right)^{-1} \text{if } i \in cop. \end{cases} \tag{30}$$

*Carbon tax change (supranational target case):*

$$\widehat{1+\lambda^i} = \begin{cases} 1 \quad \text{if } i \notin cop, \\ \frac{\sum_{k \in cop} \hat{\xi}^k_R \xi^k_R \sum_l \hat{\alpha}^k_{lE} \alpha^k_{lE} \sum_j (\hat{\pi}^{kj}_l \pi^{kj}_l / \hat{\tau}^{kj}_l \tau^{kj}_l) \gamma^j_l Y^{j'}}{\sum_{k \in cop} \xi^k_R \sum_l \alpha^k_{lE} \sum_j (\pi^{kj}_l / \tau^{kj}_l) \gamma^j_l Y^j} \left( \frac{\overline{R}^{cop'}}{R^{cop}} \hat{r} \right)^{-1} \quad \forall \quad i \in cop. \end{cases} \tag{31}$$

*Tariff change (CBAM case):*

$$\hat{\tau}^{ij}_l = \begin{cases} 1 + \lambda^{j'} \hat{\xi}^i_R \xi^i_R \hat{\alpha}^i_{lE} \alpha^i_{lE} & \text{if} \quad i \notin \text{cop} \wedge j \in cop, \\ 1 & \text{if} \quad i \in \text{cop} \vee j \notin cop. \end{cases} \tag{32}$$

*Extraction tax change:*

$$\widehat{1+\lambda_s} = \frac{\sum_i \hat{\xi}^i_R \xi^i_R \sum_l \hat{\alpha}^i_{E,l} \alpha^i_{lE} \sum_j (\hat{\pi}^{ij}_l \pi^{ij}_l / (\hat{\tau}^{ij}_l \tau^{ij}_l)) \gamma^j_l Y^{j'}}{\sum_i \xi^i_R \sum_l \alpha^i_{lE} \sum_j (\pi^{ij}_l / \tau^{ij}_l) \gamma^j_l Y^j} \left( \frac{\overline{R}^{W'}_s}{R^W} \hat{r} \right)^{-1}. \tag{33}$$

*Production cost change:*

$$\hat{c}^i_l = \left( \alpha^i_{lE} (\hat{e}^i)^{1-\rho} + (1 - \alpha^i_{lE}) (\hat{w}^i_l)^{1-\rho} \right)^{\frac{1}{1-\rho}}. \tag{34}$$

*Cost share changes:*

$$\hat{\alpha}^i_{lE} = \left( \frac{\hat{e}^i}{\hat{c}^i_l} \right)^{1-\rho}. \tag{35}$$

*Trade share change:*

$$\hat{\pi}^{ij}_l = \frac{\left( \hat{\tau}^{ij}_l \hat{c}^i_l \right)^{1-\sigma_l}}{\sum_k \pi^{kj}_l \left( \hat{\tau}^{kj}_l \hat{c}^k_l \right)^{1-\sigma_l}}. \tag{36}$$

*Price index change:*

$$\hat{P}_l^j = \left(\sum_i \pi_l^{ij} \left(\hat{\tau}_l^{ij} \hat{c}_l^i\right)^{1-\sigma_l}\right)^{1/(1-\sigma_l)}. \tag{37}$$

*Fossil fuel supply change:*

$$\hat{R}^W = \left(\frac{\hat{r}}{\prod_i \left(\prod_l \left(\hat{P}_l^i\right)^{\gamma_l^i}\right)^{\omega^i}}\right)^{\eta}. \tag{38}$$

*Counterfactual income:*

$$\begin{aligned} Y^{j'} &= \hat{w}_E^j \sum_f I_{Ef}^j + \sum_l \hat{w}_l^j \sum_f I_{lf}^j + \hat{R}^W \widehat{(1+\lambda_s)} \hat{r} I_R^j \\ &+ \left(\frac{\lambda^{j'}}{1+\lambda^{j'}}\right) \hat{\xi}_R^j \xi_R^j \sum_l \hat{\alpha}_{E,l}^j \alpha_{lE}^j \sum_i \frac{\hat{\pi}_l^{ji} \pi_l^{ji}}{\hat{\tau}_l^{ij} \tau_l^{ij}} \gamma_l^i Y^{i'} + \sum_l \sum_i (\hat{\tau}_l^{ij} \tau_l^{ij} - 1) \frac{\hat{\pi}_l^{ij} \pi_l^{ij}}{\hat{\tau}_l^{ij} \tau_l^{ij}} \gamma_l^j Y^{j'}. \end{aligned} \tag{39}$$

*Factor price change:*

$$\hat{w}_l^i = \frac{(1 - \hat{\alpha}_{lE}^i \alpha_{lE}^i) \sum_j \frac{\hat{\pi}_l^{ij} \pi_l^{ij}}{\hat{\tau}_l^{ij} \tau_l^{ij}} \gamma_l^j Y^{j'}}{I_l^i} \quad \textit{and} \tag{40}$$

$$\hat{w}_E^i = \frac{(1 - \hat{\xi}_R^j \xi_R^j) \sum_l \hat{\alpha}_{lE}^i \alpha_{lE}^i \sum_j \frac{\hat{\pi}_l^{ij} \pi_l^{ij}}{\hat{\tau}_l^{ij} \tau_l^{ij}} \gamma_l^j Y^{j'}}{I_E^i}. \tag{41}$$

*Energy price change:*

$$\hat{e}^i = \left(\xi_R^i \left(\widehat{(1+\lambda^i)} \widehat{(1+\lambda_s)} \hat{r}\right)^{1-\rho_E} + (1 - \xi_R^i)(\hat{w}_E^i)^{1-\rho_E}\right)^{\frac{1}{1-\rho_E}}. \tag{42}$$

*Cost share - energy production - changes:*

$$\hat{\xi}_R^i = \left(\frac{\widehat{(1+\lambda^i)} \widehat{(1+\lambda_s)} \hat{r}}{\hat{e}^i}\right)^{1-\rho_E}. \tag{43}$$

*Fossil fuel price change:*

$$\hat{r} = \frac{\sum_i \left(\frac{1}{1+\lambda^{i'}}\right) \hat{\xi}_R^i \xi_R^i \sum_l \hat{\alpha}_{lE}^i \alpha_{lE}^i \sum_j \frac{\hat{\pi}_l^{ij} \pi_l^{ij}}{\hat{\tau}_l^{ij} \tau_l^{ij}} \gamma_l^j Y^{j'}}{\sum_i \left(\frac{1}{1+\lambda^i}\right) \xi_R^i \sum_l \alpha_{lE}^i \sum_j \frac{\pi_l^{ij}}{\tau_l^{ij}} \gamma_l^j Y_j} \left(\widehat{(1+\lambda_s)} \hat{R}^W\right)^{-1}. \tag{44}$$

## 1.7 Calibration and Parameter Assumptions

We bring the model to the data using the Global Trade Analysis Project (GTAP) 11 database (Aguiar et al., 2022). We use the most recent base year 2017. We keep GTAP's full regional disaggregation

(141 countries and 19 aggregate regions), but aggregate the 65 GTAP sectors to one energy sector, one nontradable sector, and 13 tradable non-energy sectors (see Appendix A for the sectoral concordance).

From GTAP's multi-region input output tables, we obtain production cost shares $\alpha^i_{lf}$, $\alpha^i_{lE}$, $\xi^i_f$ and $\xi^i_R$. GTAP also provides estimates for the sectoral elasticities of substitution $\sigma_l$. We follow Larch and Wanner, 2024 and obtain fitted baseline trade shares $\pi^{ij}_l$ based on estimated bilateral trade costs. For the trade cost estimation, we complement the trade data from GTAP by gravity variables from CEPII (Head, Mayer, and Ries, 2010) and Mario Larch's RTA database (Egger and Larch, 2008).

The model parametrization involves three additional key elasticities for which we borrow values from the literature. For the elasticity of substitution between energy and other production factors, we rely on Bretschger and Jo (2024) and put $\rho = 0.6$. We take the elasticity of substitution between fossil fuel and other inputs in energy production from Golosov et al. (2014) as $\rho_E = 0.72$. Finally, we calculate an emission-weighted average of the fuel-specific supply elasticities from Boeters and Bollen, 2012 to specify our fossil supply elasticity to $\eta = 2.35$.

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# Appendix

## A Sectoral Aggregation

The 15 sectors (including energy) comprise the following GTAP 11 industries:

**Agriculture**: pdr (Paddy rice), wht (Wheat), gro (Cereal grains nec), v_f (Vegetables, fruit, nuts), osd (Oil seeds), c_b (Sugar cane, sugar beet), pfb (Plant-based fibers), ocr (Crops nec), ctl (Cattle, sheep, goats, horses), oap (Animal products nec), rmk (Raw milk), wol (Wool, silk-worn cocoons), frs (Forestry), fsh (Fishing).

**Apparel**: wap (Wearing apparel), lea (Leather products).

**Chemical**: chm (Chemical products), bph (Basi pharmaceutical products), rpp (Rubber and plastic products).

**Energy**: ely (Electricity), gdt (Gas manufacture, distribution), coa (Coal), oil (Oil), gas (Gas)

**Equipment**: eeq (Eletrical equipment), mvh (Motor vehicles and parts), otn (Transport equipment nec).

**Food**: cmt (Bovine meat products), omt (Meat products nec), vol (Vegetable oils and fats), mil (Dairy products), pcr (Processed rice), sgr (Sugar), ofd (Food products nec), b_t (Beverages and tobacco products).

**Machinery**: ele (Computer, electronic and optic), ome (Machinery and equipment nec).

**Metal**: i_s (Ferrous metals), nfm (Metals nec), fmp (Metal products).

**Mineral**: p_c (Petroleum, coal products), nmm (Mineral products nec), oxt (Other extraction).

**Non-Tradables**: wtr (Water), cns (Construction), osg (Public Administration and defense), edu (Education), hht (Human health and social work activities), dwe (Dwellings).

**Other**: omf (Manufactures nec).

**Paper**: ppp (Paper products, publishing).

**Service**: trd (Trade), afs (Accomodation, Food and service activties), otp (Transport nec), wtp (Sea transport), atp (Air transport), whs (Warehousing and support activities), cmn (Communication), ofi (Financial Services nec), ins (Insurance), rsa (Real estate activities), obs (Business services nec), ros (Recreation and other services).

**Textile**: tex (Textiles).

**Wood**: lum (Wood products).