Voluntary Emission Restraints in Developing Economies: The Role of Trade Policy *

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Abstract

We study the role of trade policy in one of the most pressing climate policy challenges that developing countries face: meeting voluntary emission restraints (VERs). To do so, we develop a new general equilibrium trade model that extends Caliendo and Parro (2015) in three dimensions. First, we model extractive sectors that feature a continuum of producers with heterogeneous productivity, demanding labor, dirty natural resources, and intermediate goods from all industries. Second, we consider that production generates different amounts of emissions across sectors and countries, and households experience disutility from carbon emissions, modeled as a pure externality as in Shapiro (2021). Third, we model a general set of taxes along the value chain—on production, intermediate and final consumption, and on labor—which allows for different options of carbon taxes and tariffs that impact emissions and other outcomes in general equilibrium. In our quantitative analysis, we focus on two groups of policies: those that are in the traditional realm of trade policy, related to tariff reform and potential emission biases; and those that combine a Pigouvian carbon tax with border adjustments. Our main findings point to a questionable role of trade policy as a climate policy in developing economies. Although it is effective in mitigating emission leakages, such leakages are small in magnitude, and border adjustment tariffs have collateral effects in terms of trade declines, and in many countries, welfare losses. These findings contrast with the implications of climate policy in large economies, where emission leakages are much more significant and the impact on trade less costly. Our main results also indicate that carbon taxes and tariffs will not be enough for most developing countries to meet their net-zero emission targets dictated by the VERs.

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1 Introduction

As temperatures rise and extreme weather events follow, the pressure is on for governments to address climate change. With a daunting political economy putting an optimal harmonized global carbon tax off the table, there has been a race towards unilateral, preferential, and multilateral initiatives that mix second-best policies to meet mitigation objectives.

Trade policy have been particularly prominent among them.[1] This is not surprising. Unilateral climate policies creates its own justification for trade policy. It opens opportunities for free riding on mitigation, while potentially disrupting comparative advantages. In this environment, trade policy emerged as a popular solution to the fear of emission and competitive "leakages".

There is some precedent work that has studied the effectiveness of trade policy as an environment policy (e.g., Copeland et al., 2022). Yet, most of the discussion has been focused on large countries like the U.S., China and the E.U. While this seems justifiable—these are the world's largest economies, greenhouse gas (GHG) emitters, and users of trade-related climate measures—they do not necessarily face the same policy dilemmas confronted by smaller, developing economies.

There are good reasons for that. First, developing countries are smaller, and unlike large economies, they have less reasons to worry about second-order impacts of domestic carbon measures on carbon leakage. Second, trade is responsible for a significant part of their GDP; and finally, since their shares of global emission range are limited, potential trade-related welfare losses due to trade-related climate measures (TrCMs) might be significantly higher than potential emission-related externality gains.

In this paper, we focus on trade policy's potential contribution for one of the most pressing climate policy challenges these countries face: meeting voluntary emission restraints (VERs), better known as "nationally determined contribution (NDC)", submitted under the

[1] Between 2009 and 2020, 3,460 trade-related climate measures (TrCMs) were reported to the WTO (World Trade Organization, 2023). Carbon border tariffs, enforceable environmental chapters in preferential trade agreements and a myriad of regulations and private sustainability standards stand out.

auspices of the 2015 Paris Agreement. These NDCs are climate action plans that signatories of the agreement are required to submit periodically, setting quantitative targets for GHG emissions, as well as adaption goals.[2] As of today, all 193 parties of the agreement–82 percent of which are developing countries–have at least one NDC, covering approximately 95 percent of the global emissions. Ninety-three percent of countries set emission targets for 2030, with the rest also including longer-term targets.[3] In addition, countries have pledged to meet "net-zero emissions" or "carbon neutrality" targets by the year 2050 or later.[4]

For the purposes of our analysis, we focus on the net-zero emissions target for a representative sample of developing countries in LAC, Africa, and Asia.[5] We also focus our analysis on a conspicuous subsample of TrCMs. They are divided into two groups: those that are in the traditional realm of trade policy, related to tariff reform and potential emission biases a la Shapiro (2021); and those that combine a Pigouvian carbon tax with border adjustments.[6]

To study the role of trade policy—as a stand-alone instrument and combined with climate policies—in meeting the zero-emission targets, and its impact on trade and welfare, we developed a new quantitative general equilibrium framework. The starting point is Caliendo and Parro (2015); namely, a framework with multiple countries, multiple sectors, intermediate goods, input-output linkages, and trade policy.

We extend this framework in three main dimensions. First, we model extractive sectors (e.g., coal, oil, gas). We assume a continuum of producers with heterogeneous productivity to produce goods in extractive sectors. Firms demand labor, dirty natural resources, and intermediate goods from all industries. Natural resources are non-traded specific factors (e.g.,

[2] UNFCCC (2023).

[3] UN (2024).

[4] The initial frequency was five years (starting in 2020), but, as the climate crisis worsened, it has been shortened, in practice, to two years, as countries were required to raise the ambition of their targets in 2022.

[5] The aim is to cover countries that occupy distinct positions in the "smallness spectrum," that is, in their ability to impact international prices, particularly across fossil fuel extractive sectors and the so-called energy-intensive trade-exposed industries (EITE), which account for most of the global emissions in tradables. Fischer and Fox (2018) provide a detailed list of EITE as defined by American Clean Energy and Security (ACES) Act of 2009.

[6] One of the downsides of this option is to overlook land use emissions and related mitigation measures (e.g., the EU Deforestation Free Regulation-EUDR), which are particularly relevant for a sizable number of developing countries.

mines, oil reserves, etc.) used to produce goods in a given extractive sector that can be traded across countries. The rest of the economy is composed of non-extractive sectors, where there are also heterogeneous firms producing in tradable and non-tradable sectors using labor and intermediate goods with input-output linkages as in Caliendo and Parro (2015). Second, we consider that production generates different amount of CO_2e emissions across sectors and countries, and households experience desutility from carbon emissions, modeled as a pure externality as in Shapiro (2021). Third, we model a general set of taxes along the value chain—on production, intermediate and final consumption, and on labor—which allows for different options of carbon taxes. In our framework, trade policy as well as each of these taxes impact emission in general equilibrium. In particular, we show how to account for the tax structure in the market clearing conditions in our framework that determine equilibrium prices, production, and therefore, emissions across countries and sectors.

We take the model to a world with 104 countries, including 48 developing economies with net-zero emission targets, and 34 sectors (29 tradable sectors). We use data from the 2014 GTAP 10 multi-region input-output table (GTAP-MRIO) (Carrico et al., 2020) to obtain production, trade, and input and factor shares across countries and sectors. We also obtain greenhouse gas emissions (GHG) across countries and sectors from GTAP. The different taxes in our model are computed using information on revenues and expenses from GTAP, as well as other sources as described in the quantitative section. We use emission intensities and estimates of the social cost of carbon (SCC) to discipline carbon taxes and carbon border tariffs, and we discipline the damage function in the household's utility following Shapiro (2021).

Our framework allows for the study of emissions and other trade-related outcomes of different carbon taxes, TrCMs, and taxes in general equilibrium. Our quantitative analysis focuses on a subset of them. In particular, we concentrate on studying the effects of changes in import tariffs with and without a production carbon tax. To this end, we organize the analysis around two sets of counterfactuals. In the first set, we explore the effects of removing potential emission biases in the countries' import tariffs à la Shapiro (2021), with and without trade liberalization. In the second set, we look at the impact of a production carbon tax, with and without a carbon border tariff (carbon tariff hereafter) to mitigate leakages. We also explore variations in sector incidence (EITE versus all sectors) and in international environment (with and without carbon taxes among the world's largest economies). To compute these counterfactual scenarios, we show how to compute exact-hat algebra (Dekle et al., 2008, Costinot and Rodríguez-Clare, 2014, Caliendo and Parro, 2015) in a framework with a general set of set of taxes and emission externalities.

We find that trade policy has large trade effects but little effects on emissions in net-zero developing countries. Hence, it is not very effective for climate policies that directly target emissions. Carbon taxes are the most effective policy tool to reduce emissions in developing countries, but they come with the cost of a fall in trade and welfare. Our findings also suggest that carbon taxes and tariffs, even when set at the currently estimated global social cost of carbon (SCC), will not be enough for most developing countries to meet their net-zero emission targets.

Trade policy in the form of carbon tariffs is effective in mitigating emission leakages. However, these leakages in a typical developing country hardly matter for global emissions, and carbon tariffs come at the cost of magnifying the decline in trade and resulting in welfare losses for a significant group of countries. This finding contrasts with the implications of climate policy in large economies, where emission leakages are much more significant and the impact on trade less costly.

These results are robust to changes in the sectoral incidence of the tax and to different global environments. The use of carbon tariffs appears to be questionable for developing countries, even when large economies impose carbon taxes and tariffs. There appears to be no environmental or trade grounds for retaliation.

Our paper is related to a growing literature that incorporates environmental dimensions into quantitative, general equilibrium macro and trade models as in Aichele (2013); Egger and Nigai (2015); Shapiro (2016); Larch and Wanner (2017); Larch and Wanner (2024); Shapiro and Walker (2018); Shapiro (2021); Kortum and Weisbach (2021); Caron and Fally (2022), Conte et al. (2022), Weisbach et al. (2023), Golosov et al. (2014), Farrokhi and Lashkaripour (2021), Garcia-Lembergman et al. (2024a, 2024b). These works have studied the role of different policies on the environment from different angles such as the effects of carbon taxes in Europe, optimal carbon policies, the role of multinational firms, among others. We depart from most of them, though, by developing a new quantitative framework with emissions, extractive sectors, input-output linkages, and a broad set of policy instruments, as discussed previously. As a result, we contribute to both the trade and public finance literatures by providing a general equilibrium framework that allows to study quantitatively the role of different taxes on trade, emissions, and welfare. Second, our quantitative framework maps exactly into the GTAP world input-output dataset for a large number of countries of sectors, which allows us to study, as described previously, the role of different policies in developing countries, contrasting previous literature that has exclusively focused on environmental policies in Europe and other developed countries. This is an important aspect of our analysis since, as discussed previously, developing countries do not necessarily face the same environmental policy dilemmas as developed countries. In fact, our results show that the role and effects of trade policy on the environment are radically different from that in developed countries.

The rest of the paper is organized as follows. Section 2 develops a quantitative general equilibrium trade framework with emissions and taxes. In Section 3 we perform our quantitative analysis. In subsection 3.1 we describe how we take our framework to data, and in subsection 3.2 we discuss the design of the policy experiments that we study in our quantitative analysis. In subsection 3.3 we discuss our main findings, and Section 4 concludes. We relegate the detail of the derivations of the model's equilibrium conditions, data descriptions, and the descriptions of additional results to the technical appendix.

2 A Model with Trade, Emissions, and Taxes

In this section we describe a quantitative general equilibrium model to evaluate the effect of different policies on emissions across countries. The model features N countries indexed by n, i, and in each country there are J sectors indexed by j, k. Sectors are of two types: extractive and non-extractive. A continuum of producers with heterogeneous productivity produces goods in extractive sectors. To produce in extractive sectors, firms demand labor, dirty natural resources, and intermediate goods with input-output linkages. Natural resources are fixed in supply across countries and sectors and, as mentioned earlier, non-traded, but output in the extractive sectors can be traded across countries. The rest of the economy is composed of non-extractive sectors (tradables and non-tradables), where there are also heterogeneous producers that demand labor and intermediate goods with input-output linkages as in Caliendo and Parro (2015). Producers emit different amounts of emissions across sectors and countries, and households experience disutility from carbon emissions that we model as pure a externality as in Shapiro (2021). In addition, we include a general set of taxes that might affect emissions in general equilibrium: i) taxes on production, $t^j_{n,p}$, ii) taxes on consumption of materials (intermediates goods), $t^j_{n,m}$, iii) taxes on consumption of final goods, $t^j_{n,c}$, iv) taxes on the use of labor, $t^j_{n,l}$, and v) tariffs, τ^j_{ni}. In what follows, we use this notation to define t and τ as one plus the respective tax or tariff, respectively.

We start with the problem of a representative household in each country in the next subsection.

2.1 Households

In each country n there is a mass L_n of representative households, who supply one unit of labor inelastically. A representative household in country n maximizes utility by consuming final goods C^j_n from each sector j. The preferences of the household are given by $u(C_n) = \prod_{j=1}^{J} \left(C^j_n\right)^{\alpha^j_n} \left[1 + \delta \left(Z - Z_0\right)\right]^{-1}$, where α^j_n is the share of income spent on final consumption in region n on sector j, with $\sum_{j=1}^{J} \alpha^j_n = 1$.

The expression $\left[1+\delta\left(Z-Z_0\right)\right]^{-1}$ represents the disutility of carbon. The term Z_0 represents global emissions in a baseline scenario and Z are global emissions in an alternative policy scenario. We let δ be a damage parameter that we calibrate such that a one ton increase in emissions leads to reduction in global welfare that matches the SCC estimates. As described previously, emissions are treated as pure externality and the representative household does not take the last term into account when maximizing utility.

Households choose their consumption bundle of in order to maximize utility subject to the budget constraint $I_n = \sum_{j=1}^{j} t_{n,c}^{j} P_n^j C_n^j$. The budget constraint states that the sum of final goods expenditures, tax inclusive, in all sectors equals household's income I_n, which is derived from several sources: labor income, factor payment from dirty natural resources, lump-sum transfers from tax revenues, and trade deficits. We, therefore, assume that households are the owners of all production factors in the economy. The local price index in country n is given by $P_n = \prod_{j=1}^{J}\left(\frac{P_n^j}{\alpha_n^j}\right)^{\alpha_n^j}$.

2.2 Extractive and Intermediate Good Producers

As explained above, the economy features two types of sectors: extractive and non-extractive. A continuum of intermediate goods $\omega^j \in [0,1]$ is produced in each sector j, either extractive or non-extractive. Extractive and non-extractive producers have heterogeneous productivity to produce a good ω^j. Firms differ in terms of efficiency in production, and we denote by z_n^j the efficiency of producing good ω^j in country n.

Firms extract dirty energy resources (coal, gas, or oil) by producing with a constant return to scale technology that use labor, dirty natural resources, and material inputs from all sectors. In particular, the production function of a variety ω^j in extractive sectors is given by:

$$q_n^j\left(\omega^j\right) = z_n^j\left(\omega^j\right)\left[l_n^j(\omega^j)\right]^{\gamma_n^{l,j}}\left[e_n^j\left(\omega^j\right)\right]^{\gamma_n^{e,j}}\prod_{k=1}^{J}\left[m_n^{k,j}\left(\omega^j\right)\right]^{\gamma_n^{k,j}}, \tag{2.1}$$

where l_n^j and e_n^j are the demands for labor and dirty natural resources respectively, and $m_n^{k,j}$ is the demand for materials from sector k used to produce in sector j. Natural resources in sector j, e_n^j, are specific to the production in the extractive sector j and they can be thought as gas mines to produce gas, oil reserves to produce oil, etc. The factor shares $\gamma_n^{l,j}$ and $\gamma_n^{e,j}$ are the share of labor and dirty natural resources in output, and $\gamma_n^{k,j}$ is the share of materials from sector k used to produce in sector j. Production exhibits constant return to scale, so that $\sum_{k=1}^{J} \gamma_n^{k,j} = 1 - \left(\gamma_n^{l,j} + \gamma_n^{e,j}\right)$.

In non-extractive sectors, heterogeneous producers also produce with a constant return to scale technology, but only demand labor and materials to produce intermediate goods, namely $\gamma_n^{e,j} = 0$ and $\sum_{k=1}^{J} \gamma_n^{k,j} = 1 - \gamma_n^{l,j}$.

With perfectly competitive markets, firms price at unit cost, $c_n^j / z_n^j \left(\omega^j\right)$, where c_n^j is the cost of an input bundle in sector j and country n. In extractive sectors, the input bundle costs are given by

$$c_n^j = t_{n,p}^j \Upsilon_n^j \left(t_{n,l}^j w_n\right)^{\gamma_n^{l,j}} \left(r_n^j\right)^{\gamma_n^{e,j}} \prod_{k=1}^{J} \left(t_{n,m}^k P_n^k\right)^{\gamma_n^{k,j}}, \tag{2.2}$$

where is Υ_n^j a constant specific to each country and sector.[7] The cost of an input bundle in country n is affected by a tax on production in sector j, and by taxes on the use of labor and materials from all sectors. These taxes increase the cost of producing good j in country n. For material inputs and labor, the magnitude of this burden is given by both the magnitude of the tax and by its relevance in the production structure of sector j in country n. The terms w_n and r_n^j are the wage in country n, and the rent of energy resources in country n and sector j. The price of the composite of materials from sector k is given by P_n^k.

Following the discussion above, the input bundle costs for non-extractive firms are not exposed to the rent of energy resources, namely $\gamma_n^{e,j} = 0$.

In location n, sourcing intermediate goods from location i entails an iceberg-type shipping cost denote by $d_{ni}^j \geq 1$. In addition, firms in n sourcing goods from i pay an ad-valorem tariff, where τ_{ni}^j is defined as one plus the tariff rate. It follows that $d_{nn}^j = \tau_{nn}^j = 1$.

[7] For extractive firms the constant is equal to $\Upsilon_n^j = \left(\gamma_n^{l,j}\right)^{-\gamma_n^{l,j}} \left(\gamma_n^{e,j}\right)^{-\gamma_n^{e,j}} \prod_{k=1}^{J} \left(\gamma_n^{k,j}\right)^{-\gamma_n^{k,j}}$ while for non-extractive firms it is equal to $\Upsilon_n^j = \left(\gamma_n^{l,j}\right)^{-\gamma_n^{l,j}} \prod_{k=1}^{J} \left(\gamma_n^{k,j}\right)^{-\gamma_n^{k,j}}$. See the appendix for the complete derivations.

Firms source intermediate goods from the lowest-cost supplier around all locations, and therefore, the effective price paid in country n for a variety ω^j is given by

$$p_n^j\left(\omega^j\right) = \min_i \left\{ \frac{c_i^j d_{ni}^j \tau_{ni}^j}{z_i^j\left(\omega^j\right)} \right\} \tag{2.3}$$

In a non-tradable sector, we have that $d_{ni}^j = \infty$, and therefore $p_n^j(\omega^j) = c_n^j / z_n^j(\omega^j)$.

2.3 Final Good Producers

The producer of the composite final good aggregates intermediate goods purchased from the lowest-cost suppliers with a CES production technology. The resulting composite good is used either for the production of intermediate goods or final consumption.

As in Eaton and Kortum (2002), we assume that firms in country n and sector j draw productivities, $z_n^j\left(\omega^j\right)$, from a Fréchet distribution, with a location parameter, $\lambda_n^j \geq 0$ and a shape parameter θ^j. Using the properties of the Fréchet distribution, we solve for the distribution of prices, and obtain the sectoral price index in country n and sector j, which is given by

$$P_n^j = A_n^j \left[\sum_{i=1}^{N} \lambda_i^j (c_i^j d_{ni}^j \tau_{ni}^j)^{-\theta^j} \right]^{-\frac{1}{\theta^j}}, \tag{2.4}$$

where A_n^j is a constant.[8]

2.4 Sectoral Bilateral Trade Shares

The total expenditures on sector j goods in country n is given by $X_n^j = P_n^j Q_n^j$, and we denote by X_{ni}^j the expenditure in country n on sector j goods sourced from country i. Therefore, the expenditure share in country n on sector j goods purchased from country i, π_{ni}^j is defined as $\pi_{ni}^j = X_{ni}^j / X_n^j$. Using again the properties of the Fréchet distribution, we have that the sectoral bilateral trade shares are given by

$$\pi_{ni}^j = \frac{\lambda_i^j \left[c_i^j d_{ni}^j \tau_{ni}^j\right]^{-\theta^j}}{\sum_{h=1}^{N} \lambda_h^j \left[c_h^j d_{nh}^j \tau_{nh}^j\right]^{-\theta^j}}. \tag{2.5}$$

[8]The detailed derivation of the equation above is presented in the appendix.

Notice that in non-tradable sectors, it follows that $\pi_{nn}^j = 1$. It's also important to emphasize again that in extractive sectors, although the energy natural resources are non tradable, output in those sectors is traded across countries, locally and globally, as the trade patterns in the data show.

2.5 Market Clearing Conditions

Total expenditure on sector j goods in country n is the sum of demand for intermediate goods by firms, $P_n^j \sum_{k=1}^J \int m_n^{j,k}\left(\omega^k\right) d\omega^k$, and demand for final goods by households, $P_n^j C_n^j$. Hence, the expression for total expenditure in country n and sector j is given by

$$X_n^j = \sum_{k=1}^J \frac{\gamma_n^{j,k}}{t_{n,p}^k t_{n,m}^j} \sum_{i=1}^N X_i^k \frac{\pi_{in}^k}{\tau_{in}^k} + \frac{\alpha_n^j I_n}{t_{n,c}^j}, \tag{2.6}$$

where the first term on the right-hand side is the demand for intermediate production, and the second term is the demand from final consumers. Income of a representative household in country n, I_n, is given by

$$I_n = w_n L_n + \sum_{j=1}^J r_n^j E_n^j + T_n + D_n, \tag{2.7}$$

where $w_n L_n$ is the payment to labor, $\sum_{j=1}^J r_n^j E_n^j$ is the total revenues from each dirty energy resources j, T_n represents lump-sum tax transfers to consumers stemming from all taxes.[9] Finally, the term D_n is the trade deficit in country n.[10]

The lump-sum tax transfer T_n in country n is composed of the revenue generated by each tax in our framework, namely revenue from tax on labor, $T_{n,l}$, revenue from tax on consumption of materials, $T_{n,m}$, revenue from tax on consumption of final goods, $T_{n,c}$, revenue

[9]See the appendix for a complete derivation of the expenditure function in terms of expenditure shares.

[10]Following Caliendo and Parro (2015) and Dekle et al. (2008), we allow trade to be unbalanced at the sectoral and country level. The only requirement is that this trade deficit is balanced at the world level. We treat it as an exogenous term which does not change with counterfactuals. However, sectoral trade deficits are endogenously determined.

from production tax, $T_{n,p}$, and revenue from import tariffs, $T_{n,\tau}$. In particular,

$$T_{n,l} = \sum_{s=1}^{J}\sum_{i=1}^{N}\left(t_{n,l}^{s}-1\right)\frac{\gamma_n^{l,s}}{t_{n,l}^{s}}X_i^s\frac{\pi_{in}^{s}}{t_{n,p}^{s}\tau_{in}^{s}},$$

$$T_{n,m} = \sum_{s=1}^{J}\sum_{i=1}^{N}\sum_{k=1}^{J}\left(t_{n,m}^{k}-1\right)\frac{\gamma_n^{k,s}}{t_{n,m}^{k}}X_i^s\frac{\pi_{in}^{s}}{t_{n,p}^{s}\tau_{in}^{s}},$$

$$T_{n,c} = \sum_{s=1}^{J}\left(t_{n,c}^{s}-1\right)\frac{\alpha_n^s I_n}{t_{n,c}^{s}},$$

$$T_{n,p} = \sum_{s=1}^{J}\sum_{i=1}^{N}\left(t_{n,p}^{s}-1\right)X_i^s\frac{\pi_{in}^{s}}{t_{n,p}^{s}\tau_{in}^{s}},$$

$$T_{n,\tau} = \sum_{s=1}^{J}\sum_{i=1}^{N}\left(\tau_{ni}^{s}-1\right)X_n^s\frac{\pi_{ni}^{s}}{\tau_{ni}^{s}}.$$

Finally, the labor market clearing conditions, and the market clearing condition for the energy market are given by

$$w_n L_n = \sum_{j=1}^{J}\frac{\gamma_n^{l,j}}{t_{n,p}^{j}t_{n,l}^{j}}\sum_{i=1}^{N}X_i\frac{\pi_{in}^{j}}{\tau_{in}^{j}}, \tag{2.8}$$

$$r_n^j E_n^j = \frac{\gamma_n^{e,j}}{t_{n,p}^{j}}\sum_{i=1}^{N}X_i\frac{\pi_{in}^{j}}{\tau_{in}^{j}}. \tag{2.9}$$

2.6 Welfare with Emissions

In the following sections, we study the effects of trade policy and carbon taxes on three main outcomes of interest: emissions, trade, and welfare. We have already described the trade structure in the previous subsections. Regarding emissions, the production of intermediate goods generates carbon emissions. In particular, emissions due to production of good j in country n is given by

$$Z_n^j = \frac{\psi_n^j Y_n^j}{P_n^j}, \tag{2.10}$$

where ψ_n^j is the emission intensity of output in country n and sector j, measured in metric tons of carbon emission per unit of output, and it varies by country and sector. The term

Y_n^j represents output in sector j for country n in US dollar, and Y_n^j/P_n^j is a measure of real output.[11]

Welfare, W_n, is derived from the consumer problem, and can expressed as

$$W_n = \frac{I_n}{\prod_{j=1}^{J} \left(\frac{t_{n,c}^j P_n^j}{\alpha_n^j}\right)^{\alpha_n^j} \left[1 + \delta \left(Z - Z_0\right)\right]}. \tag{2.11}$$

2.7 General Equilibrium

The general equilibrium of the quantitative trade framework with emissions and taxes is defined as as follow:

Definition: *An equilibrium under a structure of taxes* $\tilde{\tau}_n = \{t_{n,p}^j, t_{n,m}^j, t_{n,c}^j, t_{n,l}^j, \tau_{ni}^j\}$ *for all country* n *is a vector of factor prices* $\{\mathbf{w}, \mathbf{r}\}$ *for all countries and sectors that satisfies equilibrium conditions (1) to (10).*

Equilibrium in relative changes: Following Dekle et al. (2008), Costinot and Rodríguez-Clare (2014), and Caliendo and Parro (2015), instead of solving for an equilibrium under policy $\tilde{\tau}$ we solve for changes in sectoral prices and factor prices after changing from policy $\tilde{\tau}$ to policy $\tilde{\tau}'$. We now define the equilibrium in relative changes (exact-hat algebra). In particular, we define a variable x the endogenous outcome x in the initial equilibrium under a policy structure $\tilde{\tau}$, and x' the endogenous outcome in the counterfactual equilibrium under a policy structure $\tilde{\tau}'$. Hence, we define the relative change $\hat{x} = x'/x$ as the relative change in the outcome x due to the change in the policy structure $\hat{\tilde{\tau}} = \tilde{\tau}'/\tilde{\tau}$.

Therefore, the equilibrium conditions in relative changes are given by

Cost of input bundle:

$$\hat{c}_n^j = \hat{t}_{n,p}^j \left(\hat{t}_{n,l}^j \hat{w}_n\right)^{\gamma_n^{l,j}} \left(\hat{r}_n^j\right)^{\gamma_n^{e,j}} \prod_{k=1}^{J} \left(\hat{t}_{n,m}^k \hat{P}_n^k\right)^{\gamma_n^{k,j}} \tag{2.12}$$

[11] Note that global emissions equal the summation of emissions across all countries and sectors in the world: $Z_0 = \sum_{j=1}^{J} \sum_{n=1}^{N} Z_n^j$

Price index:

$$\hat{P}_n^j = \left[\sum_{i=1}^{N} \pi_{ni}^j \left(\hat{c}_i^j \hat{\tau}_{ni}^j \right)^{-\theta^j} \right]^{-\frac{1}{\theta^j}} \tag{2.13}$$

Expenditure shares:

$$\hat{\pi}_{ni}^j = \left[\frac{\hat{c}_i^j \hat{\tau}_{ni}^j}{\hat{P}_n^j} \right]^{-\theta^j} \tag{2.14}$$

Total expenditure:

$$X_n'^j = \sum_{k=1}^{J} \frac{\gamma_n^{j,k}}{t_{n,p}'^k t_{n,m}'^j} \sum_{i=1}^{N} X_i'^k \frac{\pi_{in}'^k}{\tau_{in}'^k} + \frac{\alpha_n^j}{t_{n,c}'^j} I_n' \tag{2.15}$$

Labor market clearing:

$$\hat{w}_n = \frac{\sum_{j=1}^{J} \frac{\gamma_n^{l,j}}{t_{n,p}'^j t_{n,l}'^j} \sum_{i=1}^{N} X_i' \frac{\pi_{in}'^j}{\tau_{in}'^j}}{w_n L_n} \tag{2.16}$$

Energy resource market clearing:

$$\hat{r}_n^j = \frac{\frac{\gamma_n^{e,j}}{t_{n,p}'^j} \sum_{i=1}^{N} X_i' \frac{\pi_{in}'^j}{\tau_{in}'^j}}{r_n^j E_n^j} \tag{2.17}$$

By computing the equilibrium in relative changes, we do not need to identify trade costs d_{ni}^j and fundamental productivities λ_n^j. The relevant information on these fundamentals is contained in the actual trade and production allocations. Computing the equilibrium in relative changes requires information on sectoral trade shares π_{ni}^j, payment to each production factor $w_n L_n$ and $r_n^j E_n^j$, input and factor shares γ_s, final consumption shares α_s, the set of taxes $\tilde{\tau}$, and the trade elasticities θ^j. In the next section we describe the data sources to obtain these parameters and allocations. As discussed previously, important outcomes in our quantitative analysis are emissions and welfare. To conduct the analysis, we need to obtain emission data across countries and sectors, and discipline the damage function δ, as we describe in the next section.

It is important to highlight that an advantage of solving our framework with emission and taxes in relative changes is that we do not need to compute the emission intensity per unit of output ψ_n^j to perform counterfactual analysis. By expressing equation (2.10) in hat-changes, we can see that computing emissions in counterfactual scenarios is information only requires information on factual emissions Z_n^j and the equilibrium change in real gross output $\hat{Y}_n^j/\hat{P}_n^j$ that results from solving the counterfactual general equilibrium.

To solve for the equilibrium in relative changes, we start by guessing a vector for the changes in wages, $\hat{\mathbf{w}} = (\hat{w_1}, ..., \hat{w_N})$ and a vector for the changes in energy rent prices, $\hat{\mathbf{r}}=$ $[(\hat{r}_1^1, ..., \hat{r}_N^1), (\hat{r}_1^2, ..., \hat{r}_N^2), (\hat{r}_1^3, ..., \hat{r}_N^3)]$. Given these initial guesses, we then solve for sectoral price indices $\hat{P}_n^j(\hat{\mathbf{w}}, \hat{\mathbf{r}})$ using equations (2.12) and (2.13). We then compute the sectoral bilateral trade shares and expenditure shares using (2.14) and (2.15). We then check if the labor market clearing condition (2.16) and energy market clearing condition (2.17) are satisfied. If market clearing conditions do not hold, we adjust our initial guess of $(\hat{\mathbf{w}}, \hat{\mathbf{r}})$ and repeat the algorithm until convergence is reached.

3 Quantitative Analysis

3.1 Taking the Model to the Data

We discipline our model with data from the 2014 GTAP 10 multi-region input-output table (GTAP-MRIO) (Carrico et al., 2020) - the latest available year. We take our framework to a world of 104 countries and 34 sectors (29 tradables).

As discussed in the previous section, to compute the model in relative changes and perform counterfactual analysis, we need information on sectoral bilateral trade shares π_{ni}^j, factor payments $w_n L_n$ and $r_n^j E_n^j$, factor, inputs, and final consumption shares $\gamma_n^{l,j}, \gamma_n^{e,j}, \gamma_n^{k,j}, \alpha_n^j$, tariffs and tax rates, $\tau_{ni}^j, t_{n,c}^j, t_{n,m}^j, t_{n,l}^j, t_{n,p}^j$, emissions Z_n^j, the damage parameter δ, and the trade elasticities, θ^j.

From GTAP data, we obtain sectoral bilateral trade shares, factor payments, gross output, and the production and final consumption shares. In particular, using information on country n expenditures of sector j's goods from country i, X_{ni}^j, we construct sectoral bilateral trade shares, $\pi_{ni}^j = X_{ni}^j/X_n^j$. The labor shares, $\gamma_n^{l,k}$, energy shares, $\gamma_n^{e,k}$, and intermediate good's shares, $\gamma_n^{j,k}$, are obtained by dividing the value added from labor, energy and intermediate consumption, respectively, by gross output. Final consumption shares, α_n^j

are calculated by inverting the expression for total expenditure in (2.6), and using the data described in this section to obtain the inputs needed in the expression for total expenditure.[12]

Greenhouse gases emissions for the year 2014 across sectors and countries, Z_n^j, are obtained from GTAP. The set of tax rates in our framework are also computed using information from the GTAP database. Production tax rates, $t_{n,p}^j$, final consumption tax rates, $t_{n,c}^j$, material tax rates, $t_{n,m}^k$, and labor tax rates, $t_{n,l}^j$, were computed by dividing the corresponding tax revenues at the country sector level by their respective expenses. Tariffs, τ_{ni}^j, are obtained from two sources. Our main source is the GTAP data. We calculate an applied bilateral tariffs by sector diving what was collected in tariff duties by the total bilateral import value plus international trade and transport margins. However, when there is no trade for a particular country pair-sector, this ratio is undefined and we cannot calculate the tariff rate. For those cases we use nominal simple average tariffs processed by Moreira and Dolabella (2023) from WITS HS6 to the original GTAP aggregation. We compute trade elasticities, θ^j, for each of our sectors as a output-weighted average of the original GTAP elasticities.

Lastly, the damage parameter, δ, is calibrated such that a one ton increase in emissions leads to a \$163 reduction in global welfare, according to an estimate of the global social cost of GHG (EPA, 2023). For more information and details on the calibration of the model and data sources, please refer to the appendix.

3.2 Design of Counterfactual Scenarios

Our counterfactual scenarios are motivated by the importance of evaluating the potential role of trade policy in meeting developing countries' VERs. They are designed to offer answers to critical policy questions such as: Can trade policy do the job alone? What if they are combined with climate policies such as carbon taxes? What are the trade and welfare impacts of different policy mixes in diverse global environments?

Target and sample. We focus on those medium and small developing economies that

[12] We normalize the resulting final consumption shares so that they remain non-negatives.

have pledged to meet "net-zero emissions" or "carbon neutrality" VERs by 2050 or later.[13] Even though in most cases emission commitments have earlier, intermediate targets–mostly for 2030– these are methodologically too heterogeneous to allow for a meaningful cross-country analysis. Net zero and carbon neutrality are understood as "overlapping concepts" with similar meaning (IPCC, 2023). They both require that GHG emissions to be offset by an equivalent removal of these gases from the atmosphere. However, they are understood to have jurisdictional differences. Net zero would cover just territorial, while carbon neutrality would also include extra-territorial emissions (so-called value chain emissions) with allowances for purchases of carbon offsets abroad. Both concepts have some ambiguity on the gases covered.[14]

For analytical simplicity, we assume in our counterfactuals that all those VERs refer to territorial emissions, covering all GHGs. We broadly refer these pledges as net-zero VERs. We also focus on the policy impact on gross emissions. There are three reasons for that. First, carbon capture technologies are still on their infancy[15]; second, even though the potential for land use abatement (afforestation and reforestation) is far from negligible (an estimated of 25 per cent of global CO_2 emissions), it is very concentrated in a few large countries (Bastin et al., 2019); and third, as discussed earlier, land use emissions are exogenous to our model. As a robustness test, we use recent estimates for afforestation and restoration potential at the country level (Bastin et al., 2019) to have a sense of how far trade policies can go if countries exploit all their land-use, abatement potential.

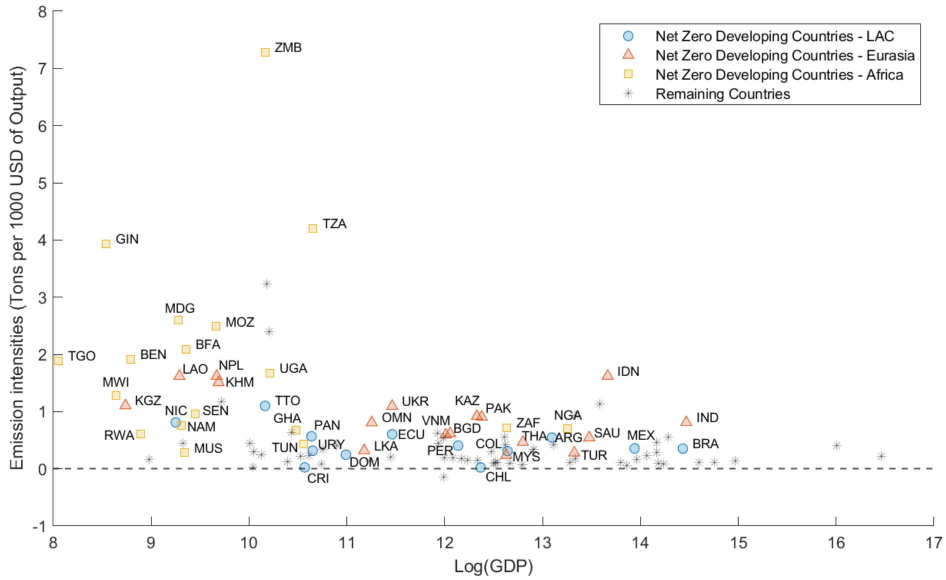
Our sample of 104 countries includes 48 of the 108 net-zero developing economies, classified under three regions: Latin America and the Caribbean, Africa, and Eurasia. We exclude from the counterfactual analysis China and Developing Europe. The former for its size and market power, which entail trade and emission dynamics that are akin to a large, devel-

[13] Our definition of developing economies is based on the IMF-WEO classification of "developing and emerging economies".

[14] Data on the countries NDCs was retrieved form the Net-Zero Tracker (see Lang et al., 2024). We also consider Ecuador, which has a target of "zero carbon", in our group of net-zero developing economies.

[15] See Bart (2023).

Figure 1. Economic Size and GHG Emission Intensities of Net Zero Developing Economies.



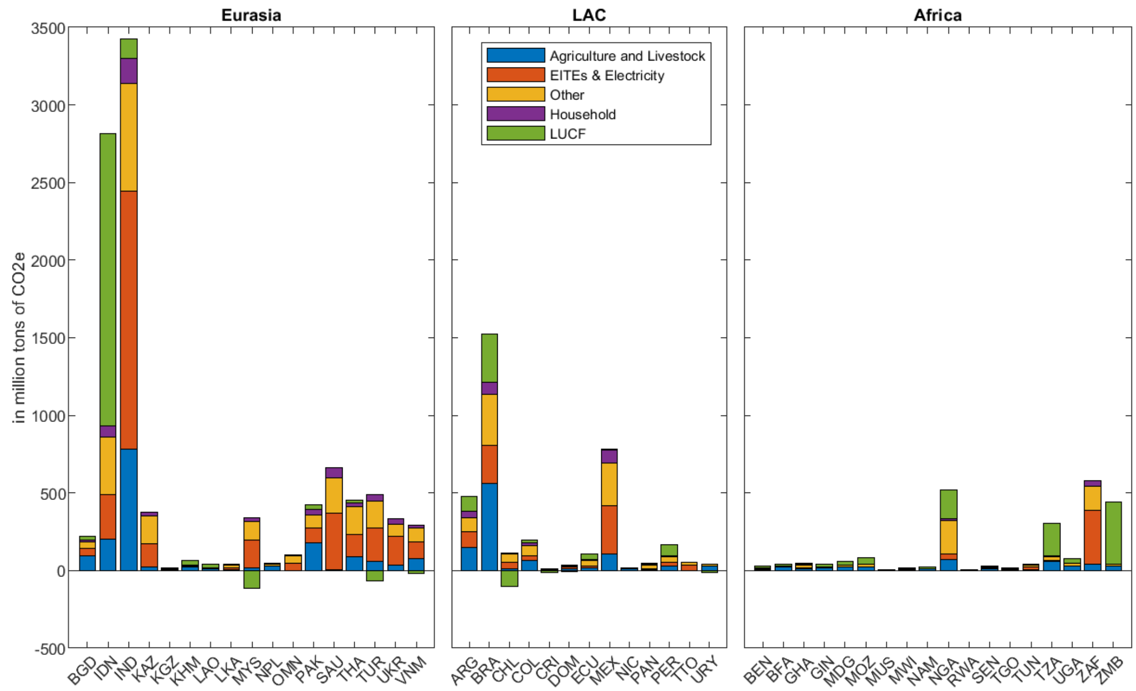
Source: GTAP10 - MRIO.

oped economy. The latter because its trade and environment policies are tied to developed European Union (EU). Despite these exclusions, the sample covers a wide spectrum of size and energy "cleanliness" (see Figure 1), allowing the results to capture marked differences in these two dimensions. Overall, our sample of the net-zero developing countries' represent 31% of global emissions and 63% of the developing countries' emissions . Figure 2 shows how emissions considered in our sample spread across broad sectors and countries. The figure also highlights negative emissions in some countries attributable to Land-Use-Change and Forestry (LUCF) activities. The negative emissions from land use are taken into account in the net-zero emission targets. In terms of GDP, our net-zero developing economies cover 18% of global GDP and 30% of all developing countries' GDP.

We divided our counterfactual scenarios into two sets: stand-alone trade policy and climate-cum-trade actions, using, in both cases, the net-zero target as the policy metric.

Stand-alone trade policy. The first set of counterfactual scenarios studies how far trade policy can go alone on mitigation, while minimizing trade and potential welfare losses.

Figure 2. GHG Emission of Net Zero Developing Economies.



Source: GTAP10 - MRIO.

It is inspired by Shapiro (2021) findings that the structure of protection in most countries provides a subsidy to emissions as tariffs—driven by tariff escalation—favor trade in emission-intensive goods.

We study two trade policy responses. We begin with a trade reform that, à la Shapiro, would harmonize tariffs around the countries' bilateral mean to eliminate potential emission biases of trade policy. Alternatively, we consider a tariff harmonization that is combined with trade liberalization. In this case, only MFN tariffs take part in the convergence and the target is the OECD MFN average rather than the countries' own bilateral mean, which brings the average tariff down to about 3.5%.[16] This second trade policy design accounts for the fact that tariffs might be bound by either WTO or preferential trade agreements. It also takes into consideration that the simple harmonization of tariff rates around the countries' bilateral mean might carry high inefficiency costs—as Moreira and Dolabella (2023) have

[16]For country-sectors whose preferential tariffs are higher than the OECD MFN mean, we also change those preferential tariffs to the OECD MFN mean to avoid renegotiating PTA benefits.

shown, this would imply substantial increase in tariffs for intermediate goods in some regions and sectors.

Climate-cum-trade actions. In the second set of counterfactuals, trade policy plays a supporting role to climate actions trained at net-zero targets. We start with a scenario where proactive, climate conscious countries impose a unilateral Pigouvian carbon tax on the direct production emissions of EITE and electricity sectors (hereafter EITE-E), similar to the current scheme being implement by the EU.[17] The carbon tax is based on the latest US EPA (2023) SCC estimate: approximately US$ 163 per ton of carbon emissions.[18]

For each country-sector pair a carbon tax surcharge is calculated according to the following formula:

$$ct^j_{n,p} = \frac{Z^j_n cp}{Y^j_n}, \tag{3.18}$$

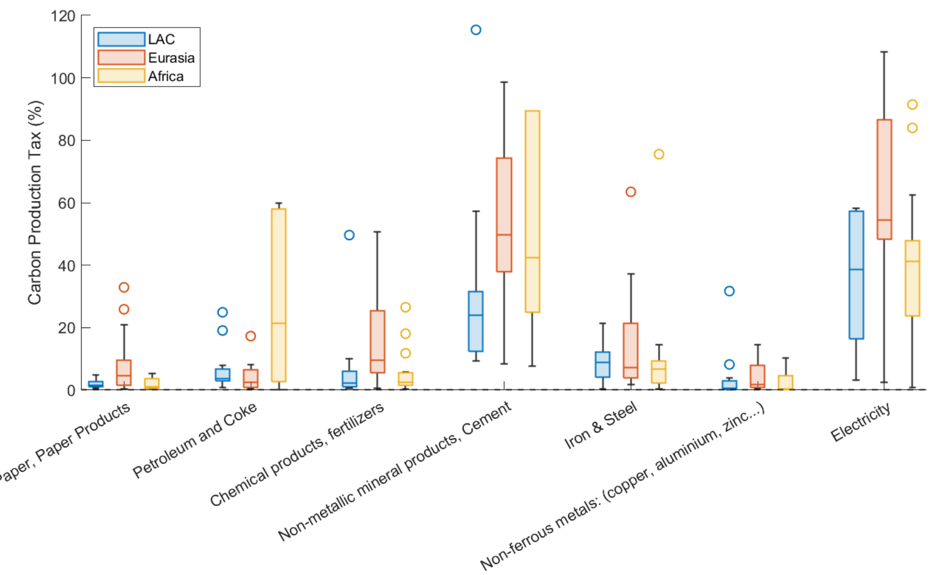
where $ct^j_{n,p}$ is the carbon tax surcharge applied by country n to sector j, Z^j_n are emissions in million tons from country n in sector j, Y^j_n in the gross output from country n in sector j in million US dollar and cp is the carbon price (which we set to be equal to the SCC) in US dollar per tons. This formula gives us an ad-valorem tax expressed as a percentage of the value of output, along the lines of UNCTAD (2021). Figure 3 shows what a US$163 tax per ton of carbon would represent in terms of $ct^j_{n,p}$ for each EITE-E sectors in our sample of net-zero developing countries. Having computed the unilateral carbon tax according this formula, the counterfactual tax on production is given by $t^{j\prime}_{n,p} = t^j_{n,p} + ct^j_{n,p}$.

As the carbon tax may lead to emission and competitive leaks, countries consider the option of using a carbon tariff—disciplined to reflect the imported goods emission intensity

[17] We consider the following sectors as EITE industries: Paper and Paper Products, Petroleum and Coke, Chemicals and Fertilizers, Manufacture of Other Non-Metallic Mineral Products, Iron and Steel, Non-Ferrous Metals. Electricity is not per se an EITE sector due to its low trade exposure but because it is subject to the EU carbon trading system and we opted to consider it in our counterfactuals. Whenever we mention the group of EITE-E sectors we are referring to the above-mentioned EITE sectors as well as the electricity sector.

[18] We take the latest estimates by of the social cost of CO_2, CH_4, N_2O provided by EPA (2023) and transform them into CO_2e units. After obtaining a social cost for each gas of US$190, US$57 and US$204, respectively, we weight each price by its participation in total GHG emissions and obtain a global social cost of GHG of around 163US$. FGAS was not considered for the calculation.

Figure 3. CO2 Carbon Tax on Production: Dispersion over Net-Zero Developing Countries



Source: Carbon tax computed as in (3.18), and using data from GTAP10 - MRIO.

—to mitigate these distortions.[19] We compute these border-adjustment tariffs analogous to that of the carbon tax surcharge, namely

$$c\tau^j_{ni} = \frac{Z^j_i cp}{Y^j_i}, \tag{3.19}$$

where $c\tau^j_{ni}$ is the carbon tariff applied by country n on country i exports in sector j. Similarly, we compute our counterfactual tax on production as $\tau^{j\prime}_{ni} = \tau^j_{ni} + c\tau^j_{ni}$.

To assess the carbon tariff contribution to mitigate the leaks and its ultimate impact on trade and welfare, in the next subsection we compute counterfactuals with and without the border adjustment. Furthermore, we consider a more extensive proposal to tax GHG emissions. In particular, we consider a carbon tax as in (3.18) but applied to all GHG gases across all sectors.

In a second group of counterfactuals of this climate-cum-trade-policy set, countries face a different global environment. They consider their policy options in a scenario where their largest markets in the US, the EU, and China introduce coordinated carbon taxes and

[19]For a detailed discussion of carbon border taxes see Böhringer et al. (2022)

tariffs. This is not very distant from what is already occurring in the real world, with the eminent implementation of the EU Carbon Border Adjustment Mechanism (CBAM) and the discussion of similar proposals in the US and the UK.[20] In this setting, countries also have to consider the effects of trade policy as retaliatory/coercive tool to minimize potential market access and terms-of-trade losses associated with their partners' climate action. To keep this "interactive" exercise close to reality, carbon tax and tariffs are applied only to carbon emissions and to EITE-E and electricity sectors. This is, for instance, the approach of the EU CBAM, at least in its initial phase. Table 1 summarizes counterfactuals for each of the developing countries in our net-zero sample.

Table 1. Summary of Counterfactual Scenarios

Counterfactual	EITE-E & CO2	All sectors & All GHG
Stand alone trade policy		
CTF1: Tariffs set to bilateral mean		
CTF2: Tariffs set to OECD MFN mean		
Climate-cum trade policy: Acting alone		
CTF3: Carbon tax on production	✓	
CTF4: Carbon tax on production + carbon tariff	✓	
CTF5: Carbon tax on production		✓
CTF6: Carbon tax on production + carbon tariff		✓
Climate-cum trade policy: Acting in the context of a large country climate club		
CTF7: US, EU, and CHN introduce coordinated carbon tax + carbon tariff	✓	
CTF8: Developing countries introduce carbon tax	✓	
CTF9: Developing countries introduce carbon tax + carbon tariff	✓	

Note: The above table outlines the counterfactual policies analyzed in the subsequent section. Columns 2 and 3 specify the sectoral and emissions coverage of each policy.

[20] China has yet to propose or introduce any carbon tariff but has recently launched an emission trading system (ETS) (See Xiaoying, 2023). For the EU, US and UK proposals see, respectively, European Parlament (2023), Fair Transition and Competition Act (2021) and United Kingdom Government (2023).

3.3 Economic Effects of Trade and Climate Policies

In this section we quantify the trade, emission, and welfare effects of implementing the policies described in the previous subsection. We separate our quantitative analysis in two sets. First we study the effects of each developing country imposing a trade or a combination of trade and climate policies individually. We then move to analyze how the effects and the choices about these policies change in a scenario where large economies implement their own climate policies.

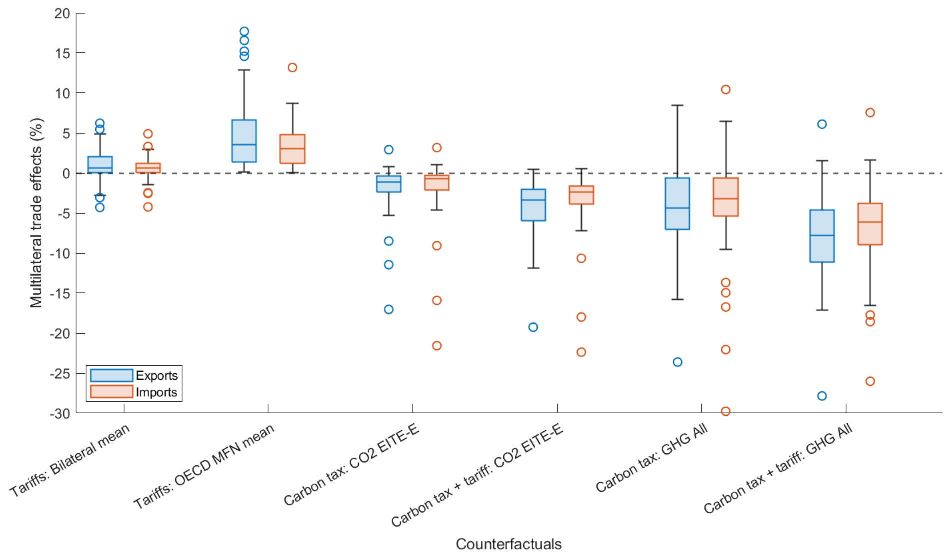
3.3.1 Acting Alone

Trade Effects. The trade effects of the various the policy scenarios described previously are displayed in Figure 4. The x-axis presents six distinct counterfactuals. The first two analyze the effects of trade policies alone. The third and fourth counterfactuals examine the impact of a carbon tax imposed on EITE and electricity sectors, with and without carbon tariffs, respectively. The fifth and sixth counterfactuals extend the analysis to include a GHG tax that encompasses all sectors. The results for each net-zero developing country are displayed in boxplots. In particular, for each counterfactual we plot two boxplots, each one depicting the change in exports and imports, respectively.[21]

Trade and climate policies have generally significant trade effects in the net-zero developing countries. Eliminating the sectoral variation and setting tariffs to the bilateral average (first column in the figure) generally increases trade for most developing countries studied. Around three-fourths of the countries experience an increase in trade, with the median country imports and exports rising by about 0.6%. The second column in the figure shows that combining tariff harmonization with liberalization by converging the MFN tariffs to the OECD MFN mean leads to larger trade effects, with the median country imports and exports rising about 3% and 3.5%, respectively.

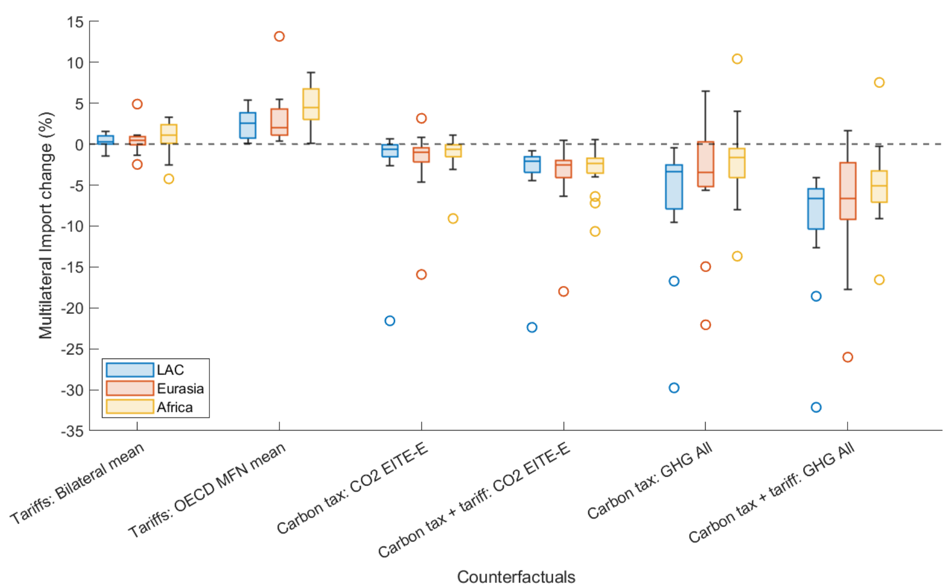
[21]Boxplots graphically depict data distribution, with the box showing the middle 50% of the distribution (interquartile range) and the median marked by a line inside the box. The whiskers extend from the box to the furthest data points within 1.5 times the interquartile range. Any data points beyond this range are considered outliers and are depicted as individual circles.

Figure 4. Trade Effects of Developing Countries Acting Alone



Note: Each counterfactual is evaluated individually for each on of the 48 Net Zero developing countries in our sample. The effects for each country are then summarized in boxplots, indicating the percentage change from the baseline scenario. A few outlines were not displayed in the graph: Carbon Tax: GHG All (PAN,exp.-30.3%) Carbon Tax + CBAM: GHG All (PAN,exp.-33.6%; TTO,imp.-32.1%.)

Figure 5. Import Effects of Developing Countries Acting Alone, by Regions



Note: Each counterfactual is evaluated individually for each on of the 48 Net Zero developing countries in our sample. The effects for each country are then summarized in boxplots, indicating the percentage change from the baseline scenario.

Taxing carbon domestically (third column in the figure) has a negative effect on trade. In particular, most countries experience a drop in trade as a consequence of a carbon tax targeting EITE-E industries. The fourth column in the figure shows that when a carbon tax is combined with a carbon tariff, exports and imports drop further. Finally, the fifth column in the figure shows that a carbon tax that covers all sectors leads, as expected, to a larger decline in trade, which is also magnified by a carbon tariff, as shown in the last column. Figure 5 presents these effects across developing regions. For instance, countries in Africa see their imports and exports (not shown) grow more than in other regions when they reduce import tariffs to the OECD mean given their initially higher level. In addition, the carbon tax applied to EITE-E sectors has a bigger negative impact on trade in Eurasian countries. When applied to all sectors, the largest trade decline is in Latin American countries. These effects are driven by the sectoral pattern of specialization across the regions.

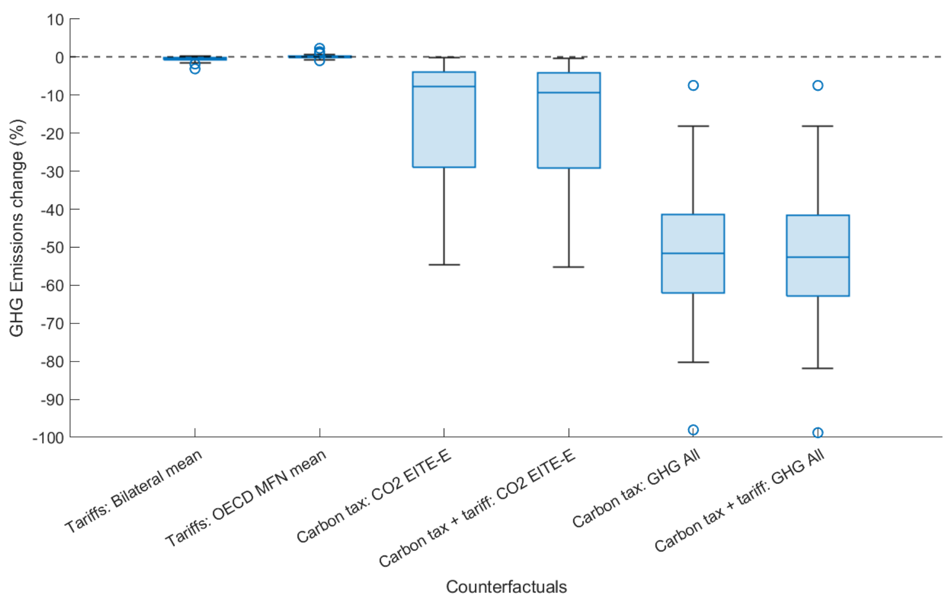
Emission Effects. Figure 6 shows the effectiveness of the various policy scenarios in driving developing countries towards their net-zero emissions goals. Each boxplot depicts the relative change in national GHG emissions relative to a baseline scenario without any policy intervention.

The first takeaway from the figure is the limited efficacy of trade policy alone to reduce emissions. The first two columns in the figure show that it has mild effects on emissions. As an illustration, the first column shows that the largest decline in emissions are in Panama (-3.8%), India (-1.8%) and Thailand (-1.5%), substantially far from the net-zero target of 100%. Combining tariff harmonization with liberalization (second column) also generates minimal overall impact on emissions, and no country comes even close to achieving their GHG mitigation goals.

On the other hand, the implementation of a carbon tax specifically targeting EITE-E and electricity sectors, akin to current policies in the EU, has a larger effect in reducing emissions, albeit with varying effects across developing countries (third column). While the median countries (Togo and Ghana) achieve a reduction of 7.7%, certain countries experience even more substantial reductions, such as Chile (see note in the figure), Malaysia and South Africa, which achieve a reduction of 193%, 55% and 52%, respectively. The heterogeneity in the emission effects across countries is in part explained by the relative significance of EITE-E sectors in the production structure of each country. Chile is the only country that achieve the net-zero emission target with a carbon tax on EITE and electricity sectors. It is among a few exceptional cases due to its carbon capture gains with reforestation (i.e. negative land use change and forestry emissions). A less stringent carbon tax would be enough for the country to achieve its net-zero target.

The EITE-E sectors were the ones experiencing the largest reduction in emissions. For most countries in our sample, electricity was the sector contributing the most for emission reduction in this scenario. As an example, reduction in emissions from electricity accounted for 47.2% of national emissions reductions in the median country.[22] We also observed a small

Figure 6. Emission Effects of Developing Countries Acting Alone



Note: Each counterfactual is evaluated individually for each on of the 48 Net Zero developing countries in our sample. The effects for each country are then summarized in boxplots, indicating the percentage change from the baseline scenario. A few outlines were not displayed in the graph: Chile CTF3 and CTF4:-193%, CTF5: -423%, CTF6 -433% ; Costa Rica CTF5: -226% CTF6: -235%.

[22]Here we take the emission changes in each sector and divide by the total emissions reduction at the country level to compute the contribution of each sector to reduce domestic emissions.

amount emission leakages across non-EITE-E sectors due to higher taxes in EITE-E sectors. For instance, resources redirected from taxed sectors, lead to increased emissions in sectors such as cattle, rice, and other animal products. The fourth column shows that carbon tariffs barely affect the countries' emissions.

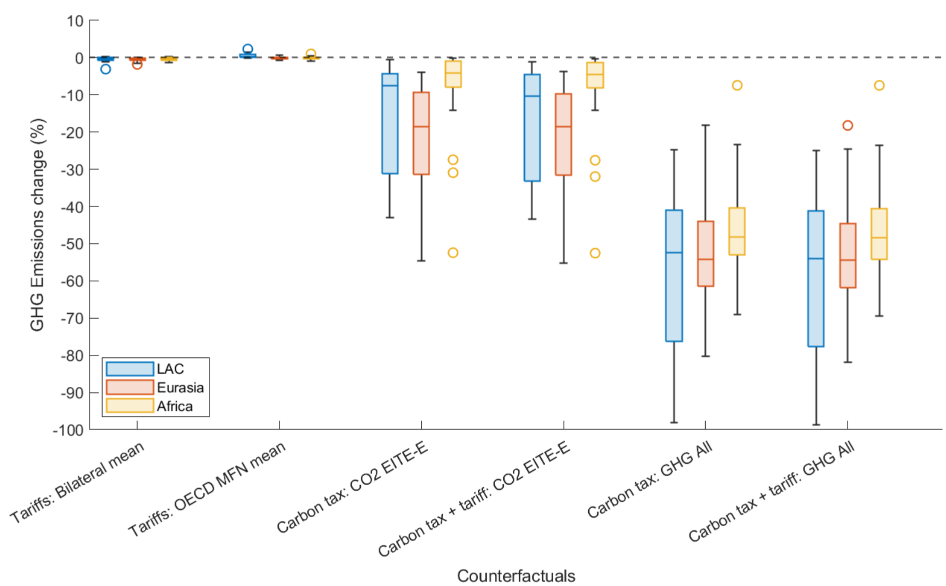
Furthermore, when countries expand the carbon tax scope to encompass all GHG emissions across all sectors (fifth column), the effects become more pronounced. This policy leads to meaningful reductions in emissions for many countries, with the median country (Guinea) achieving a reduction of 52%. The magnitude of emission reductions are also heterogeneous across countries. For example, half of the countries see their emissions drop range from 41.5% (e.g. Brazil, third quartile) to 62% (e.g., India, first quartile). Importantly, two countries achieve their net-zero target: Chile with a reduction of 423.2% and Costa Rica 226.9%. Uruguay almost gets there with a reduction of 98.1% (see note in the figure). These accomplishments are built on high negative emissions from land use change and forestry, which puts less pressure on the other emissions. When the carbon tax is expanded to all sectors, the cattle-raising contributes the most to mitigation, explaining 30.1% of domestic reduction in emissions in the median country (Bangladesh). In this scenario, there is almost no intersectoral leakages. When a all-sectors carbon tax is paired with a carbon tariff, there are only limited additional effects (sixth column).

Figure 7 presents the emission effects by regions. A carbon tax akin to the EU proposal would be more effective in Eurasia than in Latin America and Africa. In particular, it is largely ineffective in Africa - except for a few individual countries - due to the relatively small size of the EITE-E sectors in that region. When the carbon tax covers all sectors, Latin American countries tend to be more successful in moving closer to the net-zero targets compared to other regions, which tends to reflect the greater importance of agriculture-related emissions.

As the fourth and sixth columns show, adding a carbon tariff does not significantly affect emissions. This is not surprising, as they are not designed to reduce domestic emissions, but to mitigate carbon leakage. That is, potential emission and competitive spillovers arising from the carbon tax. This issue raises relevant questions: Does carbon leakage matter for developing countries, both in terms of domestic and global emissions? Is trade policy capable of averting it?

In Figure 8 we compute carbon leakage by dividing the change in million tons of GHG emissions abroad by the total amount of GHG reduced due to the domestic carbon tax, in absolute terms. For instance, the Dominican Republic reduces 7.48 million tons of carbon emission after imposing a carbon tax on EITE-E sectors, which leads GHG emissions abroad to increase by 0.47 million tons. We then obtain a carbon leakage of (0.47/7.48)*100 = 6.3%. If the Dominican Republic were to impose a carbon tariff, its domestic emissions would drop by -7.65 million tons but now emissions abroad would also reduce by 0.24 million tons, which means a complete elimination of the leakage, with emission abroad representing -3.1% (=[-0.24/7.65]*100) of the domestic GHG reduction.

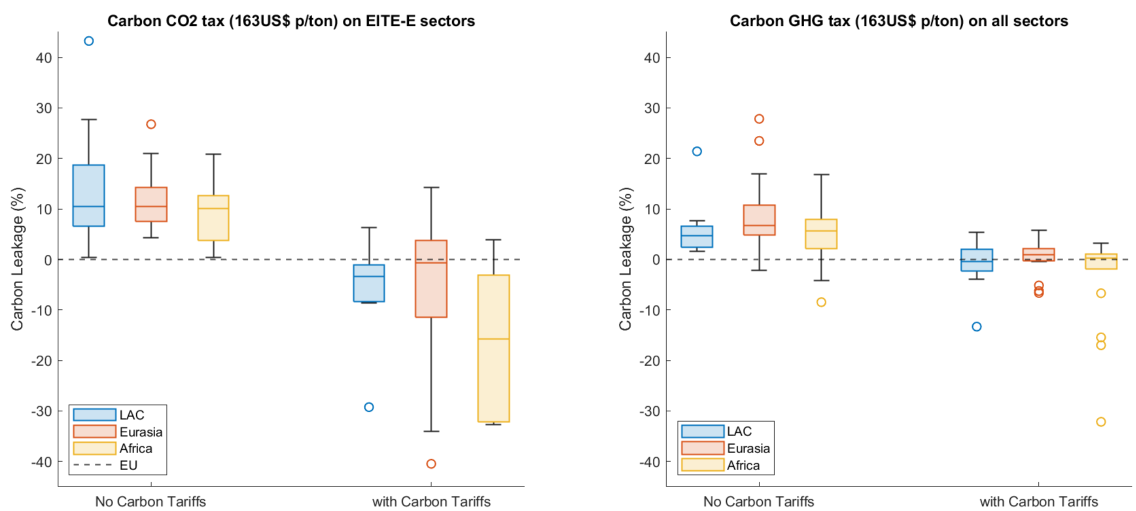
Figure 7. Emission Effects of Developing Countries Acting Alone, by Region



Note: Each counterfactual is evaluated individually for each on of the 48 net zero developing countries in our sample. The effects for each country are then summarized in boxplots, indicating the percentage change from the baseline scenario. A few outlines were not displayed in the graph: Chile CTF3 and CTF4:-193%, CTF5: -423%, CTF6 -433% ; Costa Rica CTF5: -226% CTF6: -235%.

The left panel in Figure 8 compares the effects of a carbon tax on EITE-E sectors (first column), and the combined effects of a carbon tax and tariff. The figure illustrates the effectiveness of trade policy to mitigate emission leakages. The three box-plots in the first column show that the median country faces a carbon leakage of around 10% across all regions, which falls within the lower end of carbon leakage estimates for industrialized economies (Böhringer et al., 2022). There is, though, a high dispersion within regions such as Latin America, with leakages ranging from 0.5% in Chile to 43.3% in Uruguay. When we turn to a scenario with a carbon tariff, we observe that most of the countries, specially in Latin America and Africa, manage to eliminate (and more than eliminate) the emission leakages.

Figure 8. Carbon Leakage When Developing Countries Act Alone, by Region

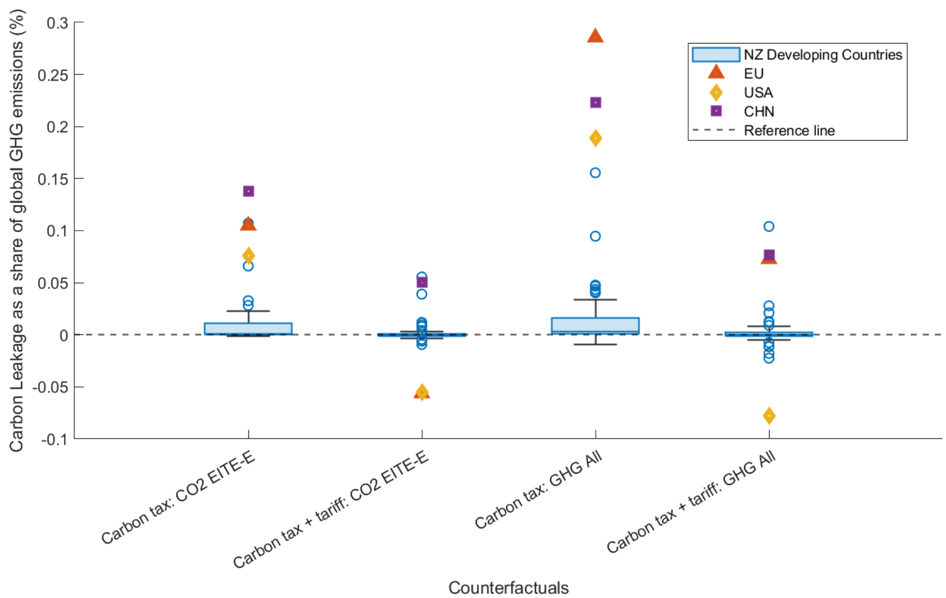


Note: Each counterfactual is evaluated individually for each on of the 48 Net-Zero developing countries in our sample. The effects for each country are then summarized in boxplots, indicating the change in emissions from the rest of the world as a percentage from the absolute reduction in domestic emissions. A few outlines were not displayed in Panel A. No carbon tariff scenario: MOZ,-693%, NAM,70%. Carbon tariff scenario: MOZ,-831%, NAM,-886%, BFA,-120%, URY,-82%.

Trade policy also shows to be effective to eliminate emission leakages when the carbon tax is applied to all sectors (right panel), although in this case emission leakages are relatively smaller, which is explained by the fact that less trade exposed sectors are also targeted.

Even if trade policy seems to be effective in mitigating emissions leakages in developing countries, the question of its relevance remains. As we have shown, these leakages are, on average, a relative small share of domestic emissions, but more importantly, they tend to

Figure 9. Carbon Leakage as Share of Global Emissions: Net-Zero Developing v/s Large Economies



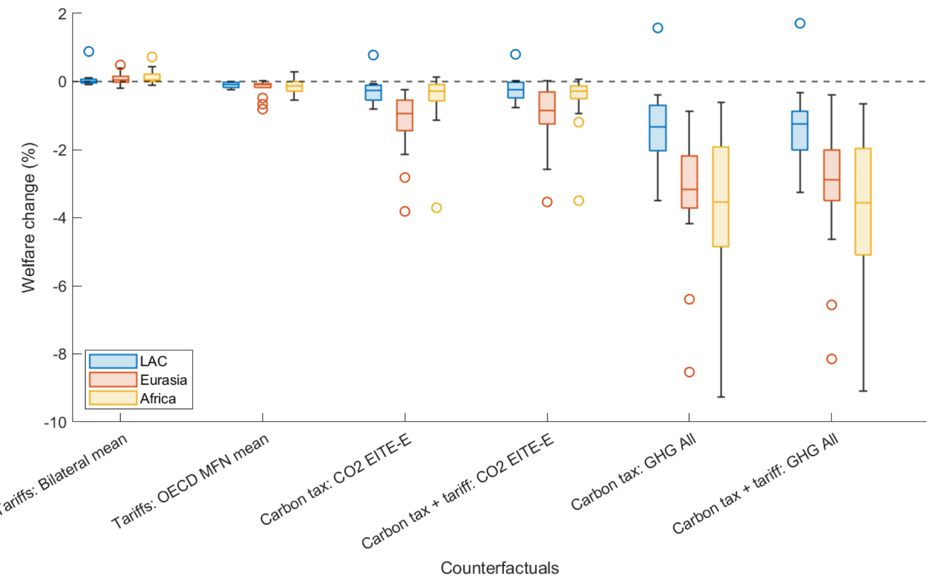
Note: Each counterfactual is evaluated individually for each on of the 48 Net-Zero developing countries in our sample. The effects for each country are then summarized in boxplots, indicating the change in emissions from the rest of the world as a percentage of global GHG emissions.

barely matter for global emissions – the primary source of concern. This is clear in Figure 9, which displays carbon leakage as share of global emission in the net-zero developing countries (boxplots), EU, United States, and China. The first column shows that the emission leakages after a carbon tax on EITE-E sectors are negligible in most net-zero developing countries, and an order of magnitude smaller than those of the EU, United States, and China. Accordingly, the carbon tariff mitigation is also an order of magnitude smaller (second column). This contrast is even starker in an all-gases-all-sectors scenario (last two columns).

The question of relevance becomes even more pointed when the negative trade effects, discussed earlier, and potential welfare losses, discussed next, are brought into the equation.

Overall, our main findings in this section point to a questionable role of trade policy as a climate policy. Although it is effective in mitigating emission leakages, such leakages are small in magnitude, and carbon tariffs have collateral effects in terms of trade declines, and in many countries, welfare losses.

Figure 10. Welfare Effects When Developing Countries Act Alone, by Region



Note: Each counterfactual is evaluated individually for each on of the 48 Net-Zero developing countries in our sample. The effects for each country are then summarized in boxplots, indicating the percentage change from the baseline scenario.

Welfare Effects. Figure 10 displays the welfare effects across Latin America, Africa and Eurasia net-zero developing countries. The first two columns show that the implementation of trade policy alone appears to have a relatively modest impact on welfare. The imposition of a carbon tax in EITE-E sectors (third column) results in overall welfare losses, and a carbon tax applied to all sector (fifth column) leads to larger welfare losses. These findings suggest a trade-off between welfare and emissions reductions for most countries. In the scenarios where carbon tariffs are deployed (fourth and sixth columns), the median marginal welfare effects of carbon tariffs are small and very heterogeneous within and across regions with a number of countries experiencing welfare losses. Most African countries tend to be negatively affected in both carbon tariff scenarios, while there seems to be small gains in the other regions. In addition, even in those countries that stand to gain, the benefits are so small that they are most likely to be offset by the carbon tariff's prohibitive administrative costs.[23]

[23] See Appendix D for more country specific details. Böhringer et al. (2022) discuss the large implementation challenges of carbon taxes, such as calculating the embodied emissions, choosing which sectors should be eligible for adjustment, how far down the supply chains, and complying with WTO rules.

These results suggest that the case for developing countries carbon tariff is weak at best. As shown earlier, these countries should not worry about their emission leakages as they hardly matter for global emissions. On top of that, welfare effects that could potentially compensate for emission leakages are either too small or are, in fact, losses even before accounting for administrative costs.

3.3.2 Acting in the context of a large country climate club

In this section, we consider a scenario where the United States, the European Union, and China form a climate club with European flavors. That is, this coalition imposes a domestic carbon tax on the production of EITE-E goods and a carbon tariff to non-member countries trained at their exports' emission intensity –along the lines of the EU CBAM.[24] As before, we assume a SCC equivalent to $163. Our goal is to understand the effectiveness of trade policy in meeting developing countries net-zero VERs when there is a coordinated climate activism among the world's largest economies.

Given the formation of the climate club, we consider three counterfactual scenarios. In the first scenario, we study the climate and economic effects when developing countries do not change their trade or climate policies in response to the coalition. In the second scenario, each developing country responds by simultaneously imposing a domestic carbon tax on production. In the third scenario, each developing country simultaneously imposes a domestic carbon tax on production aligned with a carbon tariff on all partner countries. We leave out the stand-alone-trade-policy and the all-gases-all-sectors scenarios this time because, as seen earlier, the results are very similar and do not add to the analysis.

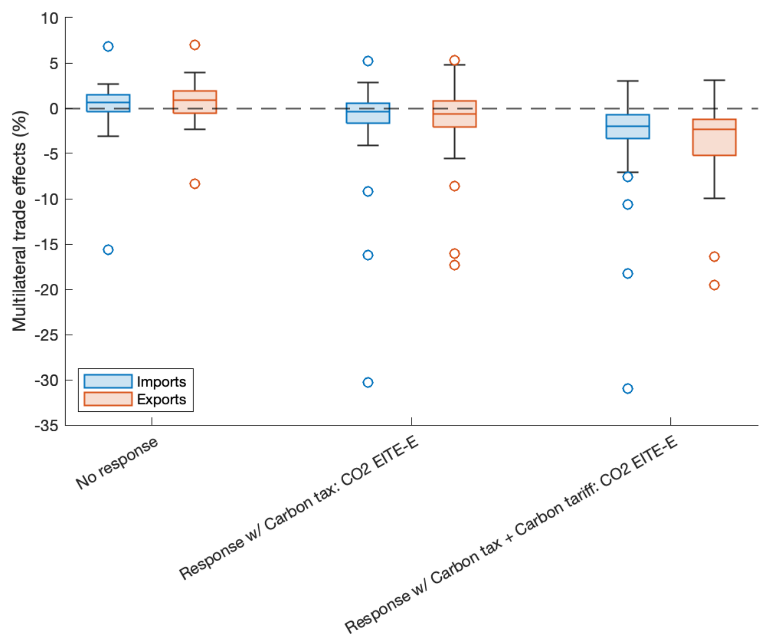
Trade Effects. Figure 11 reports the trade effects in each net-zero developing country in our sample. As before, each boxplot represents the percent change in imports or exports from each counterfactual for each country relative to the baseline economy with no policy intervention. We can see in the figure that when countries do not change their policies in

[24] This is a more trade-friendly version of the traditional climate club proposal, as first put forward by Nordhaus (2015). In this original version, the carbon tariff is trained to be merely coercive, bearing no relationship with emission intensities.

response to the coalition, trade tends to expand. An increase in the relative cost of production from members of the coalition increase both imports and exports in about two-thirds of the developing countries in our sample. The median countries experienced a 0.61% increase in imports (Kyrgyzstan) and 0.89% increase in exports (Argentina).

When countries respond by changing their carbon policy, trade declines. Imposing a carbon tax as a response reduces trade flows in about 65% of the net-zero countries in our sample with the median countries experiencing a 0.41% reduction in imports (Benin) and a 0.68% reduction in exports (Colombia). Aligning domestic carbon policy with a carbon tariff decreases trade flows even further for 88% of countries in our sample.

Figure 11. Trade Effects with a Large Country Climate Club

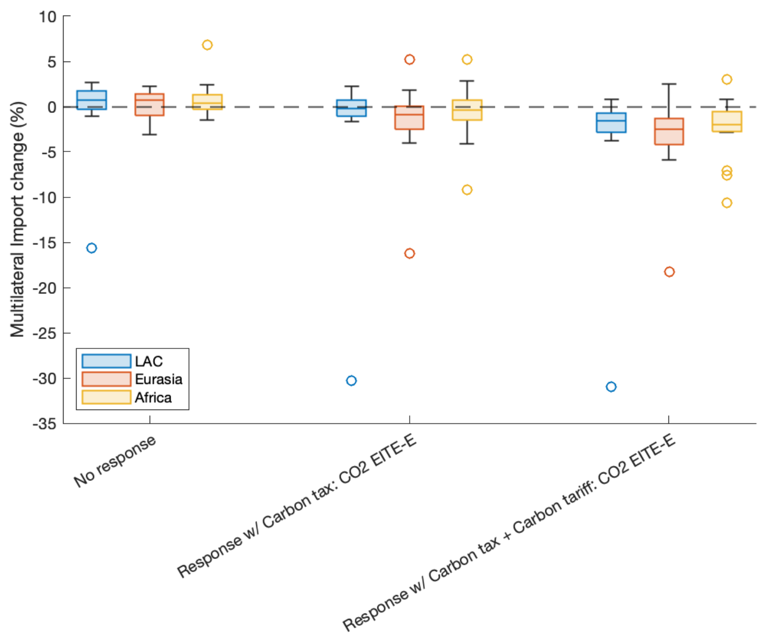


Note: Columns 2 and 3 of the box-plots are evaluated individually for each one of the 48 net-zero developing countries in our sample. The effects for each country are then summarized in box-plots, indicating the percentage change from the baseline scenario.

These trade effects of the formation of the coalition are heterogeneous across regions. Figure 12 breaks down the distribution of the percentage changes in imports and exports for countries in Africa, Eurasia, and Latin America. The first column shows that when developing countries do not respond to the coalition formed by large economies, most countries in

Latin America gain while many countries in Eurasia tend to lose reflecting a higher exposure to the EITE-E sectors from members of the coalition. Moreover, as discussed before, trade in each region tends to fall when countries decide to respond, and the largest reductions in trade for all regions come from a domestic carbon tax aligned with a border adjustment.

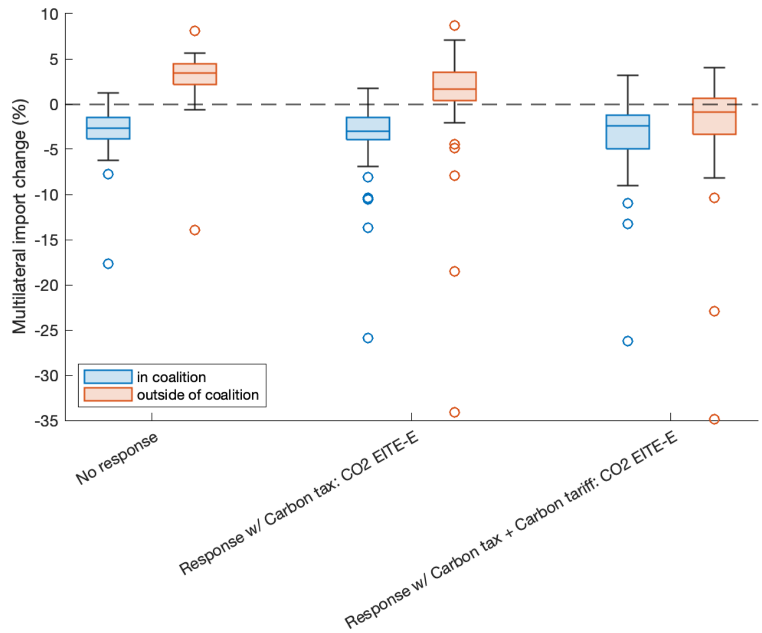
Figure 12. Trade Effects with a Large Country Climate Club by Region



Note: Columns 2 and 3 of the box-plots are evaluated individually for each one of the 48 net-zero developing countries in our sample. The effects for each country are then summarized in box-plots, indicating the percentage change from the baseline scenario.

The formation of a climate club also changes the direction of trade flows. Figure 13 shows the percent change in imports by partner. As expected, trade with members of the coalition becomes more costly. As a result, the share of net-zero developing countries that reduce imports from members of the climate club exceeds 85% in all three counterfactual scenarios. Moreover, the change in relative costs leads to increased imports from partner countries outside of the coalition. The third column in the figure shows that marginal trade effects of a carbon tariff are relatively small.

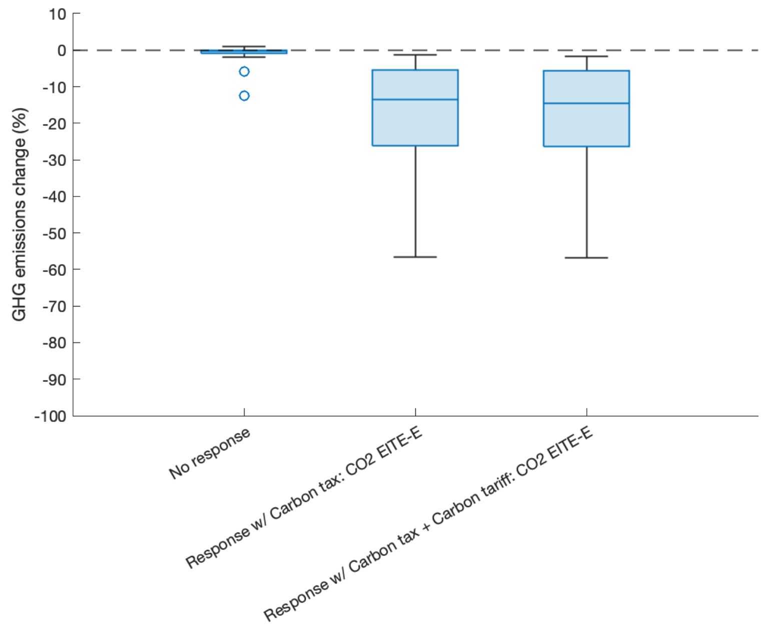
Figure 13. Trade Effects with Member and Non-Member States



Note: Columns 2 and 3 of the box-plots are evaluated individually for each one of the 48 net-zero developing countries in our sample. The effects for each country are then summarized in box-plots, indicating the percentage change from the baseline scenario.

Emission Effects. We turn to analyze how the formation of the coalition and the corresponding responses from developing countries affects their GHG emissions. Figure 14 shows that the formation of the coalition has little to no impact on the national emissions of developing countries which is to be expected. However, when countries respond by implementing some combination of carbon policy, we see reductions similar in magnitude to the results in section 3.3.1. All countries reduce their emissions when imposing a carbon tax and when aligning a carbon tariff, but this time no country achieves their net-zero target under any policy response. This difference with respect to our findings in section 3.3.1. stem from the fact that a carbon tax in large economies, everything else constant, foster trade and production in developing economies, and as result when developing countries implement similar measures, the impact of a carbon tax on their production and emissions is smaller in the presence of the coalition.

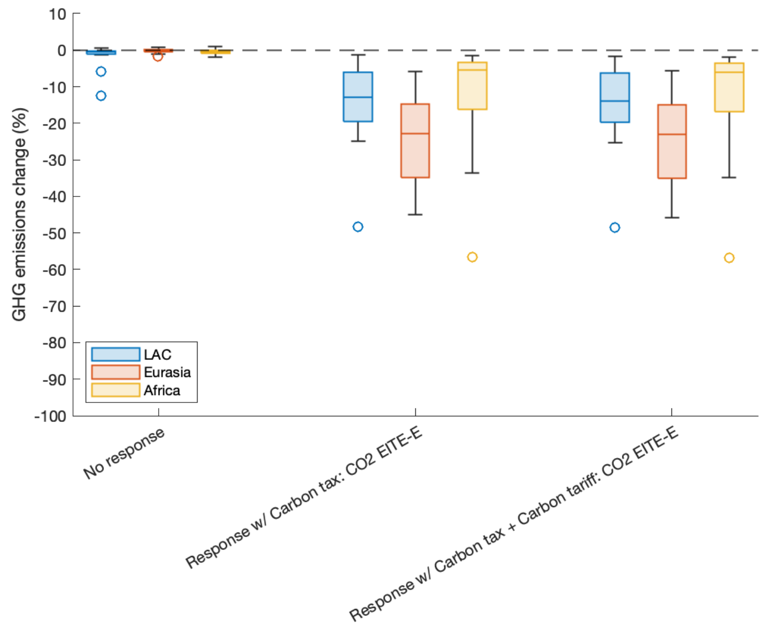
Figure 14. Emission Effects with a Large Country Climate Club



Note: Columns 2 and 3 of the box-plots are evaluated individually for each one of the 48 net-zero developing countries in our sample. The effects for each country are then summarized in box-plots, indicating the percentage change from the baseline scenario.

Figure 15 further disaggregates the national emissions changes by region. National emissions fall in all regions when countries respond, but responses are most effective in reducing emissions in Eurasia. When imposing a carbon tax, the median country in Eurasia reduced national emissions by 22.7% (Indonesia), while the median countries in Latin America and Africa reduce emissions by 12.9% (Panama) and 5.7% (Rwanda). Aligning a carbon tariff with a carbon tax marginally reduces the national emissions for the median countries by an additional 0.3, 1.0, and 0.8 percentage points for Eurasia, LAC, and Africa respectively. These results further support our conclusion from section 3.3.1 in that changes to trade policy have a limited impact in reaching emissions targets.

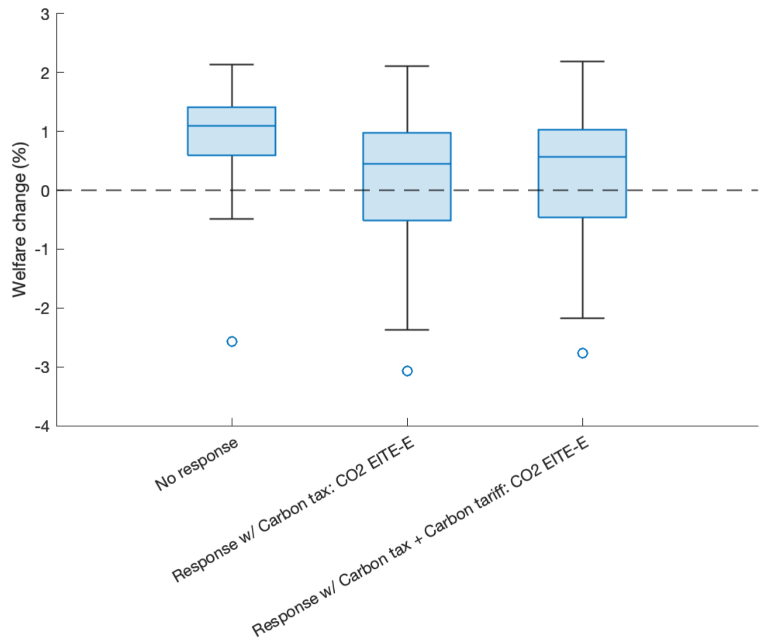
Figure 15. Emission Effects with a Large Country Climate Club by Region



Note: Columns 2 and 3 of the box-plots are evaluated individually for each one of the 48 net-zero developing countries in our sample. The effects for each country are then summarized in box-plots, indicating the percentage change from the baseline scenario.

Welfare Effects. In Figure 16, we analyze how the formation of the coalition affects welfare in each counterfactual scenario. In all three scenarios, the formation of the coalition improves welfare in the majority of developing countries committed to net-zero. The coalition formed by large economies leads to welfare gains for 88% of the net-zero countries in our sample (first column). A carbon tax imposed by developing economies reduces the share of countries that experience welfare gains to 69% (second column), and aligning a carbon tariff with domestic carbon policy leads to marginally higher welfare gains in the net-zero developing countries (third column).

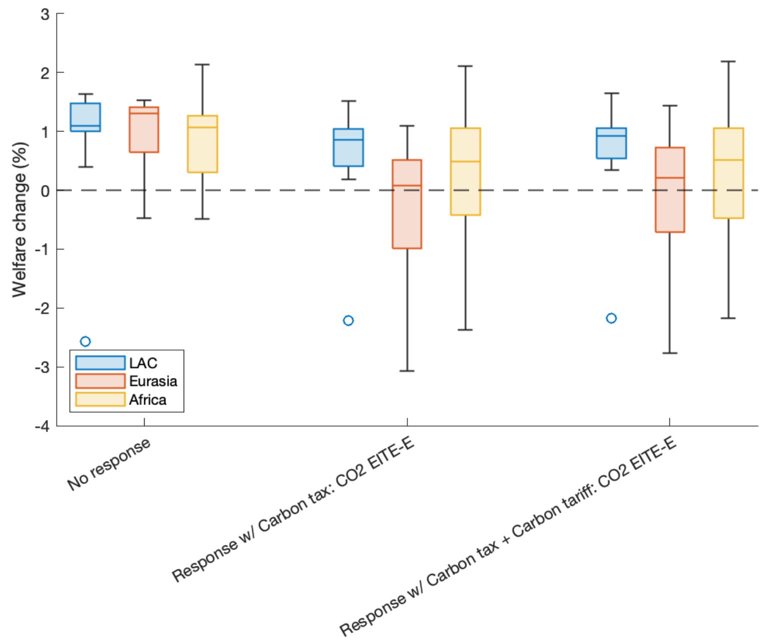
Figure 16. Welfare Effects with a Large Country Climate Club



Note: Columns 2 and 3 of the box-plots are evaluated individually for each one of the 48 net-zero developing countries in our sample. The effects for each country are then summarized in box-plots, indicating the percentage change from the baseline scenario.

Figure 17 disaggregates the welfare effects by region. When the coalition forms, nearly all regions stand to gain by not responding. When countries do respond, the winners tend to be concentrated among Latin American countries. Countries in Eurasia and Africa are more exposed to the EITE-E sectors from the coalition and have a higher proportion of countries losing relative to Latin America. Similar to the welfare effects in section 3.3.1, the formation of the climate club leads to an overall reduction in real income for nearly all countries. However, since the US, China, and the EU are such prominent emitters, for many countries this negative income effect is outweighed by the welfare gains from a reduction in global emissions.

Figure 17. Welfare Effects with a Large Country Climate Club by Region



Note: Columns 2 and 3 of the box-plots are evaluated individually for each one of the 48 net-zero developing countries in our sample. The effects for each country are then summarized in box-plots, indicating the percentage change from the baseline scenario.

4 Final Remarks

Our findings offer considerable insights on what is at stake for the average developing country when it comes to the use of trade as a climate policy. Overall, trade policy comes up as a very poor substitute for climate measures that directly target the emissions externality. There seems to be a much stronger case against its use in these countries than in large economies, where the literature had already raised doubts about its efficacy, particularly when used unilaterally.

Assessed against the need to meet net-zero VERs, different variations of trade-related climate measures seem to follow the same pattern of trading negligible (local and global) emission effects for, in most cases, palpable trade and welfare losses. When acting alone–in its most trade-friendly form– trade and welfare costs are minimized or even reversed, but tariff harmonization offers little in terms of reducing emissions.

Our findings also suggest that carbon taxes and tariffs, even when set at the currently estimated global SCC, will not be enough for most developing countries to meet their net-zero emission targets. Improvements in emission efficiency will be needed, most likely driven by a combination of more stringent environmental regulation and greater access to foreign technology and inputs — the so-called technique effect of trade (Grossman and Krueger, 1991).

When paired with more effective direct climate actions, in the form of a carbon tariff, it does offer some benefits in terms of mitigating emission leakages. However, those leakages usually are not significant at home, let alone at the global level. In addition, those adjustment tariffs have collateral effects in terms of trade and welfare costs.

The use of carbon tariffs also appears to be questionable in a tit-for-tat scenario, where developing countries respond to trade-related climate action in their major trade partners. If trade is the only concern, doing nothing appears to be the dominant strategy.

All in all, our findings suggest that developing countries should be cautioned in resorting to trade as a climate policy. It is clearly not a good substitute for directly climate action and might come with significant collateral effects.

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Technical Appendix

Voluntary Emission Restraints in Developing Economies: The Role of Trade Policy

May 1, 2024

Part A
Model Derivation

A1 The Consumer Problem

Households are consumers of non-tradable final goods, C_n^j. We assume that households generate income by selling their labor and in the form of tax rebates distributed by the government. Households in each region have a measure of L_n representative households. We assume that labor is a fixed supply factor and it is sold to producers for price w_n. Finally consumers have the following preferences:

$$U_n = \prod_{j=1}^{J} \left(C_n^j\right)^{\alpha_n^j} \left[1 + \delta\left(Z - Z_0\right)\right]^{-1} \text{ where } \sum_{j=1}^{J} \alpha_n^j = 1$$

where α_n^j represents the share of income spent on final consumption in region n on sector j, and $\left[1 + \delta\left(Z - Z_0\right)\right]^{-1}$ represents the disutility of carbon. Z_0 are global emissions in the baseline and Z are global emissions from a counterfactual policy. We let δ be a damage parameter calibrated such that a one ton increase in emissions leads to a \$163 reduction in global welfare as cited in the literature (Shapiro, 2021).

Agents spend their income, I_n, buying composite intermediate goods from all sectors and paying the tax-inclusive price of $t_c^j P_n^j$. This gives us the following identity:

$$\sum_{j=1}^{J} t_c^j P_n^j C_n^j = I_n$$

where $t_{n,c}^j = 1 + \bar{t}_{n,c}^j$ represents the tax on the consumption of final goods in region n on sector j and P_n^j is the price level in region n sector j.

A1.1 Utility maximization

Agents maximize utility subject to their budget constraint.

$$\max_{\left\{C_n^j\right\}} \prod_{j=1}^{J} \left(C_n^j\right)^{\alpha_n^j} \left[1 + \delta\left(Z - Z_0\right)\right]^{-1} \text{ s.t. } \sum_{j=1}^{j} t_{c,n}^j P_n^j C_n^j = I_n$$

Setting up the Lagrangian and taking the first order conditions (FOC):

$$L\left(C_n^j, C_n^k\right) = \prod_{j=1}^{J} \left(C_n^j\right)^{\alpha_n^j} \left[1 + \delta\left(Z - Z_0\right)\right]^{-1} + \lambda\left(I_n - \sum_{j=1}^{J} t_{c,n}^j P_n^j C_n^j\right)$$

$$\frac{\partial L\left(C_n^j, C_n^k\right)}{\partial C_n^j}: \quad \frac{\alpha_n^j}{C_n^j} \prod_{j=1}^{J} \left(C_n^j\right)^{\alpha_n^j} \left[1 + \delta\left(Z - Z_0\right)\right]^{-1} = \lambda t_{c,n}^j P_n^j \tag{A1.1}$$

$$\frac{\partial L\left(C_n^j, C_n^k\right)}{\partial C_n^k}: \quad \frac{\alpha_n^k}{C_n^k} \prod_{k=1}^{J} \left(C_n^k\right)^{\alpha_n^k} \left[1 + \delta\left(Z - Z_0\right)\right]^{-1} = \lambda t_{c,n}^k P_n^k \tag{A1.2}$$

$$\frac{\partial L\left(C_n^j, C_n^k\right)}{\partial \lambda}: \quad \sum_{j=1}^{J} t_{c,n}^j P_n^j C_n^j = I_n \tag{A1.3}$$

Using the FOC for two different goods j and k, (1.1) and (1.2):

$$\begin{aligned}
\frac{\frac{\alpha_n^j}{C_n^j} \prod_{j=1}^{J} \left(C_n^j\right)^{\alpha_n^j} \left[1 + \delta\left(Z - Z_0\right)\right]^{-1}}{\frac{\alpha_n^k}{C_n^k} \prod_{k=1}^{J} \left(C_n^k\right)^{\alpha_n^k} \left[1 + \delta\left(Z - Z_0\right)\right]^{-1}} &= \frac{\lambda t_{c,n}^j P_n^j}{\lambda t_{c,n}^k P_n^k} \\
\frac{\frac{\alpha_n^j}{C_n^j}}{\frac{\alpha_n^k}{C_n^k}} &= \frac{t_{c,n}^j P_n^j}{t_{c,n}^k P_n^k} \\
\frac{\alpha_n^j C_n^k}{C_n^j \alpha_n^k} &= \frac{t_{c,n}^j P_n^j}{t_{c,n}^k P_n^k} \\
C_n^j &= \frac{\alpha_n^j C_n^k t_{c,n}^k P_n^k}{\alpha_n^k t_{c,n}^j P_n^j} && \text{(A1.4)}
\end{aligned}$$

Substituting in (1.4) in (1.3):

$$\begin{aligned}
\sum_{j=1}^{j} \frac{\alpha_n^j C_n^k t_{c,n}^k P_n^k}{\alpha_n^k} &= I_n \\
\frac{C_n^k t_{c,n}^k P_n^k}{\alpha_n^k} \sum_{j=1}^{j} \alpha_n^j &= I_n \\
C_n^k &= \frac{\alpha_n^k I_n}{t_{c,n}^k P_n^k} \\
P_n^k C_n^k &= \frac{\alpha_n^k I_n}{t_{c,n}^k} && \text{(A1.5)}
\end{aligned}$$

which gives us the value spend on consumption good j in terms of national income and the consumption tax of sector k.

A1.2 Expenditure minimization

Analogously, the expenditure minimization problem faced by household is given by

$$\min_{\{C_n^j\}} \sum_{j=1}^{J} t_{n,c}^j P_n^j C_n^j \text{ s.t. } \bar{U}_n = \prod_{j=1}^{J} \left(C_n^j\right)^{\alpha_n^j} \left[1 + \delta\left(Z - Z_0\right)\right]^{-1}$$

Our goal will be to solve for the household's indirect utility function to construct a metric for welfare.

$$L\left(C_n^j, C_n^k\right) = \sum_{j=1}^{J} t_{n,c}^j P_n^j C_n^j + \lambda\left(\bar{U}_n - \prod_{j=1}^{J} \left(C_n^j\right)^{\alpha_n^j} \left[1 + \delta\left(Z - Z_0\right)\right]^{-1}\right)$$

$$\frac{\partial L\left(C_n^j, C_n^k\right)}{\partial C_n^j} : t_{n,c}^j P_n^j = \lambda \frac{\alpha_n^j}{C_n^j} \prod_{j=1}^{J} \left(C_n^j\right)^{\alpha_n^j} \left[1 + \delta\left(Z - Z_0\right)\right]^{-1} \tag{A1.6}$$

$$\frac{\partial L\left(C_n^j, C_n^k\right)}{\partial C_n^k} : t_{n,c}^k P_n^k = \lambda \frac{\alpha_n^k}{C_n^k} \prod_{j=1}^{J} \left(C_n^j\right)^{\alpha_n^j} \left[1 + \delta\left(Z - Z_0\right)\right]^{-1} \tag{A1.7}$$

$$\frac{\partial L\left(C_n^j, C_n^k\right)}{\partial \lambda} : \bar{U}_n = \prod_{j=1}^{J} \left(C_n^j\right)^{\alpha_n^j} \left[1 + \delta\left(Z - Z_0\right)\right]^{-1} \tag{A1.8}$$

Taking the ratio of (1.6) and (1.7)

$$\frac{t_{n,c}^j P_n^j}{t_{n,c}^k P_n^k} = \frac{\lambda \frac{\alpha_n^j}{C_n^j} \prod_{j=1}^{J} \left(C_n^j\right)^{\alpha_n^j} \left[1 + \delta\left(Z - Z_0\right)\right]^{-1}}{\lambda \frac{\alpha_n^k}{C_n^k} \prod_{j=1}^{J} \left(C_n^j\right)^{\alpha_n^j} \left[1 + \delta\left(Z - Z_0\right)\right]^{-1}}$$

$$\frac{t_{n,c}^j P_n^j}{t_{n,c}^k P_n^k} = \frac{C_n^k \alpha_n^j}{C_n^j \alpha_n^k}$$

$$C_n^j = \frac{t_{n,c}^k P_n^k C_n^k \alpha_n^j}{t_{n,c}^j P_n^j \alpha_n^k} \tag{A1.9}$$

which is the same as (1.4). Substituting it into (1.8) we will arrive at our indirect utility function

$$\begin{aligned}
\bar{U}_n &= \prod_{j=1}^{J} \left(C_n^j\right)^{\alpha_n^j} \left[1 + \delta\left(Z - Z_0\right)\right]^{-1} \\
&= \prod_{j=1}^{J} \left(\frac{t_{n,c}^k P_n^k C_n^k \alpha_n^j}{t_{n,c}^j P_n^j \alpha_n^k}\right)^{\alpha_n^j} \left[1 + \delta\left(Z - Z_0\right)\right]^{-1} \\
&= \prod_{j=1}^{J} \left(\frac{\alpha_n^j}{t_{n,c}^j P_n^j}\right)^{\alpha_n^j} \frac{t_{n,c}^k P_n^k C_n^k}{\alpha_n^k} \left[1 + \delta\left(Z - Z_0\right)\right]^{-1} \qquad \text{(A1.10)}
\end{aligned}$$

By rearranging equation (1.5) we get that $I_n = \frac{t^k_{n,c} P^k_n C^k_n}{\alpha^k_n}$. Substituting this expression into (1.10) we are able to finish solving for welfare function in terms of income now,

$$\begin{aligned}\bar{U}_n &= \prod_{j=1}^{J} \left(\frac{\alpha^j_n}{t^j_{n,c} P^j_n} \right)^{\alpha^j_n} \frac{t^k_{n,c} P^k_n C^k_n}{\alpha^k_n} \left[1 + \delta \left(Z - Z_0\right)\right]^{-1} \\ &= \prod_{j=1}^{J} \left(\frac{\alpha^j_n}{t^j_{n,c} P^j_n} \right)^{\alpha^j_n} I_n \left[1 + \delta \left(Z - Z_0\right)\right]^{-1} \\ \bar{U}_n &= \frac{I_n}{\prod_{j=1}^{J} \left(\frac{t^j_{n,c} P^j_n}{\alpha^j_n} \right)^{\alpha^j_n} \left[1 + \delta \left(Z - Z_0\right)\right]}\end{aligned}$$

which finally gives us the welfare function after including a tax on consumption. Note that the first term in the denominator equals the price index for consumption goods and the second the disutility from carbon.

A1.3 Summary

$$P^k_n C^k_n = \frac{\alpha^k_n I_n}{t^k_{c,n}} \tag{A1.11}$$

$$\bar{U}_n = \frac{I_n}{\prod_{j=1}^{J} \left(\frac{t^j_{n,c} P^j_n}{\alpha^j_n} \right)^{\alpha^j_n} \left[1 + \delta \left(Z - Z_0\right)\right]} \tag{A1.12}$$

A2 The Intermediate Goods Producer Problem

Intermediate goods, $\omega^j \in [0, 1]$, are produced in each sector j where ω^j represents the variety in sector j. There are two types of intermediate producers: extraction and non-extraction firms. Extraction firms use three types of inputs: labor, dirty natural resources, and materials from all other sectors. Their production function of variety ω^j is given by

$$q^j_n(\omega^j) = z^j_n \left(\omega^j\right) \left[l^j_n(\omega^j)\right]^{\gamma^{l,j}_n} \left[e^j_n \left(\omega^j\right)\right]^{\gamma^{e,j}_n} \prod_{k=1}^{J} \left[m^{k,j}_n \left(\omega^j\right)\right]^{\gamma^{k,j}_n}$$

where z^j_n represents the realized technology draw specific to each country and sector, l^j_n and e^j_n represent the demands for labor and dirty natural resources respectively, $\gamma^{l,j}_n$ and $\gamma^{e,j}_n$ represent the share of labor and dirty natural resources used for the production of ω^j. $m^{k,j}_n$ represents the materials used from sector k to produce ω^j, and finally $\gamma^{k,j}_n$ represents the share of materials from sector k used to produce ω^j with $\sum_{j=1}^{J} \gamma^{k,j}_n = 1 - \left(\gamma^{l,j}_n + \gamma^{e,j}_n\right)$. The factor of production, e^j_n is immobile across sectors and countries. For instance, oil reserves can only be used by firms extracting oil, while coal reserves can only be used in the production of firms mining coal.

The non-extractive firms produce under a similar production function, but using only labor and materials from all other sectors:

$$q_n^j(\omega^j) = z_n^j\left(\omega^j\right)\left[l_n^j(\omega^j)\right]^{\gamma_n^{l,j}}\prod_{k=1}^{J}\left[m_n^{k,j}\left(\omega^j\right)\right]^{\gamma_n^{k,j}}$$

For both types of producers we assume that the production of intermediate goods is constant returns to scale and that markets are perfectly competitive. Producers of final goods and materials use ω^j as their inputs, therefore any changes to the cost structure in any given sector will indirectly affect all sectors in the economy. Given this, our goal will be to show how this cost structure reacts to changes in a tax to the consumption of labor, dirty natural resources, materials, and/or domestic production.

In the following subsection we show the cost minimization faced by extractive firms. The derivation is similar for non-extractive producers, .

A2.1 Cost minimization

To determine the cost to produce ω^j, producers price at unit cost and therefore solve the following price minimization problem. In this section we omit the the variety notation ω^j for simplicity.

$$\min_{\left\{l_n^j, e_n^{h,j}, \left\{m_n^{k,j}\right\}_{k=1}^{J}\right\}} t_{n,p}^j\left[t_{n,l}^j w_n l_n^j + r_n^j e_n^j + \sum_{k=1}^{J} t_{n,m}^k P_n^k m_n^{k,j}\right]$$
$$\text{s.t. } 1 = z_n^j\left(l_n^j\right)^{\gamma_n^{l,j}}\left(e_n^j\right)^{\gamma_n^{h,j}}\prod_{k=1}^{J}\left(m_n^{k,j}\right)^{\gamma_n^{k,j}}$$

The first step is define our Lagrangian

$$L\left(l_n^j, e_n^j, \left\{m_n^{k,j}\right\}_{k=1}^{J}\right) = t_{n,p}^j\left[t_{n,l}^j w_n l_n^j + r_n^j e_n^j + \sum_{k=1}^{J} t_{n,m}^k P_n^k m_n^{k,j}\right] + \lambda\left[1 - z_n^j\left(l_n^j\right)^{\gamma_n^{l,j}}\left(e_n^j\right)^{\gamma_n^{e,j}}\prod_{k=1}^{J}\left(m_n^{k,j}\right)^{\gamma_n^{k,j}}\right]$$

$$\frac{\partial L}{\partial l_n^j} : t_{n,p}^j t_{n,l}^j w_n = \lambda\left[z_n^j \gamma_n^{l,j}\left(l_n^j\right)^{\gamma_n^{l,j}-1}\left(e_n^j\right)^{\gamma_n^{e,j}}\prod_{k=1}^{J}\left(m_n^{k,j}\right)^{\gamma_n^{k,j}}\right] \tag{A2.1}$$

$$\frac{\partial L}{\partial e_n^j} : t_{n,p}^j r_n^j = \lambda\left[z_n^j \gamma_n^{e,j}\left(e_n^j\right)^{\gamma_n^{e,j}-1}\left(l_n^j\right)^{\gamma_n^{l,j}}\prod_{k=1}^{J}\left(m_n^{k,j}\right)^{\gamma_n^{k,j}}\right] \tag{A2.2}$$

$$\frac{\partial L}{\partial m_n^{s,j}} : t_{n,p}^j t_{n,m}^s P_n^{s,j} = \lambda\left[z_n^j \gamma_n^{s,j}\left(m_n^{s,j}\right)^{-1}\left(l_n^j\right)^{\gamma_n^{l,j}}\left(e_n^j\right)^{\gamma_n^{e,j}}\prod_{k=1}^{J}\left(m_n^{k,j}\right)^{\gamma_n^{k,j}}\right] \tag{A2.3}$$

Taking the ratio of (2.1) to (2.3) and (2.1) to (2.2) we get the following

$$
\begin{aligned}
\frac{t^j_{n,p} t^j_{n,l} w_n}{t^j_{n,p} t^s_{n,m} P^s_n} &= \frac{\lambda \left[z^j_n \gamma^{l,j}_n \left(l^j_n\right)^{\gamma^{l,j}_n - 1} \left(e^j_n\right)^{\gamma^{e,j}_n} \prod_{k=1}^J \left(m^{k,j}_n\right)^{\gamma^{k,j}_n} \right]}{\lambda \left[z^j_n \gamma^{s,j}_n \left(m^{s,j}_n\right)^{-1} \left(l^j_n\right)^{\gamma^{l,j}_n} \left(e^j_n\right)^{\gamma^{e,j}_n} \prod_{k=1}^J \left(m^{k,j}_n\right)^{\gamma^{k,j}_n} \right]} \\
\frac{t^j_{n,l} w_n}{t^s_{n,m} P^s_n} &= \frac{\gamma^{l,j}_n m^{s,j}_n}{\gamma^{s,j}_n l^j_n} \\
m^{s,j}_n &= \frac{t^j_{n,l} w_n \gamma^{s,j}_n l^j_n}{t^s_{n,m} P^{s,j}_n \gamma^{l,j}_n} \qquad \text{(A2.4)} \\
\frac{t^j_{n,p} t^j_{n,l} w_n}{t^j_{n,p} r^j_n} &= \frac{\lambda \left[z^j_n \gamma^{l,j}_n \left(l^j_n\right)^{\gamma^{l,j}_n - 1} \left(e^j_n\right)^{\gamma^{e,j}_n} \prod_{k=1}^J \left(m^{k,j}_n\right)^{\gamma^{k,j}_n} \right]}{\lambda \left[z^j_n \gamma^{e,j}_n \left(e^j_n\right)^{\gamma^{e,j}_n - 1} \left(l^j_n\right)^{\gamma^{l,j}_n} \prod_{k=1}^J \left(m^{k,j}_n\right)^{\gamma^{k,j}_n} \right]} \\
\frac{t^j_{n,l} w_n}{r^j_n} &= \frac{\gamma^{l,j}_n e^j_n}{\gamma^{e,j}_n l^j_n} \\
e^j_n &= \frac{t^j_{n,l} w_n \gamma^{e,j}_n l^j_n}{r^j_n \gamma^{l,j}_n} \qquad \text{(A2.5)}
\end{aligned}
$$

Substituting equations (2.4) and (2.5) back into equation (2.1) we get

$$
\begin{aligned}
t^j_{n,p} t^j_{n,l} w_n &= \lambda \left[z^j_n \gamma^{l,j}_n \left(l^j_n\right)^{\gamma^{l,j}_n - 1} \left(e^j_n\right)^{\gamma^{e,j}_n} \prod_{k=1}^J \left(m^{k,j}_n\right)^{\gamma^{k,j}_n} \right] \\
t^j_{n,p} t^j_{n,l} w_n &= \lambda \left[z^j_n \gamma^{l,j}_n \left(l^j_n\right)^{\gamma^{l,j}_n - 1} \left(\frac{t^j_{n,l} w_n \gamma^{e,j}_n l^j_n}{r^j_n \gamma^{l,j}_n} \right)^{\gamma^{e,j}_n} \prod_{k=1}^J \left(\frac{t^j_{n,l} w_n \gamma^{k,j}_n l^j_n}{t^k_{n,m} P^k_n \gamma^{l,j}_n} \right)^{\gamma^{k,j}_n} \right] \\
t^j_{n,p} t^j_{n,l} w_n &= \lambda \left[z^j_n \gamma^{l,j}_n \left(l^j_n\right)^{\gamma^{l,j}_n - 1} \left(t^j_{n,l} w_n \gamma^{e,j}_n l^j_n\right)^{\gamma^{e,j}_n} \left(r^j_n \gamma^{l,j}_n\right)^{-\gamma^{e,j}_n} \left(\frac{t^j_{n,l} w_n l^j_n}{\gamma^{l,j}_n} \right)^{1-(\gamma^{e,j}_n + \gamma^{l,j}_n)} \prod_{k=1}^J \left(\frac{\gamma^{k,j}_n}{t^k_{n,m} P^k_n} \right)^{\gamma^{k,j}_n} \right] \\
t^j_{n,p} &= \lambda \left[z^j_n \left(t^j_{n,l} w_n\right)^{-\gamma^{l,j}_n} \left(\gamma^{e,j}_n\right)^{\gamma^{e,j}_n} \left(r^j_n\right)^{-\gamma^{e,j}_n} \left(\gamma^{l,j}_n\right)^{\gamma^{l,j}_n} \prod_{k=1}^J \left(\frac{\gamma^{k,j}_n}{t^k_{n,m} P^k_n} \right)^{\gamma^{k,j}_n} \right] \\
\lambda &= t^j_{n,p} \left[\left(z^j_n\right)^{-1} \left(t^j_{n,l} w_n\right)^{\gamma^{l,j}_n} \left(\gamma^{e,j}_n\right)^{-\gamma^{e,j}_n} \left(r^j_n\right)^{\gamma^{e,j}_n} \left(\gamma^{l,j}_n\right)^{-\gamma^{l,j}_n} \prod_{k=1}^J \left(\frac{t^k_{n,m} P^k_n}{\gamma^{k,j}_n} \right)^{\gamma^{k,j}_n} \right] \\
\lambda &= t^j_{n,p} \left(z^j_n\right)^{-1} \left(\gamma^{l,j}_n\right)^{-\gamma^{l,j}_n} \left(\gamma^{e,j}_n\right)^{-\gamma^{e,j}_n} \prod_{k=1}^J \left(\gamma^{k,j}_n\right)^{-\gamma^{k,j}_n} \left(t^j_{n,l} w_n\right)^{\gamma^{l,j}_n} \left(r^j_n\right)^{\gamma^{e,j}_n} \prod_{k=1}^J \left(t^k_{n,m} P^k_n\right)^{\gamma^{k,j}_n}
\end{aligned}
$$

Defining a constant Υ_n^j as

$$\Upsilon_n^j = \left(\gamma_n^{l,j}\right)^{-\gamma_n^{l,j}} \left(\gamma_n^{e,j}\right)^{-\gamma_n^{e,j}} \prod_{k=1}^{J} \left(\gamma_n^{k,j}\right)^{-\gamma_n^{k,j}}$$

The cost of an input bundle for a extractive firm is defined by

$$c_n^j = t_{n,p}^j \Upsilon_n^j \left(t_{n,l}^j w_n\right)^{\gamma_n^{l,j}} \left(r_n^j\right)^{\gamma_n^{e,j}} \prod_{k=1}^{J} \left(t_{n,m}^k P_n^k\right)^{\gamma_n^{k,j}} \tag{A2.6}$$

with the marginal cost is given by $\lambda = \frac{c_n^j}{z_n^j}$. For non-extractive firms, the energy endowment share, $\gamma_n^{e,j}$, is equal to zero and the term $\left(r_n^j\right)^{\gamma_n^{e,j}} = 1$. Since firms price at marginal cost, we can see that the price to supply variety ω^j to the domestic market is given by

$$p_n^j\left(\omega^j\right) = \frac{c_n^j}{z_n^j\left(\omega^j\right)}$$

and after adding up iceberg trade costs, d_{ni}^j, and tariffs, τ_{ni}^j the price to supply variety ω^j from any given country i to country n is given by

$$p_n^j\left(\omega^j\right) = \frac{c_i^j d_{ni}^j \tau_{ni}^j}{z_i^j\left(\omega^j\right)}$$

Finally, we impose that producers in country n search all over the world for the lowest cost supplier, therefore the price that country n actually faces is given by

$$p_n^j\left(\omega^j\right) = \min_i \left\{ \frac{c_i^j d_{ni}^j \tau_{ni}^j}{z_i^j\left(\omega^j\right)} \right\} \tag{A2.7}$$

A2.2 Profit Maximization

Alternatively, we can set up the intermediate good problem for extractive firms as an unconstrained after-tax profit maximization:

$$max_{\left\{l_n^j, e_n^j, \left\{m_n^{k,j}\right\}_{k=1}^{J}\right\}} \quad p_n^j \left(t_{n,p}^j\right)^{-1} z_n^j \left(l_n^j\right)^{\gamma_n^{l,j}} \left(e_n^j\right)^{\gamma_n^{e,j}} \prod_{k=1}^{J} \left(m_n^{k,j}\right)^{\gamma_n^{k,j}} - \left(t_{n,l}^j w_n l_n^j + r_n^j e_n^j + \sum_{k=1}^{J} t_{n,m}^k P_n^k m_n^{k,j}\right)$$

This optimization problem will give us the same solution as minimizing costs.

A2.3 Summary

$$c_n^j = t_{n,p}^j \Upsilon_n^j \left(t_{n,l}^j w_n\right)^{\gamma_n^{l,j}} \left(r_n^j\right)^{\gamma_n^{e,j}} \prod_{k=1}^{J} \left(t_{n,m}^k P_n^k\right)^{\gamma_n^{k,j}} \tag{A2.8}$$

$$p_n^j\left(\omega^j\right)=\min_i\left\{\frac{c_i^j d_{ni}^j \tau_{ni}^j}{z_i^j\left(\omega^j\right)}\right\} \tag{A2.9}$$

A3 The Composite Intermediate Goods Producer Problem

In this section, we study the role of the composite intermediate goods producer who produces Q_n^j in country n and sector j. The composite intermediate goods producer demands varieties from the rest of the world ω^j to produce both final goods C_n^j and materials which $m^{j,k}$ which are used to produce ω^k across all sectors.

Their demand for ω^j is given by a Ethier (1982) or Dixit and Stiglitz (1977) aggregator represented as

$$Q_n^j=\left[\int v_n^j\left(\omega^j\right)^{1-1/\sigma^j} d\omega^j\right]^{\sigma^j/(\sigma^j-1)}$$

where $v_n^j(\omega^j)$ represents the demand of intermediate goods ω^j from the lowest cost supplier and $\sigma^j>0$ is the elasticity of substitution across intermediate goods within sector j. We assume that composite intermediate goods are profit maximizing and since taxes do not directly enter in this section, solving for our price index is exactly as in Caliendo and Parro (2015).

A3.1 Profit maximization

To solve for the price index P_n^j in terms of the price of our varieties ω^j producers solve the following profit maximization problem,

$$\max_{\left\{v_n^j(\omega^j)\right\}} P_n^j Q_n^j-\int p_n^j\left(\omega^j\right) v_n^j\left(\omega^j\right) d\omega^j$$

The FOC of our objective function can be written as

$$\frac{\sigma}{\sigma-1} P_n^j\left[\int v_n^j(\omega^j)^{\frac{\sigma-1}{\sigma}} d\omega^j\right]^{\frac{1}{\sigma-1}} \frac{\sigma-1}{\sigma} v_n^j\left(\omega^j\right)^{\frac{-1}{\sigma}}-p_n^j\left(\omega^j\right)=0$$

Solving for the demand of intermediate goods can now be reduced to solving for $v_n^j\left(\omega^j\right)$ from our FOC.

$$\begin{aligned} 0&=P_n^j\left[\int v_n^j(\omega^j)^{\frac{\sigma-1}{\sigma}} d\omega^j\right]^{\frac{1}{\sigma-1}} v_n^j\left(\omega^j\right)^{\frac{-1}{\sigma}}-p_n^j\left(\omega^j\right)\\ v_n^j\left(\omega^j\right)^{\frac{-1}{\sigma}}&=\left(P_n^j\right)^{-1}\left[\int v_n^j(\omega^j)^{\frac{\sigma-1}{\sigma}} d\omega^j\right]^{\frac{-1}{\sigma-1}} p_n^j\left(\omega^j\right)\end{aligned}$$

$$
\begin{aligned}
v_n^j\left(\omega^j\right) &= \left(P_n^j\right)^{\sigma}\left[\int v_n^j(\omega^j)^{\frac{\sigma-1}{\sigma}}d\omega^j\right]^{\frac{\sigma}{\sigma-1}}\left(p_n^j\left(\omega^j\right)\right)^{-\sigma^j} \\
v_n^j\left(\omega^j\right) &= \left(\frac{p_n\left(\omega^j\right)}{P_n^j}\right)^{-\sigma} Q_n^j \qquad \text{(A3.1)}
\end{aligned}
$$

A3.2 Cost minimization

In this section we will solve the cost minimization problem to solve for our price index at unit cost. Producers face the following optimization problem

$$
\min_{\left\{v_n^j(\omega^j)\right\}} \int p_n^j\left(\omega^j\right) v_n^j d\omega^j \text{ s.t. } Q_n^j = 1
$$

The results of this problem will tell us the value for P_n^j which will be given by our Lagrange multiplier λ.

$$
\begin{aligned}
L\left(v_n^j\left(\omega^j\right),\lambda\right) &= \int p_n^j\left(\omega^j\right) v_n^j\left(\omega^j\right)d\omega^j + \lambda\left(1-\left[\int v_n^j\left(\omega^j\right)^{\frac{\sigma^j-1}{\sigma^j}}d\omega^j\right]^{\frac{\sigma^j}{\sigma^j-1}}\right) \\
\frac{\partial L}{\partial v_n^j\left(\omega^j\right)} &: p_n^j\left(\omega^j\right) - \lambda\left[\int v_n^j\left(\omega^j\right)^{\frac{\sigma^j-1}{\sigma^j}}d\omega^j\right]^{\frac{1}{\sigma^j-1}} v_n^j\left(\omega^j\right)^{\frac{-1}{\sigma^j}} = 0 \\
\frac{\partial L}{\partial \lambda} &: \left[\int v_n^j\left(\omega^j\right)^{\frac{\sigma^j-1}{\sigma^j}}d\omega^j\right]^{\frac{\sigma^j}{\sigma^j-1}} = 1 \qquad \text{(A3.2)}
\end{aligned}
$$

Solving for demand we get

$$
\begin{aligned}
0 &= p_n^j\left(\omega^j\right) - \lambda\left[\int v_n^j\left(\omega^j\right)^{\frac{\sigma^j-1}{\sigma^j}}d\omega^j\right]^{\frac{1}{\sigma^j-1}} v_n^j\left(\omega^j\right)^{\frac{-1}{\sigma^j}} \\
v_n^j\left(\omega^j\right)^{\frac{-1}{\sigma^j}} &= p_n^j\left(\omega^j\right)\lambda^{-1}\left[\int v_n^j\left(\omega^j\right)^{\frac{\sigma^j-1}{\sigma^j}}d\omega^j\right]^{\frac{-1}{\sigma^j-1}} \\
v_n^j\left(\omega^j\right) &= p_n^j\left(\omega^j\right)^{-\sigma^j}\lambda^{\sigma^j}\left[\int v_n^j\left(\omega^j\right)^{\frac{\sigma^j-1}{\sigma^j}}d\omega^j\right]^{\frac{\sigma^j}{\sigma^j-1}} \\
v_n^j\left(\omega^j\right) &= p_n^j\left(\omega^j\right)^{-\sigma^j}\lambda^{\sigma^j} \\
v_n^j\left(\omega^j\right) &= \left(\frac{p_n^j\left(\omega^j\right)}{\lambda}\right)^{-\sigma^j} \qquad \text{(A3.3)}
\end{aligned}
$$

And notice the symmetry between the cost minimization and our profit maximization problem. This confirms what we already knew in that $\lambda = P_n^j$. Substituting (3.3) back into (3.2) to solve for λ directly we get

$$
1 = \left[\int v_n^j\left(\omega^j\right)^{\frac{\sigma^j-1}{\sigma^j}}d\omega^j\right]^{\frac{\sigma^j}{\sigma^j-1}}
$$

$$1 = \left[\int \left(\left(\frac{p_n^j\left(\omega^j\right)}{\lambda}\right)^{-\sigma^j}\right)^{\frac{\sigma^j-1}{\sigma^j}} d\omega^j\right]^{\frac{\sigma^j}{\sigma^j-1}}$$

$$1 = \lambda^{\sigma^j}\left[\int p_n^j\left(\omega^j\right)^{1-\sigma^j} d\omega^j\right]^{\frac{\sigma^j}{\sigma^j-1}}$$

$$\lambda = \left[\int p_n^j\left(\omega^j\right)^{1-\sigma^j} d\omega^j\right]^{\frac{1}{1-\sigma^j}}$$

$$P_n^j = \left[\int p_n^j\left(\omega^j\right)^{1-\sigma^j} d\omega^j\right]^{\frac{1}{1-\sigma^j}} \tag{A3.4}$$

A3.3 Summary

$$P_n^j = \left[\int p_n^j\left(\omega^j\right)^{1-\sigma^j} d\omega^j\right]^{\frac{1}{1-\sigma^j}} \tag{A3.5}$$

A4 Price Index

In the previous section, we solve for the composite intermediate price index in terms of the price of ω^j. Now, we will use properties of the Fréchet distribution to solve for P_n^j in terms of international prices, costs and technology.

In the previous section we found that P_n^j can be given by

$$P_n^j = \left[\int p_n^j\left(\omega^j\right)^{1-\sigma^j} d\omega^j\right]^{\frac{1}{1-\sigma^j}}$$

To solve for P_n^j in terms of costs, we need to use the assumption that firms in country n draw productivities, $z_n^j\left(\omega^j\right)$ from a Fréchet distribution, i.e.,

$$F_n^j\left(z_n^j\right) = \exp\left[-\lambda_n^j\left(z_n^j\right)^{-\theta^j}\right] \tag{A4.1}$$

From the previous sections, we know that the price that firms country i pay for intermediate good ω^j is defined by $p_i^j\left(\omega^j\right) = \min_n\left\{\frac{c_n^j d_{in}^j \tau_{in}^j}{z_n^j}\right\}$. Without loss of generality, fix n for country i such that $p_i^j\left(\omega^j\right) = \frac{c_n^j d_{in}^j \tau_{in}^j}{z_n^j} \Rightarrow z_n^j = \frac{c_n^j d_{in}^j \tau_{in}^j}{p_i^j}$. Thus, we can rewrite the probability distributions for country n as

$$\begin{aligned} F_n^j &= \exp\left[-\lambda_n^j\left(\frac{c_n^j d_{in}^j \tau_{in}^j}{p_i^j}\right)^{-\theta^j}\right] \\ &= \exp\left[-\lambda_n^j\left(c_n^j d_{in}^j \tau_{in}^j\right)^{-\theta^j}\left(p_i^j\right)^{\theta^j}\right] \end{aligned}$$

Now, let's consider the probability that country n pays price $p^j_{ni} < p^j$ given by

$$\begin{aligned}
\mathbb{P}\left(p^j_{ni} \leq p^j\right) &= \mathbb{P}\left(\frac{c^j_n d^j_{in} \tau^j_{in}}{z^j_n} < p^j\right) \\
&= \mathbb{P}\left(\frac{c^j_n d^j_{in} \tau^j_{in}}{p^j} < z^j_n\right) \\
&= 1 - \mathbb{P}\left(z^j_n \leq \frac{c^j_n d^j_{in} \tau^j_{in}}{p^j}\right) \\
&= 1 - F^j_i\left(z^j_n\right) \\
&= 1 - \exp\left[-\lambda^j_i \left(c^j_n d^j_{in} \tau^j_{in}\right)^{-\theta^j} \left(p^j\right)^{\theta^j}\right]
\end{aligned}$$

Notice that $\mathbb{P}\left(p^j_{ni} > p^j\right) = \exp\left[-\lambda^j_i \left(c^j_n d^j_{in} \tau^j_{in}\right)^{-\theta^j} \left(p^j\right)^{\theta^j}\right]$. Therefore, we can say that the probability that country n pays more than p from around the world is given by

$$\prod_{i=1}^{N} \exp\left[-\lambda^j_i \left(c^j_n d^j_{in} \tau^j_{in}\right)^{-\theta^j} \left(p^j\right)^{\theta^j}\right]$$

Thus, we can restate our problem as asking what is the probability that country n pays some price p^j_n less than p from around the world

$$\begin{aligned}
\mathbb{P}\left(p^j_n \leq p\right) &= 1 - \prod_{i=1}^{N} \exp\left[-\lambda^j_i \left(c^j_n d^j_{in} \tau^j_{in}\right)^{-\theta^j} \left(p^j\right)^{\theta^j}\right] \\
&= 1 - \exp\left[-\left(p^j\right)^{\theta^j} \Psi^j_n\right]
\end{aligned}$$

where $\Psi^j_n = \sum_{i=1}^{N} \lambda^j_i \left(c^j_n d^j_{in} \tau^j_{in}\right)^{-\theta^j}$. Because p^j_n is the realization of the random variable p, then we can say that p^j_n must also have Fréchet distribution,

$$\mathbb{P}\left(p \leq p^j_n\right) = \exp\left[-\left(p^j_n\right)^{\theta^j} \Psi\right]$$

Given that p^j_n is Fréchet with shape parameter θ^j, then we can say that $\left(p^j_n\right)^{\theta^j}$ must be exponentially distributed. Let's let $g(x) = \left(p^j_n\right)^{\theta^j} = y$, then by the Delta method we can say that the density of y is given by

$$f_y(y) = \Psi^j_n e^{-\Psi^j_n y}$$

which is exponentially distributed with parameter Ψ^j_n. Recall our original function,

$$P^j_n = \left[\int p^j_n\left(\omega^j\right)^{1-\sigma^j} d\omega^j\right]^{\frac{1}{1-\sigma^j}}$$

To solve for P_n^j, we need to change the measure of our random variable $p_n^j(\omega^j)$. The general formula to do so is given by

$$\int_\Omega y f_y(y)\, dy$$

Therefore, we can say that since

$$\int p_n^j \left(\omega^j\right)^{\theta^j} d\omega^j = \int \Psi_n^j y e^{-y\Psi_n^j} dy$$

then,

$$\left(P_n^j\right)^{1-\sigma^j} = \int \Psi_n^j y^{\frac{1-\sigma^j}{\theta^j}} e^{-y\Psi_n^j} dy$$

Finally, we can consider the change of variables where we let $u = \Psi_n^j y$.

$$\begin{aligned}
\left(P_n^j\right)^{1-\sigma^j} &= \int \Psi_n^j y^{\frac{1-\sigma^j}{\theta^j}} e^{-y\Psi_n^j} dy \\
&= \int \Psi_n^j \left(\Psi_n^j\right)^{-\frac{1-\sigma^j}{\theta^j}} \left(\Psi_n^j\right)^{\frac{1-\sigma^j}{\theta^j}} y^{\frac{1-\sigma^j}{\theta^j}} e^{-u} \frac{du}{\Psi_n^j} \\
\left(P_n^j\right)^{1-\sigma^j} &= \left(\Psi_n^j\right)^{-\frac{1-\sigma^j}{\theta^j}} \int \left(\Psi_n^j y\right)^{\frac{1-\sigma^j}{\theta^j}} e^{-u} du \\
P_n^j &= \left(\Psi_n^j\right)^{-\frac{1}{\theta^j}} \left[\int \left(\Psi_n^j y\right)^{\frac{1-\sigma^j}{\theta^j}} e^{-u} du\right]^{\frac{1}{\theta^j}} \\
P_n^j &= \left(\Psi_n^j\right)^{-\frac{1}{\theta^j}} A^j
\end{aligned}$$

Where $A^j = \left[\int \left(\Psi_n^j y\right)^{\frac{1-\sigma^j}{\theta^j}} e^{-u} du\right]^{\frac{1}{\theta^j}}$ is a Gamma function evaluated at $\xi^j = 1 + \frac{1-\sigma^j}{\theta^j}$. And recall that we defined Ψ_n^j as $\Psi_n^j = \sum_{i=1}^N \lambda_i^j (c_i^j d_{ni}^j \tau_{ni}^j)^{-\theta^j}$. Thus, we can conclude that

$$P_n^j = A^j \left[\sum_{i=1}^N \lambda_i^j (c_i^j d_{ni}^j \tau_{ni}^j)^{-\theta^j}\right]^{-\frac{1}{\theta^j}} \tag{A4.2}$$

A4.1 Summary

$$P_n^j = A^j \left[\sum_{i=1}^N \lambda_i^j (c_i^j d_{ni}^j \tau_{ni}^j)^{-\theta^j}\right]^{-\frac{1}{\theta^j}} \tag{A4.3}$$

A5 Expenditure Shares

In this section, we solve for expenditure shares in terms as function of technologies, prices, and trade costs. The total expenditures on sector j goods in country n is given by $X_n^j = P_n^j Q_n^j$. We denote by X_{ni}^j to be the expenditure in country n of sector j goods from country i. Therefore, we can define the expenditure share in country n of sector j goods from country i as

$$\pi_{ni}^j = \frac{X_{ni}^j}{X_n^j}$$

A5.1 Solving

We can solve for expenditure shares as a function of technologies, prices, and trade costs using the following properties of the exponential distribution,

$$\mathbb{P}\left(X_k = \min\left\{X_1, ..., X_n\right\}\right) = \frac{\lambda_k}{\sum_{i=1}^n \lambda_i} \tag{A5.1}$$

where for all n, X_n is exponentially distributed and λ_n represents the parameter of distribution.

Notice that X_{ni}^j is the realization of the expenditure shares from country n on country i in sector j. Therefore, it must be true that the i was the lost-cost supplier from around the world for country n. Thus, we can interpret π_{ni}^j as the probability that $p_{ni}^j = \min_m p_{nm}^j$ where we now have

$$X_{ni}^j = \mathbb{P}\left(p_{ni}^j = \min_m p_{nm}^j\right) X_n^j$$

We know from the previous section that $\left(p_{ni}^j\right)^{\theta^j}$ has exponential distribution with parameter $\lambda_i^j \left[\tilde{x}_n^j t_{n,p}^j \kappa_{in}^j\right]^{-\theta^j}$. Therefore we can conclude that,

$$\begin{aligned} \pi_{ni}^j &= \mathbb{P}\left(p_{ni}^j \leq \min_m p_{nm}^j\right) \\ \pi_{ni}^j &= \frac{\lambda_i^j \left[c_i^j d_{ni}^j \tau_{ni}^j\right]^{-\theta^j}}{\sum_{h=1}^N \lambda_h^j \left[c_h^j d_{nh}^j \tau_{nh}^j\right]^{-\theta^j}} \end{aligned} \tag{A5.2}$$

A5.2 Summary

$$\pi_{ni}^j = \frac{\lambda_i^j \left[c_i^j d_{ni}^j \tau_{ni}^j\right]^{-\theta^j}}{\sum_{h=1}^N \lambda_h^j \left[c_h^j d_{nh}^j \tau_{nh}^j\right]^{-\theta^j}} \tag{A5.3}$$

A6 Market Clearing Conditions and Total Expenditures

In this section, we derive total expenditures. Total expenditures on goods j from country n is the sum of the expenditure on composite intermediate goods by households and firms. It is given by

$$X_n^j = \sum_{s=1}^{J} \frac{\gamma_n^{j,s}}{t_{n,m}^j t_{n,p}^s} \sum_{i=1}^{N} X_i^s \frac{\pi_{in}^s}{\tau_{in}^s} + \frac{\alpha_n^j}{t_{n,c}^j} I_n \tag{A6.1}$$

where

$$I_n = w_n L_n + \sum_{j=1}^{J} r_n^j E_n^j + T_n + D_n \tag{A6.2}$$

A6.1 Total expenditures

We impose that our expenditure in sector j must be equal to our output generated in sector j. Income generated from this sector which can also be expressed as the revenue generated by the composite intermediate goods sales of sector j given by,

$$P_n^j \sum_{s=1}^{J} \int m_n^{j,s} (\omega^s) \, d\omega^s \tag{A6.3}$$

and the final consumption sales $P_n^j C_n^j$. Recall that from equation (1.5) we can express household expenditures in sector j in terms of household income by

$$P_n^j C_n^j = \frac{\alpha_n^j I_n}{t_{n,c}^j} \tag{A6.4}$$

The first term can be interpreted as considering the share of j in sector s demanded domestically and from the rest of the world, i.e.,

$$P_n^j \sum_{s=1}^{J} \int m_n^{j,s} (\omega^s) \, d\omega^s = \sum_{s=1}^{J} \frac{\gamma_n^{j,s}}{t_{n,m}^j} \sum_{i=1}^{N} X_i^s \frac{\pi_{in}^s}{t_{n,p}^s \tau_{in}^s} \tag{A6.5}$$

Combining (6.5) and (6.4), we arrive at total income generated in j and finally imposing market clearing condition that expenditures in j must equal income we end with

$$X_n^j = \sum_{k=1}^{J} \frac{\gamma_n^{j,s}}{t_{n,m}^j} \sum_{i=1}^{N} X_i^s \frac{\pi_{in}^s}{t_{n,p}^s \tau_{in}^s} + \frac{\alpha_n^j I_n}{t_{n,c}^j}$$

However, we are not done. Recall that there are several taxes used throughout the model, and to solve the model, we must have our expenditure in terms of our factor prices. Substituting income, we see that

$$X_n^j = \sum_{s=1}^{J} \frac{\gamma_n^{j,s}}{t_{n,m}^j} \sum_{i=1}^{N} X_i^s \frac{\pi_{in}^s}{t_{n,p}^s \tau_{in}^s} + \frac{\alpha_n^j}{t_{n,c}^j} \left(w_n L_n + \sum_{s=1}^{J} r_n^j E_n^j + T_n + D_n \right)$$

but T_n can be further separated into the revenue generated by labor, intermediate goods consumption, final goods consumption, production and tariffs:

$$T_n = T_{n,l} + T_{n,m} + T_{n,c} + T_{n,p} + T_{n,\tau}$$

where are each defined by

$$\begin{aligned}
T_{n,l} &= \sum_{s=1}^{J} \sum_{i=1}^{N} \left(t_{n,l}^s - 1 \right) \frac{\gamma_n^{l,s}}{t_{n,l}^s} X_i^s \frac{\pi_{in}^s}{t_{n,p}^s \tau_{in}^s} \\
T_{n,m} &= \sum_{s=1}^{J} \sum_{i=1}^{N} \sum_{k=1}^{J} \left(t_{n,m}^k - 1 \right) \frac{\gamma_n^{k,s}}{t_{n,m}^k} X_i^s \frac{\pi_{in}^s}{t_{n,p}^s \tau_{in}^s} \\
T_{n,c} &= \sum_{s=1}^{J} \left(t_{n,c}^s - 1 \right) \frac{\alpha_n^s I_n}{t_{n,c}^s} \\
T_{n,p} &= \sum_{s=1}^{J} \sum_{i=1}^{N} \left(t_{n,p}^s - 1 \right) X_i^s \frac{\pi_{in}^s}{t_{n,p}^s \tau_{in}^s} \\
T_{n,\tau} &= \sum_{s=1}^{J} \sum_{i=1}^{N} \left(\tau_{ni}^s - 1 \right) X_n^s \frac{\pi_{ni}^s}{\tau_{ni}^s}
\end{aligned}$$

In the first step we solve for income:

$$\begin{aligned}
I_n &= w_n L_n + \sum_{s=1}^{J} r_n^j E_n^j + T_n + D_n \\
&= w_n L_n + \sum_{s=1}^{J} r_n^j E_n^j + \sum_{s=1}^{J} \sum_{i=1}^{N} \left(t_{n,l}^s - 1 \right) \frac{\gamma_n^{l,s}}{t_{n,l}^s} X_i^s \frac{\pi_{in}^s}{t_{n,p}^s \tau_{in}^s} \\
&+ \sum_{s=1}^{J} \sum_{i=1}^{N} \sum_{k=1}^{J} \left(t_{n,m}^k - 1 \right) \frac{\gamma_n^{k,s}}{t_{n,m}^k} X_i^s \frac{\pi_{in}^s}{t_{n,p}^s \tau_{in}^s} \\
&+ \sum_{s=1}^{J} \left(t_{n,c}^s - 1 \right) \frac{\alpha_n^s I_n}{t_{n,c}^s} + \sum_{s=1}^{J} \sum_{i=1}^{N} \left(t_{n,p}^s - 1 \right) X_i^s \frac{\pi_{in}^s}{t_{n,p}^s \tau_{in}^s} + \sum_{s=1}^{J} \sum_{i=1}^{N} \left(\tau_{ni}^s - 1 \right) X_n^s \frac{\pi_{ni}^s}{\tau_{ni}^s} +
\end{aligned}$$

$$I_n \left[1 - \sum_{s=1}^{J} \left(t_{n,c}^s - 1 \right) \frac{\alpha_n^s}{t_{n,c}^s} \right] = w_n L_n + \sum_{s=1}^{J} r_n^j E_n^j + \sum_{s=1}^{J} \sum_{i=1}^{N} \left(t_{n,l}^s - 1 \right) \frac{\gamma_n^{l,s}}{t_{n,l}^s} X_i^s \frac{\pi_{in}^s}{t_{n,p}^s \tau_{in}^s}$$

$$
\begin{aligned}
&+\sum_{s=1}^{J}\sum_{i=1}^{N}\sum_{k=1}^{J}\left(t_{n,m}^{k}-1\right)\frac{\gamma_n^{k,s}}{t_{n,m}^{k}}X_i^s\frac{\pi_{in}^s}{t_{n,p}^s\tau_{in}^s}\\
&+\sum_{s=1}^{J}\sum_{i=1}^{N}\left(t_{n,p}^{s}-1\right)X_i^s\frac{\pi_{in}^s}{t_{n,p}^s\tau_{in}^s}+\sum_{s=1}^{J}\sum_{i=1}^{N}\left(\tau_{ni}^{s}-1\right)X_n^s\frac{\pi_{ni}^s}{\tau_{ni}^s}+D_n
\end{aligned}
$$

Notice that we can say

$$
\begin{aligned}
1-\sum_{s=1}^{J}\left(t_{n,c}^{s}-1\right)\frac{\alpha_n^s}{t_{n,c}^s} &= \sum_{s=1}^{J}\alpha_n^s-\sum_{s=1}^{J}\left(t_{n,c}^{s}-1\right)\frac{\alpha_n^s}{t_{n,c}^s}\\
&=\sum_{s=1}^{J}\left[\alpha_n^s-\left(t_{n,c}^{s}-1\right)\frac{\alpha_n^s}{t_{n,c}^s}\right]\\
&=\sum_{s=1}^{J}\left[\frac{t_{n,c}^s\alpha_n^s-\alpha_n^s t_{n,c}^s+\alpha_n^s}{t_{n,c}^s}\right]\\
\tilde{\alpha}_n &\equiv \sum_{s=1}^{J}\left[\frac{\alpha_n^s}{t_{n,c}^s}\right]
\end{aligned}
$$

Substituting we have

$$
\begin{aligned}
I_n\tilde{\alpha}_n &= w_nL_n+\sum_{s=1}^{J}r_n^jE_n^j+\sum_{s=1}^{J}\sum_{i=1}^{N}\left(t_{n,l}^{s}-1\right)\frac{\gamma_n^{l,s}}{t_{n,l}^{s}}X_i^s\frac{\pi_{in}^s}{t_{n,p}^s\tau_{in}^s}+\sum_{s=1}^{J}\sum_{i=1}^{N}\sum_{k=1}^{J}\left(t_{n,m}^{k}-1\right)\frac{\gamma_n^{k,s}}{t_{n,m}^{k}}X_i^s\frac{\pi_{in}^s}{t_{n,p}^s\tau_{in}^s}\\
&+\sum_{s=1}^{J}\sum_{i=1}^{N}\left(t_{n,p}^{s}-1\right)X_i^s\frac{\pi_{in}^s}{t_{n,p}^s\tau_{in}^s}+\sum_{s=1}^{J}\sum_{i=1}^{N}\left(\tau_{ni}^{s}-1\right)X_n^s\frac{\pi_{ni}^s}{\tau_{ni}^s}+D_n\\
I_n &= \tilde{\alpha}_n^{-1}\left[w_nL_n+\sum_{s=1}^{J}r_n^jE_n^j+\sum_{s=1}^{J}\sum_{i=1}^{N}\left(t_{n,l}^{s}-1\right)\frac{\gamma_n^{l,s}}{t_{n,l}^{s}}X_i^s\frac{\pi_{in}^s}{t_{n,p}^s\tau_{in}^s}\right]\\
&+\tilde{\alpha}_n^{-1}\left[\sum_{s=1}^{J}\sum_{i=1}^{N}\sum_{k=1}^{J}\left(t_{n,m}^{k}-1\right)\frac{\gamma_n^{k,s}}{t_{n,m}^{k}}X_i^s\frac{\pi_{in}^s}{t_{n,p}^s\tau_{in}^s}+\sum_{s=1}^{J}\sum_{i=1}^{N}\left(t_{n,p}^{s}-1\right)X_i^s\frac{\pi_{in}^s}{t_{n,p}^s\tau_{in}^s}\right]\\
&+\tilde{\alpha}_n^{-1}\left[\sum_{s=1}^{J}\sum_{i=1}^{N}\left(\tau_{ni}^{s}-1\right)X_n^s\frac{\pi_{ni}^s}{\tau_{ni}^s}+D_n\right] \qquad \text{(A6.6)}
\end{aligned}
$$

Now, we substitute the income equation back in the expenditure equation

$$
\begin{aligned}
X_n^j &= \sum_{s=1}^{J}\frac{\gamma_n^{j,s}}{t_{n,m}^{j}}\sum_{i=1}^{N}X_i^s\frac{\pi_{in}^s}{t_{n,p}^s\tau_{in}^s}\\
&+\frac{\alpha_n^j}{t_{n,c}^j\sum_{s=1}^{J}\left[\frac{\alpha_n^s}{t_{n,c}^s}\right]}\left[w_nL_n+\sum_{s=1}^{J}r_n^jE_n^j+D_n\right]
\end{aligned}
$$

$$+\frac{\alpha_n^j}{t_{n,c}^j \sum_{s=1}^J \left[\frac{\alpha_n^s}{t_{n,c}^s}\right]} \left[\sum_{s=1}^J \left(t_{n,l}^s - 1\right) \frac{\gamma_n^{l,s}}{t_{n,l}^s t_{n,p}^s} \sum_{i=1}^N X_i^s \frac{\pi_{in}^s}{\tau_{in}^s}\right]$$
$$+\frac{\alpha_n^j}{t_{n,c}^j \sum_{s=1}^J \left[\frac{\alpha_n^s}{t_{n,c}^s}\right]} \left[\sum_{s=1}^J \sum_{k=1}^J \left(t_{n,m}^k - 1\right) \frac{\gamma_n^{k,s}}{t_{n,m}^k t_{n,p}^s} \sum_{i=1}^N X_i^s \frac{\pi_{in}^s}{\tau_{in}^s}\right]$$
$$+\frac{\alpha_n^j}{t_{n,c}^j \sum_{s=1}^J \left[\frac{\alpha_n^s}{t_{n,c}^s}\right]} \left[\sum_{s=1}^J \frac{\left(t_{n,p}^s - 1\right)}{t_{n,p}^s} \sum_{i=1}^N X_i^s \frac{\pi_{in}^s}{\tau_{in}^s}\right]$$
$$+\frac{\alpha_n^j}{t_{n,c}^j \sum_{s=1}^J \left[\frac{\alpha_n^s}{t_{n,c}^s}\right]} \left[\sum_{s=1}^J \sum_{i=1}^N \left(\tau_{ni}^s - 1\right) X_n^s \frac{\pi_{ni}^s}{\tau_{ni}^s}\right]$$

Rearranging:

$$X_n^j = \sum_{s=1}^J \frac{\gamma_n^{j,s}}{t_{n,m}^j} \sum_{i=1}^N X_i^s \frac{\pi_{in}^s}{t_{n,p}^s \tau_{in}^s}$$
$$+\frac{\alpha_n^j}{t_{n,c}^j \sum_{s=1}^J \left[\frac{\alpha_n^s}{t_{n,c}^s}\right]} \left[w_n L_n + \sum_{s=1}^J r_n^j E_n^j + D_n\right]$$
$$+\frac{\alpha_n^j}{t_{n,c}^j \sum_{s=1}^J \left[\frac{\alpha_n^s}{t_{n,c}^s}\right]} \left[\sum_{s=1}^J \left[\left(t_{n,l}^s - 1\right) \frac{\gamma_n^{l,s}}{t_{n,l}^s t_{n,p}^s} + \sum_{k=1}^J \left(t_{n,m}^k - 1\right) \frac{\gamma_n^{k,s}}{t_{n,m}^k t_{n,p}^s} + \frac{\left(t_{n,p}^s - 1\right)}{t_{n,p}^s}\right] \sum_{i=1}^N X_i^s \frac{\pi_{in}^s}{\tau_{in}^s}\right]$$
$$+\frac{\alpha_n^j}{t_{n,c}^j \sum_{s=1}^J \left[\frac{\alpha_n^s}{t_{n,c}^s}\right]} \left[\sum_{s=1}^J \sum_{i=1}^N \left(\tau_{ni}^s - 1\right) X_n^s \frac{\pi_{ni}^s}{\tau_{ni}^s}\right]$$

A6.2 Labor and energy market clearing conditions

Next, we also impose market clearing conditions on the use of inputs to production, that will be later used to solve the model. The labor market clearing condition is given by:

$$w_n L_n = \sum_{j=1}^J \frac{\gamma_n^{l,j}}{t_{n,p}^j t_{n,l}^j} \sum_{i=1}^N X_i \frac{\pi_{in}^j}{\tau_{in}^j} \tag{A6.7}$$

Dirty energy resources cannot be used by any other sector except its own extraction sector, therefore the following factor market clearing condition does not have a summation over j:

$$r_n^j E_n^j = \frac{\gamma_n^{e,j}}{t_{n,p}^j} \sum_{i=1}^N X_i \frac{\pi_{in}^j}{\tau_{in}^j} \tag{A6.8}$$

Equation (A6.7) means that the total amount of labor remuneration received by households in country n must equal what intermediate good firms in country n spend in salaries.

A similar rationale can be drawn from the energy market clearing condition equation (A6.8).

A6.3 Summary

$$
\begin{aligned}
X_n^j = & \sum_{s=1}^{J} \frac{\gamma_n^{j,s}}{t_{n,m}^j} \sum_{i=1}^{N} X_i^s \frac{\pi_{in}^s}{t_{n,p}^s \tau_{in}^s} \\
& + \frac{\alpha_n^j}{t_{n,c}^j \sum_{s=1}^{J} \left[\frac{\alpha_n^s}{t_{n,c}^s}\right]} \left[w_n L_n + \sum_{s=1}^{J} r_n^j E_n^j + D_n \right] \\
& + \frac{\alpha_n^j}{t_{n,c}^j \sum_{s=1}^{J} \left[\frac{\alpha_n^s}{t_{n,c}^s}\right]} \left[\sum_{s=1}^{J} \left[\left(t_{n,l}^s - 1\right) \frac{\gamma_n^{l,s}}{t_{n,l}^s t_{n,p}^s} + \sum_{k=1}^{J} \left(t_{n,m}^k - 1\right) \frac{\gamma_n^{k,s}}{t_{n,m}^k t_{n,p}^s} + \frac{\left(t_{n,p}^s - 1\right)}{t_{n,p}^s} \right] \sum_{i=1}^{N} X_i^s \frac{\pi_{in}^s}{\tau_{in}^s} \right] \\
& + \frac{\alpha_n^j}{t_{n,c}^j \sum_{s=1}^{J} \left[\frac{\alpha_n^s}{t_{n,c}^s}\right]} \left[\sum_{s=1}^{J} \sum_{i=1}^{N} \left(\tau_{ni}^s - 1\right) X_n^s \frac{\pi_{ni}^s}{\tau_{ni}^s} \right] \\
w_n L_n = & \sum_{j=1}^{J} \frac{\gamma_n^{l,j}}{t_{n,p}^j t_{n,l}^j} \sum_{i=1}^{N} X_i \frac{\pi_{in}^j}{\tau_{in}^j} \\
r_n^j E_n^j = & \frac{\gamma_n^{e,j}}{t_{n,p}^j} \sum_{i=1}^{N} X_i \frac{\pi_{in}^j}{\tau_{in}^j}
\end{aligned}
$$

A7 Equilibrium Conditions

A7.1 Summary of equilibrium conditions in levels

In this section we will summarize the necessary equilibrium conditions we've studied throughout this document in levels.

$$
\begin{aligned}
c_n^j &= \Upsilon_n^j \left(t_{n,l}^j w_n\right)^{\gamma_n^{l,j}} \left(r_n^j\right)^{\gamma_n^{e,j}} \prod_{k=1}^{J} \left(t_{n,m}^k P_n^k\right)^{\gamma_n^{k,j}} \\
P_n^j &= A^i \left[\sum_{i=1}^{N} \lambda_i^j \left(c_i^j d_{ni}^j \tau_{ni}^j\right)^{-\theta^j} \right]^{\frac{-1}{\theta^j}} \\
\pi_{ni}^j &= \frac{\lambda_i^j \left[c_i^j d_{ni}^j \tau_{ni}^j\right]^{-\theta^j}}{\sum_{h=1}^{N} \lambda_h^j \left[c_h^j d_{nh}^j \tau_{nh}^j\right]^{-\theta^j}} \\
X_n^j &= \sum_{s=1}^{J} \frac{\gamma_n^{j,s}}{t_{n,m}^j} \sum_{i=1}^{N} X_i^s \frac{\pi_{in}^s}{t_{n,p}^s \tau_{in}^s} + \frac{\alpha_n^j}{t_{n,c}^j} I_n
\end{aligned}
$$

$$w_n L_n = \sum_{j=1}^{J} \frac{\gamma_n^{l,j}}{t_{n,p}^j t_{n,l}^j} \sum_{i=1}^{N} X_i \frac{\pi_{in}^j}{\tau_{in}^j}$$

$$r_n^j E_n^j = \frac{\gamma_n^{e,j}}{t_{n,p}^j} \sum_{i=1}^{N} X_i \frac{\pi_{in}^j}{\tau_{in}^j}$$

where $I_n = w_n L_n + \sum_{j=1}^{J} r_n^j E_n^j + T_n + D_n$.

A7.2 Equilibrium condition in relative changes

Now, we will derive each equilibrium condition in changes

A7.2.1 Cost

$$c_n^j = t_{n,p}^j \Upsilon_n^j \left(t_{n,l}^j w_n\right)^{\gamma_n^{l,j}} \left(r_n^j\right)^{\gamma_n^{e,j}} \prod_{k=1}^{J} \left(t_{n,m}^k P_n^k\right)^{\gamma_n^{k,j}}$$

$$\hat{c}_n^j = \frac{t_{n,p}^{j\prime} \Upsilon_n^j \left(t_{n,l}^{\prime j} w_n^{\prime}\right)^{\gamma_n^{l,j}} \left(r_n^{\prime j}\right)^{\gamma_n^{e,j}} \prod_{k=1}^{J} \left(t_{n,m}^{\prime k} P_n^{\prime k}\right)^{\gamma_n^{k,j}}}{t_{n,p}^j \Upsilon_n^j \left(t_{n,l}^j w_n\right)^{\gamma_n^{l,j}} \left(r_n^j\right)^{\gamma_n^{e,j}} \prod_{k=1}^{J} \left(t_{n,m}^k P_n^k\right)^{\gamma_n^{k,j}}}$$

$$\hat{c}_n^j = \hat{t}_{n,p}^j \left(\hat{t}_{n,l}^j \hat{w}_n\right)^{\gamma_n^{l,j}} \left(\hat{r}_n^j\right)^{\gamma_n^{e,j}} \prod_{k=1}^{J} \left(\hat{t}_{n,m}^k \hat{P}_n^k\right)^{\gamma_n^{k,j}}$$

A7.2.2 Price index

$$P_n^j = A^i \left[\sum_{i=1}^{N} \lambda_i^j \left(c_i^j d_{ni}^j \tau_{ni}^j\right)^{-\theta^j}\right]^{\frac{-1}{\theta^j}}$$

$$\hat{P}_n^j = \frac{A^i \left[\sum_{i=1}^{N} \lambda_i^j \left(c_i^{\prime j} d_{ni}^{\prime j} \tau_{ni}^{\prime j}\right)^{-\theta^j}\right]^{\frac{-1}{\theta^j}}}{A^i \left[\sum_{i=1}^{N} \lambda_i^j \left(c_i^j d_{ni}^j \tau_{ni}^j\right)^{-\theta^j}\right]^{\frac{-1}{\theta^j}}}$$

$$\hat{P}_n^j = \frac{\left[\sum_{i=1}^{N} \lambda_i^j \left(c_i^{\prime j} d_{ni}^{\prime j} \tau_{ni}^{\prime j}\right)^{-\theta^j} \frac{\lambda_i^j \left(c_i^j d_{ni}^j \tau_{ni}^j\right)^{-\theta^j}}{\lambda_i^j \left(c_i^j d_{ni}^j \tau_{ni}^j\right)^{-\theta^j}}\right]^{\frac{-1}{\theta^j}}}{\left[\sum_{i=1}^{N} \lambda_i^j \left(c_i^j d_{ni}^j \tau_{ni}^j\right)^{-\theta^j}\right]^{\frac{-1}{\theta^j}}}$$

$$\hat{P}_n^j = \frac{\left[\sum_{i=1}^{N} \left(\hat{c}_i^j \hat{d}_{ni}^j \hat{\tau}_{ni}^j\right)^{-\theta^j} \lambda_i^j \left(c_i^j d_{ni}^j \tau_{ni}^j\right)^{-\theta^j}\right]^{\frac{-1}{\theta^j}}}{\left[\sum_{i=1}^{N} \lambda_i^j \left(c_i^j d_{ni}^j \tau_{ni}^j\right)^{-\theta^j}\right]^{\frac{-1}{\theta^j}}}$$

$$\hat{P}_n^j = \left[\sum_{i=1}^{N} \pi_{ni}^j \left(\hat{c}_i^j \hat{d}_{ni}^j \hat{\tau}_{ni}^j \right)^{-\theta^j} \right]^{\frac{-1}{\theta^j}}$$

A7.2.3 Expenditure shares

$$\pi_{ni}^j = \frac{\lambda_i^j \left[c_i'^j d_{ni}'^j \tau_{ni}'^j \right]^{-\theta^j}}{\sum_{h=1}^N \lambda_h^j \left[c_i^j d_{ni}^j \tau_{ni}^j \right]^{-\theta^j}}$$

$$\hat{\pi}_{ni}^j = \frac{\frac{\lambda_i^j \left[c_i'^j d_{ni}'^j \tau_{ni}'^j \right]^{-\theta^j}}{\sum_{h=1}^N \lambda_h^j \left[c_i'^j d_{ni}'^j \tau_{ni}'^j \right]^{-\theta^j}}}{\frac{\lambda_i^j \left[c_i^j d_{ni}^j \tau_{ni}^j \right]^{-\theta^j}}{\sum_{h=1}^N \lambda_h^j \left[c_i^j d_{ni}^j \tau_{ni}^j \right]^{-\theta^j}}}$$

$$\hat{\pi}_{ni}^j = \left[\frac{\lambda_i^j \left[c_i'^j d_{ni}'^j \tau_{ni}'^j \right]^{-\theta^j} \sum_{h=1}^N \lambda_h^j \left[c_i^j d_{ni}^j \tau_{ni}^j \right]^{-\theta^j}}{\lambda_i^j \left[c_i^j d_{ni}^j \tau_{ni}^j \right]^{-\theta^j} \sum_{h=1}^N \lambda_h^j \left[c_i'^j d_{ni}'^j \tau_{ni}'^j \right]^{-\theta^j}} \right]$$

$$\hat{\pi}_{ni}^j = \left[\hat{c}_i^j \hat{d}_{ni}^j \hat{\tau}_{ni}^j \right]^{-\theta^j} \left[\frac{1}{\hat{P}_n^j} \right]^{-\theta^j}$$

$$\hat{\pi}_{ni}^j = \left[\frac{\hat{c}_i^j \hat{d}_{ni}^j \hat{\tau}_{ni}^j}{\hat{P}_n^j} \right]^{-\theta^j}$$

A7.2.4 Expenditures

$$X_n^j = \sum_{s=1}^J \frac{\gamma_n^{j,s}}{t_{n,m}^j} \sum_{i=1}^N X_i^s \frac{\pi_{in}^s}{t_{n,p}^s \tau_{in}^s} + \frac{\alpha_n^j}{t_{n,c}^j} I_n$$

$$\begin{aligned}
X_n'^j = & \sum_{s=1}^J \frac{\gamma_n^{j,s}}{t_{n,m}'^j} \sum_{i=1}^N X_i'^s \frac{\pi_{in}'^s}{t_{n,p}'^s \tau_{in}'^s} \\
& + \frac{\alpha_n^j}{t_{n,c}'^j \sum_{s=1}^J \left[\frac{\alpha_n^s}{t_{n,c}'^s} \right]} \left[w_n' L_n + \sum_{s=1}^J r_n'^s E_n^s + \sum_{s=1}^J \sum_{i=1}^N \left(t_{n,l}'^s - 1 \right) \frac{\gamma_n^{l,s}}{t_{n,l}'^s} X_i'^s \frac{\pi_{in}'^s}{t_{n,p}'^s \tau_{in}'^s} \right] \\
& + \frac{\alpha_n^j}{t_{n,c}'^j \sum_{s=1}^J \left[\frac{\alpha_n^s}{t_{n,c}'^s} \right]} \left[\sum_{s=1}^J \sum_{k=1}^J \left(t_{n,m}'^k - 1 \right) \frac{\gamma_n^{k,s}}{t_{n,m}'^k t_{n,p}'^s} \sum_{i=1}^N X_i'^s \frac{\pi_{in}'^s}{\tau_{in}'^s} \right] \\
& + \frac{\alpha_n^j}{t_{n,c}'^j \sum_{s=1}^J \left[\frac{\alpha_n^s}{t_{n,c}'^s} \right]} \left[\sum_{s=1}^J \frac{\left(t_{n,p}'^s - 1 \right)}{t_{n,p}'^s} \sum_{i=1}^N X_i'^s \frac{\pi_{in}'^s}{\tau_{in}'^s} + \sum_{s=1}^J \sum_{i=1}^N \left(\tau_{ni}'^s - 1 \right) X_n'^s \frac{\pi_{ni}'^s}{\tau_{ni}'^s} + D_n \right]
\end{aligned}$$

$$X_n'^j = \sum_{s=1}^J \frac{\gamma_n^{j,s}}{t_{n,m}'^j} \sum_{i=1}^N X_i'^s \frac{\pi_{in}'^s}{t_{n,p}'^s \tau_{in}'^s}$$

$$+\frac{\alpha_n^j}{t_{n,c}'^j \sum_{s=1}^J \left[\frac{\alpha_n^s}{t_{n,c}'^s}\right]}\left[\hat{w}_n w_n L_n + \sum_{s=1}^J \hat{r}_n^s r_n^s E_n^s + D_n + \sum_{s=1}^J \sum_{i=1}^N \left(t_{n,l}'^s - 1\right)\frac{\gamma_n^{l,s}}{t_{n,l}'^s} X_i'^s \frac{\pi_{in}'^s}{t_{n,p}'^s \tau_{in}'^s}\right]$$

$$+\frac{\alpha_n^j}{t_{n,c}'^j \sum_{s=1}^J \left[\frac{\alpha_n^s}{t_{n,c}'^s}\right]}\left[\sum_{s=1}^J \sum_{k=1}^J \left(t_{n,m}'^k - 1\right)\frac{\gamma_n^{k,s}}{t_{n,m}'^k t_{n,p}'^s} \sum_{i=1}^N X_i'^s \frac{\pi_{in}'^s}{\tau_{in}'^s} + \sum_{s=1}^J \frac{\left(t_{n,p}'^s - 1\right)}{t_{n,p}'^s} \sum_{i=1}^N X_i'^s \frac{\pi_{in}'^s}{\tau_{in}'^s}\right]$$

$$+\frac{\alpha_n^j}{t_{n,c}'^j \sum_{s=1}^J \left[\frac{\alpha_n^s}{t_{n,c}'^s}\right]}\left[\sum_{s=1}^J \sum_{i=1}^N \left(\tau_{ni}'^s - 1\right) X_n'^s \frac{\pi_{ni}'^s}{\tau_{ni}'^s}\right]$$

Rearranging terms, the LHS gives us

$$\begin{aligned}
&X_n'^j - \sum_{s=1}^J \left(\frac{\gamma_n^{j,s}}{t_{n,m}'^j t_{n,p}'^s}\right) \sum_{i=1}^N X_i'^s \frac{\pi_{in}'^s}{\tau_{in}'^s} \\
&\quad - \sum_{s=1}^J \left(\frac{\alpha_n^j}{t_{n,c}'^j \sum_{s=1}^J \left[\frac{\alpha_n^s}{t_{n,c}'^s}\right]}\left[\sum_{k=1}^J \left(\frac{\gamma_n^{k,s}\left(t_{n,m}'^k - 1\right)}{t_{n,m}'^k t_{n,p}'^s}\right) + \frac{\left(t_{n,p}'^s - 1\right)}{t_{n,p}'^s} + \frac{\gamma_n^{l,s}\left(t_{n,l}'^s - 1\right)}{t_{n,l}'^s t_{n,p}'^s}\right]\right) \sum_{i=1}^N X_i'^s \frac{\pi_{in}'^s}{\tau_{in}'^s} \\
&\quad - \frac{\alpha_n^j}{t_{n,c}'^j \sum_{s=1}^J \left[\frac{\alpha_n^s}{t_{n,c}'^s}\right]}\left[\sum_{s=1}^J \sum_{i=1}^N \left(\tau_{ni}'^s - 1\right) X_n'^s \frac{\pi_{ni}'^s}{\tau_{ni}'^s}\right]
\end{aligned}$$

and the RHS

$$\frac{\alpha_n^j}{t_{n,c}'^j \sum_{s=1}^J \left[\frac{\alpha_n^s}{t_{n,c}'^s}\right]}\left[\hat{w}_n w_n L_n + \sum_{s=1}^J \hat{r}_n^s r_n^s E_n^s + D_n\right]$$

The LHS will give us matrix given an $N \times J$ matrix which we can invert to solve for $X_n'^j$

A7.2.5 Factor Market Clearing Conditions

Using the factor market clearing condition, we can solve for a new $\hat{w}_n^*$ and $\hat{r}_n^*$that would bring the market to and equilibrium. For the labor market condition, we have:

$$\begin{aligned}
\sum_{j=1}^J w_n L_n^j &= \sum_{j=1}^J \frac{\gamma_n^{l,j}}{t_{n,p}^j t_{n,l}^j} \sum_{i=1}^N X_i \frac{\pi_{in}^j}{\tau_{in}^j} \\
\hat{w}_n^* w_n L_n &= \sum_{j=1}^J \frac{\gamma_n^{l,j}}{t_{n,p}'^j t_{n,l}'^j} \sum_{i=1}^N X_i' \frac{\pi_{in}'^j}{\tau_{in}'^j} \\
\hat{w}_n^* &= \frac{\sum_{j=1}^J \frac{\gamma_n^{l,j}}{t_{n,p}'^j t_{n,l}'^j} \sum_{i=1}^N X_i' \frac{\pi_{in}'^j}{\tau_{in}'^j}}{w_n L_n}
\end{aligned}$$

For each of the extraction sectors using a dirty energy resource, we have:

$$
\begin{aligned}
r_n^j E_n^j =& \frac{\gamma_n^{e,j}}{t_{n,p}^j} \sum_{i=1}^N X_i \frac{\pi_{in}^j}{\tau_{in}^j} \\
\hat{r}_n^{j*} r_n^j E_n^j =& \frac{\gamma_n^{e,j}}{t_{n,p}'^j} \sum_{i=1}^N X_i' \frac{\pi_{in}'^j}{\tau_{in}'^j} \\
\hat{r}_n^{j*} =& \frac{\frac{\gamma_n^{e,j}}{t_{n,p}'^j} \sum_{i=1}^N X_i' \frac{\pi_{in}'^j}{\tau_{in}'^j}}{r_n^j E_n^j}
\end{aligned}
$$

A7.3 Summary

$$
\hat{c}_n^j = \hat{t}_{n,p}^j \left(\hat{t}_{n,l}^j \hat{w}_n\right)^{\gamma_n^{l,j}} \left(\hat{r}_n^j\right)^{\gamma_n^{e,j}} \prod_{k=1}^J \left(\hat{t}_{n,m}^k \hat{P}_n^{k,j}\right)^{\gamma_n^{k,j}} \tag{A7.1}
$$

$$
\hat{P}_n^j = \left[\sum_{i=1}^N \pi_{ni}^j \left(\hat{c}_i^j \hat{d}_{ni}^j \hat{\tau}_{ni}^j\right)^{-\theta^j}\right]^{\frac{-1}{\theta^j}} \tag{A7.2}
$$

$$
\hat{\pi}_{ni}^j = \left[\frac{\hat{c}_i^j \hat{d}_{ni}^j \hat{\tau}_{ni}^j}{\hat{P}_n^j}\right]^{-\theta^j} \tag{A7.3}
$$

$$
\begin{aligned}
X_n'^j &- \sum_{s=1}^J \left(\frac{\gamma_n^{j,s}}{t_{n,m}'^j t_{n,p}'^s}\right) \sum_{i=1}^N X_i'^s \frac{\pi_{in}'^s}{\tau_{in}'^s} \\
&- \sum_{s=1}^J \left(\frac{\alpha_n^j}{t_{n,c}'^j \sum_{s=1}^J \left[\frac{\alpha_n^s}{t_{n,c}'^s}\right]} \left[\sum_{k=1}^J \left(\frac{\gamma_n^{k,s}\left(t_{n,m}'^k - 1\right)}{t_{n,m}'^k t_{n,p}'^s}\right) + \frac{\left(t_{n,p}'^s - 1\right)}{t_{n,p}'^s} + \frac{\gamma_n^{l,s}\left(t_{n,l}'^s - 1\right)}{t_{n,l}'^s t_{n,p}'^s}\right]\right) \sum_{i=1}^N X_i'^s \frac{\pi_{in}'^s}{\tau_{in}'^s} \\
&- \frac{\alpha_n^j}{t_{n,c}'^j \sum_{s=1}^J \left[\frac{\alpha_n^s}{t_{n,c}'^s}\right]} \left[\sum_{s=1}^J \sum_{i=1}^N \left(\tau_{ni}'^s - 1\right) X_n'^s \frac{\pi_{ni}'^s}{\tau_{ni}'^s}\right] \\
&= \frac{\alpha_n^j}{t_{n,c}'^j \sum_{s=1}^J \left[\frac{\alpha_n^s}{t_{n,c}'^s}\right]} \left[\hat{w}_n w_n L_n + \sum_{s=1}^J \hat{r}_n^s r_n^s E_n^s + D_n\right]
\end{aligned} \tag{A7.4}
$$

$$
\hat{w}_n^* w_n L_n = \sum_{j=1}^J \frac{\gamma_n^{l,j}}{t_{n,p}'^j t_{n,l}'^j} \sum_{i=1}^N X_i' \frac{\pi_{in}'^j}{\tau_{in}'^j} \tag{A7.5}
$$

$$
\hat{r}_n^{j*} r_n^j E_n^j = \frac{\gamma_n^{e,j}}{t_{n,p}'^j} \sum_{i=1}^N X_i' \frac{\pi_{in}'^j}{\tau_{in}'^j} \tag{A7.6}
$$

A8 Emissions

The production of intermediate good generates CO_2 emissions. Emissions due to production of good j in country n is given by:

$$Z_n^j = \frac{\psi_n^j Y_n^j}{P_n^j} \tag{A8.1}$$

where ψ_n^j is the CO_2 intensity of output in country n and sector j. It is measured in metric tons of CO_2 per real dollar of output. This coefficient varies by country and sector. Note that global emissions equal the summation of emission across all countries and sectors $Z_0 = \sum_{j=1}^{J} \sum_{n=1}^{N} Z_n^j$.

A8.1 Emissions in relative changes

Given that we are solving the model in relative change we cannot calculate the level of prices in the counterfactual scenario. For this reason we solve for emissions in relative terms:

$$\hat{Z}_n^j = \frac{\psi_n^j Y_n'^j / Y_n^j}{\psi_n^j P_n'^j / P_n^j} = \frac{\hat{Y}_n^j}{\hat{P}_n^j} \tag{A8.2}$$

Note that we assume that the emission intensity of each country-sector does not change. Emissions in the counterfactual scenario are than calculated using the baseline emissions and the change in emissions, $Z_n^{j\prime} = Z_n^j \hat{Z}_n^j$. Summing up counterfactual emissions across sectors and countries gives us: $Z = \sum_{j=1}^{J} \sum_{n=1}^{N} Z_n^{j\prime}$.

Part B
Model Calibration and Solution

B1 Taking the model to the data

In order to calibrate the model we obtain most of the data directly from the GTAP Multi-Regional Input-Output (MRIO) table. More precisely, we need to calculate the structural parameters $\pi^j_{ni}, \gamma^{l,j}_n, \gamma^{e,j}_n, \gamma^{k,j}_n, \alpha^j_n$, tariffs and tax rates, $\tau^j_{ni}, t^j_{n,c}, t^j_{n,m}, t^j_{n,l}, t^j_{n,p}$ and emissions and emission intensities, Z^j_n, ψ^j_n

Expenditure shares, π^j_{ni}, are calculated with information on country n expenditures of sector j's goods from country i, X^j_{ni}. This variable is computed by adding up what each sector j in country i (rows of the MRIO) sells to country n (columns). In other words, we are adding up sales from country i in sectors j that are sent to i) intermediate production of all sector j and to ii) final demand consumption in country n. Because expenditure shares include all expenses including taxes and tariffs, we must consider them in this calibration. Sales to intermediate consumption already include taxes paid in the production process. However, sales to final consumption do not include the final consumption tax paid. Therefore, we inflate final demand expenditures in the MRIO by their respective final consumption tax expenditures. Summing over intermediate and final goods over all country i's, we obtain total expenditures of sector j in country n, X^j_n, which is used to calculate expenditure shares $\pi^j_{ni} = X^j_{ni}/X^j_n$.

Intermediate good's shares of the production function are also drawn from the MRIO. The share of sector k's spending on sector's j goods $\gamma^{j,k}_n$, is calculated as the share of sector j (what is bought from all countries) in sector k over the total intermediate consumption of sector k (sum over all countries and sectors) plus the value added expenses (labor and energy resourses). The **labor, $\gamma^{l,k}_n$, and energy shares, $\gamma^{e,k}_n$,** are calculated by dividing the value added from labor and energy, respectively, by the total intermediate consumption of sector k plus the value added expenses.

Emissions at baseline are retrieved from GTAP. We take emissions by sector and country and divided it by the value of output to get the emission intensities $\psi^j_n = Z^j_n/Y^j_n$.

Data on **taxes** expenditures are from GTAP's MRIO. We calibrate the model with baseline taxes, that is, our baseline economy already include the taxes in place in 2014. **Labor tax rates**, $t^j_{n,l}$, were computed by adding value added taxes expenses and dividing by total value added for each sector and country. From this computation we exclude taxes and value added from natural resource from the dirty energy sectors. Each producing sector j in country n face a different **material tax rates**, $t^k_{n,m}$, or intermediate consumption taxes, for each sector k from which they source their inputs. We calculate this tax by dividing consumption tax revenues from intermediate consumption in each sector divided by the sum of materials expenses from sector k purchased from all sources by all sectors in country n. **Final consumption tax rates**, $t^j_{n,c}$, are calculated by taking the ratio of final consumption taxes expenditures over the sum of final consumption from domestic and foreign suppliers by sector and country. **Production tax rates**, $t^j_{n,p}$, use information from production tax expenses by sector and country in the nominator and the sum of all intermediate expenses and value added from each sector and country in the denominator.

Tariffs, τ_{ni}^{j}, are obtained from two sources. Our main source is the GTAP data. We calculate bilateral tariffs by sector diving what was collected in tariff duties by the total bilateral import value plus international trade and transport margins. This is our main source of tariffs. However, when there is no trade in goods for a particular countrypair-sector, this ratio is undefined and we cannot calculate the tariff rate. For those cases we turn to WITS HS6 data processed by Moreira and Dolabella (2023). They aggregated around 160 million tariffs from 175 origins, 175 destinations over 5,000 products (HS6 level) to the GTAP10 country-sector classification using simple averages. Initially, we compute the simple average of tariffs within each of the 29 tradable sectors for every countrypair. Then we compute trade-weighted tariffs for our regions (containing more than one country). We then substitute these values whenever there is a missing tariff from the GTAP data.

B1.1 Calculating final consumption shares α_n^j

Starting with expenditures we have,

$$X_n^j = \sum_{k=1}^{J} \frac{\gamma_n^{j,k}}{t_{n,m}^j} \sum_{i=1}^{N} X_i^k \frac{\pi_{in}^k}{t_{n,p}^k \tau_{in}^k} + \frac{\alpha_n^j}{t_{n,c}^j} I_n$$

Our goal is to substitute income and isolate α_n^j

$$\begin{aligned} I_n = & \left[\sum_{s=1}^{J} \frac{\alpha_n^j}{t_{c,n}^j}\right]^{-1} \left[w_n L_n + \sum_{s=1}^{J} r_n^j E_n^j + \sum_{s=1}^{J}\sum_{i=1}^{N} \left(t_{n,l}^s - 1\right) \frac{\gamma_n^{l,s}}{t_{n,l}^s} X_i^s \frac{\pi_{in}^s}{t_{n,p}^s \tau_{in}^s}\right] \\ & + \left[\sum_{s=1}^{J} \frac{\alpha_n^j}{t_{c,n}^j}\right]^{-1} \left[\sum_{s=1}^{J}\sum_{i=1}^{N}\sum_{k=1}^{J} \left(t_{n,m}^k - 1\right) \frac{\gamma_n^{k,s}}{t_{n,m}^k} X_i^s \frac{\pi_{in}^s}{t_{n,p}^s \tau_{in}^s} + \sum_{s=1}^{J}\sum_{i=1}^{N} \left(t_{n,p}^s - 1\right) X_i^s \frac{\pi_{in}^s}{t_{n,p}^s \tau_{in}^s}\right] \\ & + \left[\sum_{s=1}^{J} \frac{\alpha_n^j}{t_{c,n}^j}\right]^{-1} \left[\sum_{s=1}^{J}\sum_{i=1}^{N} \left(\tau_{ni}^s - 1\right) X_n^s \frac{\pi_{ni}^s}{\tau_{ni}^s} + D_n\right] \end{aligned}$$

After separating terms, we can simplify our expression and define a variable B_n such that

$$\begin{aligned} B_n \equiv & \, w_n L_n + \sum_{s=1}^{J} r_n^j E_n^j + \sum_{s=1}^{J}\sum_{i=1}^{N} \left(t_{n,l}^s - 1\right) \frac{\gamma_n^{l,s}}{t_{n,l}^s} X_i^s \frac{\pi_{in}^s}{t_{n,p}^s \tau_{in}^s} \\ & + \sum_{s=1}^{J}\sum_{i=1}^{N}\sum_{k=1}^{J} \left(t_{n,m}^k - 1\right) \frac{\gamma_n^{k,s}}{t_{n,m}^k} X_i^s \frac{\pi_{in}^s}{t_{n,p}^s \tau_{in}^s} + \sum_{s=1}^{J}\sum_{i=1}^{N} \left(t_{n,p}^s - 1\right) X_i^s \frac{\pi_{in}^s}{t_{n,p}^s \tau_{in}^s} \\ & + \sum_{s=1}^{J}\sum_{i=1}^{N} \left(\tau_{ni}^s - 1\right) X_n^s \frac{\pi_{ni}^s}{\tau_{ni}^s} + D_n \end{aligned}$$

Income now reduces to the following

$$I_n = \left[\sum_{s=1}^{J} \frac{\alpha_n^j}{t_{c,n}^j}\right]^{-1} B_n$$

After substituting income back into our expenditure function, we can separate the alphas

$$X_n^j = \sum_{k=1}^{J} \frac{\gamma_n^{j,k}}{t_{n,m}^j} \sum_{i=1}^{N} X_i^k \frac{\pi_{in}^k}{t_{n,p}^k \tau_{in}^k} + \frac{\alpha_n^j}{t_{n,c}^j} \left[\sum_{s=1}^{J} \frac{\alpha_n^j}{t_{c,n}^j}\right]^{-1} B_n$$

$$\alpha_n^j = \left[\sum_{s=1}^{J} \frac{\alpha_n^j}{t_{n,c}^j}\right] \frac{t_{n,c}^j \left[X_n^j - \sum_{k=1}^{J} \frac{\gamma_n^{j,k}}{t_{n,m}^j} \sum_{i=1}^{N} X_i^k \frac{\pi_{in}^k}{t_{n,p}^k \tau_{in}^k}\right]}{B_n}$$

Let's now define a new variable for each country and sector given by

$$\Phi_n^j = \frac{t_{n,c}^j \left[X_n^j - \sum_{k=1}^{J} \frac{\gamma_n^{j,k}}{t_{n,m}^j} \sum_{i=1}^{N} X_i^k \frac{\pi_{in}^k}{t_{n,p}^k \tau_{in}^k}\right]}{B_n}$$

Thus, our problem reduces to solving for the eigenvector for the following system of equations for each country

$$\begin{bmatrix} \frac{\Phi_n^1}{t_{c,1}^1} & \frac{\Phi_n^1}{t_{c,1}^2} & \cdots & \frac{\Phi_n^1}{t_{c,n}^J} \\ \frac{\Phi_n^2}{t_{c,n}^1} & \frac{\Phi_n^2}{t_{c,n}^2} & \cdots & \frac{\Phi_n^2}{t_{c,n}^J} \\ \vdots & \vdots & \ddots & \vdots \\ \frac{\Phi_n^J}{t_{c,n}^1} & \frac{\Phi_n^J}{t_{c,n}^2} & \cdots & \frac{\Phi^J}{t_{c,n}^J} \end{bmatrix} \begin{bmatrix} \alpha_n^1 \\ \alpha_n^2 \\ \vdots \\ \alpha_n^J \end{bmatrix} = \begin{bmatrix} \alpha_n^1 \\ \alpha_n^2 \\ \vdots \\ \alpha_n^J \end{bmatrix}$$

B1.2 Calibration of the damage parameter δ

Consumers dislike carbon emissions. In order to introduce a negative impact from carbon in our model we need to calibrate a damage parameter that will transform emissions into quantitative welfare losses. This is done by assuming a uniform global damage parameter, that is all countries have the same disutility from carbon. As in Shapiro (2021) we let δ be a damage parameter calibrated such that a one ton increase in emissions leads to a \$163 reduction in global welfare. We start this calibration by summing the utility function of consumers across countries:

$$\sum_{n=1}^{N} U_n = \sum_{n=1}^{N} \prod_{j=1}^{J} \left(C_n^j\right)^{\alpha_n^j} \left[1 + \delta \left(Z - Z_0\right)\right]^{-1}$$

Recall that all else constant, we know that $\prod_{j=1}^{J} \left(C_n^j\right)^{\alpha_n^j} = U_n$. Additionally, we can define global welfare as the sum of each country's utility, $W = \sum_{n=1}^{N} U_n$. Given that our emission data is expressed in million tons, if we assume that increasing one ton in global emissions, $Z = Z_0 + 1$, decreases global welfare by \$163, we can modify the above equation as follows:

$$\begin{aligned} W - 163 &= W \left[1 + \delta \left(Z_0 + 1 - Z_0\right)\right]^{-1} \\ W - 163 &= W \left[1 + \delta\right]^{-1} \\ 1 + \delta &= \frac{W}{W - 163} \\ \delta &= \frac{W}{W - 163} - 1 \end{aligned}$$

Given that we cannot calculate welfare at baseline, because we do not have the vector of prices, we assume prices are constant and use global income in \$ units instead:

$$\delta = \frac{\sum_{n=1}^{N} I_n}{\left(\sum_{n=1}^{N} I_n\right) - 163} - 1$$

B2 Algorithm for solving the model

1. Simultaneously guess a vector of of wages, $\hat{w} = (w_1, ..., w_N)$ and a vector of energy rent prices for each of three dirty energy factors j, $\hat{\boldsymbol{r}} = [\hat{r}^1, \hat{r}^2, \hat{r}^3] = [(\hat{r}_1^1, ..., \hat{r}_N^1), (\hat{r}_1^2, ..., \hat{r}_N^2), (\hat{r}_1^3, ..., \hat{r}_N^3)]$.
2. Calculate the $\hat{c}_n^j\left(\hat{w}, \hat{\boldsymbol{r}}\right)$ using equation (8.1) and then $\hat{P}_n^j\left(\hat{w}, \hat{\boldsymbol{r}}\right)$ using equation (8.2).
3. Solve for expenditure shares $\pi_{ni}^{\prime j}\left(\hat{w}, \hat{\boldsymbol{r}}\right)$ consistent with results from step 2.
4. In order obtain the counterfactual total expenditures, $X_n^{\prime j}\left(\hat{w}, \hat{\boldsymbol{r}}\right)$, we re-writing the system of equations in matrix form:

$$\Omega(\hat{w}, \hat{\boldsymbol{r}})\mathbf{X} = \Delta(\hat{w}, \hat{\boldsymbol{r}})$$

   where $\mathbf{X}$ is the vector of expenditures for each sector and country and $\Delta(\hat{w}, \hat{\boldsymbol{r}})$ is a vector containing the shares of each sector and country in final demand, value added, taxes on labor, and aggregate trade deficit by country:

$$\Delta(\hat{w}, \hat{\boldsymbol{r}}) = \begin{bmatrix} \frac{\alpha_1^1}{t_{1,c}^{1\prime} \sum_{j=1}^{J} (\alpha_1^j / t_{1,c}^{j\prime})} \left(\sum_{j=1}^{J} \left[t_{1,l}^{j\prime} \hat{w}_1 w_1 L_1^j + \hat{r}_1^j r_1^j E_1^j\right] + D_1\right) \\ \vdots \\ \frac{\alpha_1^J}{t_{1,c}^{J\prime} \sum_{j=1}^{J} (\alpha_1^j / t_{1,c}^{j\prime})} \left(\sum_{j=1}^{J} \left[t_{1,l}^{j\prime} \hat{w}_1 w_1 L_1^j + \hat{r}_1^j r_1^j E_1^j\right] + D_1\right) \\ \vdots \\ \frac{\alpha_N^1}{t_{c,N}^{1\prime} \sum_{j=1}^{J} (\alpha_N^j / t_{N,c}^{j\prime})} \left(\sum_{j=1}^{J} \left[t_{N,l}^{j\prime} \hat{w}_N w_N L_N^j + \hat{r}_N^j r_N^j E_N^j\right] + D_N\right) \\ \vdots \\ \frac{\alpha_N^J}{t_{c,N}^{J\prime} \sum_{j=1}^{J} (\alpha_N^j / t_{N,c}^{j\prime})} \left(\sum_{j=1}^{J} \left[t_{N,l}^{j\prime} \hat{w}_N w_N L_N^j + \hat{r}_N^j r_N^j E_N^j\right] + D_N\right) \end{bmatrix}_{JN \times 1}.$$

The matrix $\boldsymbol{\Omega}(\hat{w}, \hat{\boldsymbol{r}})$ is a square matrix of dimensions $JN \times JN$. $\Omega(\hat{w}, \hat{\boldsymbol{r}})$ captures the general equilibrium effects of how changes in tariffs from one sector and one country impact expenditure in all other sectors of the economy and the world. $\Omega(\hat{w}, \hat{\boldsymbol{r}})$ is constructed as follows:

$$\boldsymbol{\Omega}(\hat{w}, \hat{\boldsymbol{r}}) = I - \tilde{T}(\hat{w}, \hat{\boldsymbol{r}}) - \digamma(\hat{w}, \hat{\boldsymbol{r}})$$

where I is an identity matrix, $\tilde{T}(\hat{w}, \hat{\boldsymbol{r}})$ is a square matrix equivalent to the second term in equation (7.4) and $\digamma(\hat{w}, \hat{\boldsymbol{r}})$ is equivalent to the third term in the left hand side of equation (7.4). All of these matrices are JN x JN in size. The square matrix $\digamma(\hat{w}, \hat{\boldsymbol{r}})$ is constructed using the following vectors,

$$A_n = \begin{pmatrix} \frac{\alpha_n^1}{t_{c,n}^{1'} \sum_{j=1}^{J} (\alpha_n^j / t_{c,n}^{j'})} \\ \vdots \\ \frac{\alpha_n^J}{t_{c,n}^{J'} \sum_{j=1}^{J} (\alpha_n^j / t_{c,n}^{j'})} \end{pmatrix}_{J \times 1}, \tilde{F}_n'(\hat{w}, \hat{\boldsymbol{r}}) = \Big(\Big(1 - F_n^{1'}(\hat{w}, \hat{\boldsymbol{r}})\Big) \cdots \Big(1 - F_n^{J'}(\hat{w}, \hat{\boldsymbol{r}})\Big) \Big)_{1 \times J},$$

where $F_n^{j'}(\hat{w}, \hat{\boldsymbol{r}}) = \sum_{i=1}^{N} \frac{\pi_{ni}^{j'}(\hat{w}, \hat{\boldsymbol{r}})}{\tau_{ni}^{j'}}$. Then the matrix $\digamma(\hat{w}, \hat{\boldsymbol{r}})$ is defined as

$$\digamma(\hat{w}, \hat{\boldsymbol{r}}) = \begin{pmatrix} A_1 \otimes \tilde{F}_1'(\hat{w}, \hat{\boldsymbol{r}}) & 0_{J \times J} & \cdots & 0_{J \times J} & 0_{J \times J} \\ 0_{J \times J} & A_2 \otimes \tilde{F}_2'(\hat{w}, \hat{\boldsymbol{r}}) & \cdots & \vdots & \vdots \\ 0_{J \times J} & 0_{J \times J} & \ddots & 0_{J \times J} & 0_{J \times J} \\ \vdots & \vdots & \cdots & A_{N-1} \otimes \tilde{F}_{N-1}'(\hat{w}, \hat{\boldsymbol{r}}) & 0_{J \times J} \\ 0_{J \times J} & 0_{J \times J} & \cdots & 0_{J \times J} & A_N \otimes \tilde{F}_N'(\hat{w}, \hat{\boldsymbol{r}}) \end{pmatrix}_{JN \times JN}.$$

The square matrix $\tilde{T}(\hat{w}, \hat{\boldsymbol{r}})$ is given by:

$$\tilde{T}(\hat{w}, \hat{\boldsymbol{r}}) = \begin{pmatrix} \chi_1^{1,1} \tilde{\pi}_{1,1}^{1\prime}(\hat{w}, \hat{\boldsymbol{r}}) & \cdots & \chi_1^{1,J} \tilde{\pi}_{1,1}^{J\prime}(\hat{w}, \hat{\boldsymbol{r}}) & \cdots & \chi_1^{1,1} \tilde{\pi}_{N,1}^{1\prime}(\hat{w}, \hat{\boldsymbol{r}}) & \cdots & \chi_1^{1,J} \tilde{\pi}_{N,1}^{J\prime}(\hat{w}, \hat{\boldsymbol{r}}) \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ \chi_1^{J,1} \tilde{\pi}_{1,1}^{1\prime}(\hat{w}, \hat{\boldsymbol{r}}) & \cdots & \chi_1^{J,J} \tilde{\pi}_{1,1}^{J\prime}(\hat{w}, \hat{\boldsymbol{r}}) & \cdots & \chi_1^{J,1} \tilde{\pi}_{N,1}^{1\prime}(\hat{w}, \hat{\boldsymbol{r}}) & \cdots & \chi_1^{J,J} \tilde{\pi}_{N,1}^{J\prime}(\hat{w}, \hat{\boldsymbol{r}}) \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ \chi_N^{1,1} \tilde{\pi}_{1,N}^{1\prime}(\hat{w}, \hat{\boldsymbol{r}}) & \cdots & \chi_N^{1,J} \tilde{\pi}_{1,N}^{J'}(\hat{w}, \hat{\boldsymbol{r}}) & \cdots & \chi_N^{1,1} \tilde{\pi}_{N,N}^{1,}(\hat{w}, \hat{\boldsymbol{r}}) & \cdots & \chi_N^{1,J} \tilde{\pi}_{N,N}^{J\prime}(\hat{w}, \hat{\boldsymbol{r}}) \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ \chi_N^{J,1} \tilde{\pi}_{1,N}^{1\prime}(\hat{w}, \hat{\boldsymbol{r}}) & \cdots & \chi_N^{J,J} \tilde{\pi}_{1,N}^{J'}(\hat{w}, \hat{\boldsymbol{r}}) & \cdots & \chi_N^{J,1} \tilde{\pi}_{N,N}^{1\prime,}(\hat{w}, \hat{\boldsymbol{r}}) & \cdots & \chi_N^{J,J} \tilde{\pi}_{N,N}^{J\prime}(\hat{w}, \hat{\boldsymbol{r}}) \end{pmatrix}_{JN \times JN}$$

where $\chi_n^{j,s}$ and $\tilde{\pi}_{in}^{s'}(\hat{w}, \hat{\boldsymbol{r}})$ are defined as follows:[25]

$$\tilde{\pi}_{in}^{s'}(\hat{w}, \hat{\boldsymbol{r}}) = \frac{\pi_{in}^{s'}(\hat{w}, \hat{\boldsymbol{r}})}{\tau_{in}^{s'}}$$

$$\chi_n^{j,s} = \frac{\gamma_n^{j,s}}{t'^{j}_{n,m} t'^{s}_{n,p}} + \frac{\alpha_n^j}{t'^{j}_{n,c} \sum_{s=1}^{J} \left[\frac{\alpha_n^s}{t'^{s}_{n,c}}\right]} \left[\frac{1}{t'^{s}_{n,p}} \sum_{k=1}^{J} \frac{\gamma_n^{k,s}\left(t'^{k}_{n,m} - 1\right)}{t'^{k}_{n,m}} + \frac{\left(t'^{s}_{n,p} - 1\right)}{t'^{s}_{n,p}} + \frac{\gamma_n^{l,s}\left(t'^{s}_{n,l} - 1\right)}{t'^{s}_{n,l} t'^{s}_{n,p}}\right]$$

With this terms at hand, we can proceed to calculate, $\boldsymbol{\Omega}(\hat{w}, \hat{\boldsymbol{r}}) = I - F(\hat{w}, \hat{\boldsymbol{r}}) - \tilde{T}(\hat{w}, \hat{\boldsymbol{r}})$. We solve for the vector $\mathbf{X}(\hat{w}, \hat{\boldsymbol{r}})$ by inverting the matrix $\Omega(\hat{w}, \hat{\boldsymbol{r}})$.

$$\mathbf{X}(\hat{w}, \hat{\boldsymbol{r}}) = \boldsymbol{\Omega}^{-1}(\hat{w}, \hat{\boldsymbol{r}}) \Delta(\hat{w}, \hat{\boldsymbol{r}}).$$

5. Solve for a new vector of $\hat{w}^*$ and $\hat{\boldsymbol{r}}^*$ using the factor market clearing conditions

6. Compare our initial guess $(\hat{w}, \hat{\boldsymbol{r}})$ with the equilibrium factor prices $(\hat{w}^*, \hat{\boldsymbol{r}}^*)$. If one of these conditions do not hold, we adjust our initial guess of $(\hat{w}, \hat{\boldsymbol{r}})$ based on $(\hat{w}^*, \hat{\boldsymbol{r}}^*)$ and repeat the algorithm until convergence is reached, that is $||\hat{w}^* - \hat{w}|| < \epsilon$ and $||\hat{\boldsymbol{r}}^* - \hat{\boldsymbol{r}}|| < \epsilon$.

[25] Here sector j and country n are associated to the rows of $\tilde{T}(\hat{w}, \hat{\boldsymbol{r}})$. Sector s and country i are associated to the columns of the same matrix.

Part C
Data Description

C1 Sample Description

The GTAP 10 database comprises 65 sectors and 141 regions. Departing form this aggregation we calibrate our model to 104 country/regions and 34 sectors. The following tables summarizes our aggregation of country and sectors with som.

Table C1. List of Net-Zero Developing Countries

	Long Description	GTAP sectors	% of Global Value Added	% of Global GHG Emissions	Elasticity
1	Rice	pdr	0.37%	1.73%	1.90
2	Other Grains	wht, gro	0.56%	0.86%	1.49
3	Vegetables and fruits	v_f	0.89%	0.46%	3.30
4	Other Crops	osd, c_b, pfb, ocr	0.78%	0.77%	2.60
5	Cattle	ctl	0.31%	6.78%	1.90
6	Other Animal Products	oap, rmk	0.75%	1.77%	2.61
7	Forestry, Fishing and Wool	wol, frs, fsh	1.54%	0.28%	2.37
8	Coal Mining	coa	0.49%	3.50%	4.40
9	Oil Extractio	oil	3.25%	2.60%	2.80
10	Gas Extraction	gas	0.69%	0.93%	3.75
11	Other Mining Extraction	oxt	0.82%	0.32%	2.50
12	Food manufacturing, Beverages, and Tobacco	cmt, omt, vol, mil, pcr, sgr, ofd, b_t	3.00%	0.68%	2.88
13	Textiles, Wearing apparel and Leather	tex, wap, lea	1.28%	0.21%	3.02
14	Lumber	lum	0.46%	0.07%	4.20
15	Paper, Paper Products	ppp	0.82%	0.35%	2.90
16	Petroleum and Coke	p_c	0.36%	3.78%	1.30
17	Chemical products, fertilizers	chm	1.40%	4.01%	1.90
18	Pharmaceuticals, medicinal and botanical prod.	bph	0.68%	0.07%	3.25
19	Rubber and plastics products	rpp	0.88%	0.26%	2.00
20	Non-metallic mineral products, Cement	nmm	0.89%	6.66%	1.90
21	Iron & Steel	i_s	0.95%	2.68%	5.20
22	Non-ferrous metals: (copper, aluminium, zinc...)	nfm	0.66%	0.69%	4.05
23	Fabricated metal products and other manufact.	fmp, omf	1.91%	0.30%	2.68
24	Computer, electronic and optical products	ele	1.41%	1.01%	4.40
25	Electrical equipment	eeq	0.75%	0.22%	2.45
26	Machinery and equipment n.e.c.	ome	1.70%	0.14%	1.90
27	Motor vehicles and transport equipment	mvh, otn	1.68%	0.13%	2.43
28	Electricity	ely	1.57%	25.09%	2.10
29	Gas manufacture, distribution	gdt	0.23%	0.78%	2.60
30	Water supply and activities	wtr	0.99%	4.66%	5.05
31	Services	cns, trd, afs, whs, cmn, ofi, ins, rsa, obs, ros, osg, edu, hht, dwe	64.58%	2.80%	2.37
32	Land, pipeline transport	otp	2.60%	6.51%	1.90
33	Water transport	wtp	0.38%	1.13%	3.30
34	Air transport	atp	0.35%	2.51%	1.90
	Total		100.00%	84.70%	

Source: GTAP10 MRIO 2014. Note: GHG emissions do not sum up to 100% because we cannot attribute LUCF and Household emissions to an specific production sector. Values obtained after the baseline calibration.

Table C2. List of Net-Zero Developing Countries

Country Code	Country/Regions	% of Global Value Added	% of Global GHG Emissions	Net Zero Countries
39	India (IND)	3.06%	6.74%	✓
12	Brazil (BRA)	2.95%	3.00%	✓
56	Mexico (MEX)	1.80%	1.54%	✓
38	Indonesia (IDN)	1.37%	5.54%	✓
79	Saudi Arabia (SAU)	1.13%	1.30%	✓
90	Turkey (TUR)	0.97%	0.84%	✓
63	Nigeria (NGA)	0.91%	1.02%	✓
2	Argentina (ARG)	0.78%	0.94%	✓
87	Thailand (THA)	0.58%	0.89%	✓
16	Colombia (COL)	0.49%	0.39%	✓
98	South Africa (ZAF)	0.49%	1.14%	✓
61	Malaysia (MYS)	0.49%	0.44%	✓
69	Pakistan (PAK)	0.38%	0.83%	✓
14	Chile (CHL)	0.37%	0.02%	✓
45	Kazakhstan (KAZ)	0.36%	0.74%	✓
71	Peru (PER)	0.30%	0.33%	✓
8	Bangladesh (BGD)	0.27%	0.43%	✓
97	Viet Nam (VNM)	0.26%	0.54%	✓
93	Ukraine (UKR)	0.15%	0.65%	✓
23	Ecuador (ECU)	0.15%	0.21%	✓
68	Oman (OMN)	0.12%	0.20%	✓
51	Sri Lanka (LKA)	0.11%	0.08%	✓
22	Dominican Republic (DOM)	0.09%	0.05%	✓
91	Tanzania, United Republic of (TZA)	0.07%	0.60%	✓
94	Uruguay (URY)	0.07%	0.06%	✓
70	Panama (PAN)	0.07%	0.10%	✓
17	Costa Rica (CRI)	0.06%	0.00%	✓
89	Tunisia (TUN)	0.06%	0.08%	✓
31	Ghana (GHA)	0.06%	0.09%	✓
92	Uganda (UGA)	0.04%	0.15%	✓
88	Trinidad and Tobago (TTO)	0.04%	0.11%	✓
99	Zambia (ZMB)	0.04%	0.87%	✓
47	Cambodia (KHM)	0.03%	0.12%	✓
66	Nepal (NPL)	0.03%	0.10%	✓
58	Mozambique (MOZ)	0.02%	0.16%	✓
80	Senegal (SEN)	0.02%	0.06%	✓
7	Burkina Faso (BFA)	0.02%	0.08%	✓
59	Mauritius (MUS)	0.02%	0.01%	✓
62	Namibia (NAM)	0.02%	0.04%	✓
50	Lao PDR (LAO)	0.02%	0.08%	✓
55	Madagascar (MDG)	0.02%	0.12%	✓
64	Nicaragua (NIC)	0.02%	0.04%	✓
78	Rwanda (RWA)	0.01%	0.01%	✓
6	Benin (BEN)	0.01%	0.05%	✓
46	Kyrgyzstan (KGZ)	0.01%	0.03%	✓
60	Malawi (MWI)	0.01%	0.03%	✓
32	Guinea (GIN)	0.01%	0.08%	✓
86	Togo (TGO)	0.01%	0.03%	✓
	Total	18.34%	30.98%	

Source: GTAP10 MRIO 2014. Note: Values obtained after the baseline calibration.

Table C3. Remaining Country/Regions

Country Code	Country/Regions	% of Global Value Added	% of Global GHG Emissions	Net Zero Countries
95	United States of America (USA)	22.46%	12.72%	✓
15	China (CHN)	14.18%	23.01%	✓
44	Japan (JPN)	5.04%	2.39%	✓
20	Germany (DEU)	4.06%	1.66%	
30	United Kingdom (GBR)	3.49%	1.15%	✓
77	Russian Federation (RUS)	2.55%	4.25%	✓
29	France (FRA)	2.42%	0.78%	✓
42	Italy (ITA)	2.30%	0.75%	
13	Canada (CAN)	2.26%	1.85%	✓
3	Australia (AUS)	2.04%	1.27%	✓
48	Korea, Republic of (KOR)	1.85%	1.11%	✓
24	European Free Trade Association (EFT)	1.66%	0.27%	✓
26	Spain (ESP)	1.56%	0.61%	
19	Czech Republic (CZE)	0.99%	0.20%	
65	Netherlands (NLD)	0.93%	0.43%	
96	Venezuela (Bolivarian Republic of) (VEN)	0.79%	0.71%	
1	United Arab Emirates (ARE)	0.64%	0.45%	✓
73	Poland (POL)	0.63%	0.69%	
85	Sweden (SWE)	0.57%	0.13%	✓
5	Belgium (BEL)	0.51%	0.27%	✓
25	Egypt (EGY)	0.48%	0.60%	
81	Singapore (SGP)	0.45%	0.18%	✓
21	Denmark (DNK)	0.44%	0.14%	✓
4	Austria (AUT)	0.43%	0.17%	
72	Philippines (PHL)	0.42%	0.31%	
41	Israel (ISR)	0.36%	0.16%	✓
40	Ireland (IRL)	0.33%	0.15%	
28	Finland (FIN)	0.31%	0.18%	
67	New Zealand (NZL)	0.28%	0.15%	✓
74	Portugal (PRT)	0.26%	0.17%	✓
49	Kuwait (KWT)	0.26%	0.27%	✓
76	Romania (ROU)	0.26%	-0.11%	
33	Greece (GRC)	0.24%	0.35%	
37	Hungary (HUN)	0.15%	0.13%	✓
83	Slovakia (SVK)	0.12%	0.06%	✓
34	Guatemala (GTM)	0.09%	0.08%	
9	Bulgaria (BGR)	0.07%	0.10%	✓
53	Luxembourg (LUX)	0.07%	0.03%	✓
36	Croatia (HRV)	0.06%	0.05%	
52	Lithuania (LTU)	0.06%	0.05%	✓
10	Bahrain (BHR)	0.05%	0.08%	✓
84	Slovenia (SVN)	0.05%	0.03%	✓
11	Bolivia (BOL)	0.04%	0.29%	
75	Paraguay (PRY)	0.04%	0.37%	
18	Cyprus (CYP)	0.04%	0.03%	
82	El Salvador (SLV)	0.04%	0.03%	
54	Latvia (LVA)	0.04%	0.00%	✓
27	Estonia (EST)	0.04%	0.05%	✓
35	Honduras (HND)	0.03%	0.10%	
43	Jamaica (JAM)	0.02%	0.02%	
57	Malta (MLT)	0.01%	0.01%	
100	Rest of Africa (RAF)	1.27%	3.76%	-
101	Rest of Asia (RAS)	2.25%	3.11%	-
102	Rest of Middle East (RME)	0.98%	2.14%	-
103	Rest of Europe (ROE)	0.24%	0.55%	-
104	Rest of World (ROW)	0.48%	0.55%	-
	Total	81.66%	69.02%	

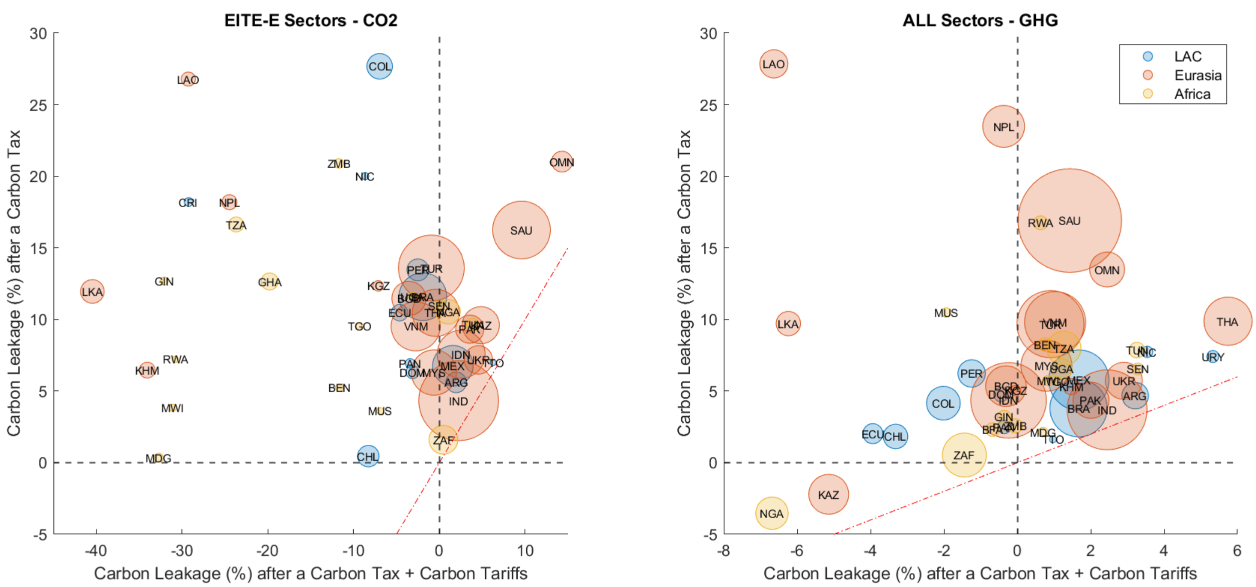
Source: GTAP10 MRIO 2014. Note: Values obtained after the baseline calibration.

Part D
Additional Results

D1 Emissions Effects

In section 3.3.1 we observe that the carbon tariffs are effective in reducing the leakage but these reductions are small taking into account global emissions. Figure D1 combines information on carbon leakage without (y-axis) and with carbon tariffs (x-axis) for each individual economy. Additionally, the circle sizes represent the amount of GHG reduction (in M.tons) induced in the rest of the world when a country implements a CBAM structure. Taking as example the Dominican Republic, without a CBAM emissions abroad increase by 0.51 M.tons, with a CBAM a reduction of 0.24 M.tons was observed. Therefore trade policy was able to reduce 0.47-(-0.24) = 0.75 M.tons of GHG. Therefore, the sizes of the circles shows in which developing country is trade policy more capable of affecting emissions in absolute terms.

Figure D1. Carbon Leakage and Emission Reductions

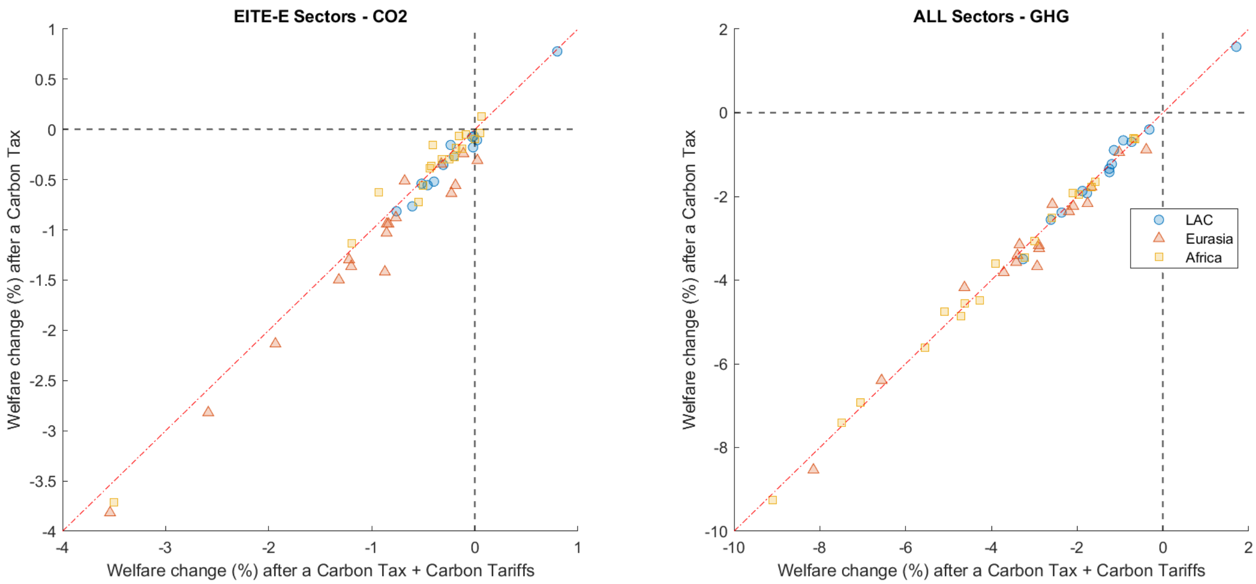


Note: Panel A plots carbon leakage under CTF3 (y-axis) and CTF4 (x-axis). Panel B plots carbon leakage under CTF5 (y-axis) and CTF6 (x-axis). The size of the circles represent the reduction of emissions induced by introducing a carbon tariff. For reference in Panel A, the largest reduction happens in India and it represents a reduction of 26.2 M.ton. In Panel B, Saudi Arabia represent a reduction of 44.1 M.tons.A few outliers were excluded for visualization purposes in Panel A (NAM, MOZ, BFA URY) and Panel B (NAM, MOZ, GHA, CRI)

D2 Welfare Effects

Figure D2 compares the welfare effects for counterfactuals with and without carbon tariffs when Net-Zero developing countries act alone. This allow us to visualize with countries are better or worse-off. In general welfare effects are not very different, with countries being slightly better off after the imposition of the carbon tariffs.

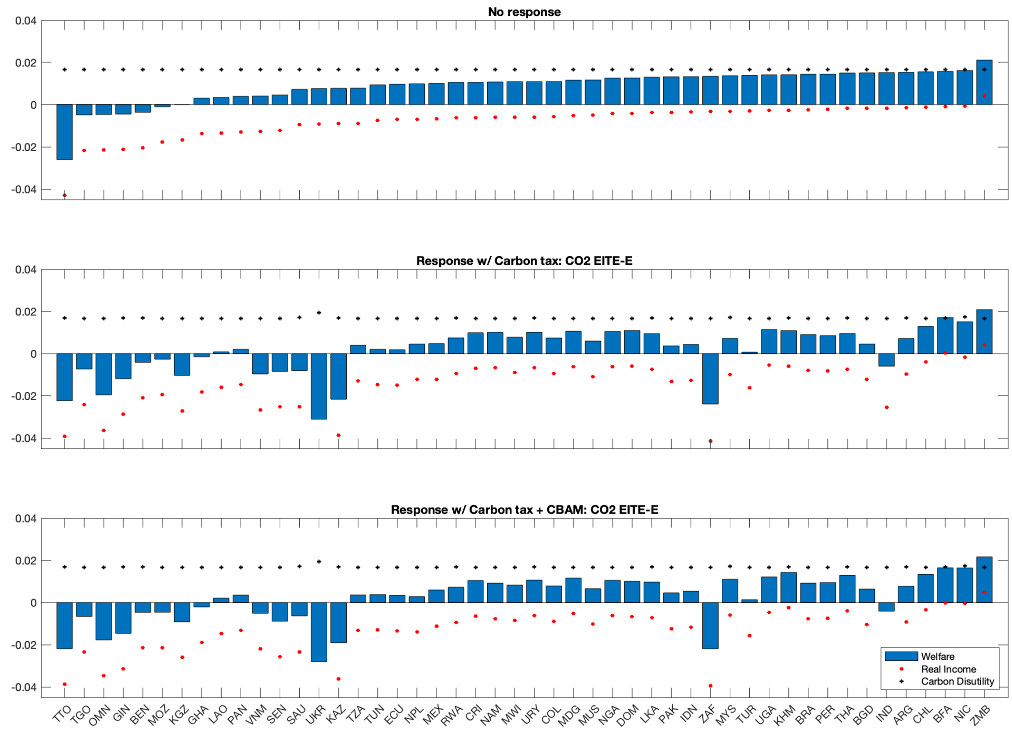
Figure D2. Welfare Effects with and without Carbon Tariffs



Note: The figure compares the welfare effects from the imposition of a carbon CO2 tax on EITE-E sectors (Panel A) with and without carbon tariffs; as well as a carbon GHG tax on all sectors (Panel A) with and without carbon tariffs.

In section 3.3.2, we show that most countries stand to gain by not responding when the US, EU, and CHN form a coalition. However, many countries still gain regardless of their policy response. Figure D3, decomposes the channels by which changes in carbon policy impact national welfare. Despite nearly every country in our sample experiencing reductions in real income due to the coalition's formation, these are offset by significant decreases in the disutility from carbon due to major reductions in global emissions from members of the coalition.

Figure D3. Welfare Decomposition



Note: The first, second, and third row report the results from when the net-zero developing countries do not respond, respond with a carbon tax on production, and respond with a carbon tax on production aligned with a carbon tariff respectively. Using the fact that $d\ln \hat{U}_n = d\ln \frac{\hat{I}_n}{\hat{P}_n} + d\ln f(Z)$. The blue bars represent percent changes in national welfare ($d\ln \hat{U}_n$), the red dots represent percent changes in real income ($d\ln \frac{\hat{I}_n}{\hat{P}_n}$), and the black dots represent the percent change in the global disutility from carbon ($\ln f(Z)$).