Effective Paths to Carbon Reduction: A Global Framework for Trade and Energy Policy Evaluation

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Abstract

Reducing global carbon emissions requires effective and politically feasible reforms in both trade and energy policies. This paper develops a general equilibrium framework to evaluate the trade-offs associated with such reforms. Using a sufficient statistics methodology, we quantify the impacts of trade and energy policy changes on global emissions and real consumption, accounting for global energy supply chains, input-output linkages, and scale economies. Our analysis reveals that past trade liberalization has increased real consumption by 4.2% but also raised global emissions by 1.2% through improved energy input efficiency, aligning with the Jevons Paradox. Countries that gain more from trade also contribute more to export and import-led emissions, suggesting that contingent trade reforms that link market access to carbon pricing compliance could effectively reduce emissions. In contrast, fossil fuel energy subsidies have increased emissions by 2.9% while reducing domestic consumption in subsidizing countries and providing positive terms-of-trade externalities for trading partners. This result indicates that energy subsidies are driven by domestic political considerations and have a negligible *net* externality on foreign countries. Consequently, global policy reforms must account for these political constraints to be viable. Our findings suggest that contingent trade policy reforms that afford governments flexibility for intra-national redistribution offer a promising path for global carbon reduction.

1 Introduction

There is growing consensus among policymakers that reducing global carbon emissions requires comprehensive reforms in both trade and energy policies. In response, several governments have started implementing carbon pricing mechanisms to regulate local energy markets. Simultaneously, border policy measures are being revised to tackle carbon emissions on an international scale.

As policymakers advance these reforms, they encounter a wide range of policy options, each with varying levels of effectiveness and political feasibility. The urgency of the climate crisis underscores

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the need to discern which reforms are both effective and politically viable, and which should be prioritized. A clear understanding of these priorities is essential to avoid repeating the failures of past environmental agreements.

This paper offers a general framework for evaluating the trade-offs associated with energy and trade policy reforms. Our approach unfolds in two steps: First, we develop a sufficient statistics methodology to quantify the impacts of trade and energy policy reforms on global emissions and real consumptions, taking into account global energy supply chains, input-output linkages, scale economies, and other relevant factors. Second, we apply this methodology to isolate and measure the impacts of existing trade and energy policies on global emissions, and determine how emissions would respond to hypothetical policy reforms. Building on these findings, we identify policy reforms that have the greatest potential for reducing global emissions.

Our analysis shows that past trade liberalization episodes (via customs unions, trade agreements, etc.) have delivered a 4.2% increase in real consumption globally, but have concurrently led to an 1.2% increase in global emissions. This result aligns with the Jevons Paradox, as trade integration increases the efficiency of energy inputs, thereby raising overall energy consumption.[1] We also find that countries with greater consumption gains from trade exhibit higher emissions associated with trade. This alignment indicates that conditional trade reforms—like linking preferential market access to carbon pricing compliance—can effectively mitigate emissions, more than offsetting the 1.2% increase in the emissions due to past liberalization episodes.

By comparison, fossil fuel energy subsidies have contributed to a 2.9% increase in global emissions while simultaneously reducing domestic consumption in subsidizing countries and benefiting their trade partners through positive terms-of-trade externalities. These positive externalities often offset the negative impacts of increased emissions, suggesting that existing energy subsidies produce minimal international externalities. This implies that such policies are likely motivated by domestic political economy concerns. As a result, global policy reforms must account for these political constraints to be politically viable. Overall, our findings suggest that contingent trade policy reforms that afford governments flexibility for intra-national redistribution offer a viable and effective path for global carbon reduction.

Section 2 introduces our theoretical model of the global economy, encompassing multiple interconnected countries and industries. We categorize industries into primary energy (e.g., crude oil, natural gas, coal), secondary energy (e.g., refined petroleum, electricity), and non-energy sectors (e.g., chemicals, electronics, transportation). All industries engage in international trade. Primary energy production utilizes labor, location-specific reserves, and traded intermediate inputs. Other industries employ labor and traded intermediate inputs, including both primary and secondary energy. We incorporate economies of scale in production of non-energy industries. Carbon emissions are generated from both industrial energy input use and household energy consumption.

Section 3 presents our sufficient statistics methodology for evaluating trade and energy policy

[1] Reflecting Jevons Paradox, we additionally find that moving countries to autarky would lead to an 11.9% reduction in global real consumption and an 18.6% decrease in global emissions.

reforms. We derive a formula linking emissions reduction from policy reform to changes in two sufficient statistics, weighted by relevant elasticities: (1) industry-level employment shares and (2) domestic expenditure shares. Our analysis indicates that trade liberalization unambiguously increases emissions if energy is sufficiently substitutable for labor in production. This finding echoes Jevons paradox: trade liberalization enhances energy production efficiency through access to traded intermediate inputs while making energy inputs more cost-effective in downstream industries due to trade-induced productivity gains. Consequently, trade reduces the price of energy inputs relative to labor, thereby increasing overall energy consumption and emissions. However, these effects are consistently accompanied by significant real consumption gains. In contrast, energy subsidies increase emissions by expanding labor share in energy production but negatively impact real consumption through price distortions and adverse terms of trade effects.

Section 4 applies our sufficient statistics formulas to global data on trade, production, and energy use to identify effective carbon reduction policies. Our analysis reveals that current trade agreements have increased global real consumption by 4.2% while raising global emissions by 1.2%. Notably, countries with higher emissions due to trade disproportionately benefit from these consumption gains. This correlation suggests that contingent trade reforms could effectively leverage consumption benefits to motivate countries to address the global carbon emissions externality.

Fossil fuel subsidies, in turn, have contributed to a 2.9% increase in global emissions. Carbon leakage dampens the emission impact of removing fossil fuel subsidies as it leads to an increase in energy exports where the policy reforms take place, lowering world energy prices and raising emissions elsewhere. The mirror side of carbon leakage is the positive terms-of-trade externality that is generated for countries whose energy imports increase. Overall, these subsidies typically harm domestic consumption while benefiting trading partners, indicating that they stem from domestic political considerations with minimal net global externality (as negative emission externalities are offset by positive terms of trade externalities). Consequently, fossil fuel energy price reforms must take these political constraints into account to be viable.

Related Literature. This paper contributes to several strands of the literature. First, we complement studies of the impact of trade on the environment, e.g., Antweiler et al. [2001], Cristea et al. [2013], Shapiro [2016], Larch and Wanner [2017], Shapiro [2021], and as surveyed recently by Copeland et al. [2021]. We develop a framework that allows for a rich set of empirically-relevant channels in production and emission in the global economy, including economies of scale, input-output linkages, and a detailed specification of fossil fuels along the global supply chain. We additionally derive the sufficient statistics for the quantitative analysis of welfare and climate impact of trade and energy policies, augmented by theoretical propositions that shed light on the tradeoff between consumption gains from trade and the climate costs of trade.

Our work also contributes to recent studies of the interplay between trade and climate policy, e.g., Kortum and Weisbach [2021] and Farrokhi and Lashkaripour [2024]. This paper evaluates currently-implemented policies instead of characterizing optimal policy. Lastly, we speak to the

vast literature on quantitative trade theory as surveyed by Costinot and Rodríguez-Clare [2014]. Our work places fossil fuel energy and the climate externality in the center of such analyses to draw a more comprehensive picture of the gains from trade.

2 Theoretical Framework

The global economy consists of multiple countries, indexed by $i, j \in \mathbb{N}$, and multiple industries divided into primary energy industries $k \in \mathbb{E}_1$ (such as crude oil, natural gas, and coal), secondary energy industries $k \in \mathbb{E}_2$ (such as refined petroleum and electricity), and downstream non-energy industries $k \in \mathbb{F}$ (such as chemicals, electronics, and transportation) with $\mathbb{E} \equiv \mathbb{E}_1 \cup \mathbb{E}_2$ denoting all energy industries and $\mathbb{K} \equiv \mathbb{E} \cup \mathbb{F}$ denoting the entire set of industries. Each country i is endowed by exogenously-given L_i workers and $\{R_{i,k}\}_{k\in\mathbb{E}_1}$ energy reserves, where $R_{i,k}$ is the specific input required in the production of primary energy $k \in \mathbb{E}_1$. Workers are perfectly mobile across industries but immobile across countries and each worker supplies one unit of labor inelastically. All industries are tradeable. CO_2 emissions are generated by the combustion of primary or secondary energy when they are used as inputs in the production of secondary energy and non-energy downstream industries, or when consumed by households.

Consumers and producers are infinitesimal and so they do not internalize the impact of their consumption or production decisions on climate change.

Households. A representative household in country i has the following utility function that subtracts the disutility from global carbon emissions from the utility derived from consumption:

$$U_i = \mathrm{C}_i\left(\left\{C_{i,k}^{(H)}\right\}_{k\in\mathbb{K}}\right)\Delta_i\left(Z^{(global)}\right). \tag{1}$$

Here, $C_i(.)$ is country i's real consumption, which aggregates over household consumption quantities $C_{i,k}^{(H)}$ of each good $k \in \mathbb{K}$, and $\Delta_i(.)$ is country i's climate-change damage function, which measures the loss per unit of real consumption from a marginal increase in global carbon emissions, $Z^{(global)}$. Utility maximization delivers household's expenditure share on industry k by

$$\beta_{i,k} = \mathrm{b}_{i,k}\left(\{P_{i,k}\}_{k\in\mathbb{G}}, E_i\right) \tag{2}$$

satisfying $\sum_{k\in\mathbb{G}}\beta_{i,k} = 1$, where $P_{i,k}$ is the price index of good k in country i and $E_i = \Sigma_k P_{i,k}C_{i,k}^{(H)}$ is total expenditure.

Primary Energy Industry. Each primary energy industry ($k \in \mathbb{E}_1$) employs exogenously given $k-$specific energy reserves, $R_{i,k}$, as specific input and labor, $L_{i,k}$, as variable input under the following Cobb-Douglas production technology:

$$Q_{i,k} = \varphi_{i,k}\left(\frac{L_{i,k}}{\alpha_{i,k}}\right)^{\alpha_{i,k}^{l}}\left(\frac{R_{i,k}}{1-\alpha_{i,k}}\right)^{1-\alpha_{i,k}^{l}}, \qquad k \in \mathbb{E}_1 \tag{3}$$

where $\varphi_{i,k}$ is an exogenous productivity parameter and $Q_{i,k}$ is country i's supply of primary energy $k \in \mathbb{E}_1$. Production flows of primary energy k from each origin i are internationally traded subject to trade costs $d_{ij,k}$, with the price in the destination market j to be given by:

$$P_{ij,k} = d_{ij,k} P_{ii,k}, \qquad \text{where} \qquad P_{ii,k} = \frac{1}{\varphi_{i,k}} w_i^{\alpha^l_{i,k}} r_{i,k}^{1-\alpha^l_{i,k}}, \qquad k \in \mathbb{E}_1 \tag{4}$$

where w_i is the national wage rate in country i, and $r_{i,k}$ is the rental rate of $k-$specific reserves.

By cost minimization, the inverse supply schedule of each primary energy can be expressed as $P_{ii,k} = \bar{p}_{i,k} w_i Q_{i,k}^{\rho_{i,k}}$, where $\bar{p}_{i,k} = \left(\varphi_{i,k} \left(\frac{R_{i,k}}{1-\alpha_{i,k}} \right)^{1-\alpha^l_{i,k}} \right)^{-1/\alpha^l_{i,k}}$ is an exogenous supply shifter and $\rho_{i,k} \equiv \left(1 - \alpha^l_{i,k}\right) / \alpha^l_{i,k} > 0$ is the inverse supply elasticity.

Firms in Secondary Energy and Downstream Industries. Each secondary-energy or downstream industry $k \in \mathbb{E}_2 \cup \mathbb{F}$ in origin i is served by a continuum of firms that compete under monopolistic competition and free entry. A pool of ex-ante identical firms can pay a fixed entry cost, $c_{i,k} f^{(e)}_{i,k}$, to supply their differentiated variety from origin i–industry k, where $c_{i,k}$ is the same as the unit cost of production described below. After paying the fixed entry cost, each firm draws a total factor productivity $\varphi_{i,k}(\omega)$ and employs labor and intermediate inputs under a constant-returns-to-scale aggregator $\mathrm{q}_{i,k}(.)$ to serve markets. Specifically, firm ω in the set of entrants $\Omega_{ij,k}$ supplies $q_{ij,k}(\omega)$ units of output to market j by combining $l_{ijk}(\omega)$ units of labor and $m_{ij,kg}(\omega)$ units of intermediate goods $g \in \mathbb{K} \equiv \mathbb{E}_1 \cup \mathbb{E}_2 \cup \mathbb{F}$—including all forms of energy, primary or secondary, and non-energy goods,[2]

$$q_{ij,k}(\omega) = \varphi_{i,k}(\omega)\, \mathrm{q}_{i,k}\left(l_{ij,k}(\omega), \{m_{ij,kg}(\omega)\}_{g \in \mathbb{G}} \right), \qquad k \in \mathbb{E}_2 \cup \mathbb{F}$$

Supply quantity $q_{ij,k}(\omega)$ is inclusive of iceberg trade cost, $d_{ij,k}$, associated with shipping varieties of good k from origin i to destination j.[3] A representative firm aggregates firm-level varieties from each origin country-industry into a composite bundle and ships them out to each market. Specifically, the composite bundle from origin country i–industry k to be shipped out to market j, $Q_{ij,k}$, takes a CES form:

$$Q_{ij,k} = \left[\int_{\omega \in \Omega_{ij,k}} q_{ij,k}(\omega)^{\frac{\gamma_k - 1}{\gamma_k}} d\omega \right]^{\frac{\gamma_k}{\gamma_k - 1}}, \qquad k \in \mathbb{E}_2 \cup \mathbb{F}$$

[2] We suppose that firms are heterogenous in terms of their total factor productivity, but there are no fixed costs associated with serving export destinations. This assumption helps us bring our model to firm-level data later in our estimation without the requirement to track firms selections into export markets here in theory. Introducing exports fixed costs will make our model a version of Melitz (2003), which can be shown to be isomorphic in terms of observable aggregates to the model presented here. See Farrokhi-Lashkaripour (2024).

[3] Considering the role of energy along the supply chain, the cost share of primary energy is empirically large in secondary energy industries, e.g., the cost share of crude oil in the refined petroleum industry and those of natural gas and coal in the electricity industry. In turn, downstream industries such as textiles or transportation typically purchase energy in the form of secondary energy.

where γ_k is the elasticity of substitution between firm-level varieties in industry k. Note that $Q_{ij,k}$ is inclusive of iceberg trade costs, $Q_{ij,k} = d_{ij,k}C_{ij,k}$, whereas $C_{ij,k}$ is the consumption of the variety from country i–industry k in market j by both households as final consumption and industries as intermediate inputs.

Faced by the same wage rate w_i and prices of intermediate goods $\{P_{i,g}\}_{g\in\mathbb{G}}$, cost minimization implies that the marginal cost of product $\omega \in \Omega_{ij,k}$ equals $c_{i,k}/\varphi_{i,k}(\omega)$,

$$c_{i,k} = \mathsf{c}_{i,k}\left(w_i, \{P_{i,g}\}_{g\in\mathbb{G}}\right), \qquad k \in \mathbb{E}_2 \cup \mathbb{F} \tag{5}$$

where $\mathrm{c}_{i,k}(.)$ is a homogeneous-of-degree-one cost function associated with the production function $\mathrm{q}_{i,k}(.)$. Similarly, the cost share of labor $\alpha^l_{i,k}$ and intermediate goods $\alpha^g_{i,k}$, which are independent of firm productivity $\varphi_{i,k}(\omega)$, are given by:

$$\alpha^l_{i,k} = \mathsf{a}^l_{i,k}\left(w_i, \{P_{i,g}\}_{g\in\mathbb{G}}\right), \quad \alpha^g_{i,k} = \mathsf{a}^g_{i,k}\left(w_i, \{P_{i,g}\}_{g\in\mathbb{G}}\right), \qquad k \in \mathbb{E}_2 \cup \mathbb{F} \tag{6}$$

The mass of entrant firms in each country-industry $M_{i,k}$ is pinned down by the free entry condition, ensuring that aggregate profits $\frac{1}{\gamma_k}P_{ii,k}Q_{i,k}$ equal the entry costs, $c_{i,k}f^{(e)}_{i,k}M_{i,k}$, in each country and industry,

$$M_{i,k} = \frac{P_{ii,k}Q_{i,k}}{\gamma_k c_{i,k} f^{(e)}_{i,k}}, \qquad \text{where} \qquad Q_{i,k} = \sum_{j\in\mathbb{N}} Q_{ij,k}$$

Firms charge a constant markup over marginal cost, which implies the following price index for composite variety ij,k:

$$P_{ij,k} = M_{i,k}^{\frac{1}{1-\gamma_k}} \frac{\gamma_k}{\gamma_k - 1}\frac{d_{ij,k}}{\overline{\varphi}_{i,k}} c_{i,k}, \qquad \text{where} \qquad \overline{\varphi}_{i,k} \equiv \left[\int_{\omega\in\Omega_{i,k}} \varphi_{i,k}(\omega)^{\gamma_k - 1} d\omega\right]^{\frac{1}{\gamma_k - 1}}$$

where $\overline{\varphi}_{i,k}$ is aggregate industry-level productivity. Replacing for $M_{i,k}$, the price index can be expressed as:

$$P_{ij,k} = d_{ij,k}P_{ii,k}, \qquad \text{where} \qquad P_{ii,k} = \overline{p}_{ii,k} c_{i,k} Q_{i,k}^{\frac{-1}{\gamma_k}}, \qquad k \in \mathbb{E}_2 \cup \mathbb{F} \tag{7}$$

where $\overline{p}_{ii,k}$ is a constant.[4]

International Trade and Price Indices. For each industry k, there is a representative distributer in each country i who purchases varieties $\{C_{ji,k}\}_i$ from international suppliers $j = 1, .., N$,

[4]Specifically,

$$\overline{p}_{ii,k} = \left(\gamma_k f^{(e)}_{i,k}\right)^{1/\gamma_k}\left(\frac{\gamma_k}{(\gamma_k - 1)\overline{\varphi}_{i,k}}\right)^{\frac{\gamma_k - 1}{\gamma_k}}$$

aggregates them into a composite bundle using a CES technology,

$$C_{i,k} = \left(\sum_{j=1}^{N} b_{ji,k} C_{ji,k}^{\frac{\sigma_{k-1}}{\sigma_k}} \right)^{\frac{\sigma_k}{\sigma_k - 1}}$$

and sells this bundle to domestic households and industries:

$$C_{i,k} = C_{i,k}^{(H)} + C_{i,k}^{(I)}, \quad \text{where} \quad C_{i,k}^{(I)} = \sum_{g \in \mathbb{E}_2 \cup \mathbb{F}} M_{i,gk} \tag{8}$$

where $M_{i,gk} = \int_{\omega \in \Omega_{i,k}} m_{ij,gk}(\omega) d\omega$ is the intermediate use of good k by industry g. The distributor's demand for variety (ji, k) is, accordingly, a function of total expenditure on varieties, $X_{i,k} = \sum_j P_{ji,k} C_{ji,k}$, and the vector of international prices. The within-industry expenditure share on variety ji, k (origin j–destination i–industry k) is denoted by $\lambda_{ji,k}$, which equals:

$$\lambda_{ji,k} \equiv \frac{P_{ji,k} C_{ji,k}}{\sum_n P_{ni,k} C_{ni,k}} = b_{ji,k} \left(\frac{P_{ji,k}}{P_{i,k}} \right)^{1-\sigma_k}, \qquad k \in \mathbb{G} \tag{9}$$

where σ_k is the elasticity of substitution between varieties within industry k, and $C_{ji,k}$ is the composite bundle of consumption in destination country i from the variety of origin j in industry k, with corresponding demand shifter, $b_{ji,k}$. The price of the composite bundle, $P_{i,k}$, is determined by:

$$P_{i,k} = \left[\sum_j b_{ji,k} P_{ji,k}^{1-\sigma_k} \right]^{\frac{1}{1-\sigma_k}}, \qquad k \in \mathbb{G} \tag{10}$$

We have so far presented the model focusing on economies in which the use of energy is not regulated by energy or climate policy. If we were to introduce a tax or subsidy on the use of energy, then the after-tax price of energy would correspond to $\{P_{i,k}\}_{k \in \mathbb{E}}$ plus the carbon tax applied to each industry or household in country i. Specifically, the after-tax/subsidy price of energy $k \in \mathbb{E}$ in country i should be replaced by $P_{i,k}\left(1 + \tau_{i,kg}^{(I)}\right)$ when used in industry g and $P_{i,k}\left(1 + \tau_{i,k}^{(H)}\right)$ when used by households.

General Equilibrium. General equilibrium is a vector of wage rates $\{w_i\}_i$ and rental rates on energy reserves $\{r_{i,k}\}_{i,k \in \mathbb{E}_1}$ such that final expenditure shares, $\beta_{i,k}$, given by Eq. 2, maximize the utility function 1, production quantities and producer prices of primary energy goods are given by Eqs. 3-4, marginal costs, input cost shares and producer prices of the secondary energy and non-energy goods by Eqs. 5-6-7, trade shares and consumer price indices of all goods by Equations 9-10, where aggregate consumption sums over intermediates and final consumption according to Eq. 8; and, labor markets clear per industry,

$$w_i L_{i,k} = \alpha_{i,k}^{l} \sum_j \lambda_{ij,k} X_{j,k}, \qquad (i \in \mathbb{N}, k \in \mathbb{K});$$

markets of energy reserves clear,

$$r_{i,k}R_{i,k} = \left(1 - \alpha^{l}_{i,k}\right) \sum_{j} \left[\lambda_{ij,k} X_{j,k}\right], \qquad (i \in \mathbb{N}, k \in \mathbb{E}_1);$$

and, the balance of budget holds:

$$E_i = T_i + w_i L_i + \sum_{k \in \mathbb{E}_1} \left[r_{i,k} R_{i,k}\right]$$

where T_i is total taxes collected from (or total subsidies paid to) the use of energy goods $k \in \mathbb{E}$,

$$T_i = \sum_{k \in \mathbb{E}} \left[\left(\frac{\tau^{(H)}_{i,k} - 1}{\tau^{(H)}_{i,k}} \right) \beta_{i,k} E_i + \sum_{g \in \mathbb{E}_2 \cup \mathbb{F}} \left(\frac{\tau^{(I)}_{i,kg} - 1}{\tau^{(I)}_{i,kg}} \right) \alpha^{k}_{i,g} Y_{i,g} \right]$$

CO_2 Emissions. The use of primary and secondary energy $g \in \mathbb{E} \equiv \mathbb{E}_1 \cup \mathbb{E}_2$ by households or industries generates CO_2 emissions, which are proportional to their use of energy up to technical coefficients, $\bar{v}$, as the emission per unit of energy use, which we treat as exogenous parameters. Specifically, CO2 emissions associated with energy $g \in \mathbb{E}$ used by final consumers and for producing good $k \in \mathbb{G}$ in country i equal:

$$\begin{cases} Z^{(H)}_{i,g} = \bar{v}_{i,gH} C^{(H)}_{i,g} = \bar{v}_{i,gH} \frac{\beta_{i,g} Y_j}{P_{i,g}} \\ Z^{(I)}_{i,gk} = \bar{v}_{i,gk} C^{(I)}_{i,gk} = \bar{v}_{i,gk} \frac{\alpha^{g}_{i,k}}{\alpha^{l}_{i,k}} \frac{w_i}{P_{i,g}} \ell_{i,k} L_i \end{cases}, \qquad \text{for energy } g \in \mathbb{E}$$

By aggregation, energy $g \in \mathbb{E}$ used by all industries in country i is:

$$Z^{(I)}_{i,g} = \sum_{k} Z^{(I)}_{i,gk} = \frac{w_i}{P_{i,g}} \sum_{k} \left[\bar{v}_{i,gk} \frac{\alpha^{g}_{i,k}}{\alpha^{l}_{i,k}} \ell_{i,k} \right] L_i$$

Finally, national and global emissions are given by:

$$Z_i = \sum_{g \in \mathbb{E}} \left[Z^{(H)}_{i,g} + Z^{(I)}_{i,g} \right], \qquad Z^{(global)} = \sum_{i \in \mathbb{N}} Z_i$$

3 Theoretical Analysis: Impact of Trade and Energy Policies on Real Consumption and Emissions

In this section we provide a theoretical characterization of how government policies influence local and global carbon emissions. In doing so, we adopt a Cobb-Douglas functional form for production functions $q_{i,k}(.)$ and the upper-tier of preferences $C_i(.)$, which lend themselves to closed-form expressions. We are specifically interested in two types of policies: *(i)* changes in trade barriers driven

by *trade policy* such as trade agreements *(ii)* changes in energy input prices which classify under *energy policy* such as fossil fuel subsidies. Specifically,

$$\{\hat{\tau}_{i,g}\}_{g\in\mathbb{E}} \sim \text{energy policy shock} \qquad\qquad \left\{\hat{d}_{in,g}\right\}_{i,n,g} \sim \text{trade policy shock}$$

The change in country i's emissions in response to the above-noted policy shocks is determined by the following accounting relationship:

$$\hat{Z}_i = \sum_{g\in\mathbb{E}}\sum_{k\in\mathbb{K}} z_{i,gk}\hat{Z}_{i,gk} \qquad \text{where} \qquad z_{i,gk} \equiv Z_{i,kg}/Z_i.$$

where $g \in \mathbb{E}$ in the first summation indicates that only the use of energy (primary or secondary) generates emissions, whereas $k \in \mathbb{K}$ in the second summation indicates that all industries may use energy. To save space, we have adopted a notation by which there is a fictitious industry among non-energy industries that only purchases energy goods and sells them to final consumers while generating no value added. This choice of notation accommodates households' consumption of energy in our analysis presented in this section. The change in global emissions can be then calculated as the weighted sum of changes in national-level emissions:

$$\hat{Z}^{(global)} = \sum_{i\in\mathbb{C}} \pi_i \hat{Z}_i \qquad \text{where} \qquad \pi_i \equiv Z_i/Z^{(global)}$$

This equation indicates that the global change in carbon emissions is a weighted sum of the changes in emissions resulting from the use of each energy type $g \in \mathbb{E}$ in the production of each good $k \in \mathbb{K}$ across all countries $i \in \mathbb{C}$. The weights, denoted by $z_{i,gk}$, represent the share of global emissions attributed to the energy input transaction—country i's use of energy g in its industry k. To characterize the change in emissions associated with the use of energy input type $g \in \mathbb{E}$ in the production of good $k \in \mathbb{K}$, we specify emission levels as $Z_{i,gk} = \bar{v}_{i,gk}C_{i,gk}$, where $\bar{v}_{i,gk}$ is an engineering constant. We, moreover, assume a Cobb-Douglas input aggregator, with country and industry-specific weights. Namely,

$$c_{i,k} = \bar{C}_{i,k} \times w_i^{\alpha^l_{i,k}} r_{i,k}^{\alpha^r_{i,k}} \prod_{g\in\mathbb{G}} \left(\tilde{P}_{i,g}^{\alpha^g_{i,k}}\right)$$

where $r_{i,k}$ denotes the rental rate for energy reserves in primary energy sector $k = 0$ and $\alpha^l_{i,k} + \alpha^r_{i,k} + \sum_{g\in\mathbb{G}} \alpha^g_{i,k} = 1$. Note that the share of reserves in production is only non-zero in primary energy sectors and zero otherwise, i.e., $\alpha^r_{i,k} > 0$ if $k \in \mathbb{E}_0$ and $\alpha^r_{i,k} = 0$ for all $k \notin \mathbb{E}_0$. The intermediate input price index, $\tilde{P}_{i,g} = \tau_{i,g}P_{i,g}$, is the after tax price, where the input tax $\tau_{i,g}$ is non-zero only for energy inputs ($g \in \mathbb{E}$). Under the assumptions, we can formulate the change in emissions as follows

$$\hat{Z}_{i,gk} \sim \hat{Q}_{i,gk} = \hat{\ell}_{i,k}\left(\frac{\hat{\tilde{P}}_{i,g}}{\hat{w}_i}\right)^{-1}, \qquad (\forall g \in \mathbb{E},\ k \in \mathbb{K})$$

where the second line derive from the fact that the relative cost share of inputs is constant under the Cobb-Douglas parameterization. The above equation equates the change in emissions associated with energy use in a given industry with the changes in the relative price of energy to labor inputs, $\hat{\tilde{P}}_{i,g}/\hat{w}_i$, and the scale of production as measured by $\hat{\ell}_{i,k}$.

Next, we characterize the change in the relative price of labor-to-energy in terms of changes in observable share variables. Considering our parametric specification for $c_{i,k}$, the change in the price of the variety (i,i,k) in response to the policy shocks can be specified as

$$\hat{P}_{ii,k} = \hat{c}_{i,k} \times \hat{M}_{i,k}^{\frac{1}{1-\gamma_k}} = \hat{w}_i^{\alpha^l_{i,k}} \hat{r}_i^{\alpha^r_{i,k}} \prod_{g \in \mathbb{G}} \left(\hat{\tilde{P}}_{i,g}^{\alpha^g_{i,k}} \right) \hat{\ell}_{i,k}^{\frac{1}{1-\gamma_k}},$$

where The constant elasticity import demand system within industries implies that $\hat{P}_{i,k} = \hat{P}_{i,k} \hat{\lambda}_{ii,k}^{\frac{1}{\sigma_k - 1}}$, where $\hat{P}_{i,k}$ is the pre-tax price index of the composite variety associated with industry k goods in country i. Invoking this relationship and noting that $\hat{\tilde{P}}_{i,g} = \hat{\tau}_{i,g} \hat{P}_{i,g}$, the above equation deliver the following formula for the change in the composite intermediate input sourced from industry k

$$\hat{\tilde{P}}_{i,k} = \hat{\tau}_{i,k}\, \hat{w}_i^{\alpha^l_{i,k}} \hat{r}_i^{\alpha^r_{i,k}} \prod_{g \in \mathbb{G}} \left(\hat{\tilde{P}}_{i,g}^{\alpha^g_{i,k}} \right) \hat{\ell}_{i,k}^{\frac{1}{1-\gamma_k}}\, \hat{\lambda}_{ii,k}^{\frac{1}{\sigma_k - 1}}.$$

The system of equations specified above implicitly determines $\left\{ \hat{\tilde{P}}_{i,k} \right\}_k$ in terms of $\left\{ \hat{w}_i, \hat{r}_i, \hat{\tau}_{i,k}, \hat{\ell}_{i,k}, \hat{\lambda}_{ii,k} \right\}$. Inverting this system and performing some algebraic simplifications yields

$$\hat{\tilde{P}}_{i,k} = \hat{w}_i \times \prod_{g \in \mathbb{G}} \left(\hat{\lambda}_{ii,g}^{\frac{a_{i,gk}}{\sigma_g - 1}} \hat{\ell}_{i,g}^{\frac{a_{i,gk}}{1-\gamma_g}} \right) \times \prod_{k' \in \mathbb{E}} \left(\hat{\tau}_{i,k'}^{a_{i,k'k}} \right) \times \prod_{k' \in \mathbb{E}} \left(\hat{\ell}_{i,k'}^{\alpha^r_{i,k'} a_{i,k'k}} \right)$$

Plugging this equation back into the above equation, yields the following expression for the change in the price of energy to labor input $g \in \mathbb{E}$:

$$\frac{\hat{\tilde{P}}_{i,g}}{\hat{w}_i} = \underbrace{\prod_{k \in \mathbb{G}} \left(\hat{\lambda}_{ii,k}^{\frac{a_{i,kg}}{\sigma_k - 1}} \right)}_{\text{trade-related effects}} \times \overbrace{\underbrace{\prod_{k \in \mathbb{G}} \left(\hat{\ell}_{i,k}^{\frac{a_{i,kg}}{1-\gamma_k}} \right)}_{\text{scale economies}} \times \underbrace{\prod_{k' \in \mathbb{E}} \left(\hat{\tau}_{i,k'}^{a_{i,k'g}} \right)}_{\text{energy policy}} \times \underbrace{\prod_{k' \in \mathbb{E}_0} \hat{\ell}_{i,k'}^{\alpha^r_{i,k'} a_{i,k'g}}}_{\text{extraction price}}}^{\text{domestic economy adjsutments}}$$

To give intuition, the first term encompasses all trade-related effects. All the information about how trade impacts the relative price labor-to-energy inputs is encapsulated in the domestic expenditure shares. The remaining three terms represent adjustments to the domestic economy. It is important to note the role of input-output linkages in the above formula. since energy production uses non-energy inputs, adjustment to non-energy prices through trade and scale effects influence the price of energy inputs. Without such linkages, the above expression would simply reduce to $\hat{P}_{i,g}/\hat{w}_i = \hat{\lambda}_{ii,g}^{\frac{1}{\sigma_g - 1}} \hat{\ell}_{i,g}^{\frac{1}{1-\gamma_g}} \hat{\tau}_{i,g}\, \hat{\ell}_{i,g}^{\alpha^r_{i,g}}$. Using the expression for $\hat{w}_i/\hat{P}_{i,g}$ we obtain an equation for the change in global

emissions, presented below.[5]

Proposition 1. *The change in emissions in response to a energy and trade policy shock,* $\left\{\hat{\tau}_{i,g}, \hat{d}_{in,g}\right\}_{i,n,g}$, *can be determined as follows*

$$\hat{Z}_i = \sum_{k\in\mathbb{G}}\sum_{g\in\mathbb{E}}\left[z_{i,gk}\ \hat{\ell}_{i,k} \times \prod_{k'\in\mathbb{G}}\left(\hat{\ell}_{i,k'}^{\frac{a_{i,k'g}}{\gamma_{k'}-1}}\hat{\lambda}_{ii,k'}^{\frac{a_{i,k'g}}{1-\sigma_{k'}}}\right) \times \prod_{g'\in\mathbb{E}}\left(\hat{\tau}_{i,g}^{-a_{i,g'g}}\right) \times \prod_{g'\in\mathbb{E}_0}\left(\hat{\ell}_{i,g'}^{-\alpha^r_{i,g'}a_{i,g'g}}\right)\right]$$

requiring information on the following sufficient statistics: factual emission shares, π*, the policy-led change in labor shares,* $\hat{\ell}$*, and the policy-led change in domestic expenditure shares,* $\hat{\lambda}_{ii}$*. The change in global emissions can be obtained as* $\hat{Z}^{(global)} = \sum_i \left[\pi_i \hat{Z}_i\right]$*, given the factual emissions shares.*

The provide intuition, note that above equation represents a weighted sum of the change in energy to labor input prices. In particular, $\hat{Z}^{(global)} = \sum_i \sum_{g\in\mathbb{E}} \omega_{i,g}\left(\frac{\hat{P}_{i,g}}{w_i}\right)^{-1}$, where $\omega_{i,g} = \sum_k z_{i,gk}\hat{\ell}_{i,k}$. The change in energy to labor input prices can be decomposed into four different effects:

1. $\prod_{k'\in\mathbb{G}}\left(\hat{\ell}_{i,k'}^{\frac{a_{i,k'g}}{\gamma_{k'}-1}}\right)$ accounts for how upstream scale effects influence the price of energy type g. In the presence of scale economies, the price of intermediate inputs used by the energy type g will undergo change when policy expand or shrinks production in certain industries. For instance, the energy price $\tilde{P}_{i,g}$ declines if policy increases the scale of production in industry k' whose output is used intensively for the production of energy type g, which in turn increases energy use and emissions.

2. $\prod_{k'\in\mathbb{G}}\left(\hat{\lambda}_{ii,k'}^{\frac{a_{i,k'g}}{1-\sigma_{k'}}}\right)$ accounts for trade-related effects, that channel through changes to the price of traded energy varieties and traded intermediate inputs used for energy production. A lower $\lambda_{ii,k}$ generally cheaper access to traded intermediate (energy or non-energy) inputs used by the energy sector. A lower $\lambda_{ii,g}$ for energy type g indicates cheaper access to international varieties of that energy type. In both cases, greater access to trade lowers the price of energy to labor inputs, inducing more energy consumption and emissions.

3. $\prod_{g'\in\mathbb{E}}\left(\hat{\tau}_{i,g}^{-a_{i,g'g}}\right)$ represents the effect of energy taxes on the on relative price of energy to labor inputs. These have both a direct effect on the relative input price and an indirect effect through input-output connections, since energy type g may use energy type g' as an input in production.

[5]The equation presented under Proposition 1 holds locally for an a non-parametric cost aggregator. In particular, we can invoke Shephard's lemma and the logic presented above to obtain

$$d\ln Z^{(global)} = \sum_{i\in\mathbb{C}}\sum_{k\in\mathbb{G}}\sum_{g\in\mathbb{E}}\left\{\pi_{i,gk}\left[d\ln\ell_{i,k} + \sum_{k'\in\mathbb{G}}\frac{a_{i,k'k}}{\gamma_{k'}-1}d\ln\ell_{i,k'} + \sum_{k'\in\mathbb{G}}\frac{a_{i,k'g}}{1-\sigma_{k'}}d\ln\lambda_{ii,k'} - \sum_{g'\in\mathbb{E}}a_{i,g'g}d\ln\tau_{i,g} - \sum_{g'\in\mathbb{E}_0}a_{i,g'g}\alpha^r_{i,g'}d\ln\ell_{i,g'}\right]\right.$$

where α denotes the local value of inputs shares and a represents the elements of the local inverse Leontief matrix implied by these shares.

4. $\prod_{g' \in \mathbb{E}_0} \left(\hat{\ell}_{i,g'}^{-\alpha^r_{i,g'} a_{i,g'g}} \right)$ represent the change in domestic primary energy prices due to diseconomies of scale. Raising the share of employment in primary energy extraction, exerts upward pressures on prices. These price adjustments influence both primary energy use directly and non-primary energy use indirectly through input-output connection. As such, a higher employment share in the primary energy sector translates to higher energy to labor input prices, less energy use, and lower emissions.

Proposition 1 sheds light on the impacts of trade liberalization on global emissions, which is more subtle than energy subsidies but equally non-ambiguous. A trade policy shock $\hat{d}_{in,k} < 1$ that liberalizes trade, influences emissions both by changing the allocation of labor across industries and providing cheaper access to imported energy and input varieties used for energy generation. The former is presumably a wash at the global level, since allocation towards energy intensive industries in a subset of locations will coincide with the opposite movement in the other subset of goods. The latter effect, however, contribute to more energy use and lowers global emissions, as noted by following corollary.

Corollary 1. *Holding labor allocation fixed* $\left(\hat{\ell} = 1\right)$*, trade liberalization raises emissions by lowering the relative price of energy to labor inputs within each production unit. In particular, given that* $\hat{\lambda}_{ii,k} < 1$*, Proposition 1 implies*

$$\hat{Z}^{(global)} \mid \boldsymbol{\ell} = \sum_{i,k} \sum_{g \in \mathbb{E}} \left[z_{i,gk} \prod_{k'} \hat{\lambda}_{ii,k'}^{\frac{a_{i,k'g}}{1-\sigma_{k'}}} \right] > 1.$$

Real Consumption Effects. Understanding policy trade-offs requires understanding both the impact of policy on emissions and real consumption. The following proposition characterizes the real consumption effects associated with policy.

Proposition 2. *The change in country i's real consumption in response to a global energy and trade policy shock,* $\left\{\hat{\tau}_{i,g}, \hat{d}_{in,g}\right\}_{i,n,g}$*, is given by*

$$\hat{C}_i = \hat{\kappa}_i \left(\hat{\boldsymbol{\ell}}_i; \hat{\boldsymbol{\tau}}_i \right) \times \prod_k \left[\prod_{k'} \left(\hat{\ell}_{i,k'}^{\frac{a_{i,k'k}}{\gamma_{k'}-1}} \hat{\lambda}_{ii,k'}^{\frac{a_{i,k'k}}{1-\sigma_{k'}}} \right) \prod_{g' \in \mathbb{E}} \left(\hat{\tau}_{i,g}^{-a_{i,g'k}} \right) \prod_{g' \in \mathbb{E}_0} \left(\hat{\ell}_{i,g'}^{-\alpha^r_{i,g'} a_{i,g'k}} \right) \right]^{\beta_{i,k}}$$

where $\hat{\kappa}_i(.) \equiv \hat{Y}_i / w_i$ *represents the change in the ratio of net income to wage income in country i:*

$$\hat{\kappa}_i \left(\hat{\boldsymbol{\ell}}_i; \hat{\boldsymbol{\tau}}_i \right) = \frac{\sum_k \left[\alpha^l_{i,k} + \left(\alpha^r_{i,k} + \sum_{g \in \mathbb{E}} \left(\frac{\tau_{i,g} \hat{\tau}_{i,g} - 1}{\tau_{i,g} \hat{\tau}_{i,g}} \right) \alpha^g_{i,k} \right) \ell_{i,k} \hat{\ell}_{i,k} \right]}{\sum_k \left[\alpha^l_{i,k} + \left(\alpha^r_{i,k} + \sum_{g \in \mathbb{E}} \left(\frac{\tau_{i,g} - 1}{\tau_{i,g}} \right) \alpha^g_{i,k} \right) \ell_{i,k} \right]}.$$

Emissions vs. Consumption Trade-Off. To understand policy effects let us focus on a special case of the model with one energy type denoted by zero ($g = 0$), constant-returns to scale ($\gamma \to \infty$),

and no non-energy intermediate inputs. Also, focus on trade policy shocks alone. The policy-led change in emissions in this special case can be specified as

$$\hat{Z}_i = \sum_k \left(z_{i,k} \hat{\ell}_{i,k} \right) \times \hat{\lambda}_{ii,0}^{\frac{1}{1-\sigma_0}} \hat{\ell}_{i,0}^{-\alpha_{i,0}^r},$$

and the policy-led change to real consumption is described by

$$\hat{C}_i = \hat{\kappa}_i \times \prod_k \left(\hat{\lambda}_{ii,k}^{\frac{1}{1-\sigma_k}} \right)^{\beta_{i,k}} \times \left[\lambda_{ii,0}^{\frac{1}{1-\sigma_0}} \hat{\ell}_{i,0}^{-\alpha_{i,0}^r} \right]^{\sum_k \alpha_{i,k}^0 \beta_{i,k}},$$

where $\hat{\kappa}_i = \left[\frac{\alpha_{i,0}^l + (1-\alpha_{i,0}^l) \ell_{i,0} \hat{\ell}_{i,0}}{\alpha_{i,0}^l + (1-\alpha_{i,0}^l) \ell_{i,0}} \right] \approx 1$, considering that the primary energy sector is sufficiently small in relation to the rest of the economy $\ell_{i,0} \approx 0$. The above equations illuminate the critical role of targeting. Trade restrictions on non-energy goods compromise real consumption directly through the term $\prod_k \left(\hat{\lambda}_{ii,k}^{\frac{1}{1-\sigma_k}} \right)^{\beta_{i,k}}$ but influence emissions only indirectly through the change to labor allocation, $\sum_k \left(z_{i,k} \hat{\ell}_{i,k} \right)$. These indirect effects are presumably modest relative to the direct consumption loss. An effective policy would minimize the reduction in emission relative to the concurrent loss in real consumption. This metric is approximated by

$$\frac{\Delta \ln Z_i}{\Delta \ln C_i} \approx Cov_{\ell_i} \left(\frac{z_i}{\ell_i}, \hat{\ell}_i \right) + \mathbb{E}_{\beta_i} \left[\frac{1}{\sigma - 1} \Delta \ln \lambda_{ii} \right] + \left(1 - \mathbb{E}_{\beta_i} \left[\alpha_i^0 \right] \right) \left[\frac{1}{1-\sigma_0} \Delta \lambda_{ii,0} - \alpha_{i,0}^r \Delta \ln \ell_{i,0} \right].$$

Importantly, if emission per unit of labor (z_i/ℓ_i) is sufficiently homogeneous across non-energy sectors, then restricting non-energy trade comes with a significant loss in consumption as measured by $\mathbb{E}_{\beta_i} \left[\frac{1}{\sigma - 1} \Delta \ln \lambda_{ii} \right]$, but a possibly modest change in emissions, that channel exclusively via general equilibrium spillover effects to energy production, as measured by the last term on the right-hand side above. By contrast, restricting energy trade can be more effective, is causes direct reduction in energy imports and employment, without exerting any direct consumption loss.

4 Taking the Model to Data

In this version of the paper, we have adopted a Cobb-Douglas functional form for the upper-tier demand aggregator $\mathrm{C}_i(.)$ and production functions (of secondary energy and non-energy goods) $\mathrm{q}_{i,k}(.)$, with the latter also implying the marginal cost function $\mathrm{c}_{i,k}(.)$ and input cost share functions of labor and intermediate inputs, $\mathrm{a}_{i,k}^l(.)$ and $\mathrm{a}_{i,k}^g(.)$.[6] We are particularly interested in counterfactual equilibrium outcomes in response to trade policy and energy policy shocks. Employing the method of exact hat algebra, the sufficient statistics required to calculate counterfactual outcomes are:

[6] We are currently in the process of estimating production functions of industries, allowing for non-unity demand elasticity for energy products. In terms of data, we are combining energy prices from the International Energy Agency and firm-level information from the World Bank Enterprise Survey—which is one of the rare publicly-available sources that reports firms' use of fuels and electricity across many countries. We will update our quantitative analyses when we have our estimation results.

1. *Baseline Shares and Aggregates* ($\mathcal{B}$).

   (a) *Shares.* Cost share of labor and energy reserves, $\alpha^l_{i,k}$ and $1-\alpha^l_{i,k}$ in primary energy sectors $k \in \mathbb{E}_1$, cost share of labor and intermediate goods, $\alpha^l_{i,k}$ and $\alpha^g_{i,k}$, in secondary energy and non-energy sectors $k \in \mathbb{E}_2 \cup \mathbb{F}$, households' expenditure share $\beta_{i,k}$, and international trade shares $\lambda_{ji,k}$.

   (b) *Aggregates.* National expenditure E_i, industry-level sales and expenditures, $Y_{i,g}$ and $X_{i,g}$, national-level wage bills ($w_i L_{i,k}$), rents collected from energy reserves ($r_{i,k}R_{i,k}$), carbon emissions at the level of industry and households $Z_{i,gk}$, $Z^{(H)}_{i,g}$ (which, by aggregation, imply the national and global emissions).

2. *Structural Parameters* (Θ). Demand elasticity parameters, σ_k and γ_k; and climate change damage parameter μ_i (See the specification of the climate damage function below).

3. *Baseline Taxes* ($\mathcal{T}$). Baseline rates of import tariffs $t_{ij,k}$, export subsidies $x_{ij,k}$, and energy tax/subsidy rates $\tau_{i,gk}$.

4. *Policy* ($\mathcal{P}$). Changes in trade barriers, in the form of iceberg trade costs $\left\{\hat{d}_{ij,k}\right\}$ or import tariffs and export subsidies $\{\hat{\tau}_{ij,k}, \hat{x}_{ij,k}\}$, and changes in energy input taxes/subsidies $\{\hat{\tau}_{i,gk}\}$.

We relegate the presentation of the equations that specify the system of general equilibrium in changes to the appendix. For each policy $\mathcal{P}$, the solution to this system determines changes in all equilibrium values, taking in as input the sufficient statistics, $\{\mathcal{B}, \mathcal{T}, \Theta\}$. Next, we present our data sources and calibration that provide these sufficient statistics as well as our design of policy.

Baseline Shares and Aggregates ($\mathcal{B}$). We take data on bilateral trade, gross output and value added, expenditures on intermediate goods and final consumption from the Global Trade Analysis Project (GTAP) Database which reports the global matrix of flows from any origin country-industry pair to any destination country-industry or country-household pair in the year 2014. Our sample covers the largest 50 countries in terms of GDP plus six aggregate regions, each encompassing multiple neighboring countries. Together, our sample covers the global flows of production and trade in their entirety. We divide the space of goods into 23 industries, out of which 3 are primary energy (Coal, Crude Oil, and Natural Gas), 3 are secondary energy (Refined Petroleum, Electricity, and Gas Manufacturing & Distribution), with the remaining 17 industries consisting of Agriculture, Other Mining, 11 Manufacturing industries, and 4 Service industries.

The GTAP Database readily provides the cost share of each energy input in each industry as a part of their purchases of intermediate goods. We additionally observe the value added paid by each industry to natural resources. Accordingly, we calibrate the cost share of energy reserves in each primary energy industry as the value added that it pays to natural resources divided by its total value added. With $\alpha^r_{i,k} = (1 - \alpha^l_{i,k})$ as the share of energy reserves, the inverse energy supply elasticity corresponds to $\rho_{i,k} \equiv \alpha^r_{i,k}/\alpha^l_{i,k}$. To avoid potential mis-measurements at the level of individual countries, we set $\alpha^r_{i,k} = \alpha^r_k$ for all countries $i \in \mathbb{N}$, and calibrate them based on

global averages of the value added share of natural resources. The calibrated values of α_k^r are 0.41, 0.34, and 0.37 respectively for Coal, Crude Oil, and Natural Gas (with the implied inverse supply elasticities equal to 0.70, 0.53, and 0.58).

We additionally take from the GTAP Database information on CO2 emissions, associated with the use of each of the six energy types (primary or secondary) by industries or households. The accounting of the emission flows in the data ensures there is no double counting. For example, from a unit of crude oil, only a small fraction is combusted in the production of refined petroleum, with the larger fraction burnt in the form of refined petroleum when used in downstream industries such as Chemicals or Transportation.

Structural Parameters (Θ). *Demand Elasticities.* For primary or secondary energy industries, we assume there is no within-industry love-of-variety, and so, $\gamma_k = \infty$; and we set the value of the Armington elasticity at $\sigma_k = 11.16$, which we have borrowed from Farrokhi and Lashkaripour [2024]. For non-energy industries, we set $(\sigma_k, \gamma_k) = (3.77, 5.20)$ as a common parameter value for all the eleven manufacturing industries and $(\sigma_k, \gamma_k) = (6.54, 7, 67)$ as a common choice for all the four remaining non-energy & non-manufacturing industries, both taken from Lashkaripour and Lugovskyy [2023]. Our modeling assumptions are consistent with the way these two papers estimate the above parameters, allowing us to take their estimation results with no further caveats. These values, meanwhile, are within the range of available estimates in the literature, and satisfy the necessary condition for uniqueness in our framework, that is $\sigma_k \leq \gamma_k$. In terms of ranking, the values of σ imply that the trade elasticities are lower in manufacturing than non-manufacturing, and among non-manufacturing, they are higher in energy industries. The values of γ imply that markups, $\gamma/(\gamma-1)$, are higher in manufacturing than non-manufacturing, and (by our assumption) zero in the energy industries.

Climate Damage Parameter. We borrow the following parametric form of the cost of climate damage functional from Shapiro [2021],

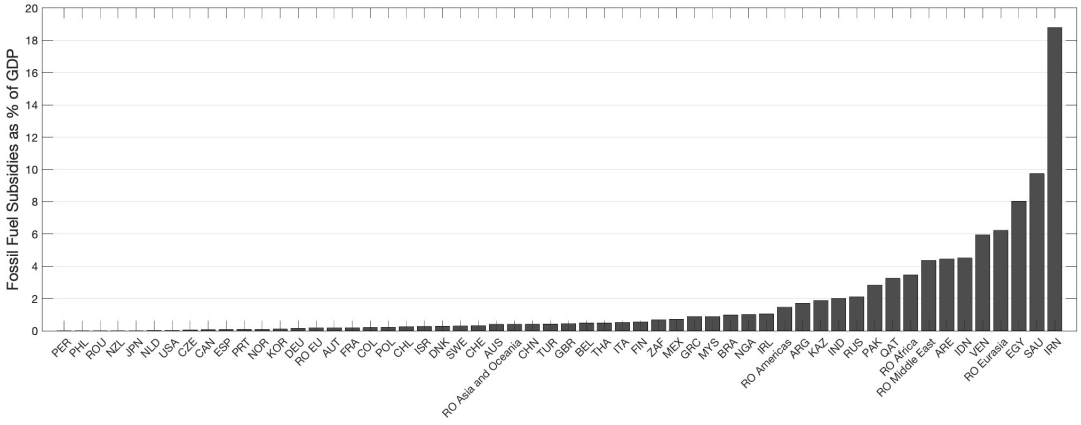
$$\Delta_i\left(Z^{(global)}\right) = \left[1 + \mu_i\left(Z^{(global)} - Z_0^{(global)}\right)\right]^{-1}$$

where μ_i governs the climate damage to country i when the level of global emission increases from the baseline of $Z_0^{(global)}$ to $Z^{(global)}$. We calibrate $\{\mu_i\}$ such that *(i)* the sum over country-level *marginal* damages, $\Sigma_i \Delta_i'\left(Z_0^{(global)}\right)$, equals the global social cost of carbon; and, *(ii)* the *marginal* damage to each country i relative to that of a reference country i_r , $\Delta_i'\left(Z_0^{(global)}\right)/\Delta_{i_r}'\left(Z_0^{(global)}\right)$, equals country i's social cost of carbon relative to that of the reference country i_r. We take the value of the global social cost of carbon from the most recent report by the United States Environmental Protection Agency (EPA) on the social cost of greenhouse gases, which corresponds to 156.2 ($/tCO2) (adjusted for our baseline year of 2014, in dollars of 2014), and obtain estimates of country-level social costs of carbon from Ricke et al. [2018].

Baseline Taxes/Subsidies ($\mathcal{T}$). As for fossil fuel subsidies, we use information provided by the Fossil Fuel Subsidy Tracker, which is a collaboration between the Organization for Economic Co-operation and Development (OECD) and the International Institute for Sustainable Development (IISD). The primary sources of these data are the International Energy Agency (IEA), the International Monetary Fund (IMF), and the OECD itself. Fossil fuel subsidies are reported for each country by the method of support mechanism, which crucially (in addition to direct taxes or transfers) covers indirect subsidies that arise due to the gap between the prices of fuels in the domestic market set by existing policy and their corresponding rates at the border.

We calibrate the ad valorem equivalent subsidy rates on the use of fossil fuels across countries in our sample by matching the ratio of total fuel subsidies to GDP of each country implied by our model with the observed ones in the data. The ratio of fossil fuel subsidies to GDP equals 0.4 percent for the median country and has a weighted average of 1.2 percent at the global level. The ratio takes particularly large values in fuel-abundant countries. In 2014, it was as high as 18.8 percent in Iran, followed by 9.7 in Saudi Arabia. The distortions created by fossil fuel subsidies is highly uneven around the world and its magnitude is sizable in a subsample of developing countries. Figure 1 shows the distribution of these subsidies as percentage of GDP for each country in our sample.

Figure 1: Fossil Fuel Subsidies as Percentage of GDP, 2014



The largest share of fossil fuel subsidies is by far allocated to the use of refined petroleum (gasoline, diesel, etc.) with a global average of 64.2%. This is followed by Natural Gas and Electricity with average shares of respectively 16.1% and 15.3%. The remaining 4.4% is the share of subsidies allocated to coal (with crude oil receiving no subsidies for its use according to our data). Since we do not observe whether coal subsidies are paid to the Electricity industry or non-energy industries, our current analysis does not include the subsidies to the use of coal. Furthermore, our calibration assumes that fossil fuel subsidies are not allocated to the use of energy by energy industries themselves, meaning that we assume they are paid only to households and non-energy industries when they use fossil fuels, that are namely natural gas (directly or via purchases of Gas Mfg. and Distr.),

electricity and refined petroleum products.

We are currently compiling the data on fossil fuel tax rates based on the information provided by the International Energy Agency. The future versions of our paper will incorporate these energy taxes. As such, the current version of the paper only allows for subsidies but not taxes on fossil fuel. Additionally, the current version sets the baseline values of import tariffs and export subsidies to zero. Trade policy shocks are, accordingly, analyzed through altering iceberg trade costs of non-energy goods.

Policy ($\mathcal{P}$). Our quantitative analysis in the next section aims at evaluating the emission and welfare impacts of energy and trade policy. As for energy policy, a recurring theme in international climate negotiations has been a call for a phase out of fossil fuel subsidies around the world. To shed light on how impactful such a policy can be, we consider removing the existing fossil fuel subsidies in all countries. Formally, this corresponds to $\hat{\tau}^{(I)}_{i,gk} = 1/\tau^{(I)}_{i,gk}$ and $\hat{\tau}^{(H)}_{i,g} = 1/\tau^{(H)}_{i,g}$ where $\tau^{(I)}_{i,gk}$ and $\tau^{(H)}_{i,g}$ equal one minus fossil fuel subsidy rate on the use of energy g in country i when used by non-energy industry k and households.

As for trade policy, our analysis seeks to answer whether trade agreements are good or bad for the environment. Specifically, we use a gravity equation estimation to uncover the impact of the WTO and regional trade agreements (RTAs) on international trade costs of non-energy industries, which yields the trade cost policy shocks, $\hat{d}_{ij,k}$.

5 Quantitative Policy Analyses

In this section, we use our calibrated model to evaluate the welfare and emission impact of existing trade agreements and fossil fuel subsidies. In all exercises that follow, we consider a version of our model with constant-returns-to-scale technologies allowing for a more straightforward interpretation of the results.

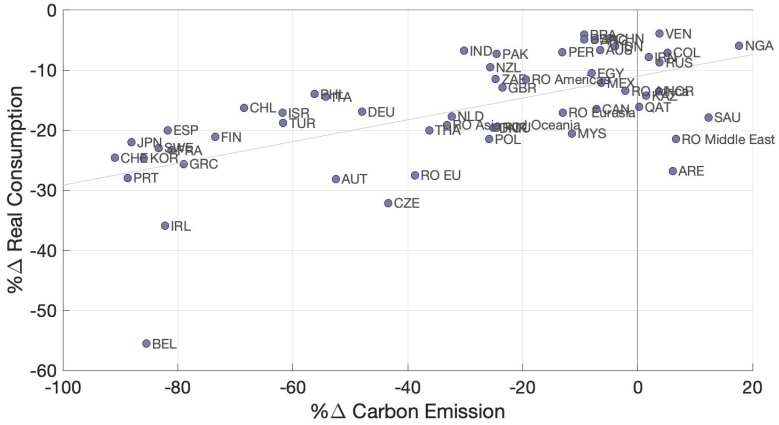
5.1 Tradeoffs between Consumption Gains and Climate Costs

To evaluate how international trade induces changes in both consumption and emissions, we consider a hypothetical counterfactual in which we move all economies to autarky. We find that the (weighted) global real consumption would fall by 11.9 percentage and the level of global emissions would fall by 18.6 percentage. The decrease in emissions, based on our calibration of the climate damage function, is equivalent to a 1.4 percentage point loss of real consumption, setting the global loss in terms of the climate-adjusted welfare at 10.5 percentage. Using a higher estimate of the social cost of carbon would further dampen the gains from trade.

The tradeoff between utility from consumption and disutility from climate damage holds as a disaggregated general pattern across individual countries. Figure 2 shows the scatter plot for countries in the sample with the percentage change in their carbon emissions ($\%\Delta Z_i$) on the x-axis and that of real consumption ($\%\Delta C_i$) on the y-axis. Countries with larger consumption gains from

trade such as Japan or Belgium —located at the lower left of the plot— would largely cut back their emissions if they were not open to trade. Conversely, countries whose consumption gains from trade are relatively small, such as Russia or Nigeria, would emit slightly higher emissions if they were in autarky.

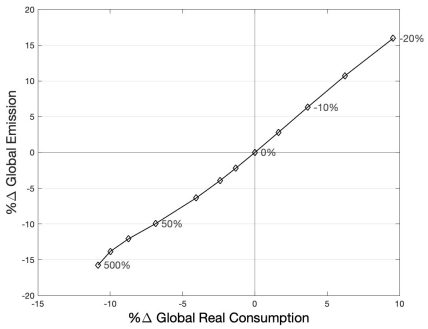
Figure 2: Consumption and Emission Impacts of Moving Countries to Autarky



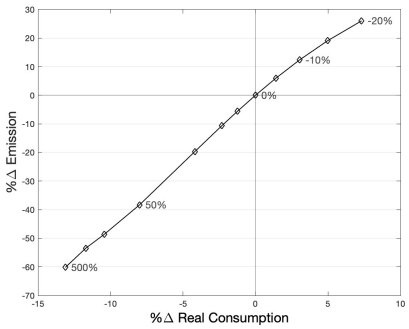
To shed further light on this tradeoff, we conduct another counterfactual exercise wherein we uniformly change all trade costs from -20% to 500% of their status-quo level. Figure 3 shows the results at the level of the world and for two individual countries, Japan as a large net importer of energy, and Saudi Arabia as a large net exporter of energy. As shown in Panel (a), at all levels of trade openness, a decrease in global emission is accompanied by a decrease in global consumption. This relationship holds for many individual countries as exemplified by the case of Japan (Panel b). However, in energy-abundant countries, raising trade costs tend to increase their emissions, as exemplified by the case of Saudi Arabia (Panel c). This is because larger trade barriers reallocate a portion of their exports of energy to domestic use, raising domestic emissions.

Figure 3: Consumption and Emission Impacts of Uniformly Changing Trade Costs

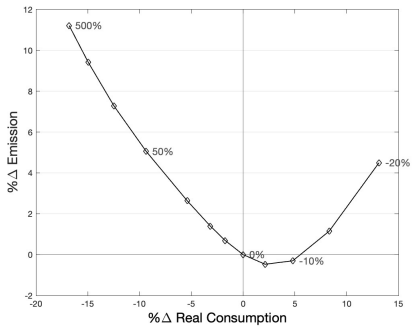
(a) World



(b) Japan



(c) Saudi Arabia



5.2 The Climate Impact of Trade Agreements

We next turn to evaluating the impact of trade agreements on global emissions. As the shock to the global economy, we use our previously-discussed estimates of trade cost changes in non-energy industries if the existing global and regional trade agreements were not in place.

Figure 4: Consumption and Emission Impacts of Removing Trade Agreements

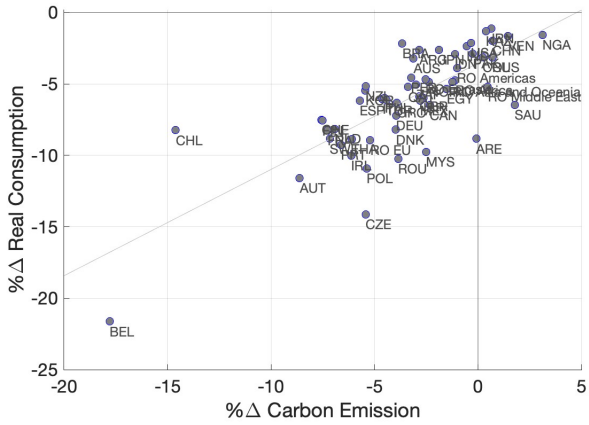


Figure 4 shows the resulting equilibrium changes in consumption and emission across countries. At the global aggregate, real consumption would fall by 4.2%, but emissions would fall only by 1.2%. This small reduction in global emissions is partly due to large rates of carbon leakage. When trade barriers raise for downstream manufacturing goods, exports of manufacturing fall particularly in countries that have a comparative advantage in manufacturing and rely on energy inputs mostly through imports, such as many European countries, Japan, and Korea. As a result, their demand for energy inputs diminishes and so does their carbon emissions. However, countries that tended to be net importers of manufacturing and were energy-abundant, such as Saudi Arabia and Nigeria, increase their industrial demand for locally-supplied energy in order to switch from foreign sources of manufacturing to the domestic suppliers. Consequently, their carbon emissions increase.

5.3 The Impact of Removing Fossil Fuel Subsidies

In this section, we examine the impact of removing fossil fuel subsidies around the world. Understanding the impact of this policy is important for two reasons. First, there have been repeated calls by advanced economies for a phase out of fossil fuel subsidies elsewhere in the world as a term of negotiation in international climate agreements. It is, therefore, crucial to produce estimates of the climate impact of removing these subsidies. If the impact is going to be small, then the efforts in making developing countries on board with the climate agenda need to be redirected to more impactful levers in climate action. However, if the global impact on emissions is going to be sizable, then the second reason becomes even more relevant, which is an understanding of the distributional consequences. The unit of our analysis is currently at the national level, and so, our focus will be

on distributional gains across countries.[7]

Figure 5: Consumption and Emission Impacts of Removing Fossil Fuel Subsidies

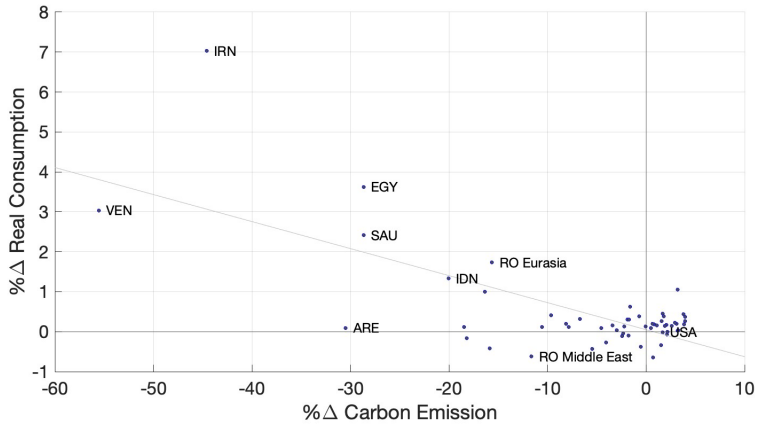


Figure 5 shows the impact of the removal of fossil fuel subsidies on real consumption and emission across countries. As expected, the impacts would be more sizable where the pre-policy distortions were larger, including Iran, Egypt, Saudi Arabia, Indonesia, and Venezuela. In these countries, emissions fall considerably and real consumption values tend to increase notably as a result of improvements in their allocative efficiency. Removing fossil fuel subsidies in energy-abundant countries leads to an increase in their energy exports, lowering world energy prices and raising emissions elsewhere. Consequently, the impact on global emissions is dampened by the increase in emissions in much of the rest of the world. For example, emissions increase by 1.5%, 1.7% and 2.1% in Canada, the United States, and Germany. Overall, the weighted change to real consumption at the aggregate level of the world would be negligible (merely, 0.25%) and the global level of emissions would fall by 2.9%.

These results suggest that the efficacy of removing fossil fuel subsidies remains limited largely because it is prone to carbon leakage. Therefore, a more comprehensive design that calls for phase out of fossil fuel subsidies requires to be augmented with policy tools that address carbon leakage.

6 Future Work

Our future work will enrich and expand our current analysis along (at least) two fronts. First, we are estimating production functions across industries using detailed energy prices from the International Energy Agency and firm-level data from the World Bank Enterprise Survey. This estimation step will allow us to calibrate our model with non-unitary energy demand elasticities. Second, the alignment between trade-induced consumption gains and higher emissions provides an opportunity for linking global trade policy reforms with climate objectives. Building on this idea, we aim at

[7]However, the distributional impacts within fuel-abundant countries is important and that is likely among the key reasons for why these distortions exist in the first place.

characterizing the possibility frontier for a comprehensive global agreement on trade and climate wherein countries' preferential market access is contingent on their carbon pricing compliance.

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7 Appendix

7.1 Equilibrium in Changes.

We consider a Cobb-Douglas functional form for the upper tier of the demand system

$$\mathsf{C}_i\left(\left\{C_{i,k}^{(H)}\right\}_{k\in\mathbb{G}}\right)=\prod_{k\in\mathbb{G}}\left(C_{i,k}^{(H)}\right)^{\beta_{i,k}}$$

and for production technologies of secondary energy and non-energy industries:

$$\mathrm{q}_{i,k}\left(l_{i,k},\{m_{i,kg}\}_{g\in\mathbb{G}}\right)=l_{ij,k}^{\alpha_{i,k}^{l}}\prod_{g\in\mathbb{K}}m_{i,kg}^{\alpha_{i,k}^{g}},\qquad k\in\mathbb{E}_2\cup\mathbb{F}$$

which implies the following cost function:

$$\mathrm{c}_{i,k}=w_i^{\alpha_{i,k}^{l}}\times\prod_{g\in\mathbb{G}}P_{i,g}^{\alpha_{i,k}^{g}},\qquad k\in\mathbb{E}_2\cup\mathbb{F}$$

Note that, in the primary energy the cost function is:

$$\mathrm{c}_{i,k}=w_i^{\alpha_{i,k}^{l}}\times r_{i,k}^{1-\alpha_{i,k}^{l}},\qquad k\in\mathbb{E}_1$$

- Sufficient Statistics:
  - substitution elasticity parameters: σ_k and γ_k
  - cost share of labor and natural reserves, $\alpha_{i,k}^{l}$ and $1-\alpha_{i,k}^{l}$ for primary energy $k\in\mathbb{E}_1$
  - cost share of labor and intermediate goods $\alpha_{i,k}^{l}$ and $\alpha_{i,k}^{g}$ for sec. energy and final goods $k\in\mathbb{E}_2\cup\mathbb{F}$
  - households' expenditure share $\beta_{i,k}$
  - trade shares $\lambda_{ji,k}$
  - wage bills ($w_iL_{i,k}$) and rents on reserves $r_{i,k}R_{i,k}$
  - Sales, expenditures, and national accounts: E_i, $Y_{i,g}$, $X_{i,g}$
  - Emissions: $Z_{i,k}$, $Z_i^{(H)}$
- Prices:

$$\begin{cases}\widehat{P}_{ij,k}=\widehat{d}_{ij,k}\widehat{P}_{ii,k}=\widehat{d}_{ij,k}\widehat{c}_{i,k}^{\frac{\gamma_k}{\gamma_k-1}}\left(\widehat{\ell}_{i,k}\widehat{w}_i\right)^{\frac{1}{\gamma_k-1}} & \text{x) } (ij,\ k\in\mathbb{K})\\ \widehat{c}_{i,k}=\widehat{w}_i^{\alpha_{i,k}^{l}}\widehat{r}_{i,k}^{\alpha_{i,k}^{r}}\prod_{g\in\mathbb{G}}\left(\widehat{\widehat{P}}_{i,gk}^{(I)}\right)^{\alpha_{i,k}^{g}} & \text{x) } (i,\ k\in\mathbb{K})\\ \widehat{P}_{i,k}=\left[\sum_n\lambda_{ij,k}\hat{P}_{nj,k}^{1-\sigma_k}\right]^{\frac{1}{1-\sigma_k}} & \text{x) } (i,\ k\in\mathbb{K})\\ \widehat{P}_{i,kg}^{(I)}=\widehat{\tau}_{i,kg}\widehat{P}_{i,g},\quad \widehat{P}_{i,g}^{(H)}=\widehat{\tau}_{i,g}^{(H)}\widehat{P}_{i,g} & \text{x) } (i,\ k\in\mathbb{K},\ g\in\mathbb{E})\end{cases}\tag{11}$$

- International expenditure shares

$$\widehat{\lambda}_{ij,k} = \left(\widehat{P}_{ij,k}/\widehat{P}_{j,k}\right)^{1-\sigma_k}, \qquad (ij,\ k \in \mathbb{K}) \tag{12}$$

- Sales, $Y_{i,k} = P_{ii,k}Q_{i,k}$,

$$\begin{cases} \widehat{Y}_{i,k} = \widehat{r}_{i,k} & k \in \mathbb{E}_1 \\ \widehat{Y}_{i,k} = \widehat{\ell}_{i,k}\widehat{w}_i & k \in \mathbb{E}_2 \cup \mathbb{F} \end{cases} \tag{13}$$

- Expenditures (after-tax values), $\widehat{X}_{i,k}X_{i,k} = X'_{i,k} = P'_{i,k}C'_{i,k}$

$$X'_{i,k} = \underbrace{\frac{1}{\tau^{(H)}_{i,k}}\beta_{i,k}\widehat{E}_i E_i}_{X^{(H)'}_{i,k}} + \underbrace{\sum_{g\in\mathbb{E}_2\cup\mathbb{F}} \frac{1}{\tau^{(I)}_{i,kg}}\alpha^k_{i,g}\widehat{Y}_{i,g}Y_{i,g}}_{X^{(I)'}_{i,k}}, \qquad k \in \mathbb{K} \tag{14}$$

- Emission:

$$\begin{cases} \widehat{Z}^{(I)}_{i,kg} = \hat{\ell}_{i,k}\left(\frac{\hat{w}_i}{\hat{P}^{(I)}_{i,gk}}\right) & \text{a) industry emission } (i,k; \quad g\in\mathbb{E}) \\ \widehat{Z}^{(H)}_{i,g} = \frac{\hat{E}_i}{\hat{P}^{(H)}_{i,g}} & \text{b) household emission } (i; \quad g\in\mathbb{E}) \\ \widehat{Z}^{(I)}_{i} = \frac{1}{Z^{(I)}_i}\sum_k\sum_{g\in\mathbb{E}}\widehat{Z}^{(I)}_{i,gk}Z^{(I)}_{i,gk} & \text{c) industrial emission, } (i) \\ \widehat{Z}^{(H)}_{i} = \frac{1}{Z^{(H)}_i}\sum_{g\in\mathbb{E}}\widehat{Z}^{(H)}_{i,g}Z^{(H)}_{i,g} & \text{d) household emission, } (i) \\ \widehat{Z}_i = \frac{1}{Z_i}\left(\widehat{Z}^{(I)}_i Z^{(I)}_i + \widehat{Z}^{(H)}_i Z^{(H)}_i\right) & \text{e) national emission} \\ \widehat{Z}^{(global)} = \sum_{i=1}^N\left[\left(Z_i/Z^{(global)}\right)\times\widehat{Z}_i\right] & \text{f) global carbon emission} \end{cases}$$

- Market Clearing Conditions:

$$\begin{cases} \hat{\ell}_{i,k}\ell_{i,k}w_i\bar{L}_i = \alpha^l_{i,k}\sum_j\left[\lambda'_{ij,k}X'_{j,k}\right] & \text{a) LMC } (i,k\in\mathbb{K}) \\ \sum_{k=1}^K\hat{\ell}_{i,k}\ell_{i,k} = 1 & \text{b) National LMC } (i) \end{cases} \tag{15}$$

$$\hat{r}_{i,k}r_{i,k}\bar{R}_{i,k} = \left(1-\alpha^l_{i,k}\right)\sum_j\left[\lambda'_{ij,k}X'_{j,k}\right], \qquad (i,k\in\mathbb{E}_1) \tag{16}$$

- Taxes and Balance of Budget

$$\widehat{T}_i T_i = \left(\frac{\tau^{(H)}_{i,k}-1}{\tau^{(H)}_{i,k}}\right)\beta_{i,k}\widehat{E}_i E_i + \sum_{g\in\mathbb{E}_2\cup\mathbb{F}}\left(\frac{\tau^{(I)}_{i,kg}-1}{\tau^{(I)}_{i,kg}}\right)\alpha^k_{i,g}\widehat{Y}_{i,g}Y_{i,g} \tag{17}$$

$$\widehat{E}_i E_i = \widehat{Y}_i Y_i + \widehat{T}_i T_i, \qquad \widehat{Y}_i Y_i = \widehat{w}_i w_i L_i + \sum_{k\in\mathbb{E}_1}\left[\widehat{r}_{i,k}r_{i,k}\bar{R}_{i,k}\right] \tag{18}$$

7.2 Numerical Algorithm.

1. Outer loop. Guess changes to wage rates of labor and rental rates of energy reserves, $(\widehat{w_i}, \widehat{r}_{i,k})$

2. Inner loop. Given changes to wages and rental rates of reserves, solve for change to labor shares $\hat{\ell}_{i,k}$ and new level of tax revenues $\left(\hat{T}_i T_i\right)$:

   (a) Form an initial guess of labor shares, $\hat{\ell}_{i,k}$.

   (b) Calculate change to sales, $\widehat{Y}_{i,k}$, according to (13), then calculate the new level of national income:

   $$\widehat{Y}_i Y_i = \sum_k \left[\left(\alpha^l_{i,k} + \alpha^r_{i,k}\right) \widehat{Y}_{i,k} Y_{i,k}\right]$$

   (c) Calculate total expenditure using (18), $\widehat{E}_i E_i = \widehat{Y}_i Y_i + \widehat{T}_i T_i$.

   (d) Calculate change to prices $\hat{P}_{ii,k}$, $\hat{P}_{ij,k}$, $\hat{P}_{i,k}$, $\widehat{\tilde{P}}^{(I)}_{i,gk}$, $\widehat{\tilde{P}}^{(H)}_{i,k}$, and trade shares $\hat{\lambda}_{ij,k}$ according to the system defined by (11) and (12).

   - Guess $\widehat{P}_{ii,k}$. Calculate $\widehat{P}_{ij,k} = \widehat{d}_{ij,k}\widehat{P}_{ii,k}$, then $\widehat{c}_{i,k}$, then update $\widehat{P}_{ii,k}$.

   (e) Calculate expenditures $\hat{X}_{i,k} X_{i,k}$ according to (14).

   (f) Update the guesses ...

   i. of tax revenues $\hat{T}_i T_i$ according to the tax equation 17.

   ii. of change to labor shares according to market clearing condition (15.a)

   $$\hat{\ell}_{i,k} = \frac{\alpha^l_{i,k}}{\ell_{i,k}\widehat{w}_i w_i \bar{L}_i} \sum_j \left[\widehat{\lambda}_{ij,k}\lambda_{ij,k} X'_{j,k}\right]$$

   If the updated guesses of $\hat{T}_i T_i$ and $\hat{\ell}_{i,k}$ are sufficiently close to their previous guesses, stop and go to Step 3. Otherwise, use the updated guess go to Step 2.(b).

3. Update the guesses of wage and rental rates:

   $$\widehat{r}_{i,k} = \frac{1}{r_{i,k}\bar{R}_{i,k}} \left[\alpha^r_{i,k}\widehat{Y}_{i,k} Y_{i,k}\right]$$

   $$\widehat{w}_i = \frac{1}{w_i \bar{L}_i} \sum_k \left[\alpha^l_{i,k}\widehat{Y}_{i,k} Y_{i,k}\right]$$

   If the updated guesses of wage and rental rates are sufficiently close to their previous guesses, stop. Otherwise, use the updated guesses and go to Step 2.