Quantifying Carbon Emissions in the Global Economy*

Ezequiel Garcia-Lembergman
Pontifical Catholic University of Chile

Natalia Ramondo
Boston University and NBER

Andrés Rodríguez-Clare
UC Berkeley and NBER

Joseph S. Shapiro
UC Berkeley and NBER

March 2025

Abstract

We develop a quantitative model of international trade and and greenhouse gas emissions, with fossil fuel markets playing a central role. We use the model for national carbon accounting, quantifying the impact of trade on carbon emissions and welfare, and assessing various environmental policies in an open economy. The model features globally traded fossil fuels that are produced with natural resources, leading to upward-sloping supply curves. When used in consumption or as inputs in production, fossil fuels release carbon into the atmosphere. We find that a country's emissions differ greatly depending on whether we consider goods consumption, goods production, or fossil fuels extraction: for instance, France looks very clean when fossil-fuel extraction is consider, but emissions are twice as large if emissions are measured according to French consumption Compared to a counterfactual world in autarky, international trade increases emissions by more than 10%, mostly because trade in fossil fuels decreases their price and increases their use worldwide. For net fuel consumers like China, taxing fossil fuel use most effectively reduces global emissions; for fossil fuel net producers like Russia, taxing fossil fuel extraction more effectively reduces emissions. Our calculations suggest that a global tax of 100$ per ton of CO_2, either to the extraction or the use of fossil fuels, would reduce emissions by half relative to the current situation. At the same time, real GDP would decline between 0.52% (extraction tax) and 0.73% (production tax).

JEL: F18, F23, H23, Q43, Q56
Keywords: carbon accounting; trade and the environment; carbon tariffs; carbon border adjustments; gravity models; energy trade

*We thank participants at various seminars and conferences, as well as Severin Borenstein, Rob Elliott, Teresa Fort, Sam Kortum, Christian Leuz, and Gianluca Orefice, for useful comments; Martin Caruso Bloeck, Lucy Hackett, Isabel Hincapie Correa, Juan Ignacio Jacoubian, Guido Lamarmora, Kerry Loaiza Marin, Petry Martynov, Matthew Murillo, Alice Schmitz, and Mingduo Zhao for excellent research assistance; and the Clausen Center and NSF SES-1950790 for generous support. Author emails: eglembergman@berkeley.edu, nramondo@bu.edu, arc@berkeley.edu, joseph.shapiro@berkeley.edu.

Introduction

Countries are increasingly linking policies on international trade, greenhouse gas emissions, and energy markets. Europe is implementing the world's first import tariff based on the carbon content of imports (a Carbon Border Adjustment Mechanism). Every major carbon tax bill proposed in the US Congress has included a carbon border adjustment. China responded to US tariffs in early 2025 by applying tariffs to its imports of US fossil fuels. Annual climate change negotiations hotly debate each country's contribution to global carbon emissions via production, consumption, and extraction decisions. Increasingly fragmented regional climate change policies lead to concerns that emissions will relocate around the world to avoid regulation ("leakage").

Trade research has recently advanced in developing quantitative frameworks that help address many important questions, particularly the magnitude of the gains from trade and the effects of trade shocks on economic outcomes (Costinot and Rodríguez-Clare, 2014; Caliendo and Parro, 2022). Research has also begun adopting quantitative trade models to study interactions between trade, the environment, and environmental policies. A more longstanding literature uses computable general equilibrium models to examine such questions.

We develop a general quantitative framework with fossil fuel markets at its core to study interactions between international trade and carbon emissions. The model incorporates canonical assumptions to account for natural resources as a factor of production for fossil fuels, and for the supply, demand, trade, and equilibrium of fossil fuel markets. We embed these features in a multi-sector, multi-country model of trade with input-output links.

We use the model for three purposes. First, we account for carbon emissions from each country according to goods consumed, goods produced and fossil fuels extracted. Second, we quantify the effects of international trade (relative to counterfactual autarky) on carbon emissions, analogous to the analysis of the gains from trade. Third, we study how counterfactual trade and environmental policies, primarily carbon taxes and tariffs, affect emissions, income, and welfare. While our approach to analyzing fossil fuel markets uses standard demand and supply arguments, most of the trade-environment literature abstracts from detailed analysis of fossil fuel markets. Our results show that carefully accounting for fossil fuel markets leads to unexplored channels and changes answers to the questions mentioned above.

More specifically, our framework begins with a general equilibrium model of trade and carbon emissions. The model features many sectors with input-output links (Caliendo and Parro 2015). Three mining sectors – coal, natural gas, and oil – use natural resources for production, generating upward-sloping supply curves. Unlike most work, which assumes that fossil fuels are differentiated, we assume that fuels are homogeneous and freely tradable. We assume that the other (non-mining) sectors have goods differentiated by country of origin (Armington assumption), face iceberg-type trade costs, and may use fossil fuels as inputs in production. Emissions come exclusively from using fossil fuels. These assumptions facilitate a simple and transparent methodology to track fossil fuel prices and emissions through international global value chains. Countries may tax fossil fuel extraction, fossil fuel use in production, or fossil fuel use in consumption.

In our framework, taxes and trade shocks have standard but non-trivial effects on market outcomes via fossil fuel markets. In a simplified setting, we show analytically that moving to trade autarky decreases the global quantity of fossil fuels demanded and extracted because their prices increases. This "price effect" makes autarky decrease emissions.

An alternative methodology, the "abatement approach," assumes that pollution (or a dirty input) combines with factors to produce output (e.g. Moigne et al. 2024). The abatement approach implies that emissions *per dollar* are fixed. This assumes away the price mechanism which is central to our analysis. In line with the science and engineering of fossil fuels, we instead assume that emissions *per physical unit* of fossil fuels are fixed, but emissions per dollar of fossil fuel may adjust in equilibrium as fossil fuel prices adjust to counterfactual scenarios. This distinction turns out to be critical in our analysis. The supply elasticity of fossil fuels, which we estimate from engineering cost data, regulates the effects of trade and environmental policies.

Following Grossman and Krueger (1993) and Copeland and Taylor (1994), we discuss how taxes or trade shocks affect emissions via three channels—scale, composition, and technique. For instance, a trade shock triggers scale effects since the expansion of non-energy sectors increases the production of fossil fuels, and hence, emissions, through sectoral linkages, as the production of fossil fuels uses non-energy inputs. Composition effects occur through reallocation of resources across sectors with different fossil fuel intensities. Technique effects result from changes in the prices of the fossil fuels.[1]

We take the model to data by compiling a wide array of existing data and estimating one new parameter. We combine data from the World Input Output Database (WIOD), Exiobase, and the International Energy Agency (IEA) to measure global production and trade flows for all goods and services, including fossil fuels, for the year 2014. Our sample includes 28 countries, including a rest-of-world aggregate, and 28 sectors, including three fossil fuel extraction sectors.

In line with recent spatial models involving energy (Arkolakis and Walsh 2023; Cruz and Rossi-Hansberg 2024), we use data on engineering supply curves across several world regions, from Welsby et al. (2021) to estimate the supply elasticity of coal, natural gas, and crude oil. Given our assumption of Cobb-Douglas technology, this parameter is equivalent to the share of natural resources in the production of these goods, or to the share of rents in the revenues of each of these sectors. It provides a key parameter for our quantitative exercises.[2]

[1]The trade-environment literature also focuses on the idea that increases in GDP per capita can create technique effects by encouraging environmental regulation (the Environmental Kuznets Curve, Grossman and Krueger (1995)). Our model excludes that channel, in part because CO_2 is a global pollutant where most benefits of abatement accrue to other countries, and therefore demand for environmental quality may scale less with real income (Cole and Elliott, 2003, provide some supporting evidence). Caron and Fally (2018) is a recent example that incorporates mechanisms leading to the Environmental Kuznets Curve.

[2]Estimates of this elasticity are scarce. For instance, the review in Boeters and Bollen 2012, p. S185 concludes that "Empirical estimates of fuel supply elasticities are scarce and display a considerable variation . . . [T]here are hardly any recent empirical studies." Arora 2014 summarize prevailing CGE models, which imply a short-run supply elasticity of natural gas for the US in the range of -0.4 to 7.2. Farrokhi and Lashkaripour (2023) calculate the cost share of carbon reserves as the value-added share of natural resources in an aggregate primary energy sector, from GTAP, and obtain an average estimate of 0.37 across countries. Abuin (2024) estimates a supply elasticity of 0.24 for and 0.77 for coal using shocks to electricity demand interacted with fossil fuel generation shares as instruments for fuel prices.

Each of our three applications – carbon accounting, trade shocks, and taxes – provides intriguing results. [3] To illustrate the differences between the three carbon accounting metrics (carbon from production, consumption, and extraction), consider the example of vehicles manufactured in Mexico, using Mexican steel produced with Canadian coal, and which are sold to consumers in the US. Production-based accounting would assign the emissions to Mexico; consumption-based accounting would assign the emissions to the US; and extraction-based accounting would assign the emissions to Canada.

Our carbon accounting calculations show that high-income countries with trade deficits, such as the US, France, and Germany, have higher emissions due to consumption than production. In contrast, middle-income countries with a trade surplus, like China, have greater emissions measured by production than to consumption. Additionally, fossil fuel producers like Canada and Russia have the greatest emissions measured by extraction. These patterns also hint at different effects of carbon taxes applied to extraction, production, or consumption, which we analyze below. For example, observing greater production than extraction-based emissions for the US than in Russia suggests that a production-based carbon tax would be more effective at reducing carbon emissions in the US, while an extraction-based carbon tax would be much more effective in Russia.

We then assess how international trade shocks affect emissions. For each counterfactual change in trade flows, we decompose the change in emissions into three channels: one reflecting changes in global fossil fuel prices; another reflecting substitution in demand; and a third accounting for trade imbalances.

Our analysis shows that moving to autarky would decrease global emissions by twelve percent. Put differently, compared to the autarky counterfactual, trade increases global carbon emissions by 13.6%. Most of the reduction in emissions due to autarky occurs via the price channel, which would be turned off with flat supply curves of fossil fuels, or in the abatement approach common in the literature. This finding quantitatively corroborates the analytical results. We actually find that turning off the price channel reverses the sign of these results. In counterfactuals that turn the price channel off, global autarky increases global production of fossil fuels and global emissions by almost two percent. More broadly, this finding indicates that accounting for the effects of trade shocks on fossil fuel prices is important to analyze the interactions of trade and environmental policies.

Not surprisingly, the effects are heterogeneous across countries. For example, moving France to autarky decreases emissions embedded in French consumption of final goods by around 70 percent, which is equally driven by increases in the prices of fossil fuels and the shift away from dirtier imported inputs. Global autarky increases emissions in net fossil-fuel exporters like Canada, Russia, and Norway, due to a decrease in the autarky price of fossil fuels. But if the price channel were not present, these countries would be cleaner in autarky. Autarky makes China dirtier since it shuts down China access to cleaner imported inputs; however, this demand effect is offset but the adjustment in the price of fossil fuels, which ends up making China much less dirty in autarky than without these price adjustments.

Finally, we calculate the effectiveness of–and leakage from–unilateral carbon taxes.For example, if

[3] We further distinguish an industry's direct emissions from the emissions embodied in the industry's value chain, which the climate change literature describes as "Scope 1" versus "Scope 3" emissions.

China, which represents more than 30% of world (production) emissions, taxed the use of fossil fuels in production, the decrease in 100 tons of CO_2 released to the environment in China would be partially offset by an increase of 18 tons in the rest of the world. The same tax applied by France would produce much higher leakage rates, but of course with much smaller magnitudes than for China. In the case of France, world emissions would be reduced by 0.2 percent (or around 68 millions tons), while for China, this decrease would be of around 5,700 millions tons worldwide —a 16 percent global reduction. In general, a carbon production tax would be more effective in terms of deterring leakage when applied to large production countries. An extraction tax would be effective when applied to fossil fuels producers, like Russia.

Of course, the way to avoid leakage altogether is to implement a global carbon tax. Our calculations suggest that a global tax of 100$ per ton of CO_2, either to the extraction or the use of fossil fuels, would reduce emissions by half relative to the current situation. For one point of reference, this magnitude is in line with comparable calculations coming from DICE models (Barrage and Nordhaus 2024a). At the same time, real GDP would decline between 0.52% (extraction tax) and 0.73% (production tax). Effects are heterogeneous across countries with, for instance, net exporters of fossil fuels gaining in terms of real GDP under a global extraction carbon tax, but losing if the global tax were applied to the use of fossil fuels, and China, which is a net importer of fossil fuels, but a net exporter of energy-intensive manufacturing goods, losing in both scenarios –but around half if the tax were to the use, rather than extraction, of fossil fuels.

We build on the growing literature on quantitative models of trade and the environment. Like many papers in that literature, we study many sectors and sectoral input-output links. Some papers have mining sectors using a natural resource in fixed supply, and the inclusion of carbon-tax policies and leakage . Our key departure from this literature is that we explicitly model the market for fossil fuels, allowing for an upward-sloping supply elasticity and price adjustments. Even in a closed economy, the supply elasticity for fossil fuels is a critical determinant of the effect of carbon taxes: if the supply of fossil fuels were perfectly elastic, prices would not change as demand decreases due to a carbon tax, and hence, emissions would decrease with quantities demanded. With an upward slopping supply curve, the equilibrium quantity of fossil fuels would not fall as much, and the effect on emissions would be mitigated.

The way we model the fossil fuel market through a standard demand-supply analysis, and its implications for carbon taxes, is closer to Kortum et al. (2023). The main difference is that, while Kortum et al. (2023) present analytical results in a simple model, we take a full-fledge general equilibrium approach, enriching the model to capture the heterogeneity observed in the data, and calculating the quantitative implications of different carbon tax schemes and trade shocks on emissions and welfare. Our approach is closest to Farrokhi and Lashkaripour (2023), which also allow for a freely-tradable energy resource produced under decreasing returns to scale. While their focus is mainly on the analysis of (optimal) climate clubs, carbon taxes, and their political economy, our focus is mainly on the effect of trade shocks and of different carbon tax schemes.[4] Moreover, we distinguish among energy resources (coal, gas, and

[4]While a uniform carbon price would provide a first-best policy response to climate change, political economy and other

oil), rather than aggregate them into one. This distinction is important since not only these sources of energy are used differently by different sectors and countries, but also they have very different emission intensities, with coal being the dirtiest, and very different world prices, with the oil price more than doubling the price of coal (for equivalent units).

Papers such as Larch and Wanner (2017), Caliendo et al. (2024), or Moigne et al. (2024) adopt an abatement approach, as originally proposed by Copeland and Taylor (1994), which describes emissions as a fixed proportion of production that firms can invest to abate, so that the fossil fuel market is not explicitly modeled. They miss the price channel explained above, which plays an important role in the effects of trade shocks and carbon policies. Even though Egger and Nigai (2014) do model energy markets explicitly, their analysis is restricted to flat supply curves for the fossil fuel resource, and does not distinguish among the different fossil fuel sectors (i.e. their emission intensity is very different for coal, gas, and oil), as well as among the different non-energy sectors, missing the heterogeneity embedded in the world input-output table.

The emerging literature applying trade models to environmental questions is also largely distinct from an industrial ecology literature, which even if far removed from international trade theory, focuses on measuring the energy and environmental goods embodied in global production and trade (Davis and Caldeira 2010; Peters et al. 2011; Lopez et al. 2019; Zhang et al. 2020; Heal 2022). This literature studies "consumption based carbon accounting," which highlights that measuring carbon emissions by where goods are consumed, rather than by where they are produced, assigns a larger responsibility to climate change to net importers, like the US, and less responsibility to net exporters, like China . In contrast with most of this literature, our paper provides theory-grounded aggregate measures and decompositions of carbon emissions according to where energy is extracted, used in production, and consumed. These accounting analyses provide a bridge to the field of industrial ecology.

The paper proceeds as follows. Section 1 presents the model. Section 2 describes the data. Section 3 discusses carbon accounting. Section 4 presents the estimation of fossil fuel supply elasticities. Section 5 analyzes counterfactual trade shocks. Section 6 analyzes carbon taxes. Section 7 concludes.

1 Model

Our quantitative model of trade and the environment allows for many sectors, including three mining sectors that extract fossil fuels (crude oil, coal, and natural gas) with upward sloping supply curves. Only fossil fuels generate CO_2 emissions.[5] Additionally, we include an input-output structure similar to Caliendo and Parro (2015). Non-mining goods are differentiated by origin (*à* la Armington), sold under

obstacles to carbon pricing have led researchers to analyze a wide range of other regional and national policies, including cap-and-trade policies in California, New England, and the European Union (Goulder et al. 2012; Martin et al. 2014; Fowlie et al. 2016), tariffs, non-tariff barriers, and other trade policies to affect CO_2 emissions or give incentives for climate change policy (Nordhaus 2015; Bohringer et al. 2016; Shapiro 2021), in addition to standards and other command-and-control policies.

[5]Our choice of modeling crude oil, natural gas, and coal as the only sectors responsible for CO_2 emissions (when burned) reflects the fact that together they are responsible for about 75% of greenhouse gas emissions (Ge et al. 2024).

perfect competition, and traded internationally incurring iceberg-trade costs. Fossil fuels, in contrast, are homogeneous and freely traded internationally.

The structure of our model allows us to track emissions from fossil fuels as they are used both in production and final demand. For example, we account for emissions both from manufacturing a vehicle and from driving it. [6]

1.1 Setup

The economy is composed of multiple countries indexed by $j, l, n = 1, ..., N$ and multiple sectors indexed by $s, k \in \mathcal{K} \equiv \{1, ..., K\}$. There are two types of sectors: mining sectors, $s \in \mathcal{K}^M$, and non-mining sectors, $s \notin \mathcal{K}^M$. Wherever possible, the index j represents the country where the mining occurs, and l and n represent the countries where production of non-mining goods and consumption take place.

Mining goods are produced with labor and a fixed factor, a natural resource, or "mines", specific to each mining sector. Country j has an endowment of L_j units of labor and mines $M_{j,s}$ for sector $s \in \mathcal{K}^M$. Labor markets are perfectly competitive.

Each country has a representative agent who aggregates all income, which includes wages and rents from the fixed factor. Preferences are Cobb-Douglas across sectors, and consumers derive disutility from global emissions,

$$U_n = \prod_{s=1}^{\mathcal{K}} C_{n,s}^{\mu_{n,s}} - \gamma_n \mathcal{E} \tag{1}$$

Here $\mu_{n,s} \in [0, 1]$ are expenditure shares satisfying $\sum_s \mu_{n,s} = 1$, , and γ_n is country n's marginal disutility of global emissions (e.g., the national social cost of carbon).

Mining sectors and emissions. Each mining good $s \in \mathcal{K}^M$ is homogenous Total production of good $s \in \mathcal{K}^M$ uses ℓ units of labor, q_k units of the mining input k, and Q_k units of the non-mining sector k input according to

$$q = M_{j,s} \left(\frac{\ell}{\alpha_{j,\ell s}} \right)^{\alpha_{j,\ell s}} \prod_{k \in \mathcal{K}^M} \left(\frac{q_k}{\alpha_{j,ks}} \right)^{\alpha_{j,ks}} \prod_{k \notin \mathcal{K}^M} \left(\frac{Q_k}{\alpha_{j,ks}} \right)^{\alpha_{j,ks}}, \tag{2}$$

with $\alpha_{j,\ell s}, \alpha_{j,ks} \in [0, 1]$. The natural resource share is $\alpha_{j,s} \equiv 1 - \alpha_{j,\ell s} - \sum_{k \in \mathcal{K}} \alpha_{j,ks} \in (0, 1)$, for all countries j. The fixed natural resource implies that mining sectors have upward-sloping supply curves, and that a share $\alpha_{j,s}$ of the sales in mining sector s and country j are rents to owners of mines. We assume that this share is common across countries: $\nu_s = \alpha_{j,s}$ for all j and mining sectors $s \in \mathcal{K}^M$.

6

Although climate change represents a dynamic problem, where long-lived carbon stocks create damages over centuries, we follow much of the research on trade and the environment in using a static model. The advantage of the static approach is that it allows us to capture the rich geographical patterns of trade, together with a rich input-output structure. A few features where dynamics are particularly relevant, such as the Hotelling Rule wherein resource prices increase over time due to extraction, are captured by our model with a static supply curve for resources. A limitation of the static framework is that we cannot estimate optimal carbon taxes that account for the dynamic patterns involved in climate change; instead, we focus on counterfactuals that ignore feedback from climate to production.

Trade in mining goods is frictionless. Together with the homogeneity assumption, the price of mining goods is therefore identical across countries: $p_{n,s} = p_s$ for $s \in \mathcal{K}^M$ and all countries n.

Carbon emissions result exclusively from the use of mining goods in production and consumption. Emissions from the use of mining good s equal a constant $e_s > 0$ multiplied by production of mining good s. Global carbon emissions are

$$\mathcal{E} = \sum_{s \in \mathcal{K}^M} \sum_j e_s q_{j,s}. \tag{3}$$

Our assumption that fossil fuels are homogeneous departs from most of the literature, which follows an Armington differentiation approach (e.g. Caliendo and Parro (2022); Moigne et al. (2024)). The homogeneity assumption is convenient and matches several realistic features of fossil fuel markets and carbon taxes. First, fossil fuels are relatively homogeneous goods—for example, many are traded in spot markets. More importantly, estimates of their demand elasticities are high, ranging from 25 to 45 (Fontagne et al., 2022), suggesting low differentiation. Second, the assumption of differentiated fossil fuels leads to unrealistic implications. For example, high-quality varieties would have high prices and high marginal products or marginal utility, leading to fewer units demanded. The opposite would be true for low-quality varieties. However, in terms of their emissions, both varieties/locations would be the same – they would emit the same amount of CO_2 per unit of the fossil fuel. More problematic are the implications for optimal carbon taxes, calculated by multiplying the social cost of carbon by the amount of emissions per unit of the good. Expensive varieties would therefore have a lower ad valorem tax, leading countries to reallocate sharply (given that they are homogeneous) to those varieties. To avoid these implications, we would need some variation at the variety-location level, such as a demand shifter or some other wedge, which is unobserved in data, and hence difficult to pin down. Despite these unappealing features, given the long tradition in the international trade literature on using Armington assumptions, several papers in the trade and environment literature assume differentiated varieties for the fossil fuel sectors. Third, the implication of global prices for fossil fuels makes the analysis of taxes and our quantitative applications fairly transparent. Finally, there are data reasons to assume homogeneous prices for fossil fuels (see Appendix D): the implied prices from using data from input-output tables on quantities and values are subject to measurement error that results in extreme values for these prices – this would then have dramatic and unrealistic implications in the counterfactual analysis.

Non-mining sectors. Within each non-mining sector $s \notin \mathcal{K}^M$, Armington varieties are aggregated with constant-elasticity-substitution (CES) $\sigma_s > 1$. As in the Caliendo-Parro model, this aggregate is then consumed or used as an input to produce mining or non-mining goods. Non-mining production is constant returns to scale, and uses ℓ units of labor, q_k units of the mining sector-k input, and Q_k of the non-mining sector k input to produce

$$q = A_{l,s} \left(\frac{\ell}{\alpha_{l,\ell s}} \right)^{\alpha_{l,\ell s}} \prod_{k \in \mathcal{K}^M} \left(\frac{q_k}{\alpha_{l,ks}} \right)^{\alpha_{l,ks}} \prod_{k \notin \mathcal{K}^M} \left(\frac{Q_k}{\alpha_{l,ks}} \right)^{\alpha_{l,ks}} \tag{4}$$

units of output, with $\alpha_{l,\ell s}, \alpha_{l,ks} \in [0,1]$ and $\alpha_{l,\ell s} + \sum_{k \in \mathcal{K}} \alpha_{l,ks} = 1$ for all l.

Varieties are tradable and subject to iceberg trade costs, $\tau_{ln,s} \geq 1$, with $\tau_{nn,s} = 1$.

1.2 Model Equilibrium

Let p_s denote the (global) price of mining good $s \in \mathcal{K}^M$, and $P_{j,k}$ denote the price index for sector k in country j. Letting w_j denote the wage in country j, the supply curve of mining good $s \in \mathcal{K}^M$ in country j is

$$Y_{j,s} \equiv p_s q_{j,s} = M_{j,s} p_s^{\frac{1}{\nu_s}} \left(w_j^{-\alpha_{j,\ell s}} \prod_{k \in \mathcal{K}^M} p_k^{-\alpha_{j,ks}} \prod_{k \notin \mathcal{K}^M} P_{j,k}^{-\alpha_{j,ks}} \right)^{\frac{1}{\nu_s}}. \tag{5}$$

Rents earned from owning mines producing good $s \in \mathcal{K}^M$ in country j are

$$\Pi_{j,s} = \nu_s Y_{j,s}. \tag{6}$$

For non-mining goods $s \notin \mathcal{K}^M$, the supply curve in country l is perfectly elastic and given by

$$p_{l,s} = A_{l,s}^{-1} w_l^{-\alpha_{l,\ell s}} \prod_{k \in \mathcal{K}^M} p_k^{-\alpha_{l,ks}} \prod_{k \notin \mathcal{K}^M} P_{l,k}^{-\alpha_{l,ks}}. \tag{7}$$

Given our assumption that country varieties of non-mining goods enter consumption and production as a CES aggregate with elasticity σ_s, the price index for good $s \notin \mathcal{K}^M$ in country n is

$$P_{n,s}^{1-\sigma_s} = \sum_l \left(\tau_{ln,s} p_{l,s} \right)^{1-\sigma_s}, \tag{8}$$

while the share of expenditure in country n and sector s devoted to goods from country l is

$$\lambda_{ln,s} = \frac{\left(\tau_{ln,s} p_{l,s} \right)^{1-\sigma_s}}{P_{n,s}^{1-\sigma_s}}. \tag{9}$$

Expenditure on any good s in country l comes from both final consumption and demand for intermediate goods used in production. Letting X_l^C denote final expenditure in country l and let $Y_{l,k}$ denote gross output of good k by country l, gross expenditure in sector s by country l is

$$X_{l,s} = \mu_{l,s} X_l^C + \sum_k \alpha_{l,sk} Y_{l,k}. \tag{10}$$

Final expenditure equals the sum of wages, rents, and exogenous transfers (i.e., trade imbalances) from the rest of the world,

$$X_l^C = w_l L_l + \sum_{s \in \mathcal{K}^M} \nu_s Y_{l,s} + \xi_l. \tag{11}$$

Exogenous transfers sum to zero across countries, $\sum_l \xi_l = 0$.

We solve three sets of market clearing conditions. The market clearing condition for non-mining good

$s \notin \mathcal{K}^M$ produced in country l is

$$Y_{l,s} = \sum_n \lambda_{ln,s} X_{n,s}, \tag{12}$$

For mining good $s \in \mathcal{K}^M$, the market clears at the world level,

$$\sum_j Y_{j,s} = \sum_n X_{n,s}.$$

Labor market clearing in country l entails

$$w_l L_l = \sum_s \alpha_{l,\ell s} Y_{l,s}. \tag{13}$$

An equilibrium is a set of goods prices, sectoral price indices, and trade shares, $\left\{p_{l,s}, P_{l,s}, \{\lambda_{ln,s}\}_n\right\}_{s \notin \mathcal{K}^M}, \{p_s\}_{s \in \mathcal{K}^M}$, gross expenditures and output, final expenditure, and wages, $\left\{X_{n,s}, Y_{n,s}, X_n^C, w_n\right\}_{s \in \mathcal{K}}$, such that equations (5)-(13) are satisfied.

1.2.1 Emissions

Global emissions can be easily computed as

$$\mathcal{E} = \sum_s \sum_j \frac{e_s}{p_s} Y_{j,s}.$$

These global emissions can be allocated to different countries according to their participation in extraction activities, leading to

$$\mathcal{E}_j^M = \sum_{s \in \mathcal{K}^M} \frac{e_s}{p_s} Y_{j,s}. \tag{14}$$

This corresponds to extraction-based emissions accounting. Alternatively, we can allocate global emissions to countries according to where fossil fuels are used in final consumption and production. This approach entails

$$\mathcal{E}_l^{P1} = \sum_{s \in \mathcal{K}^M} \frac{e_s}{p_s} X_{l,s}, \tag{15}$$

which is commonly referred as "Scope 1" emissions. The expression in equation (15) is the the most common measure of emissions used in the trade and environment literature, and they are reported by most environmental datasets (WIOD, GTAP).

We also want to allocate global emissions to countries according to the final consumption that is ultimately responsible for the fossil fuels used up along the whole global value chain. One issue here is that, since mining activities in different countries vary in their carbon emissions, the sourcing of fossil fuels matters for how global emissions are allocated to countries. Thus, if a country consumes fossil fuels imported from sources with carbon-intensive extraction methods, or if a country consumes final goods

produced either directly or indirectly with those fossil fuels, then it would be responsible for more carbon emissions according to consumption-based accounting. The problem is that, in our model, sourcing of fossil fuels is not well defined because of the assumption that these goods are homogeneous and traded at no cost. We follow the most natural approach and assume that these shares are equalized across destination countries,

$$\lambda_{jn,s} = \frac{Y_{j,s}}{\sum_{j'} Y_{j',s}}, \quad s \in \mathcal{K}^M. \tag{16}$$

Section 3 discusses implications of this assumption for the allocation of emissions to each country, but for now note that it takes a neutral perspective on sourcing – we are not penalizing any country for sourcing particularly more fossil fuels from countries with more carbon-intensive mining. Substituting (10) into (12) shows that an industry's gross output is sold as either final demand or intermediate goods' demand,

$$Y_{j,s} = \sum_n \lambda_{jn,s}\mu_{n,s}X_n^C + \sum_l \sum_k \alpha_{jl,sk}Y_{l,k}, \tag{17}$$

where $\alpha_{jl,sk} \equiv \lambda_{jl,s}\alpha_{l,sk}$. Solving for gross output levels yields

$$Y_{j,s} = \sum_{l,n,k} \chi_{jl,sk}\lambda_{ln,k}X_{n,k}^C, \tag{18}$$

where we have used $X_{n,k}^C \equiv \mu_{n,k}X_n^C$, and where $\chi_{jl,sk} \equiv (I - \{\alpha_{jl,sk}\})^{-1}$ are the elements of the Leontief inverse matrix. Since $\chi_{jl,sk}\lambda_{ln,k}X_{n,k}^C$ captures demand for fossil fuel $s \in \mathcal{K}^M$ in country j for final consumption of k in country n, then emissions due to the use of fossil fuel s extracted in country j for production of goods in country l and consumption in n is

$$\mathcal{E}_{jln,s} = \frac{e_s}{p_s} \sum_k \chi_{jl,sk}\lambda_{ln,k}X_{n,k}^C. \tag{19}$$

Of course, since only the use of fossil fuels produces emissions, $e_s = 0$ for all non-mining sectors $s \notin \mathcal{K}^M$, and hence $\mathcal{E}_{jln,s} = 0$ for all $s \notin \mathcal{K}^M$. Adding up across extraction and production countries (j and l) yields total consumption-based emissions of country n,

$$\mathcal{E}_n^C = \sum_{j,l,k,s} \mathcal{E}_{jln,ks}, \tag{20}$$

Adding up instead across production and consumption locations leads $\mathcal{E}_j^M = \sum_{l,n,k,s} \mathcal{E}_{jln,ks}$, which is of course equal to our original expression above since given equation 18.Alternatively, adding across extraction and consumption locations leads to production-based emissions,

$$\mathcal{E}_l^{P3} = \sum_{jn,ks} \mathcal{E}_{jln,ks}. \tag{21}$$

Consumption-based carbon accounting, $\mathcal{E}_n^C$ in equation (20), measures the fossil fuels embodied in final

goods consumed in a country. Extraction-based carbon accounting, $\mathcal{E}_j^M$ in equation (14), measures emissions due to fossil fuels mined in a country. Production-based carbon accounting, $\mathcal{E}_l^{P3}$ in equation (21), measures where fossil fuels are used for final goods produced in a country. This expression captures the emissions embedded all along the value chain of goods, and it is analogous to the so-called scope 3 emission measure.

For example, consider cars produced in Mexico using coal extracted in Canada, which are ultimately sold to consumers in the US for final consumption. Production-based emissions from this global value chain would be allocated to Mexico, consumption-based emissions to US, and extraction-based emissions to Canada.

The expression in Equation (15) helps to relate our emissions accounting approach to the abatement approach in the literature, which assumes that pollution is an input to production. The advantage of our approach is that by explicitly modeling the the fossil fuel market , we make clear that we need the price of fossil fuels to conduct counterfactual analysis and policy experiments related to carbon taxes, as well as for performing accounting calculations. Consequently, any assumption made about the supply elasticity of those goods is will be a key driver of the results. Caliendo et al. (2024) and Moigne et al. (2024), for example, use data on scope 1 emissions and output value in industry k and country l to calculate emissions per dollar, $f_{l,k} = \mathcal{E}_{l,k}^{P1}/Y_{l,k}$, where $\mathcal{E}_{l,k}^{P1} = \sum_s \frac{e_s}{p_s}\alpha_{l,sk}Y_{l,k}$ are emissions generated by the use of fossil fuels in production of k in country l. This implies that $f_{l,k} = \sum_s \frac{e_s}{p_s}\alpha_{l,sk}$, revealing that $f_{l,k}$ will naturally change in response to shocks to trade costs or the introduction of carbon taxes.[7] Our approach explicitly allows for adjustments in the equilibrium (world) prices of fossil fuels, while leaving constant the emission intensity *per physical* unit of fossil fuel. As Section 5 shows, this price channel turns out to be critical to understand the effects of trade shocks and carbon taxes on emissions.

2 Data

We combine data from global multi-region input-output tables and the International Energy Agency (IEA) to build a sample of 28 countries, including a category for the Rest of the World (ROW), and 28 sectors.[8] Appendix Table 6 lists sectors and Appendix Table 7 lists countries.

To measure several country or country-pair variables, we use data from the World Input Output Database (WIOD), 2016 release (Timmer et al. 2015). These variables include sectoral bilateral trade flows, sectoral gross output, expenditure, and final consumption, all in US dollars. We focus on 2014, the latest year covered by WIOD.

We modify WIOD to include additional detail on energy sectors. WIOD describes three main sectors that cover energy: mining; utilities; and refining of petroleum and coke.[9] Appendix C.2 explains how we use data from Exiobase to extend WIOD to distinguish six energy sectors: coal mining; gas mining;

[7] The implicit assumption is that there is a Leontief technology that transforms quantities of a good into emissions.
[8] Our sector classification is aligned with those of the OECD.
[9] Coke is a solid fuel produced from coal or petroleum and used primarily in metallurgy.

oil mining; electricity generation and transmission; refined petroleum; and natural gas processing and distribution.[10] The first three constitute fossil fuel mining. We separate crude from refined oil, and raw from processed gas, to later distinguish extraction from use of fossil fuels.

While WIOD provides data on quantities of energy each country uses, it does not include data on the quantities of energy each country extracts. We obtain the quantities of each fossil fuel extracted in each country from the International Energy Agency (IEA, Energy Balances).[11] We use these quantities to calculate the emissions per unit of fossil fuel extracted and fossil-fuel prices.

3 Carbon Emissions Accounting

This section explains how we allocate emissions to each country according to consumption, production, and extraction. We combine the model's expression for equilibrium emissions with aggregate data on expenditure, input-output shares, and emissions. We show how the cross-country allocation of emissions changes depending on the emissions measure used. We briefly propose a model-based decomposition of cross-country differences in consumption-based emissions. Later sections discuss what this accounting implies for the choice of different types of carbon taxes in each country.

We measure$\chi_{jl,sk}$, $\lambda_{jl,s}$, and $X^C_{ln,s}$, $\mathcal{E}_{jln,ks}$ in equation (19) using data from WIOD (augmented by Exiobase). Given the assumptions of homogeneous mining goods and frictionless trade in those goods, we adjust the trade shares in those sectors according to the expression in (16)–we do not need to make this adjustment for our accounting exercises, but we do it for consistency with our procedure for counterfactual exercises.[12] To compute the units of CO_2 emissions per dollar of fossil fuel extracted, e_s/p_s, we first calculate emissions per tons of CO_2 for each fossil fuel. We use data from the US Energy Information Administration, which estimates intensities of $e_{coal} = 0.019$, $e_{gas} = 0.007$, and $e_{oil} = 0.005$. Non-mining sectors have emission intensities of zero: $e_s = 0$ for $s \notin \mathcal{K}^M$. We compute prices for mining good $s \in \mathcal{K}^M$ as the dollar value of world gross output (from WIOD) divided by the quantities (from IEA) of mining good s,

$$p_s = \frac{\sum_j Y^{WIOD}_{j,s}}{\sum_j q^{IEA}_{j,s}}. \tag{22}$$

We obtain global prices for coal, natural gas, and crude oil, respectively, of 204, 314, and 564 dollars per ton of oil equivalent.[13]

[10] "Gas" refers to natural gas. Gasoline is the main product from petroleum refining.

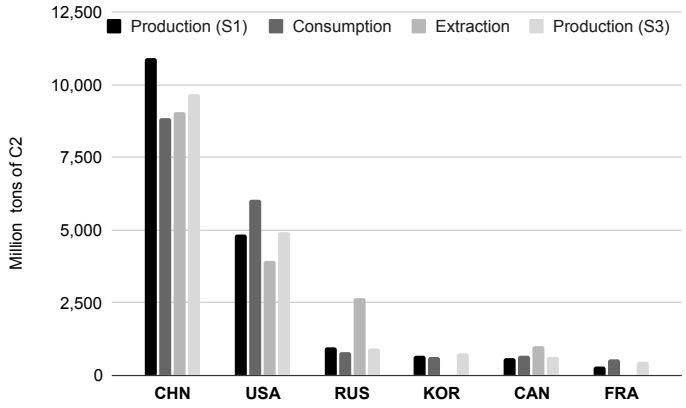
[11] The data on fossil fuel consumption used by WIOD come from the International Energy Agency (IEA).

[12] Appendix Figure 8 shows the consequences of this assumption for our different emissions measures, and compares them with the measures coming from using trade shares for fossil fuels as observed in the data.

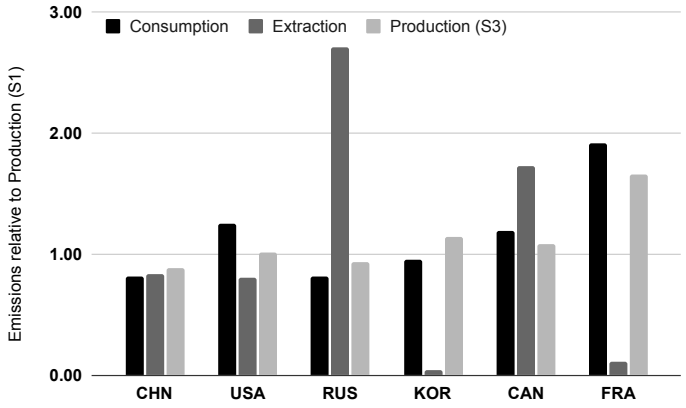
[13] Using a global price for each fossil fuel computed as in Equation (22) would match global extraction emissions as reported in the data, but it will not match the emissions reported for each country individually. However, while the benefits of having homogeneous prices are large, as explained in the previous section, the cost of not matching the data exactly is relatively low. Appendix Figure 8 shows the discrepancies between emissions calculated with the implied country prices and the implied global price. Moreover, Appendix Figure 7 shows the country-level prices implied by the WIOD and IEA data, $p_{j,s} = Y^{WIOD}_{j,s}/Q^{IEA}_{j,s}$, and how extreme values affect them.

Figure 1: Carbon accounting, selected countries.

(a) Millions tons of CO_2.



(b) Relative to production-based emissions.



Notes: Production emissions are scope 1 (i.e., excluding emissions embodied in the value chain). Calculations using data from WIOD and the expressions in (21)-(15). Production-, consumption-, extraction-, and production S1-based emissions refer to Equations (21), (20), (14), and (15), respectively.

Figure 1 reports carbon emissions according to our four measures of country emissions in Equations (21)-(15), in million tons of CO_2, for selected countries in our sample. We sort countries according to their production emissions, $\mathcal{E}_l^P$.

Figure 1 shows that production-based emissions for the US are lower than consumption-based emissions, while the opposite is true for China, a comparison which echoes previous work (Davis and Caldeira, 2010). This indicates that the US imports goods that are produced using more intensively fossil fuels than the goods their produce in their territory, while the opposite is true for China. Additionally, scope 1 production emissions are lower than scope 3 for the US, while the opposite is true for China. This comparison highlights the differences between direct emissions from using fossil fuels and emissions embodied in inputs used along the value chain, including imported inputs. Not surprisingly, Russia and Canada, two countries that are producers and net exporters of fossil fuels, have higher emissions when measured according to where the extraction of mining goods occur. The right panel of Figure 1 shows the various measures of emissions relative to production-based (scope 1) emissions to ease the comparison across measures for each country. Appendix Table 7, which describes all countries in our sample, shows several classic patterns. Net exporters of fossil fuels typically look dirtier according to the extraction-based measure of emissions. Developed countries look cleaner when measuring emissions according to production, but dirtier if measuring emissions according to consumption. The opposite is in general true for less developed countries.

Appendix E discusses two decompositions of emissions. The first provides a variance decomposition of a a country's consumption-based emissions into the share due to differences in emissions per dollar of consumption versus emissions due to consumption expenditure per capita. We find that essentially all

of the variation across countries in consumption-based emissions is due to consumption expenditure per capita. This reflects the well-known pattern that energy demand increases log-linearly with income or consumption per capita. Second, we decompose consumption-based emissions into emissions per dollar of fossil fuel used and energy expenditure per dollar of consumption.We find that energy expenditure per dollar of consumption accounts for about 80 percent of variance in consumption-based emissions, while emissions per dollar of fossil fuel used accounts for roughly the remaining 20 percent.

Before delving into the counterfactual exercises, in the next section, we describe the estimation procedure of a key parameter of the quantitative model: the supply curve elasticity for fossil fuels.

4 Estimation of the Supply Elasticity for Fossil Fuels

Applying the model quantitatively requires an estimate of decreasing returns in each mining sector, ν_s. This parameter is isomorphic to the share of natural resources in mining, and to the supply elasticity for fossil fuels. Estimates are therefore useful both for our paper and for macroeconomic energy and climate change research more broadly.

Rewriting the mining supply curve in equation (5) gives the quantity of mining good s supplied in terms of its price,

$$q_{j,s} \equiv \frac{Y_{j,s}}{p_s} = M_{j,s} p_s^{\frac{1-\nu_s}{\nu_s}} \left(w_j^{-\alpha_{j,\ell s}} \prod_{k \in \mathcal{K}} P_{j,k}^{-\alpha_{j,ks}} \right)^{\frac{1}{\nu_s}}. \tag{23}$$

Equivalently,

$$p_s = (q_{j,s})^{\frac{\nu_s}{1-\nu_s}} M_{j,s}^{-\frac{\nu_s}{1-\nu_s}} \left(w_j^{-\alpha_{j,\ell s}} \prod_{k \in \mathcal{K}} P_{j,k}^{-\alpha_{j,ks}} \right)^{-\frac{1}{1-\nu_s}}. \tag{24}$$

Conditional on the price of other inputs, w_j and $P_{j,k}$, as well as the quantity of natural resources, $M_{j,s}$, the (long-run) inverse supply elasticity for fossil fuel s is

$$\frac{\partial \ln p_s}{\partial \ln q_{j,s}} \equiv \beta_s = \frac{\nu_s}{1-\nu_s},$$

and hence,

$$\nu_s = \frac{\beta_s}{\beta_s + 1}. \tag{25}$$

We use the following regression to estimate the inverse supply elasticities,

$$\ln p_{vj,s} = \beta_s \ln q_{vj,s} + \mu_{j,s} + \zeta_{vj,s}. \tag{26}$$

We estimate equation (26) separately for each energy type s. Each observation in this regression represents a vertex v describing a region j extracting mining good s. The dependent variable $\ln p_{vj,s}$ represents the log of the marginal cost of extracting mining good s in region j from vertex v. The independent

variable, $\ln q_{vj,s}$, represents the log of the cumulative quantity of (v, j, s) extracted. The regression includes region×fossil fuel fixed effects $\mu_{j,s}$, which capture other inputs used in production—the last term in parentheses in (24). The error term $\zeta_{vj,s}$ contains measurement error in mining good prices. The coefficient β_s represents the inverse supply elasticity for a mining good, which we substitute into (25) to estimate the parameter of interest, ν_s.

We use data from Welsby et al. (2021), who provide marginal extraction cost curves for each fossil fuel separately, in each of 16 regions around the world.[14] The data combine mine- and field-level energy quantities with estimates of extraction costs by resource type and region. These cost estimates do not include transportation costs or taxes.

Figure 2 shows the raw data from Welsby (2021). Each panel describes one of the three fossil fuels, and each line describes a given region's supply curve.

The supply curves consist of horizontal segments. The left of each curve shows the cheapest sources for each fossil fuel. Moving to the right within each curve progressively adds more expensive sources. Regression equation (26) interprets flat segments as a data point $(\ln p_{vj,k}, \ln q_{vj,k})$. For example, the thick blue line in panel (b) describes the supply of Middle Eastern oil; it lies to the right of other lines because the Middle East has cheaper and more abundant oil resources than other regions. The orange right-most line panel (a) describes Chinese coal; it generally lies to the right of other lines because China's coal has greater abundance at lower cost than other regions.

Figure 3 shows the vertex of each all line segment from Figure 2, residualized by region and fossil fuel type fixed effects.

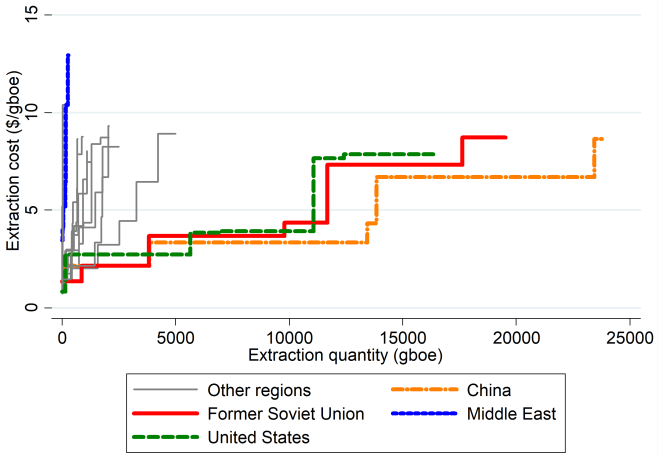
The text in the graph shows estimates of equation (26). Figure 3 shows that our estimates of the coefficient β_s range from 0.32 (0.02) for coal and 0.35 (0.05) for natural gas, to 0.68 (0.01) for oil. Pooling estimates across figures gives an inverse supply elasticity of 0.34 (0.02). Equation (25) would imply a decreasing returns parameter of $\upsilon = 0.25$. Economically, this estimate implies that natural resources account for about a fourth of the cost of fossil fuel extraction; labor and intermediate inputs account for the rest.

How do these estimates relate to existing estimates of the supply elasticity of fossil fuels? Although the supply elasticity for fossil fuels is crucial for understanding how the world will deal with climate change, the literature is thin and US-focused. Arora (2014) reviews the elasticity assumed in computable general equilibrium (CGE) models and finds that US natural gas supply elasticities ranged across models from 0.1 to 6.0 for the long-run and -0.4 to 7.2 for the short run, a remarkably wide range. Boeters and Bollen (2012) summarize a supply elasticity of one for gas and four for coal, which are a similar overall range as our estimates . In recent work, Farrokhi and Lashkaripour (2023) estimate the cost share of carbon reserves from the value added share of natural resources in the primary energy sectors, from GTAP. Their estimate ranges from 0.31 to 0.49. Abuin (2024) recovers (upstream) supply elasticities for gas and coal from IV regressions that exploit shifts in prices coming from changes in electricity demand

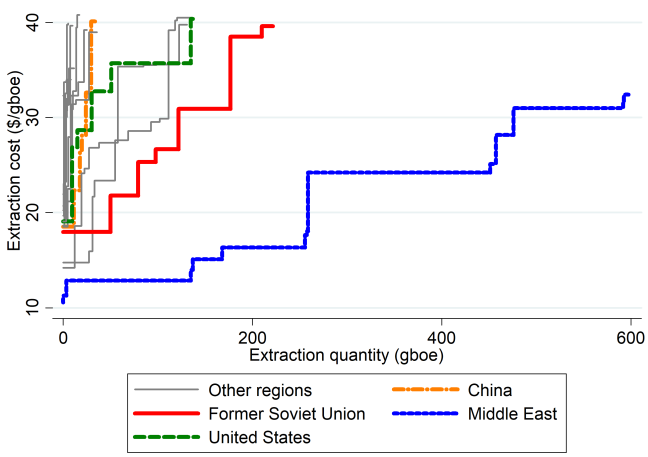
[14] McCollum and Khourdajie (2021) describe Welsby et al. (2021) as the state-of-the-art. Arkolakis and Walsh (2023) use these data to rank locations by their marginal cost of extraction, and Cruz and Rossi-Hansberg (2024) use related but earlier estimates of extraction costs from Bauer et al. (2016).

Figure 2: Fossil Fuel Extraction Costs and Quantities.

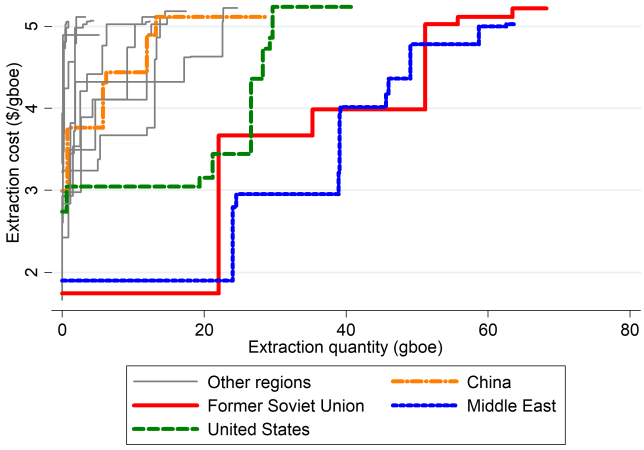
(a) Coal.



(b) Oil.

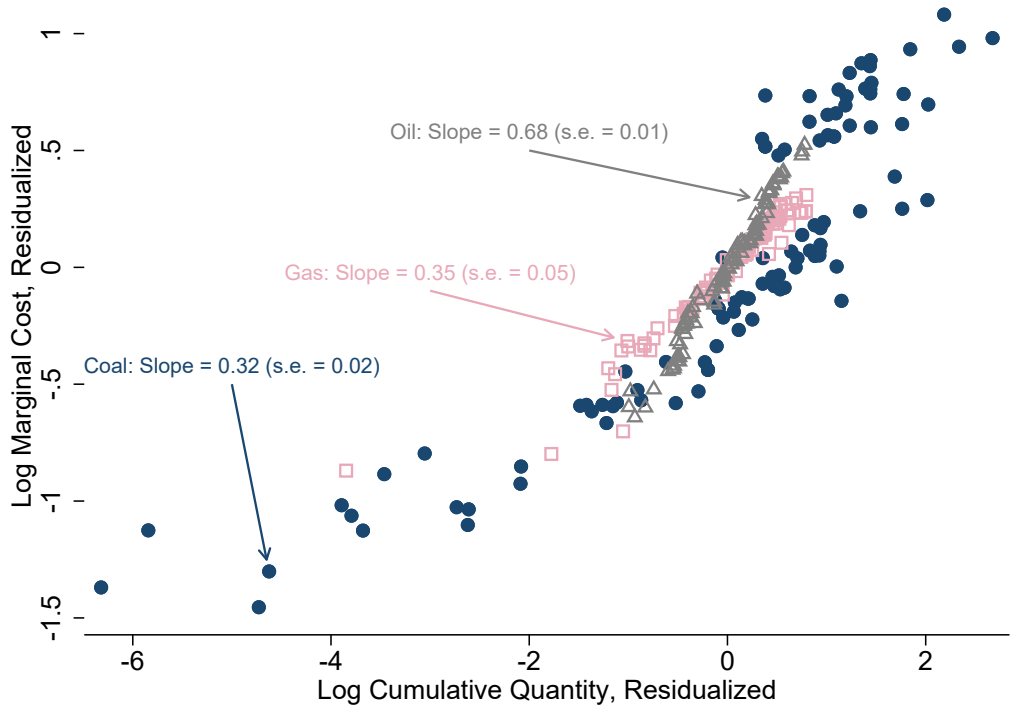


(c) Natural gas.



Note: Data from Welsby (2021).

Figure 3: Supply curve and estimates of the inverse elasticity, by fossil fuel.



Notes: Coefficients from estimating equation (24) separately for each fossil fuel. Each point represents the vertex of one line segment from Figure 2, residualized by region×fossil fuel type fixed effects. Parentheses show standard errors.

conditions.. Her estimates are around 0.24 for gas and 0.77 for coal. Broadly, our sense is that the most reliable approach in the energy and climate macro literatures uses physical estimates of extraction costs for different deposits, as we do (e.g., Bornstein et al. (2019); Cruz and Rossi-Hansberg (2024)).

5 The Quantitative Effects of Trade Shocks

To analyze counterfactual scenarios, we apply exact hat algebra (Dekle et al. 2008; Costinot and Rodríguez-Clare 2014) to the model's equilibrium conditions. Counterfactual changes in equilibrium variables then depend on original equilibrium variables in the data, parameters, and shocks. Let $\hat{x} \equiv x'/x$ denote the proportional change in the equilibrium value of variable x between the original equilibrium, x, and the counterfactual, x'. Exact hat algebra methods convert equations (5)-(13) to equations in changes, where the unknown variables are

$$\left\{\left\{\hat{\lambda}_{ln,s}, \hat{P}_{n,s}, \hat{p}_{l,s}\right\}_{s\notin\mathcal{K}^M}, \left\{\hat{p}_s, \hat{P}_{j,s}, \hat{\lambda}_{j,s}\right\}_{s\in\mathcal{K}^M}, \hat{X}_n^C, \hat{Y}_{l,s}, \hat{w}_l\right\}.$$

Here $\{\hat{\tau}_{ln,s}\}$ are the counterfactual shocks we analyze (e.g., trade policy reforms), and $\{\alpha_{l,sk}, \alpha_{l,\ell s}, \lambda_{ln,s}, \lambda_{j,s}, e_s, p_s, Y_{l,s},$ are baseline values from data (i.e. in the initial equilibrium). Additionally, $\nu_s = 0.25$ for all $s \in \mathcal{K}^M$ as Section 4 estimates, and $\sigma_s = \sigma = 5.5$ for all $s \notin \mathcal{K}^M$.. We assume that each country's share of damages γ_j is proportional to the global share of country j's real GDP, $\gamma_j = \gamma(W_j/W)$, where $W_j \equiv X_j^C/P_j$ is real income and $W \equiv \sum_n W_n$ is global welfare. Hence, $\sum_j \gamma_j = \gamma$ and $\gamma_j \mathcal{E}/W_j = \gamma\mathcal{E}/W$ for all j. We set the social cost of carbon γ equal to 100 dollars per ton of CO_2. We approximate global emissions $\mathcal{E}$ to 40 billion tons of CO_2, and world real GDP W at around 100 trillion. We then get that $\gamma\mathcal{E}/W = 0.04$.

Appendix B presents the system of equations in changes corresponding to the system of equations in levels from equations (5)-(13).

We compute counterfactual emissions using the counterfactual value of equation (19),

$$\mathcal{E}'_{jln,s} = \frac{e_s}{p'_s} \sum_k \chi'_{jl,sk} X^{C,\prime}_{ln,k}.$$

Changes in real GDP are given by

$$\hat{W}_j = \frac{\hat{X}_j^C}{\hat{P}_j^C},$$

where $\hat{P}_j^C = \prod_{s=1}^{\mathcal{K}} \hat{P}_{j,s}^{\mu_{j,s}}$ is the change in the price index associated with Cobb-Douglas utility in Equation (1).

In turn, changes in welfare combine changes in real GDP and change in global emissions,

$$\hat{U}_j = \frac{\hat{W}_j - \hat{\mathcal{E}}\,(\gamma\mathcal{E}/W)}{1 - \gamma\mathcal{E}/W}. \tag{27}$$

We consider two sets of counterfactual scenarios. The first set turns off trade globally by sending all

international trade costs to infinity. The second set of counterfactuals decreases international trade costs everywhere by 20 percent.

5.1 Emissions under Autarky

We focus on the effect of trade shocks on consumption-based emissions. Ultimately, under autarky, country-level measures of production versus consumption versus extraction emissions have identical values. We analyze autarky by sending trade costs to infinity ($\tau_{ln,s} \to \infty$ for all $l \neq n, s$). The difference between emissions for country n in the autarky equilibrium and the baseline data equals

$$\mathcal{E}_n^A - \mathcal{E}_n^C = \sum_{s \in \mathcal{K}^M} \frac{e_s}{p_{n,s}^A} \sum_k \chi_{n,sk} X_{n,k}^{C,A} - \sum_{s \in \mathcal{K}^M} \frac{e_s}{p_s} \sum_{j,l,k} \chi_{jl,sk} \lambda_{ln,k} X_{n,k}^C. \tag{28}$$

Here the superscript A denotes variables under autarky, and C describes consumption-based values. To build on the intuition of the analytical results we present next, we now show some of the key variables in the autarky equilibrium. Emissions under autarky are given by equation (29)—which coincides for all measures of emissions:

$$\mathcal{E}_n^A = \sum_{s \in \mathcal{K}^M} e_s \frac{Y_{n,s}^A}{p_{n,s}^A}. \tag{29}$$

First, it is straightforward to solve for autarky output $Y_{n,s}^A$ from the equilibrium conditions,

$$Y_{n,s}^A = X_{n,s}^A = \psi_{n,s} X_n^{f,A},$$

where $\psi_{n,s} \equiv \sum_k \chi_{n,sk} \mu_{n,k}$ is the Domar weight of sector s under autarky, and for final expenditure,

$$X_n^{f,A} = \frac{w_n^A L_n}{1 - \nu \psi_n^M},$$

with $\psi_n^M \equiv \sum_{k \in \mathcal{K}^M} \psi_{n,k}$. Second, we can write the change in the price of fossil fuel $s \in \mathcal{K}^M$ as

$$\hat{p}_{j,s} \equiv \frac{p_{j,s}^A}{p_s} = \prod_{k \notin \mathcal{K}^M} \lambda_{jj,k}^{-\chi_{j,sk}/(\sigma_s - 1)} \prod_{k \in \mathcal{K}^M} \left(\frac{Y_{j,k}^A}{Y_{j,k}} \right)^{\nu \chi_{j,sk}},$$

where under autarky these prices are specific to each country j.

Hence, manipulating the expression in (29) yields

$$\mathcal{E}_n^A = \sum_{s \in \mathcal{K}^M} e_s \frac{Y_{n,s} \hat{Y}_{n,s}}{p_s \hat{p}_{n,s}} = \sum_{s \in \mathcal{K}^M} e_s \frac{1}{\hat{p}_{n,s} p_s} \frac{\psi_{n,s} w_n L_n}{1 - \nu \psi_n^M},$$

where by choice of numeraire $w_n^A = w_n$.

Changes in real expenditure from the observed equilibrium to autarky are given by

$$\hat{W}_n = \frac{w_n L_n / \left(1 - \nu \psi_n^M\right)}{w_n L_n + \nu \sum_{k \in \mathcal{K}^M} Y_{n,k}} \prod_{s \in \mathcal{K}^M} \left(\frac{\psi_{n,s} w_n L_n}{\left(1 - \nu \psi_n^M\right) Y_{n,s}} \right)^{-\nu \psi_{n,s}} \prod_{s \notin \mathcal{K}^M} \lambda_{nn,s}^{\frac{\psi_{n,s}}{\sigma_s - 1}}.$$

If $\nu = 0$, the formula collapses to the standard gains from trade expression for multi-sector EK models in Costinot and Rodríguez-Clare (2014), $\hat{W}_n = \prod_{s \notin \mathcal{K}^M} \lambda_{nn,s}^{\frac{\psi_{n,s}}{\sigma_s - 1}}$.

5.1.1 Analytical Results

We present analytical results on how moving to autarky affects emissions. To understand the underlying mechanisms, we consider the following decomposition:

$$\mathcal{E}_n^A - \mathcal{E}_n^C = \underbrace{\sum_{s \in \mathcal{K}^M} e_s \sum_k \chi_{n,sk}^B \left(\frac{X_{n,k}^{C,A}}{p_{n,s}^A} - \frac{X_{n,k}^{C,B}}{p_s^B} \right)}_{\Delta_n^P \equiv \text{ Price channel}} + \underbrace{\sum_{s \in \mathcal{K}^M} \frac{e_s}{p_s^B} \sum_k \left(\chi_{n,sk}^A - \sum_{j,l} \chi_{jl,sk}^B \lambda_{ln,k}^B \right) X_{n,k}^{C,B}}_{\Delta_n^S \equiv \text{ Sourcing channel}} + \Delta_n^B. \quad (30)$$

To avoid the possibility of trade imbalances influencing the comparison of baseline to counterfactual data, the superscript B indicates variables in the baseline data from a scenario where we remove trade imbalances, $\xi_n = 0$ for all n.

Equation (30) decomposes the effect of autarky on emissions into three terms. The term Δ_n^P captures the change in emissions due to changes in the price of fossil fuels. These changes translate into a change in the quantities extracted of those goods. Under autarky, countries with a comparative advantage in mining goods would experience a decrease in the prices of those goods and hence an increase in emissions. Countries with a comparative disadvantage in mining goods, in turn, experience an increase in energy prices under autarky. For the price channel, we do not separate the effects coming from changes in final (nominal) expenditure from changes in fossil fuel prices because, as Proposition (1) makes clear, the effect in expenditure exists only because the supply curve of fossil fuels has a positive slope. If this curve were flat ($\nu = 0$), profits would be zero, final expenditure would be equal to labor payments, and it would be fixed by choice of numeraire. The term Δ_n^S captures additional emissions due to changes in demand for fossil fuels along the value chain. The difference in emissions between the equilibrium with and without trade balance is $\Delta_n^B \equiv \mathcal{E}_n^{C,B} - \mathcal{E}_n^C$.

To better understand the price and demand channels, we present analytical results about the effect of autarky on emissions. First, under autarky, the Cobb-Douglas production technology assumption in (2) and (4) implies that $\chi_{n,sk} = \chi_{n,sk}^B = \chi_{n,sk}^A$And second, because autarky sends international trade shares to zero, $\lambda_{ln,s} = 0$ for all $l \neq n$ and $\lambda_{ln,s} = 1$ for $l = n$. , We are able to show results for how global autarky affects global emissions totals only, $\sum_n \left(\mathcal{E}_n^A - \mathcal{E}_n^C\right) = \sum_n \left(\Delta_n^P + \Delta_n^S + \Delta_n^B\right)$.—which seems the relevant case given that total global emissions rather than their country breakdown determine climate damages

Proposition 1 [Price channel]. (a) Assume that $\nu_s = \nu = 0$ for all $s \in \mathcal{K}^M$. Then, $\sum_n \Delta_n^P = 0$.

(b) Alternately, assume that $\mu_{n,s} = \mu_s$, and $\nu_s = \nu \in (0,1)$, for all $s \in \mathcal{K}^M$. Further assume that $\alpha_{l,ks} = 0$ for all $k, s \in \mathcal{K}$. Then, $\sum_n \Delta_n^P < 0$.

Proof. See Appendix A.

In part (a) of Proposition 1, when supply curves for fossil fuels are flat, autarky does not change the price of mining goods. Moreover, because $\nu = 0$, profits are zero and final expenditure does not change –it is pinned down by the normalization of labor payments. Thus, in this scenario, the price channel has zero impact on global emissions.

In part (b) of Proposition 1, with no intermediate inputs in the production of mining and non-mining goods, and homogeneous expenditure shares and supply elasticities across countries, the price channel leads trade to increase emissions. In this case, while the world demand for each fossil fuel $s \in \mathcal{K}^M$ remains unchanged, $\sum_n X_{n,s}^{C,A} = \sum_n X_{n,s}^{C}$, the global quantity produced of each fuel decreases, $\sum_n q_{n,s}^{A} < \sum_n q_{n,s}$, decreasing global emissions. By a simple comparative advantage argument, the price of fossil fuels increases in autarky for net importers so that they would demand less, and decreases for net exporters so that they would demand more. It is not obvious, however, that these changes are such that globally quantities produced decrease while expenditure remains constant. Cobb-Douglas production functions, upward sloping supply curves, and a world market for fossil fuels, combine to deliver this result.

The assumption in part (b) of Proposition 1, which states that countries have the same sectoral expenditure shares μ_s, is necessary to keep global expenditure constant in each fossil fuel industry, between equilibria ($\sum_n X_{n,s}^{C,A} = \sum_n X_{n,s}^{C}$ for $s \in \mathcal{K}^M$). This assumption, however, is not needed to show that global quantities of fossil fuels decrease in autarky ($\sum_n q_{n,s}^{A} < \sum_n q_{n,s}$ for $s \in \mathcal{K}^M$). When expenditure shares μ_s differ across countries, autarky does change world demand in value for each fuel. The effect depends on each country's supply elasticities, which we assume the same across countries, and on each country's expenditure shares. Low supply elasticities, combined with high expenditure shares in fossil fuels, tend to make autarky decrease world demand for those goods. But the effect depends on which countries are initially exporters versus importers of fossil fuels.

The two cases in the next proposition show that the demand channel is all about changes in sourcing across countries with different intensity in their use of fossil fuels.

Proposition 2 [Sourcing Channel]. (a) Assume that $\alpha_{n,sk} = \alpha_{sk}$ for all n. Then $\sum_n \Delta_n^S = 0$. (b) Alternately, assume that $\alpha_{j,sk} = 0$ for $k \in \mathcal{K}^M$ and $\alpha_{j,sk} = 0$ for $s \notin \mathcal{K}^M$. Then, $\sum_n \Delta_n^S < 0$ if countries that use fossil fuels intensively in the production of non-mining goods have positive net export of those non-mining goods.

Proof. See Appendix A.

First, if all countries have the same input-output requirements $\sum_j \chi_{jn,sk}^{B} = \chi_{sk}$, for all industries s, summing over n in equation (30) implies that $\sum_{n,k} \left(\chi_{n,sk}^{A} - \sum_{j,l} \chi_{jl,sk}^{B} \lambda_{ln,k}^{B} \right) = 0$. These assumptions turn off the sourcing channel , so that moving to autarky does not change global emissions through this channel. A necessary condition for the sourcing channel to operate is to have some differences in input-output matrices across countries. This condition, however, is not sufficient. Part (b) of Proposition

2 imposes the additional condition where mining goods use only labor and non-mining goods use only mining goods as intermediate inputs. In this setting, trade increases emissions if countries that use fossil fuels intensively in the production of non-mining goods have comparative advantage in the production of non-mining goods and hence are net exporters of those goods.

Next, using the quantitative general version of the model, we compute the three terms of the decomposition in Equation (30), for each country.

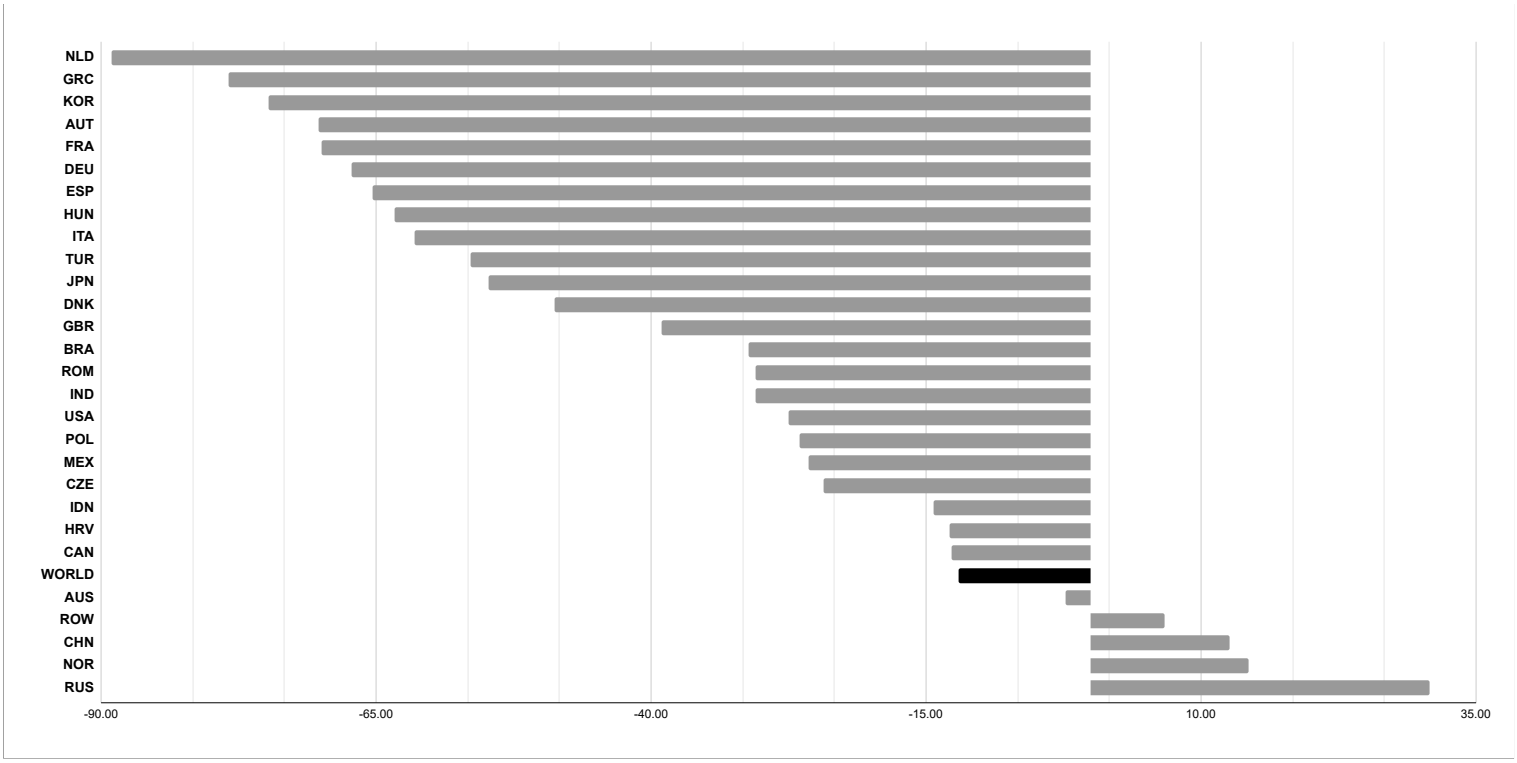
5.1.2 Quantitative Results

Propositions (1) and (2) clarify the mechanisms behind the decomposition in equation (30) regarding how the price and demand channels cause autarky to affect emissions. With this interpretation in mind, we turn to quantitatively evaluate equation (30) .

Figure 4 shows how moving each country to autarky affects the country's emissions. Global autarky would decrease global emissions by 12.1 percent–equivalently, international trade increases emissions by the same magnitude.[15] The results masks large heterogeneity across countries in the effect of trade on emissions. For example, if the world shifted to autarky, consumption-based emissions would drop by almost 70 percent in France and Germany, 55 percent in Japan, and by 27 percent in the US. Conversely, emissions would rise in China, Norway, and Russia by 12, 14, and 30 percent.

[15]Because this is a general equilibrium model, our counterfactual exercise accounts for all adjustments in prices and quantities that autarky brings. This approach differs from accounting analyses, which use the Leontief inverse of a global multi-region input-output table to learn about the emissions embodied in traded goods, but do not study the equilibrium outcome under a specific counterfactual.

Figure 4: Effect of Global Autarky on Emissions, by Country.



Notes: For each region, this figure shows autarky emissions relative to observed consumption-based emissions, measured as $\mathcal{E}_n^A/\mathcal{E}_n^C - 1$.

Table 1 shows the results of applying the decomposition in Equation (30) using the calibrated model, for selected countries and globally. Appendix Table 8 shows the results for all countries. Both tables show, for each country, the total change in emissions due to a move to autarky, as well as the emission changes coming from the price effect Δ_n^P, the sourcing effect Δ_n^S, and the elimination of trade imbalances Δ_n^B. We also report changes in real GDP as well as changes in welfare computed using equation (27).

Table 1 shows that the price channel accounts for most of the autarky's effect on emissions. The price effect decreases global emissions by 13.6 percentage points, relative to the baseline equilibrium. In contrast, the sourcing channel increases emissions under autarky, by 1.35 percentage points.

The relative importance of the price and sourcing channels for explaining autarky's effects differs by country. For France, the price and sourcing channel combine to make autarky decrease emissions by almost 70 percent, while for the US, the sourcing channel drives most of the autarky-calculated decrease in emissions. This pattern suggests that US imports are dirtier than US domestic production, i.e., the US "domestic" input-output matrix $\chi_{n,sk}$, is cleaner. Both France and the US are net importers of fossil fuels so that the price of these goods increases in those countries under autarky–hence, decreasing the quantities demanded and emissions. A move to global autarky would increase emissions in China by almost 17 percent due to a positive demand effect –as well as a positive effect due to the elimination of

Table 1: Effect of Global Autarky, Selected Countries.

Country	% $\Delta_n^P/\mathcal{E}_n^C$	% $\Delta_n^S/\mathcal{E}_n^C$	% $\Delta_n^B/\mathcal{E}_n^C$	% change in emissions	Net exports Fossil fuels	Net exports All sectors	% change in real GDP	% change in welfare
	(1)	(2)	(3)	(6)	(7)	(8)	(9)	(10)
Canada	4.5	-18.2	1.1	-12.6	78,399	18,792	-12.0	-12.0
China	-16.5	23.1	6.0	12.6	-185,439	583,854	-3.7	-3.4
France	-31.2	-38.2	-0.5	-70.0	-36,269	-15,446	-20.5	-20.8
Korea	-67.0	-18.8	11.0	-74.8	-101,567	135,150	-15.4	-15.5
Russia	30.3	-6.6	7.1	30.8	164,058	114,886	-10.4	-10.3
US	-6.6	-18.2	-2.7	-27.5	-188,963	-480,322	-3.4	-3.0
Global	-13.6	1.4	0.2	-12.1	0.0	0.0	-12.0†	-12.0†

Notes: Observed and autarky consumption-based emissions. % change in emissions refers to $\left(\mathcal{E}_n^A/\mathcal{E}_n^C - 1\right) * 100$. Δ_n^P is the price channel, Δ_n^S is the sourcing channel, and Δ_n^B is the trade imbalance channel, in equation (30). Net exports are in US dollars. Welfare changes are given by equation (27) with $\gamma\mathcal{E}/W = 0.04$. (†): Average across countries.

trade imbalances. This suggests that the Chinese value chain is dirtier than the one available to China when trade is allowed, and China ends up exporting those goods to the rest of the world. In turn, the price channel would decrease Chinese emissions in autarky: China is a net importer of fossil fuels, suggesting that the prices for those goods should increase in autarky. Conversely, the three net exporters of fossil fuels, Canada, Russia, and Norway, have price changes increasing emissions in autarky, while the sourcing channel acts to decrease emissions in those countries. For Canada, the sourcing channel is strong enough to produce an overall reduction in autarky emissions of nine percent.

Not surprisingly, a move to autarky will have negative effects in real GDP in all countries, with changes ranging from -3.4 percent for the US and -20.5 for France. The negative effect on welfare from moving to world autarky would be less than the effect on real GDP since households value positively a world with less emissions.

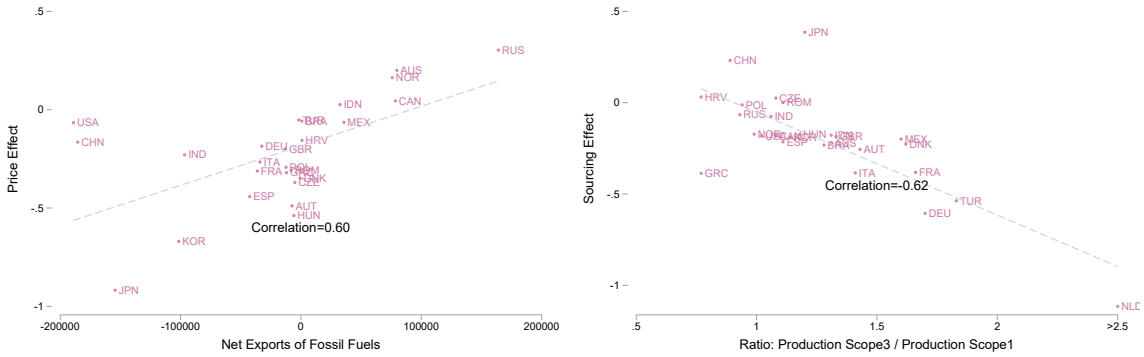
The link between the price channel and net exports of fossil fuels, and the demand channel and the "cleanliness" of the value chain of a country, that the comparisons for selected countries illustrates, is systematic. Panel (a) of Figure 5 plots Δ_n^P from equation (30) and net exports of fossil fuels, for all countries. The correlation is clearly positive: for net exporters of fossil fuels, trade decreases emissions through increasing fossil fuel prices. Panel (b) of Figure 5 relates the sourcing channel Δ_n^S from equation (30) with a measure of the difference in production emissions from fossil fuels embodied in the value chain versus the direct use of fossil fuels. We construct this measure as the ratio of production-based scope 3 to scope 1 emissions. Countries with a larger value of this ratio have dirtier value chains due to imported inputs. The negative relation shown in Panel (b) indicates that trade increases emissions for countries with dirtier value chains due to imports (i.e., for countries with a high ratio of scope 3 to scope 1 production-based emissions).

Our analysis of the change in emissions under autarky used the measure of emissions based on consumption. While at the global level using either production, extraction, or consumption based emissions for these calculations does not affect the results, at the country level, it matters. Appendix Tables 7

Figure 5: Understanding the price and sourcing channels.

(a) Price channel and net exports of fossil fuels. Corr: 0.6.

(b) Sourcing channel and value chain. Corr: -0.62.



and 8 provide the numbers to perform some of these calculations. For instance, a country like France, which barely extracts fossil fuels in the observed equilibrium, would increases extraction emissions under autarky four times since they have to provide for their fossil fuels themselves. Evidently, because the autarky prices of these fossil fuels would be extremely high, the quantity demanded–and extracted–would end up being low. The opposite happens with Russia, a producer of fossil fuels. Since prices will be much lower in autarky, they would extract less fuels and extraction-based emissions would decrease by almost 61 percent. If we based out analysis on production-based emissions (scope 1), China would experience a decrease of eight percent in emissions when moving to autarky (against an increase in consumption-based emissions of 12.6 percent). This is simply due to the fact that China is a net exporter of fossil fuels so that under autarky, since these inputs become expensive, they are used less in production directly–and hence, production emissions based on scope 1 decrease.

While autarky represents an extreme counterfactual, it demonstrates the importance of explicitly modeling the market for fossil fuels. The decomposition particularly highlights the importance of allowing for upward-slopping supply curves, and hence, the price channel. Given the importance of this analysis, Table 2 shows some sensitivity analysis of the autarky results with respect to the parameter ν governing the fossil fuel supply elasticity. We report results both using lower and higher values of ν, corresponding to higher and lower values of the supply elasticity for fossil fuels than the baseline. Sensibly, making the supply curve less elastic (i.e., $\nu = 0.35$) makes the price channel relatively more important. Imbalances and sourcing effects are not affected by ν.

5.2 Trade liberalization

We analyze how decreasing international trade costs affects emissions. We implement this counterfactual scenario by decreasing all trade costs by 20 percent. Figure 6 shows that this global counterfactual increases emissions by almost four percent, with large heterogeneity across countries. While China de-

Table 2: Effect of Global Autarky on Emissions. Sensitivity Analysis

% change	Total $\sum_n \mathcal{E}_n^A / \sum_n \mathcal{E}_n^C$ (1)	Price Channel $\sum_n \Delta_n^P / \sum_n \mathcal{E}_n^C$ (2)	Sourcing Channel $\sum_n \Delta_n^D / \sum_n \mathcal{E}_n^C$ (3)	Imbalances $\sum_n \Delta_n^B / \sum_n \mathcal{E}_n^C$ (4)
$\nu = 0.10$	-8.28	-9.85	1.35	0.22
$\nu = 0.25$	-12.06	-13.63	1.35	0.22
$\nu = 0.35$	-13.37	-14.94	1.35	0.22

Notes: Autarky relative to observed . % change refers to $(X-1)*100$. $\sum_n \Delta_n^P$ is the (global) price channel, $\sum_n \Delta_n^S$ is the (global) sourcing channel, and $\sum_n \Delta_n^B$ is the (global) trade imbalance channel, in (30).

creases consumption-based emissions by almost ten percent, Netherland's emissions increase nearly 40 percent, and the US by a little over 10 percent. Emissions only decrease in China and India; all other countries increase emissions.

What explains the different patterns across countries? As with the autarky analysis, we decompose the effect of trade liberalization on emissions into three channels: a price channel, an expenditure channel, and a sourcing channel. We use as our initial equilibrium the one with trade balances so that we better isolate the effect of reducing trade costs on emissions.

We first write the difference in emissions between the counterfactual and equilibrium with trade balance using (19),

$$\mathcal{E}_n^{C,\prime} - \mathcal{E}_n^{C,B} = \sum_{s \in \mathcal{K}^M} \frac{e_s}{p_s'} \sum_{j,l,k} \chi'_{jl,sk} \lambda'_{ln,k} \mu_{n,k} X_n'^C - \sum_{s \in \mathcal{K}^M} \frac{e_s}{p_s^B} \sum_{j,l,k} \chi^B_{jl,sk} \lambda^B_{ln,k} \mu_{n,k} X_n^{C,B}.$$

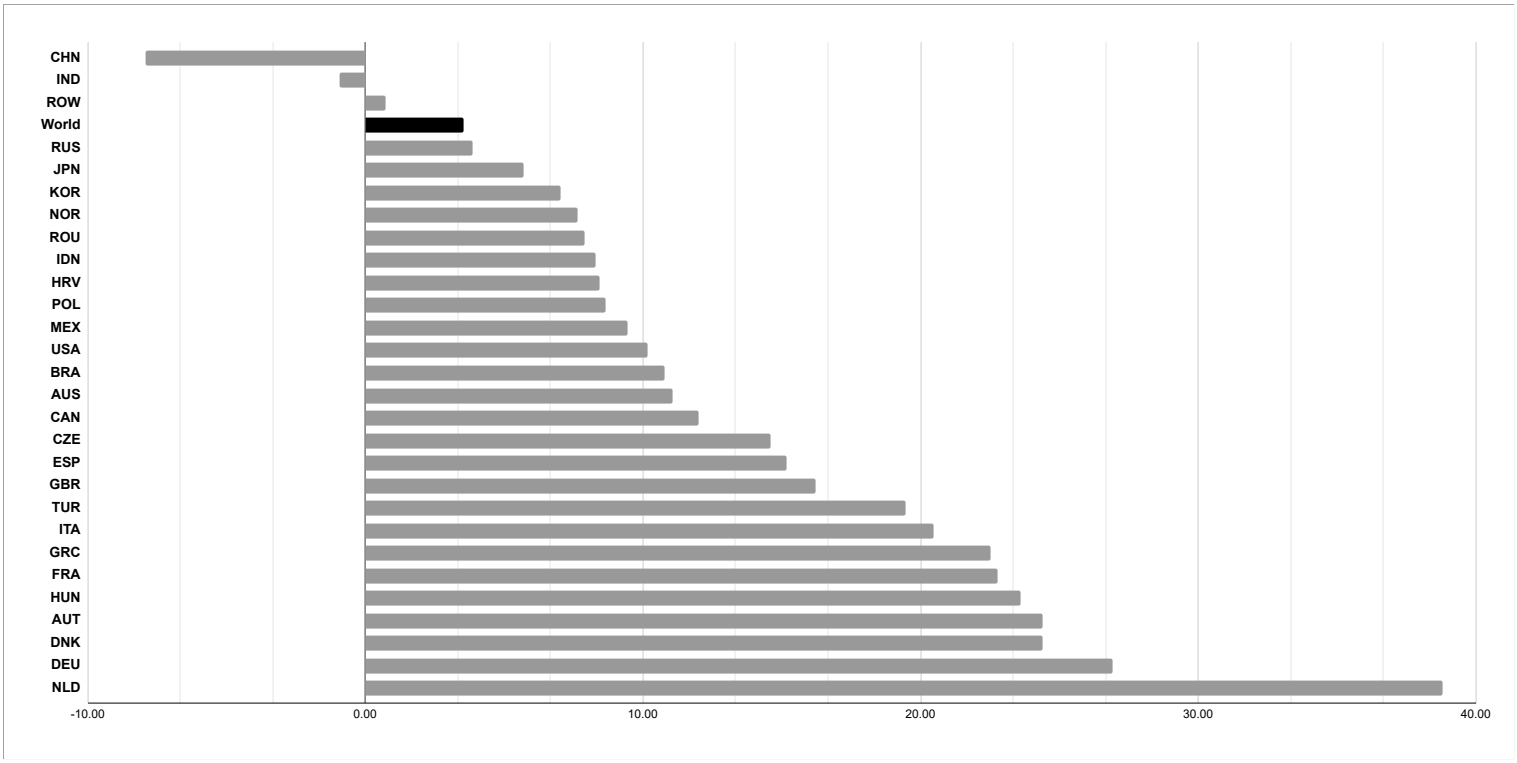
We implement the decomposition as

$$\begin{aligned} \mathcal{E}_n'^{,C} - \mathcal{E}_n^{C,B} &= \sum_{s \in \mathcal{K}^M} \left(\Delta_{n,s}^{PP} + \Delta_{n,s}^{X} + \Delta_{n,s}^{S} \right) \\ \Delta_{n,s}^{PP} &\equiv \left(\frac{e_s}{p_s'} - \frac{e_s}{p_s^B} \right) X_n'^C \sum_{j,l,k} \chi^B_{jl,sk} \lambda^B_{ln,k} \mu_{n,k} \\ \Delta_{n,s}^{X} &\equiv \frac{e_s}{p_s^B} \left(X_n'^C - X_n^{C,B} \right) \sum_{j,l,k} \chi^B_{jl,sk} \lambda^B_{ln,k} \mu_{n,k} \\ \Delta_{n,s}^{S} &\equiv \frac{e_s}{p_s'} \sum_{j,l,k} \left(\chi'_{jl,sk} \lambda'_{ln,k} - \chi^B_{jl,sk} \lambda^B_{ln,k} \right) X'^C_{n,k}. \end{aligned} \tag{31}$$

The term $\Delta_{n,s}^{PP}$ represents changes in demand due to changes in prices. The term $\Delta_{n,s}^{X}$ represents changes in demand due to changes in final expenditure. The term $\Delta_{n,s}^{S}$ represents the effect of reallocating sourcing of final and intermediates goods across countries with different emission intensities.

Table 3 shows the results of this decomposition for selected countries. This table shows that the central mechanism for a 20% decrease in trade costs to affect emissions is through global changes in the

Figure 6: Effect of Trade Liberalization on Emissions, by Country.



Notes: Emissions in an equilibrium with 20 percent lower international trade costs worldwide, relative to consumption-based emissions in an equilibrium with trade balance, $\mathcal{E}_n^{C\prime}/\mathcal{E}_n^C - 1$.

Table 3: Effect of Trade Liberalization on Emissions, Selected Countries.

	% change			
	Total $\mathcal{E}_n'^C/\mathcal{E}_n^{C,B}-1$ (1)	Price Channel $\Delta_n^{PP}/\mathcal{E}_n^{C,B}$ (2)	Expenditure Channel $\Delta_n^{X}/\mathcal{E}_n^{C,B}$ (3)	Sourcing Channel $\Delta_n^{S}/\mathcal{E}_n^{C,B}$ (4)
Canada	12.00	31.41	-22.89	3.48
China	-7.90	29.40	-29.11	-8.18
France	22.76	31.67	-22.53	13.62
Korea	7.02	31.14	-23.70	-0.43
Russia	3.86	30.67	-26.51	-0.30
US	10.16	29.61	-27.12	7.67
Global	3.53	30.22	-26.39	-0.29

Notes: Emissions in an equilibrium with 20 percent lower international trade costs worldwide, relative to consumption-based emissions in an equilibrium with trade balance, $\left(\mathcal{E}_n^{C\prime}/\mathcal{E}_n^{C,B}-1\right)*100$. Price, expenditure, and sourcing channels refer to equation (31).

world price of fossil fuels.This positive effect is offset in China by a negative demand and reallocation effects –intermediate inputs from cleaner sources get cheaper from China's perspective. For most other countries in Table 3, the reallocation towards cheaper inputs from dirtier sources compounds the increase in emissions due to lower fossil fuel prices. Again, this trade liberalization analysis highlights the quantitative importance of endogenous adjustments in fuel prices.

6 The Quantitative Effects of Carbon Taxes

This section adds various types of carbon taxes to the model and quantitatively evaluates how they affect emissions, real income, and leakage and on leakage effects.

We define leakage as the change in emissions from unregulated regions relative to the change in the region imposing the tax,

$$\mathcal{L} = -\frac{\sum_{l\neq l^R}\left(\mathcal{E}_l^t-\mathcal{E}_l\right)}{\mathcal{E}_{l^R}^t\text{-}\mathcal{E}_{l^R}}. \tag{32}$$

Here l^R denotes the country imposing the tax, the superscript t denotes the equilibrium with the carbon tax, and $\mathcal{E}$ represents emissions. If $\mathcal{L}=1$, then increases from the unregulated region fully offset decreases from the regulated region, implying full leakage. When $\mathcal{L}=0$, no leakage occurs from the regulated region to the unregulated region.

We analyze three possible types of carbon taxes. First, we analyze a tax on fossil fuel *extraction*. Second, we study a tax on a country's fossil fuel *use*, and call it a production tax. Third, we analyze a tax on fossil fuel *consumption*, which amounts to indirectly taxing the emissions in the whole value chain, either domestically or abroad. In a closed economy, these three taxes have identical effects. In an open economy, they may produce different levels of leakage, and so different impacts on emissions and

real income.

To illustrate, consider a simple input-output structure where coal is used to produce steel, which in turn is used to produce cars, which final consumers purchase. The extraction tax applies directly to the coal industry; the production tax applied directly to the steel industry, which burns the coal. The consumption tax applies directly to final consumers. The consumption tax reflects the coal used in the steel used in the production of cars. Of course, through equilibrium adjustments, each tax has indirect effects on all prices and quantities in the economy. For each tax, we report the corresponding measure of emissions from equations (21)-(14). Hence, for consumption taxes, we report consumption-based carbon accounting. The logic is that, for example, if a country has a high responsibility when emissions are measured by where fossil fuels are extracted, this country would be a good candidate for an extraction-based carbon tax.

We depart from the literature that analyzes different carbon taxes in a few ways. First, our approach builds on explicitly incorporating fossil fuels, as oppose to abatement approaches, so that the carbon tax is directly applied to the extraction or use of these goods. Second, our taxes are specific —applied per unit of fossil fuel used, and they are optimal in the sense of using the global SCC. Abatement approaches use *ad valorem* taxes on production (scope 1) emissions in an industry, which are the result of multiplying the social cost of carbon by the emission intensity *per dollar* of output in an industry. Even though those approaches choose the tax rate to be equivalent to the optimal specific tariff to fossil fuels, by assuming that the emission intensity of one dollar of output is constant, they do not capture equilibrium effects coming from changes in the price of fossil fuels, as explained in Section 1.

While the analysis of extraction and production taxes is fairly standard, the fossil fuel consumption tax has novel features. This analysis is feasible due to our approach that follows the fossil fuels through the global value chain.

6.1 Adding Carbon Taxes to the Model

Extraction taxes. We first add an extraction tax to the model with homogeneous mining goods and frictionless trade in those goods. We assume that the tax is country and fossil fuel specific, $t_{j,s}$, so that the price that producers of mining good s receive in country j equals $p_s - t_{j,s}$. The supply curve for mining good s in country j is then given by

$$Y_{j,s}^{s} = M_{j,s} \left(p_s - t_{j,s}\right)^{\frac{1}{\nu_s}} \left(w_j^{-\alpha_{j,\ell s}} \prod_{k \in \mathcal{K}^M} p_k^{-\alpha_{j,ks}} \prod_{k \notin \mathcal{K}^M} P_{j,k}^{-\alpha_{j,ks}} \right)^{\frac{1}{\nu_s}}.$$

The equilibrium condition for final expenditure is modified to reflect the inclusion of the tax and corresponding transfers to consumers, T_j,

$$X_j^C = w_j L_j + \sum_{s \in \mathcal{K}^M} \nu_s Y_{j,s}^{s} + \xi_j + T_j. \tag{33}$$

In turn, the world market-clearing condition for each fossil fuels is adjusted to reflect the difference in the price received by the producers and paid by the consumers,

$$\sum_j \left(\frac{p_s}{p_s - t_{j,s}}\right) Y_{j,s}^s = \sum_n X_{n,s} \qquad s \in \mathcal{K}^M.$$

Finally, the government budget is balanced,

$$T_j = \sum_{s \in \mathcal{K}^M} \left(\frac{t_{j,s}}{p_s - t_{j,s}}\right) Y_{j,s},$$

and labor market equilibrium is given by (13).

For the case of extraction taxes, we compute country-level extraction-based emissions,

$$\mathcal{E}_j^M = \sum_{s \in \mathcal{K}^M} e_s \frac{Y_{j,s}}{p_s - t_{j,s}}. \tag{34}$$

Production taxes. An alternative tax scheme is a fossil fuel tax at destination—instead of an extraction tax, which is charged by the source country. In this case, the purchase price of $s \in \mathcal{K}^M$ in country l is $p_s + t_{l,s}$. The price of a non-mining good $s \notin \mathcal{K}^M$ in country l is modified to capture the new fossil fuel prices,

$$p_{l,s} = A_{l,s}^{-1} w_l^{-\alpha_{l,\ell s}} \prod_{k \in \mathcal{K}^M} (p_s + t_{l,s})^{-\alpha_{l,ks}} \prod_{k \notin \mathcal{K}^M} P_{l,k}^{-\alpha_{l,ks}},$$

which in turn affects the price index for the non-mining goods, their expenditure shares, as well as the supply of mining goods in their extraction location –which is affected by the tax when the mining goods are used as inputs into the extraction activity.

The final expenditure condition is modified to capture transfers, T_l, as in (33), and the global market clearing condition for each mining good $s \in \mathcal{K}^M$ must be modified to capture the tax at destination,

$$\sum_j Y_{j,s}^s = \sum_l \left(\frac{p_s}{p_s + t_{l,s}}\right) X_{l,s}.$$

Finally, the Government balanced budget condition is given by

$$T_l = \sum_{s \in \mathcal{K}^M} \left(\frac{t_{l,s}}{p_s + t_{l,s}}\right) X_{l,s},$$

while the expenditure condition and labor market equilibrium are given by (33) and (13), respectively.

In this case, we focus on country-level production-based (scope 1) emissions,

$$\mathcal{E}_l^{P,1} = \sum_{s \in \mathcal{K}^M} \frac{e_s}{p_s + t_{l,s}} \left(\sum_k \alpha_{l,sk} Y_{l,k} + X_{l,s}^C\right). \tag{35}$$

Consumption Taxes. Our final carbon tax is applied to consumers in country n, who pay the tax on the carbon emissions coming from the entire value chain. Hence, producers need to keep track of those emissions, and choose their sourcing strategy to minimize costs. As producers change the use of fossil fuels in response to the tax, fossil fuels for production of goods eventually used for consumption in country n become more expensive. Additionally, sourcing strategies in country n change in favor of less carbon-intensive countries, making the parameters $\alpha_{l,ks}$ an important ingredient in this problem.

Differently from the carbon taxes analyzed previously, in this case, each country l produces a non-mining good $s \notin \mathcal{K}^M$ specifically for each market n. Hence, the price of good s in n changes depending on its production location l,

$$p_{l,n,s} = A_{l,s}^{-1} w_l^{\alpha_{l,\ell s}} \prod_{k \in \mathcal{K}^M} (p_{n,k} + t_{n,k})^{\alpha_{l,ks}} \prod_{k \notin \mathcal{K}^M} P_{l,n,k}^{\alpha_{l,ks}}, \quad s \notin \mathcal{K}^M.$$

For a mining good $k \in \mathcal{K}^M$, $p_{n,k}$ is the price that producers of k get when they sell their output to be used as an input along the value chain of a good consumed in n. Because fossil fuels are homogeneous goods and they are traded without frictions, their price does not vary across production locations. But this price does varies across consumption locations n because the cost changes depending on where the fossil fuels are sold.

The price index for good $s \notin \mathcal{K}^M$ is also specific to the destination n,

$$P_{l,n,s}^{1-\sigma_s} = \sum_j (\tau_{jl,s} p_{j,n,s})^{1-\sigma_s}.$$

Trade shares between country j and l reflect the fact that both the goods' prices and the price index for sector $k \notin \mathcal{K}^M$ are specific to destination n,

$$\lambda_{jl,n,k} = \frac{(\tau_{jl,k} p_{j,n,k})^{1-\sigma_k}}{P_{l,n,k}^{1-\sigma_k}}.$$

with $\sum_j \lambda_{jl,n,k} = 1$ for all $l, n, k \notin \mathcal{K}^M$. This trade share reflects the fact that good k is produced for consumption in country n.

For mining goods, suppliers of $s \in \mathcal{K}^M$ in country j pay $p_{n,k} + t_{n,k}$ for mining inputs and $P_{j,n,k}$ for non-mining inputs, and they receive price $p_{n,s}$. Thus, total output (in value) of good $s \in \mathcal{K}^M$ extracted in j is

$$Y_{j,s} = M_{j,s} \left(w_j^{-\alpha_{j,\ell s}} \max_n p_{n,s} \prod_{k \in \mathcal{K}^M} (p_{n,k} + t_{n,k})^{-\alpha_{j,ks}} \prod_{k \notin \mathcal{K}} P_{j,n,k}^{-\alpha_{j,ks}} \right)^{\frac{1}{\nu_s}}.$$

This output is sold to destination n as long as

$$n \in \arg\max_{n'} p_{n',s} \prod_{k \in \mathcal{K}^M} \left(p_{n',k} + t_{n',k}\right)^{-\alpha_{j,ks}} \prod_{k \notin \mathcal{K}} P_{j,n',k}^{-\alpha_{j,ks}},$$

which can be formalized by the following complementary slackness condition on j's supply of s to n,

$$Y_{j,n,s}\left(\max_{n'} p_{n',s}\prod_{k\in\mathcal{K}^M}\left(p_{n',k}+t_{n',k}\right)^{-\alpha_{j,ks}}\prod_{k\notin\mathcal{K}}P_{j,n',k}^{-\alpha_{j,ks}}-p_{n,s}\prod_{k\in\mathcal{K}^M}\left(p_{n,k}+t_{n,k}\right)^{-\alpha_{j,ks}}\prod_{k\notin\mathcal{K}}P_{j,n,k}^{-\alpha_{j,ks}}\right)=0,$$

and

$$Y_{j,n,s}\geq 0,\quad \sum_n Y_{j,n,s}-Y_{j,n,s}\geq 0,\quad s\in\mathcal{K}^M.$$

Here, $Y_{j,n,s}$ denotes output of mining goods $s\in\mathcal{K}^M$ produced by country$j$ for potential consumption in n.

Let $X_{l,n,k}$ denote total expenditure on good k by country l for potential consumption in n, which must satisfy

$$X_{l,n,k}=\mathbb{I}\left(l=n\right)\mu_{l,k}X_l^C+\sum_s\alpha_{l,ks}Y_{l,n,s}.$$

Here, $\mathbb{I}\left(l=n\right)$ is the indicator function for expenditure by l for self consumption $(l=n)$ on any good k –that is, final expenditure. The second term on the right-hand side captures expenditure by l on k as intermediate goods –and includes intermediate goods used to produce good s for self $(l=n.$

Market equilibrium for each mining good $s\in\mathcal{K}^M$, entails world extraction equal to world demand,

$$\sum_j Y_{j,n,s}=\frac{p_{n,s}}{p_{n,s}+t_{n,s}}\sum_l X_{l,n,s},$$

while for $s\notin\mathcal{K}^M$,

$$Y_{j,n,s}=\sum_l\lambda_{jl,n,s}X_{l,n,s}.$$

Finally, the Government budget is balanced so that total transfers to households is equal to total tax revenues,

$$T_n=\sum_{k\in\mathcal{K}^M}\frac{t_{n,k}}{p_{n,k}}\sum_j Y_{j,n,k},$$

and the expenditure condition and labor market equilibrium are given by (33) and (13), respectively.

For consumption taxes, we focus on country-level consumption-based emissions,

$$\mathcal{E}_n^C=\sum_{s\in\mathcal{K}^M}\frac{e_s}{p_{n,s}+t_{n,s}}\sum_{k,j,l}\chi_{jl,n,sk}\lambda_{ln,n,k}\mu_{n,k}X_n^C. \tag{36}$$

6.2 Quantitative Results

Our quantitative analyses use a tax rate equal to the product of the social cost of carbon and the carbon intensity. Because the SCC is in \$/tCO_2 and carbon intensity is in tCO_2/unit of fuel, the tax rate is in \$/unit fuel, so it is specific rather than ad valorem.

We start from our baseline calibration from the observed data, which assumes zero taxes. We compare it to an equilibrium with a carbon tax, based on the global SCC. As in Section 5's analysis of trade shocks, we use exact hat algebra.

First, we analyze a global carbon tax on the extraction and use of fossil fuels. Second, we analyze unilateral carbon taxes. All results use a social cost of carbon of 100\$/tCO_2. [16]

Table 4 shows that a global carbon tax, either on the extraction or the use of fossil fuels, would reduce emissions by half relative to current emissions. At the same time, real GDP would decline by 0.52% for an extraction tax or 0.73% for a use tax. Given the large reduction in emissions and SCC global welfare increases by 1.5 percent. A global carbon tax by definition has no leakage.

While the extraction and production taxes have similar aggregate effects, they have very different distributional effects. A global extraction tax increases real GDP of fossil fuel net exporters like Russia and Canada by 3 to one percent. A global tax on fossil fuel use causes them to lose 1 to 2 percent of real GDP. Welfare gains are magnified relative to real GDP impacts, while welfare losses are mitigated. In contrast, a country like Korea, experiences real GDP gains of 0.5 percent under a global use tax, but losses of 3 percent under a global extraction tax. For Korea this economic loss is high enough that welfare also decreases. China, which is a net importer of fossil fuels, but a net exporter of energy-intensive manufacturing goods, experiences real GDP losses under both a global extraction tax (3 percent) and a global use tax (1.2 percent). Reductions in emissions under a use tax, however, would more than offset the GDP loss, ultimately increasing social welfare. Appendix Table 10 presents the results for the entire sample of countries.

To benchmark these estimates, we can compare them to the Dynamic Integrated Climate-Economy model (DICE). Barrage and Nordhaus (2024b) indicate that in DICE, a global carbon tax of \$100 per ton of CO_2 decreases global CO_2 emissions by about a third.[17] Table 5 shows that a \$100 carbon tax decreases global CO_2emissions by about half. Our model differs considerably from DICE. DICE is a dynamic growth model where abatement reflects two general parameters calibrated to sources in the literature, while ours is a comparative static trade model, which uses estimated supply and demand parameters for fossil fuels. The comparison between DICE and our model suggests that estimates of global carbon taxes are roughly in a comparable ballpark, though the magnitude of the decrease in emissions that we estimate is larger than the decrease estimated by DICE.

What would be the effect of an unilateral carbon tax, either to fossil fuel extraction or use? Kortum et al. (2023) analyze this setting, accounting for leakage. We assess in which country the carbon tax is more effective and whether on extraction or use of fossil fuels.

Table 5 shows that if an extraction tax were applied in China, which represents almost 26% of world (extraction) emissions, the decrease in one ton of CO_2 released to the environment in China would be

[16] We also consider $scc = 20\$$ and $scc = 50\$$ per ton of CO_2. Results are qualitatively similar (not shown).

[17] The Optimal Cost/Benefit scenario in Barrage and Nordhaus (2024b) has global carbon price rise steadily to \$115 per ton of CO_2 in the year 2050. Their baseline begins with a carbon price of \$6 per ton of CO_2 in 2022, growing at 2.5% per year. By 2050, their baseline has a carbon tax of \$12.59 per ton of CO_2. Comparing their optimal and baseline scenarios in the year 2050 thus approximates the DICE estimate of the impact of a global carbon price of \$100 per ton of CO_2.

Table 4: Global Carbon Tax, Selected Countries.

	% change in country emissions			% change in real GDP			% change in welfare			% of world emissions		
	Ext tax	Use tax	Cons tax	Ext tax	Use tax	Cons tax	Ext tax	Use tax	Cons tax	Ext	Prod (S1)	Cons
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
Canada	-31.5	-36.9		-3.7	-1.2		-1.9	0.7		2.88	1.66	1.6
China	-62.2	-57.3	-67.1	-4.2	-1.8	-0.74	-2.3	0.0	1.3	25.8	31.0	25.5
France	-35.0	-35.6	-45.1	-0.9	-0.1	-0.91	1.1	1.8	1.3	0.09	0.82	2.0
Korea	-55.2	-37.6		-2.9	0.4		-1.0	2.4		0.09	1.93	2.3
Russia	-50.1	-60.3	-62.9	2.5	-2.0	-0.72	4.6	-0.2	1.3	7.57	2.79	1.8
US	-37.0	-30.5	-49.2	-5.7	-0.3	-0.45	-3.9	1.6	1.6	11.2	13.8	18.1
Global	-48.4	-48.0	-56.1	-2.8	-0.7	-0.61†	-0.9	1.2	1.3	100	100	100

Note: The tax is calculated as $t_s = scc \times e_s$ where $scc = 100\$/\text{ton } CO_2$, for $s \in \mathcal{K}^M$, and applied to all countries. For the extraction tax, we report changes in extraction-based emissions, while for the production tax, we report changes in production-based emissions (scope 1). Extraction emissions are calculated using (34), production (scope 1) emissions are calculated using (35). Welfare is calculated using Equation (27). (†): Average across countries.

offset by an increase of 0.56 tons in the rest of the world. A carbon use tax would be more effective: for each unit of emissions reduced in China, only around 0.18 leak away to foreign countries. While China would be the country where, if a carbon tax were applied, either to the extraction or use of fossil fuels, leakage would be the lowest, France would present the most leakage. Of course, these shares mask different magnitude changes in emissions, which, unsurprisingly, are much higher for China than France. For example, a carbon use tax in France reduces emissions globally by 0.2% million tons of CO_2, while the same tax in China decreases emissions globally by 5.7 billion tons of CO_2. Appendix Table 11presents results for each country.

In all cases, leakage regulating a lower share of world emissions decreases leakage; the negative correlation exceeds 0.70. In contrast, and quite intuitively, leakage is positively correlated with the degree of openness of the country imposing the carbon taxes, and with the degree of decreasing returns in the production of fossil fuels (i.e. higher ν) in line with analytical results (Kortum et al. 2023).

7 Conclusions

Table 5: Unilateral Carbon Tax, Selected Countries.

Regulated country	% change in world emissions			Leakage			% of world emissions		
	Ext tax	Use tax	Cons tax	Ext tax	Use tax	Cons tax	Ext	Prod (S1)	Cons
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
Canada	**-0.46**	**-0.54**	**-0.52**	**0.72**	**0.44**	**0.41**	2.9	1.7	2.0
China	**-9.4**	**-16.3**	**-12.5**	**0.56**	**0.18**	**0.39**	25.8	31.0	25.5
France	**-0.02**	**-0.2**	**-0.6**	**0.75**	**0.59**	**0.44**	0.09	0.8	1.6
Korea	**-0.02**	**-0.45**	**-0.43**	**0.74**	**0.62**	**0.61**	0.01	1.9	1.8
Russia	**-1.8**	**-1.3**	**-1.1**	**0.72**	**0.33**	**0.31**	7.5	2.8	2.3
US	**-2.2**	**-4.1**	**-6.5**	**0.66**	**0.40**	**0.45**	11.2	13.8	18.1

Note: The tax is calculated as $t_s = scc \times e_s$ where $scc = 100\$$ per ton of CO_2, for $s \in \mathcal{K}^M$, and applied by each country shown, one at the time. For the extraction tax, we report extraction-based emissions, while for the use tax, we report production-based emissions (scope 1). Extraction emissions are calculated using (34), production (scope 1) emissions are calculated using (35), and leakage is calculated using (32).

References

Abuin, C. (2024). Power decarbonization in a global energy market: The climate effect of us lng exports. Mimeo, Harvard.

Arkolakis, C. and C. Walsh (2023). Clean growth. NBER Working Paper 31615.

Arora, V. (2014). Estimates of the price elasticities of natural gas supply and demand in the united states.

Barrage, L. and W. Nordhaus (2024a). Policies, projections, and the social cost of carbon: Results from the dice-2023 model. *Sustainability Science 121*(13).

Barrage, L. and W. Nordhaus (2024b). Policies, projections, and the social cost of carbon: Results from the dice-2023 model. *Proceedings of the National Academy of Sciences 121*(13), e2312030121.

Bauer, N., J. Hilaire, R. J. Brecha, J. Edmonds, K. Jiang, E. Kriegler, H.-H. ROgner, and F. Sferra (2016). Assessing global fossil fuel availability in a scenario framework. *Energy 111*, 580–592.

Boeters, S. and J. Bollen (2012). Fossil fuel supply, leakage and the effectiveness of border measures in climate policy. *Energy Economics 34*, S181–S189.

Bohringer, C., J. C. Carbone, and T. F. Rutherford (2016). The strategic value of carbon tariffs. *American Economic Journal: Economic Policy 8*(1), 28–51.

Bornstein, G., per Krusell, and S. Rebelo (2019). Lags, costs, and shocks: An equilibrium model of the oil industry.

Caliendo, L., M. Dolabella, M. Moreira, M. Murillo, and F. Parro (2024). Voluntary emission restraints in developing economies: The role of trade policy. Mimeo, Yale.

Caliendo, L. and F. Parro (2015). Estimates of the trade and welfare effects of nafta. *Review of Economic Studies 82*(1), 144.

Caliendo, L. and F. Parro (2022). *Handbook of International Economics, Vol. 5*, Chapter Trade Policy, pp. 219–295. North-Holland.

Caron, J. and T. Fally (2018). Per capita income, consumption patterns, and co2 emissions. Mimeo, UC Berkeley. https://are.berkeley.edu/ fally/Papers/CO2paper.pdf.

Cole, M. A. and R. J. R. Elliott (2003). Determining the trade-environment composition effect: the role of capital, labor and environmental regulations. *Journal of Environmental Economics and Management 46(3)*, 363–383.

Copeland, B. R. and M. S. Taylor (1994). North-south trade and the environment. *Quarterly Journal of Economics 109(3)*, 755–787.

Costinot, A. and A. Rodríguez-Clare (2014). *Handbook of International Economics, Vol. 4*, Chapter Trade Theory with Numbers: Quantifying the Consequences of Globalization, pp. 197–262. North-Holland.

Cruz, J.-L. and E. Rossi-Hansberg (2024). The economic geography of global warming. *Review of Economic Studies 91*, 899â–939.

Davis, S. J. and K. Caldeira (2010). Consumption-based accounting of co2 emissions. *Proceedings of the National Academy of Sciences 207(12)*, 5687–5692.

Dekle, R., J. Eaton, and S. Kortum (2008). Global rebalancing with gravity: Measuring the burden of adjustment. *IMF Staff Papers 55(3)*, 511–539.

Egger, P. and S. Nigai (2014). Energy demand and trade in general equilibrium. *Environmental & Resource Economics 60*, 191–213.

Farrokhi, F. and A. Lashkaripour (2023). Can trade policy mitigate climate change? Technical report, Purdue University.

Fontagne, L., H. Guimbard, and G. Orefice (2022). Tariff-based product-level trade elasticities. *Journal of International Economics*.

Fowlie, M., M. Reguant, and S. P. Ryan (2016). Market-based emissions regulation and industry dynamics. *Journal of Political Economy 124(1)*, 249–302.

Ge, M., J. Friedrich, and L. Vigna (2024). Where do emissions come from? 4 charts explain greenhouse gas emissions by sector. World Resources Institute, https://www.wri.org/insights/4-charts-explain-greenhouse-gas-emissions-countries-and-sectors, visited 2/2/25.

Goulder, L. H., M. R. Jacobsen, and A. A. van Benthem (2012). Unintended consequences from nested state and federal regulations: The case of the pavley greenhouse-gas-per-mile limits. *Journal of Environmental Economics and Management 63*, 2.

Grossman, G. M. and A. B. Krueger (1993). *The Mexico-U.S. Free Trade Agreement*, Chapter Environmental Impacts of a North American Free Trade Agreement. M.I.T. Press.

Grossman, G. M. and A. B. Krueger (1995). Economic growth and the environment. *Quarterly Journal of Economics 110(2)*, 353–377.

Heal, G. (2022). The economics of carbon accounting and carbon offsets.

Kortum, S., D. Weisbach, M. Wang, and Y. Yao (2023). Trade, leakage, and the design of a carbon tax. *Environmental and Energy Policy and the Economy (NBER) 4*.

Larch, M. and J. Wanner (2017). Carbon tariffs: An analysis of the trade, welfare, and emission effects. *Journal of International Economics*, 195–213.

Lopez, L.-A., M.-A. Cadarso, J. Zafrilla, and G. Arce (2019). The carbon footprint of the u.s. multinationals' foreign affiliates. *Nature Communications 10*(1672), 1–11.

Martin, R., Mirabelle, Muuls, L. B. de Preux, and U. J. Wagner (2014). Industry compensation under relocation risk: A firm-level analysis of the eu emissions trading scheme. *American Economic Review 104*(8), 2482–2508.

McCollum, D. L. and A. A. Khourdajie (2021). Little room for new fossil fuel development if global temperatures are to stay below 1.5c. *Joule 5*(10), 2542–2545.

Moigne, M. L., S. Lepot, R. Ossa, M. Ritel, and D. Simon (2024). Greening ricardo: Environmental comparative advantage and the environmental gains from trade. Manuscript.

Nordhaus, W. (2015). Climate clubs: Overcoming free-riding in international climate policy. *American Economic Review 105*(4), 1339–70.

Peters, G. P., J. C. Minx, C. L. Weber, and O. Edenhofer (2011). Growth in emission transfers via international trade from 1990 to 2008. *Proceedings of the National Academy of Sciences 108(21)*, 8903–8908.

Shapiro, J. S. (2021). The environmental bias of trade policy. *Quarterly Journal of Economics 136*(2), 831–886.

Timmer, M. P., E. Dietzenbacher, B. Los, R. Stehrer, and G. J. de Vries (2015). An illustrated user guide to the world input-output database: the case of global automotive production. *Review of International Economics 23*(3), 575–605.

Welsby, D. (2021). Modelling natural gas resource uncertainties and regional gas markets: a review of curent models and an introduction to a new field-level gas production and trade model. Technical report, UK Energy Research Centre.

Welsby, D., J. Price, S. Pye, and P. Ekins (2021). Unextractable fossil fuels in a 1.5 c world. *Nature 597*, 230–234.

Zhang, Z., D. Guan, R. Wang, J. Meng, H. Zheng, K. Zhu, and H. Du (2020). Embodied carbon emissions in the supply chains of multinational enterprises. *Nature Climate Change 10*, 1096–1101.

A Proofs

Proposition 1. We first need to solve for the autarky equilibrium sectoral expenditure, $X_{n,k}^{C,A}$, and fossil fuel prices, $p_{n,s}^{A}$. We assume that $\nu_s = \nu$ for all $s \in \mathcal{K}^M$. If there were no intermediates, the quantity supplied of fossil fuel s in country j would be

$$q_{j,s} = M_{j,s} \left(p_s / w_j\right)^{\frac{1-\nu}{\nu}},$$

which equated to demand (in value) yields

$$X_{n,s}^{C,A} = M_{n,s} \left(p_{n,s}^{A} \left(w_n^A\right)^{\nu-1}\right)^{1/\nu}$$

in autarky, and

$$\sum_n X_{n,s}^{C} = \sum_n M_{n,s} \left(p_s \left(w_n\right)^{\nu-1}\right)^{1/\nu}$$

with trade. Hence,

$$p_{n,s}^{A} = \left(X_{n,s}^{C,A}\right)^{\nu} \left(w_n^A\right)^{1-\nu} M_{n,s}^{-\nu}$$

in autarky, and

$$p_s = \left(\sum_n X_{n,s}^{C}\right)^{\nu} \left(\sum_n M_{n,s} w_n^{\frac{\nu-1}{\nu}}\right)^{-\nu}$$

under trade. Plugging into (30) yields

$$\begin{aligned}\sum_{n,k} \chi_{n,sk} \left(\frac{X_{n,k}^{C,A}}{p_{n,s}^{A}} - \frac{X_{n,k}^{C}}{p_s}\right) &= \sum_n \frac{X_{n,s}^{C,A}}{\left(X_{n,s}^{C,A}\right)^{\nu} \left(M_{n,s} \left(w_n^A\right)^{\frac{\nu-1}{\nu}}\right)^{-\nu}} - \frac{\sum_n X_{n,s}^{C}}{\left(\sum_n X_{n,s}^{C}\right)^{\nu} \left(\sum_n M_{n,s} w_n^{\frac{\nu-1}{\nu}}\right)^{-\nu}} \\ &= \sum_n \left(X_{n,s}^{C,A}\right)^{1-\nu} \left(M_{n,s} \left(w_n^A\right)^{\frac{\nu-1}{\nu}}\right)^{\nu} - \left(\sum_n X_{n,s}^{C}\right)^{1-\nu} \left(\sum_n M_{n,s} w_n^{\frac{\nu-1}{\nu}}\right)^{\nu},\end{aligned} \tag{37}$$

We know that $X_{n,s}^{C,A} = \mu_{n,s} X_n^{C,A}$ with

$$X_n^{C,A} = w_n^A L_n + \mu_{j,M} X_n^{C,A},$$

and $\mu_{n,M} \equiv \sum_{s \in \mathcal{K}^M} \mu_{n,s} \nu$, which implies that

$$X_n^{C,A} = \frac{w_n^A L_n}{1 - \mu_{n,M}}. \tag{38}$$

Similarly, with $\mu_{n,s} = \mu_s$, we have that

$$\sum_n X_{n,s}^C = \mu_s \sum_n X_n^C,$$

and

$$\sum_n X_n^C = \sum_n w_n L_n + \mu_M \sum_n X_n^C.$$

Hence,

$$\sum_n X_n^C = \frac{\sum_n w_n L_n}{1 - \mu_M}. \tag{39}$$

Plugging back into (37),

$$\begin{aligned}
\sum_{n,k} \chi_{n,sk} \left(\frac{X_{n,k}^{C,A}}{p_{n,s}^A} - \frac{X_{n,k}^C}{p_s} \right) &= \sum_n \left(X_{n,s}^{C,A}\right)^{1-\nu} \left(M_{n,s} w_n^{\frac{\nu-1}{\nu}} \right)^\nu - \left(\sum_n X_{n,s}^C \right)^{1-\nu} \left(\sum_n M_{n,s} w_n^{\frac{\nu-1}{\nu}} \right)^\nu \\
&= \sum_n \left(\frac{\mu_s}{1-\mu_M} w_n^A L_n \right)^{1-\nu} \left(M_{n,s} \left(w_n^A\right)^{\frac{\nu-1}{\nu}} \right)^\nu - \left(\frac{\mu_s}{1-\mu_M} \sum_n w_n L_n \right)^{1-\nu} \left(\sum_n M_{n,s} w_n^{\frac{\nu-1}{\nu}} \right) \\
&= \left(\frac{\mu_s}{1-\mu_M} \right)^{1-\nu} \left[\sum_n \left(w_n^A L_n\right)^{1-\nu} \left(M_{n,s} \left(w_n^A\right)^{\frac{\nu-1}{\nu}} \right)^\nu - \left(\sum_n w_n L_n \right)^{1-\nu} \left(\sum_n M_{n,s} w_n^{\frac{\nu-1}{\nu}} \right)^\nu \right]
\end{aligned}$$

By choice of numerarie, $w_n^A = w_n$, and the term inside the square brackets simplifies to

$$\sum_n \left(w_n L_n\right)^{1-\nu} \left(w_n^{\frac{\nu-1}{\nu}} M_{n,s} \right)^\nu - \left(\sum_n w_n L_n \right)^{1-\nu} \left(\sum_n w_n^{\frac{\nu-1}{\nu}} M_{n,s} \right)^\nu$$

We then apply Jensen's inequality to conclude that

$$\left(\sum_n L_n \right)^{1-\nu} \left(\sum_n M_{n,s} \right)^\nu \left(\sum_n \left(\frac{L_n}{\sum_j L_j} \right)^{1-\nu} \left(\frac{M_{n,s}}{\sum_j M_{j,s}} \right)^\nu - 1 \right) \leq 0. \tag{40}$$

We have proved that with no intermediates in production and homogeneous sectoral expenditure shares across countries, the price mechanism lowers emissions as we move to autarky. With $\nu = 0$ (i.e. no curvature in mining production), the inequality in Equation (40) holds with equality, so that $\sum_{n,k} \chi_{n,sk} \left(\frac{X_{n,k}^{C,A}}{p_{n,s}^A} - \frac{X_{n,k}^C}{p_s} \right) = 0$ and $\sum_n \Delta_{n,s}^P = 0$.

We can decompose further the price channel and see whether changes in prices are accompanied by

changes in global quantities and global expenditure as well. To such end, using $w_n^A = w_n$, we can write

$$\sum_{n,k} \chi_{n,sk} \left(\frac{X_{n,k}^{C,A}}{p_{n,s}^A} - \frac{X_{n,k}^C}{p_s} \right) = \sum_n \left(X_{n,s}^{C,A}\right)^{1-\nu} \left(M_{n,s} w_n^{\frac{\nu-1}{\nu}} \right)^\nu - \sum_n \left(X_{n,s}^{C,A} \frac{\sum_n X_{n,s}^C}{\sum_n X_{n,s}^{C,A}} \right)^{1-\nu} \left(M_{n,s} w_n^{\frac{\nu-1}{\nu}} \right)^\nu + \sum_n \left(X_{n,s}^{C,A} \frac{\sum_n X_{n,s}^C}{\sum_n X_{n,s}^{C,A}} \right)^{1-\nu} \left(M_{n,s} w_n^{\frac{\nu-1}{\nu}} \right)^\nu - \left(\sum_n X_{n,s}^C \right)^{1-\nu} \left(\sum_n M_{n,s} w_n^{\frac{\nu-1}{\nu}} \right)^\nu$$

which after some algebra becomes

$$= \sum_n \left[\left(X_{n,s}^{C,A}\right)^{1-\nu} - \left(X_{n,s}^{C,A} \frac{\sum_n X_{n,s}^C}{\sum_n X_{n,s}^{C,A}} \right)^{1-\nu} \right] \left(M_{n,s} w_n^{\frac{\nu-1}{\nu}} \right)^\nu + \left[\sum_n \left(X_{n,s}^{C,A} \frac{\sum_n X_{n,s}^C}{\sum_n X_{n,s}^{C,A}} \right)^{1-\nu} \left(M_{n,s} w_n^{\frac{\nu-1}{\nu}} \right)^\nu - \left(\sum_n X_{n,s}^C \right)^{1-\nu} \left(\sum_n M_{n,s} w_n^{\frac{\nu-1}{\nu}} \right)^\nu \right] \tag{41}$$

The second terms in brackets, by Jensen's inequality, is less than one,

$$\sum_n \left(X_{n,s}^{C,A} \frac{\sum_n X_{n,s}^C}{\sum_n X_{n,s}^{C,A}} \right)^{1-\nu} \left(M_{n,s} w_n^{\frac{\nu-1}{\nu}} \right)^\nu - \left(\sum_n X_{n,s}^C \right)^{1-\nu} \left(\sum_n M_{n,s} w_n^{\frac{\nu-1}{\nu}} \right)^\nu$$
$$= \left(\sum_n X_{n,s}^C \right)^{1-\nu} \left(\sum_n M_{n,s} w_n^{\frac{\nu-1}{\nu}} \right)^\nu \left[\sum_n \left(\frac{X_{n,s}^{C,A}}{\sum_n X_{n,s}^{C,A}} \right)^{1-\nu} \left(\frac{M_{n,s} w_n^{\frac{\nu-1}{\nu}}}{\sum_n M_{n,s} w_n^{\frac{\nu-1}{\nu}}} \right)^\nu - 1 \right] \leq 1,$$

implying that for given world demand, going to autarky implies lower aggregate quantity of the good.

The first term in Equation (41) captures the effect of going to autarky on the global quantity of good s coming from the change in aggregate world demand for good s. We can re-write that term as

$$\sum_n \left[\left(X_{n,s}^{C,A}\right)^{1-\nu} - \left(X_{n,s}^{C,A} \frac{\sum_n X_{n,s}^C}{\sum_n X_{n,s}^{C,A}} \right)^{1-\nu} \right] \left(M_{n,s} w_n^{\frac{\nu-1}{\nu}} \right)^\nu$$
$$= \left(\frac{1}{\sum_n X_{n,s}^{C,A}} \right)^{1-\nu} \left[\left(\sum_n X_{n,s}^{C,A} \right)^{1-\nu} - \left(\sum_n X_{n,s}^C \right)^{1-\nu} \right] \sum_n \left(X_{n,s}^{C,A}\right)^{1-\nu} \left(M_{n,s} w_n^{\frac{\nu-1}{\nu}} \right)^\nu.$$

Using Equations (38) and (39), it is clear that for $\mu_{n,s} = \mu_s$, for all n and $s \in \mathcal{K}^M$, $\sum_n X_{n,s}^{C,A} - \sum_n X_{n,s}^C = 0$, and world demand (in value) for each fossil fuel does not change when the world moves to autarky.

Proposition 2. We can write the demand channel in (30) as

$$\Delta_s^D = \frac{e_s}{p_s} \sum_{n,k} \Omega_{sn,k} X_{n,k}^C$$

where

$$\Omega_{sn,k} \equiv \chi_{n,sk} - \sum_{j,l} \chi_{jl,sk} \lambda_{ln,k}$$

is the difference between the value of s needed for a dollar of k according to country $n's$ own input-output matrix and the corresponding value according to country $n's$ place in the world's input-output chain.

a) If $\alpha_{n,sk} = \alpha_{sk}$ for all n then $\sum_j \chi_{jn,sk} = \chi_{sk}$ for all n implying that $\sum_{n,k} \Omega_{sn,k} X^C_{n,k} = 0$. This can be shown indirectly by noting that

$$Y_{j,s} = \sum_n \lambda_{jn,s} X^C_{n,s} + \sum_l \lambda_{jl,s} \sum_k \alpha_{l,sk} Y_{l,k}$$

If $\alpha_{j,sk} = \alpha_{sk}$ then

$$Y_{j,s} = \sum_n \lambda_{jn,s} X^C_{n,s} + \sum_k \alpha_{sk} \sum_l \lambda_{jl,s} Y_{l,k}$$

Adding up over j yields

$$\sum_j Y_{j,s} = \sum_n X^C_{n,s} + \sum_k \alpha_{sk} \sum_j Y_{j,k}$$

so

$$\sum_j Y_{j,s} = \sum_k \chi_{sk} \sum_n X^C_{n,k}$$

and hence

$$\begin{aligned}\sum_{n,k} \Omega_{sn,k} X^C_{n,k} = \sum_{n,k} \left(\chi_{n,sk} - \sum_{j,l} \chi_{jl,sk} \lambda_{ln,k} \right) X^C_{n,k} &= \sum_{n,k} \chi_{n,sk} X^C_{n,k} - \sum_{j,l,n,k} \chi_{jl,sk} \lambda_{ln,k} X^C_{n,k} \\ &= \sum_{n,k} \chi_{n,sk} X^C_{n,k} - \sum_j Y_{l,s} = \sum_{n,k} \chi_{sk} X^C_{n,k} - \sum_n \chi_{sk} X^C_{n,k} = 0\end{aligned}$$

b) Consider the case in which $\alpha_{j,sk} = 0$ for all $k \in \mathcal{K}^M$ and $\alpha_{j,sk} = 0$ for all $s \notin \mathcal{K}^M$. This is the case in which coal, oil and gas, are produced without intermediates, and are the only intermediates used in any other sector. In this case $\chi_{jl,sk} = \delta_{jl,sk} + \lambda_{jl,s} \alpha_{l,sk}$, where $\delta_{jl,sk} = 1$ if $(j,s) = (l,k)$ and zero otherwise. This implies that, for a given $s \in \mathcal{K}^M$,

$$\begin{aligned}\sum_{n,k} \Omega_{sn,k} X^C_{n,k} = \sum_{n,k} \left(\chi_{n,sk} - \sum_{j,l} \chi_{jl,sk} \lambda_{ln,k} \right) X^C_{n,k} &= \sum_{n,k} \left(\delta_{sk} + \alpha_{n,sk} \right) X^C_{n,k} - \sum_{n,k} \sum_{j,l} \left(\delta_{jl,sk} + \lambda_{jl,s} \alpha_{l,sk} \right) \lambda_{ln,k} X^C_{n,k} \\ &= \sum_n X^C_{n,s} + \sum_{n,k} \alpha_{n,sk} X^C_{n,k} - \sum_n X^C_{n,s} - \sum_{n,k} \sum_l \alpha_{l,sk} \lambda_{ln,k} X^C_{n,k} \\ &= \sum_{n,k} \left(\alpha_{n,sk} - \sum_l \alpha_{l,sk} \lambda_{ln,k} \right) X^C_{n,k}.\end{aligned}$$

If countries that use intensively mining goods in production (i.e. high $\alpha_{l,sk}$) are net exporters of non-mining goods, then trade would lead to the use of more mining goods and more emissions.

B Hat Algebra

$$\hat{P}_{n,k}^{-\theta_k} = \sum_l \lambda_{ln,k} \hat{A}_{l,k} \left(\hat{\tau}_{ln,k} \hat{w}_l^{\alpha_{l,\ell k}} \prod_{h \in \mathcal{K}^M} \hat{p_h}^{\alpha_{l,hk}} \prod_{h \notin \mathcal{K}^M} \hat{P}_{l,h}^{\alpha_{l,hk}} \right)^{-\theta_k}$$

For $s \notin \mathcal{K}^M$,

$$\hat{\lambda}_{ln,k} = \frac{\hat{A}_{l,k} \left(\hat{w}_l^{\alpha_{l,\ell k}} \hat{\tau}_{ln,k} \prod_{h \in \mathcal{K}^M} \hat{p_h}^{\alpha_{l,hk}} \prod_{h \notin \mathcal{K}^M} \hat{P}_{l,h}^{\alpha_{l,hk}} \right)^{-\theta_k}}{\sum_j \lambda_{jn,k} \hat{A}_{j,k} \left(\hat{w}_j^{\alpha_{l,\ell k}} \hat{\tau}_{jn,k} \prod_{h \in \mathcal{K}^M} \hat{p_h}^{\alpha_{j,hk}} \prod_{h \notin \mathcal{K}^M} \hat{P}_{j,h}^{\alpha_{j,hk}} \right)^{-\theta_k}},$$

while for $s \in \mathcal{K}^M$,

$$\hat{Y}_{j,s}^s = \hat{M}_{j,s} \left(\hat{p}_s \hat{w}_j^{-\alpha_{j,\ell s}} \prod_{k \in \mathcal{K}^M} \hat{p_k}^{-\alpha_{j,ks}} \prod_{k \notin \mathcal{K}^M} \hat{P}_{j,k}^{-\alpha_{j,ks}} \right)^{\frac{1}{\nu}}.$$

Changes in final expenditure are given by

$$\hat{X}_l^f X_l^f = w_l L_l \hat{w}_l \hat{L}_l + \nu \sum_{s \in \mathcal{K}^M} Y_{l,s}^s \hat{Y}_{l,s}^s + \hat{\xi}_l \xi_l,$$

while changes in expenditure are

$$\hat{X}_{l,k} X_{l,k} = \mu_{l,k} X_l^f \hat{X}_l^f + \sum_{s \in \mathcal{K}^M} \alpha_{l,ks} Y_{j,s}^s \hat{Y}_{l,s}^s + \sum_{s \notin \mathcal{K}^M} \alpha_{l,ks} \left(\sum_n \lambda_{jl,s} \hat{\lambda}_{jl,s} X_{l,s} \hat{X}_{l,s} \right).$$

Gross output changes for $s \notin \mathcal{K}^M$ are given by

$$\hat{Y}_{l,s} Y_{l,s} = \sum_n \lambda_{ln,s} X_{n,s} \hat{\lambda}_{ln,s} \hat{X}_{n,s},$$

while for $s \in \mathcal{K}^M$ they are given by

$$\sum_j Y_{j,s} \hat{Y}_{j,s} = \sum_n X_{n,s} \hat{X}_{n,s}.$$

Finally, labor market clearing in country l entails

$$w_l L_l \hat{w}_l \hat{L}_l = \sum_s \alpha_{l,\ell s} Y_{l,s} \hat{Y}_{l,s}.$$

C Data Appendix

C.1 Additional Data Details

For the marginal extraction cost data we use from Welsby et al. (2021), the underlying data sources include BP, Rystad, the Energy Information Agency, the National Energy Technology Laboratory, the Organization of Petroleum Exporting Countries, the International Energy Agency, and the German Federal Institute for Geosciences and Natural Resources (BGR). In cases where reports from multiple data sources disagree, e.g., oil resources in Venezuela, Canada, and the Middle East, or gas resources in Russia, the authors utilize the measures that most closely follow definitions of proved resource reserves from the Society of Petroleum Engineers.

C.2 Expanding Energy Sectors in WIOD

We apportion the aggregated energy industries in WIOD into their subcategories to have a higher level of detail in terms of energy commodities. We use Exiobase to provide additional energy sector detail, as follows. For each WIOD sector containing energy, we expand the sector into the associated Exiobase more detailed energy sectors. We allocate the proportion of costs for a given country-industry pair from WIOD into these energy sectors using the cost shares from Exiobase. We then assume that the input cost shares of each energy sector within mining are equal and that the the same for the Electricity, Gas, and Steam aggregate sector. This procedure ensures that the resulting input-output table satisfies the required accounting identities.

Specifically, we associate WIOD's "Mining and Quarrying" sector with four Exiobase sectors: "Mining of coal and lignite; extraction of peat" (p10), which is our coal extraction sector; "Extraction of crude petroleum and services related to crude oil extraction, excluding surveying" (p10a), which is our oil extraction sector; and "Extraction of natural gas and services related to natural gas extraction, excluding surveying" and "Extraction, liquefaction, and re-gasification of other petroleum and gaseous materials" (p11.b and p11.c), which is our gas extraction sector; and Exiobase's extraction sectors for uranium, iron, copper, nickel, aluminum, precious metals, lead, zinc, other mining, and quarrying stone, sand, and clay (p12, p13.1, p13.20.11, p13.20.12, p13.20.13, p13.20.14, p13.20.15, p13.20.16, p14.1, p14.2, p14.3), which is our Other Mining sector.

Finally, we associate WIOD's "electricity, gas, steam and air conditioning supply" sector with Exiobase electricity (p40.11.a through p40.11.f plus p40.12 and p40.13), Exiobase "manufacture of gas; distribution of gaseous fuels through mains," which is our processed gas sector (p40.2); and "steam and hot water supply; water collection, purification, and distribution" (p40.3 and p.41), which we leave as another sector.

Table 6: List of sectors.

american

englishSector Code	englishSector Description
englishA	englishAgriculture
englishB10	englishCoal*
englishB11	englishNatural Gas*
englishB12	englishCrude petroleum*
englishB13	englishNon-energy mining and quarrying
englishC10T12	englishManufacture of food products, beverages and tobacco products
englishC13T15	englishManufacture of textiles, wearing apparel and leather products
englishC16	englishManufacture of wood and of products of wood and cork, except furniture; manufacture of articles of stra
englishC17T18	englishManufacture of paper and paper products & Printing and reproduction of recorded media
englishC19	englishManufacture of coke and refined petroleum products
englishC20T21	englishManufacture of chemicals and chemical products & Manufacture of basic pharmaceutical products and p
englishC22	englishManufacture of rubber and plastic products
englishC23	englishManufacture of other non-metallic mineral products
englishC24	englishManufacture of basic metals
englishC25	englishManufacture of fabricated metal products, except machinery and equipment
englishC26T28	englishManufacture of computer, electronic and optical products & Manufacture of electrical equipment & Manufacture of machinery and equipment n.e.c.
englishC29T30	englishManufacture of motor vehicles, trailers and semi-trailers, and other transport equipment
englishC31T33	englishManufacture of furniture; other manufacturing & Repair and installation of machinery a
englishD35A	englishElectricity
englishD35B	englishGas distribution
englishF	englishConstruction
englishG	englishWholesale and retail trade
englishH	englishTransportation and Storage
englishI	englishAccommodation and food service activities
englishJ	englishInformation and communications
englishKL	englishReal estate activities + Real estate activities
englishMTN	englishProfessional, scientific, technical activities, and administration activities
englishPQRSTUOTE	englishEducation, health, social work, other services, households for own use and Activities of extraterritorial organizations and bodies, defense, englishWater collection, waste management, sewage, Steam and air conditioning supply

Notes: (*) indicates fossil fuel extraction sectors.

english

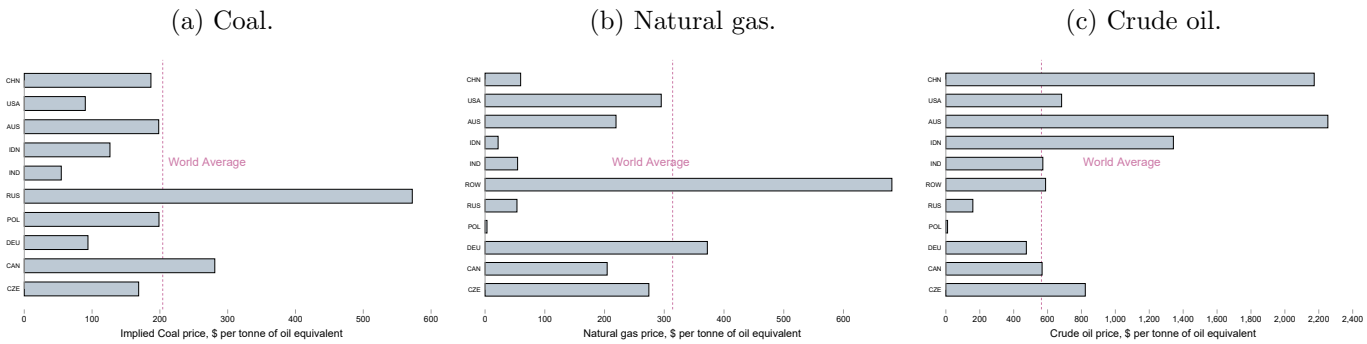
american

Table 7: Accounting for carbon emissions, by country and measure.

Country Name	Country Code	Extraction	Production(S1)	Production (S3)	Consumption
Australia	AUS	1,365	286	375	424
Austria	AUT	9	57	81	90
Brazil	BRA	471	495	632	724
Canada	CAN	1,013	585	634	696
China	CHN	9,072	10,902	9,670	8,857
Czech Republic	CZE	55	79	86	81
Germany	DEU	103	335	571	716
Denmark	DNK	40	47	76	75
Spain	ESP	29	307	340	337
France	FRA	33	290	481	555
Great Britain	GBR	402	533	708	799
Greece	GRC	7	72	56	75
Croatia	HRV	54	33	25	32
Hungary	HUN	3	43	51	52
Indonesia	IDN	920	397	518	540
India	IND	394	1,128	1,200	1,155
Italy	ITA	50	259	366	417
Japan	JPN	192	1,448	1,742	1,775
Korea	KOR	32	680	777	648
Mexico	MEX	422	246	392	408
Netherlands	NLD	130	10	158	148
Norway	NOR	698	201	199	227
Poland	POL	200	259	243	256
Romania	ROM	43	95	105	104
Rest of the world	ROW	12,774	10,468	9,648	8,886
Russia	RUS	2,665	983	919	801
Turkey	TUR	103	123	224	270
United States	USA	3,924	4,845	4,927	6,057
World	WORLD	35,204	35,204	35,204	35,204

Notes: Emissions are in million tons of CO_2. Each column refers to emission assigned according to extraction, production (S1), production (S3), and consumption, using (19).

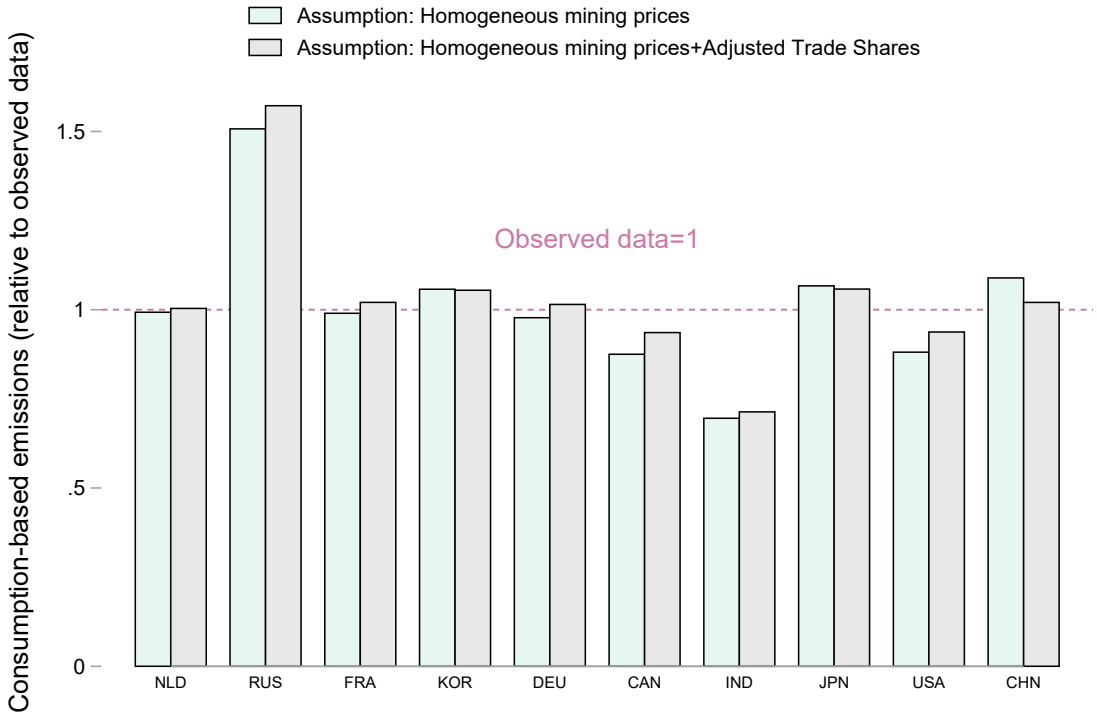
Figure 7: Implied prices for fossil fuels, by country.



Notes: The bars are implied prices for each fossil fuel, $p_{j,s}$, expressed in dollars per ton of oil equivalent, for the top ten producers of each fossil fuel. Prices are calculated as the ratio of gross output in dollars from WIOD to total quantity from IEA, $Y_{j,s}^{WIOD}/Q_{j,s}^{IEA}$. The world average is the average price, weighted by a country's global production share.

D Additional Results

Figure 8: Consumption-based emissions under different assumptions.



Notes: Consumption-based emissions for the top-ten polluting countries. Each bar represents consumption-based emissions relative to emissions implied by heterogeneous prices and no adjustments in trade shares in mining. Light-green bars show results assuming only homogeneous prices, while gray bars also include trade share adjustments.

E Decomposition Emissions

We next use the model to perform a variance decomposition of the consumption-based emission measure to understand the sources of the differences in emissions across countries. As it is standard in the literature, even though we do not model the pattern of emissions across countries at different levels of development, we first decompose emissions per capita into emissions per dollar of consumption and consumption per capita,

$$\underbrace{\ln \frac{\mathcal{E}_n^C}{L_n}}_{\text{emissions per capita}} = \underbrace{\ln \frac{\mathcal{E}_n^C}{X_n^C}}_{\text{emissions per \$ of consumption}} + \underbrace{\ln \frac{X_n^C}{L_n}}_{\text{\$ consumption per capita}} . \tag{42}$$

We can regress each term from the right-hand side on emissions per capita (the left-hand side); these coefficients sum to one. The first coefficient captures the variation in log emissions per capita coming from

Table 8: Effects of Global Autarky, by Country.

Country	Δ_n^P	Δ_n^S	Δ_n^B	Observed Emissions	Autarky Emissions	% change in emissions	Net exports Fossil fuels	Net exports All sectors	% change in real GDP	% ch in w
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(1
Australia	85	-95	-1	424	414	-2.32	79,632	-1,741	-7.3	-7
Austria	-44	-23	4	90	27	-70.19	-7,434	16,126	-16.3	-1
Brazil	-42	-168	-15	724	498	-31.14	752	-47,223	-3.3	-2
Canada	31	-127	8	696	608	-12.63	78,399	18,792	-12.0	-1
China	-1,459	2,047	527	8,857	9,972	12.59	-185,439	583,854	-3.7	-3
Czech Republic	-30	2	9	81	62	-24.33	-5,043	19,169	-23.4	-2
Germany	-133	-434	86	716	235	-67.20	-32,567	389,853	-10.3	-1
Denmark	-26	-17	7	75	38	-48.80	-738	26,674	-15.8	-1
Spain	-149	-72	2	337	117	-65.31	-42,545	6,778	-9.3	-9
France	-173	-212	-3	555	167	-69.97	-36,269	-15,446	-20.5	-2
Great Britain	-159	-148	-5	799	487	-39.08	-12,913	-18,828	-8.5	-8
Greece	-24	-29	-6	75	16	-78.42	-12,043	-18,225	-11.5	-1
Croatia	-5	1	0	32	28	-12.87	864	321	-16.4	-1
Hungary	-28	-9	5	52	19	-63.29	-5,829	10,769	-28.4	-2
Indonesia	14	-96	5	540	463	-14.32	32,464	7,630	-7.0	-6
India	-264	-87	-1	1,155	803	-30.48	-96,595	-2,184	-4.1	-3
Italy	-111	-160	15	417	160	-61.47	-34,016	68,703	-6.6	-6
Japan	-1,630	685	-28	1,775	802	-54.80	-154,366	-71,612	-8.2	-8
Korea	-434	-122	71	648	164	-74.76	-101,567	135,150	-15.4	-1
Mexico	-26	-81	2	408	303	-25.72	35,624	6,632	-11.1	-1
Netherlands	8	-165	26	148	16	-89.01	19,540	123,667	-21.8	-2
Norway	37	-39	34	227	260	14.34	75,897	62,348	-10.5	-1
Poland	-75	-3	10	256	188	-26.50	-12,419	19,041	-17.5	-1
Romania	-32	0	1	104	72	-30.53	-8,074	990	-13.0	-1
Rest of the world	43	1,132	-577	8,886	9,485	6.73	451,361	-975,407	-10.1	-1
Russia	243	-53	57	801	1,047	30.80	164,058	114,886	-10.4	-1
Turkey	-14	-145	7	270	118	-56.44	-1,772	19,607	-11.3	-1
United States	-399	-1,105	-163	6,057	4,390	-27.52	-188,963	-480,322	-3.4	-3
World	-4,798	476	76	35,204	30,959	-12.06	0.0	0.0		

Notes: Observed and autarky consumption-based emissions. % change in emissions refers to $\left(\mathcal{E}_n^A/\mathcal{E}_n^C - 1\right) * 100$. Δ_n^P is the price channel, Δ_n^S is the demand channel, and Δ_n^B is the trade imbalance channel, in equation (30). Net exports are in US dollars. Welfare changes are given by equation (27) with $\gamma\mathcal{E}/W = 0.04$.

Table 9: Effects of Trade Liberalization on Emissions, by Country.

Country	Δ_n^{PP}	Δ_n^X	Δ_n^S	Emissions with $\xi_n = 0$	Emissions with lower trade costs	% change in emissions
	(1)	(2)	(3)	(4)	(5)	(6)
Australia	18.8	1.6	26.5	420	467	11.18
Austria	4.7	7.1	12.5	98	123	24.60
Brazil	29.1	-18.4	65.6	689	765	11.06
Canada	30.4	27.5	24.6	694	777	11.88
China	444.2	-380.7	-776.4	9525	8812	-7.48
Czech Republic	4.7	10.1	-0.9	94	108	14.76
Germany	40.3	24.5	169.6	863	1097	27.18
Denmark	4.1	9.0	8.0	86	107	24.54
Spain	15.6	11.1	25.9	341	394	15.38
France	25.2	26.0	76.2	555	683	22.95
Great Britain	35.7	34.2	59.4	791	920	16.34
Greece	2.9	1.8	10.0	65	79	22.71
Croatia	1.7	2.2	-1.2	33	36	8.54
Hungary	3.0	9.0	2.2	59	73	23.77
Indonesia	23.8	-9.7	32.9	545	592	8.63
India	52.8	-10.8	-49.9	1143	1135	-0.68
Italy	18.8	2.0	71.9	449	542	20.64
Japan	75.1	-27.7	53.3	1711	1812	5.89
Korea	33.0	23.4	-2.7	747	801	7.18
Mexico	17.3	5.5	15.6	403	441	9.53
Netherlands	9.4	23.6	40.0	187	260	38.94
Norway	10.8	1.3	9.2	273	294	7.83
Poland	14.2	19.7	-9.7	273	297	8.89
Romania	5.0	5.7	-2.1	106	114	8.08
Rest of the world	361.9	108.2	-405.8	8171	8235	0.79
Russia	44.3	-5.4	-1.9	876	913	4.22
Turkey	13.9	10.7	31.3	284	340	19.69
United States	230.8	-85.9	440.7	5682	6268	10.31
World	1571.3	-174.4	-75.2	35163	36485	3.76

Notes: Change in emissions from the equilibrium with trade balance to an equilibrium with 20 percent lower international trade costs, $\left(\mathcal{E}_n^{C,'}/\mathcal{E}_n^{C,B} - 1\right) * 100$. Δ_n^{PP} is the price channel, Δ_n^X is the expenditure channel, and Δ_n^S is the sourcing channel, in Equation (43).

Table 10: The Effects of a Global Carbon Tax.

	% change in country emissions		% change in real GDP		% change in welfare		% of world emissio	
	Extraction tax	Use tax	Extraction tax	Use tax	Extraction tax	Use tax	Extraction	Productio
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Australia	-35.4	-56.8	0.5	-2.6	6.0	4.0	3.88	0.81
Austria	-18.8	-58.9	-0.6	-0.4	4.9	6.2	0.03	0.16
Brazil	-17.8	-47.8	-1.6	-1.0	3.9	5.6	1.34	1.40
Canada	-19.7	-46.7	-3.7	-2.2	1.7	4.4	2.88	1.66
China	-45.3	-69.1	-2.4	-3.4	3.0	3.1	25.77	30.97
Czech Republic	-41.0	-61.0	-1.8	-1.4	3.7	5.2	0.16	0.23
Germany	-34.6	-43.7	-0.8	-0.2	4.7	6.5	0.29	0.95
Denmark	-13.2	-62.3	-0.3	-1.0	5.2	5.6	0.11	0.13
Spain	-39.3	-55.4	-0.8	0.0	4.7	6.7	0.08	0.87
France	-22.8	-47.4	-0.5	-0.3	5.0	6.4	0.09	0.82
Great Britain	-24.7	-55.2	-0.7	-1.0	4.9	5.6	1.14	1.51
Greece	-38.2	-39.6	-3.3	1.6	2.1	8.4	0.02	0.21
Croatia	-49.2	-58.1	-4.0	-3.5	1.4	3.0	0.15	0.09
Hungary	-27.3	-39.3	-4.8	-0.4	0.6	6.2	0.01	0.12
Indonesia	-34.4	-50.2	0.1	-2.8	5.7	3.7	2.61	1.13
India	-28.9	-62.1	-1.2	-0.9	4.3	5.7	1.12	3.20
Italy	-17.0	-35.1	-2.0	-0.1	3.4	6.5	0.14	0.74
Japan	-54.0	-60.3	-1.2	-0.6	4.4	6.1	0.55	4.11
Korea	-39.3	-50.7	-1.7	0.1	3.8	6.7	0.09	1.93
Mexico	-12.1	-50.0	0.0	-1.8	5.5	4.8	1.20	0.70
Netherlands	-14.7	7.0	0.0	-0.6	5.5	6.0	0.37	0.03
Norway	-16.4	-14.2	-20.5	-3.2	-15.8	3.4	1.98	0.57
Poland	-40.5	-59.2	-2.4	-1.5	3.1	5.1	0.57	0.74
Romania	-34.6	-57.6	-2.1	-1.4	3.4	5.2	0.12	0.27
Rest of the world	-31.0	-63.1	-2.6	-3.0	2.9	3.5	36.29	29.73
Russia	-34.9	-71.9	1.9	-3.0	7.5	3.5	7.57	2.79
Turkey	-39.4	-49.8	-1.5	-1.1	4.0	5.5	0.29	0.35
United States	-23.7	-38.6	-5.1	-0.8	0.3	5.9	11.15	13.76
World	-33.2	-59.6	-2.3†	-1.3†	3.2†	5.3†	100	100

Note: The tax is calculated as $t_s = scc \times e_s$ where $scc = 100\$/\text{ton } CO_2$, for $s \in \mathcal{K}^M$, and applied to all countries. For the extraction tax, we report changes in extraction-based emissions, while for the production tax, we report changes in production-based emissions (scope 1). Extraction emissions are calculated using (34), production (scope 1) emissions are calculated using (35). Welfare is calculated using Equation (27). (†): Average across countries.

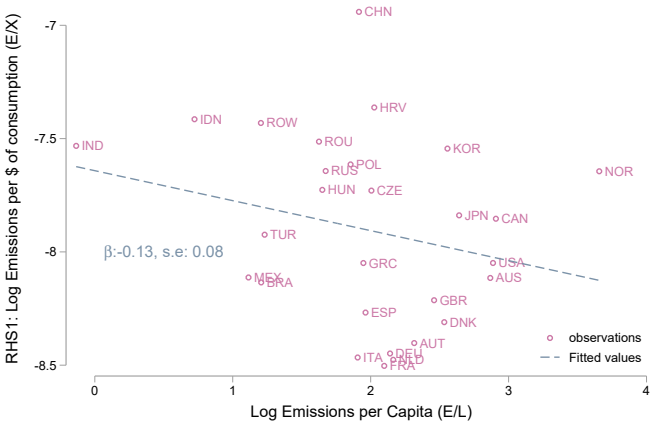
Table 11: The Effects of a Unilateral Carbon Tax.

	% change in world emissions		Leakage		% of world emissions	
	Extraction tax	Use tax	Extraction tax	Use tax	Extraction	Production (S1)
	(1)	(2)	(3)	(4)	(5)	6)
Australia	-0.915	-0.313	0.731	0.407	3.88	0.81
Austria	-0.004	-0.048	0.727	0.537	0.03	0.16
Brazil	-0.204	-0.390	0.728	0.501	1.34	1.40
Canada	-0.456	-0.547	0.715	0.440	2.88	1.66
China	-9.432	-16.28	0.559	0.176	25.77	30.97
Czech Republic	-0.041	-0.088	0.736	0.423	0.16	0.23
Germany	-0.067	-0.234	0.746	0.574	0.29	0.95
Denmark	-0.013	-0.037	0.777	0.606	0.11	0.13
Spain	-0.021	-0.241	0.736	0.581	0.08	0.87
France	-0.016	-0.194	0.752	0.594	0.09	0.82
Great Britain	-0.220	-0.516	0.693	0.386	1.14	1.51
Greece	-0.005	-0.030	0.744	0.777	0.02	0.21
Croatia	-0.047	-0.053	0.689	0.144	0.15	0.09
Hungary	-0.002	-0.030	0.728	0.586	0.01	0.12
Indonesia	-0.625	-0.354	0.703	0.444	2.61	1.13
India	-0.241	-1.148	0.737	0.442	1.12	3.20
Italy	-0.022	-0.158	0.744	0.573	0.14	0.74
Japan	-0.207	-1.540	0.545	0.379	0.55	4.11
Korea	-0.023	-0.455	0.743	0.626	0.09	1.93
Mexico	-0.136	-0.174	0.746	0.592	1.20	0.70
Netherlands	-0.046	-0.001	0.785	0.935	0.37	0.03
Norway	-0.224	-0.162	0.761	0.409	1.98	0.57
Poland	-0.149	-0.305	0.738	0.384	0.57	0.74
Romania	-0.029	-0.094	0.715	0.405	0.12	0.27
Rest of the world	-9.049	-13.148	0.576	0.267	36.29	29.73
Russia	-1.813	-1.285	0.722	0.330	7.57	2.79
Turkey	-0.075	-0.150	0.733	0.319	0.29	0.35
United States	-2.241	-4.116	0.658	0.403	11.15	13.76

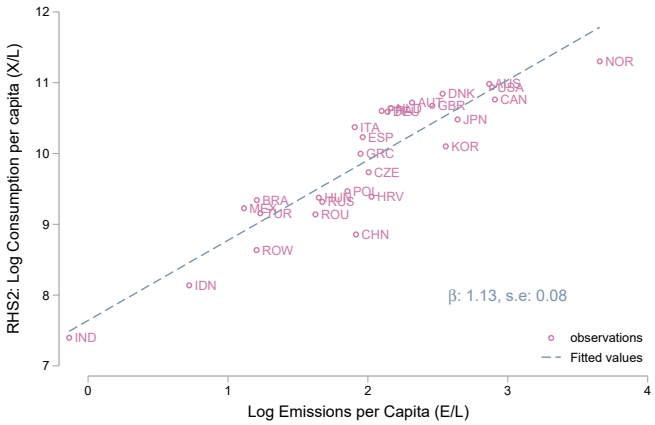
Note: The tax is calculated as $t_s = scc \times e_s$ where $scc = 100\$/\text{ton } CO_2$, for $s \in \mathcal{K}^M$, and applied to one country at the time. For the extraction tax, we report changes in extraction-based emissions, while for the production tax, we report changes in production-based emissions (scope 1). Extraction emissions are calculated using (34), production (scope 1) emissions are calculated using (35). Welfare is calculated using Equation (27).

Figure 9: Consumption-based emissions: variance decomposition.

(a) Emissions per $ of consumption: -0.13.



(b) Consumption expenditure ($) per capita: 1.13.



Notes: Graphs show a decomposition of consumption-based emissions. The left panel shows the first term in (42), while the right panel shows the second term in (42).

emissions per dollar of consumption, while the second coefficient captures the variation in log emissions per capita coming from consumption expenditure (in dollars) per capita.

Figure 9 reports results.

Emissions per dollar of consumption account for -13% of the variance in overall emissions per capita (left panel). while consumption per capita explains 113% of the variance (right panel). This comparison suggests that countries with lower emissions intensity per unit of consumption tend to have higher overall emissions per capita. This trend is partly due to large nations like Russia, India, and China, which despite their lower emissions per capita, have high emissions per dollar consumed due to their less efficient energy use in consumption. Conversely, EU countries have high consumption per capita which leads to high emissions per dollar consumed. However, they use energy more efficiently as they have low emissions per dollar.

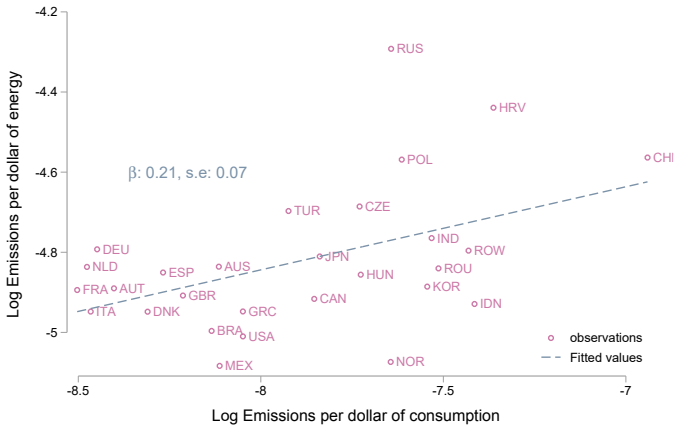
We can further decompose emissions per dollar of consumption (i.e. the first term in (42)) into two components: emissions per dollar of fossil fuels used; and emissions coming from fossil fuel expenditure per dollar of consumption,

$$\underbrace{\ln \frac{\mathcal{E}_n^C}{X_n^C}}_{\text{emissions per \$ of consumption}} = \underbrace{\ln \sum_s \frac{\sum_{j,l,k} \frac{e_s}{p_s} \chi_{jl,sk} \lambda_{ln,k} X_{n,k}^C}{\sum_{s \in \mathcal{K}^M} \sum_{j,l,k} \chi_{jl,sk} \lambda_{ln,k} X_{n,k}^C}}_{\text{emissions per \$ of fossil fuel}} + \underbrace{\ln \frac{\sum_{s \in \mathcal{K}^M} \sum_{j,l,k} \chi_{jl,sk} \lambda_{ln,k} X_{n,k}^C}{X_n^C}}_{\text{fossil fuel expenditure per \$ of consumption}}. \tag{43}$$

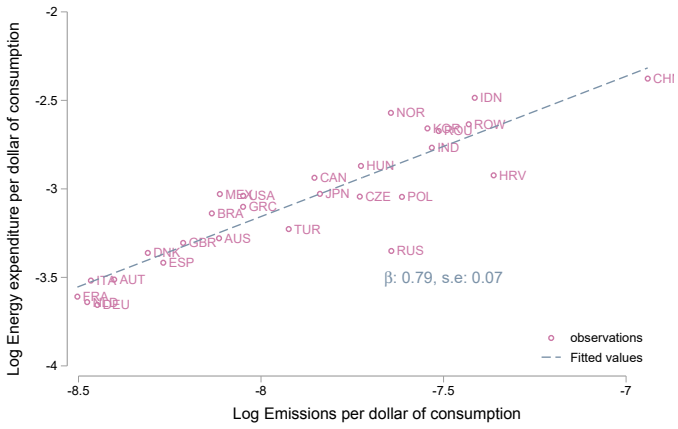
The first term is reflects a country's the fossil fuel mix. The second term reflects a country's overall expenditure on fossil fuels. Figure 10 shows the results. The first term in (43) explains 21 percent of the variation across countries in emissions per dollar. The second term captures the remaining 79 percent of the variation. This result indicates that the variability in emissions per dollar of consumption

Figure 10: Consumption-based emissions: variance decomposition.

(a) Emissions per $ of fossil fuel used: 0.21.



(b) Energy expenditure per $ of consumption: 0.79.



Notes: Consumption-based emissions. Left panel shows the first term in (43), while the right panel shows the second term in (43).

across countries mostly reflects differences in the share of expenditure devoted to fossil fuels, rather than differences in the types of fossil fuels a country uses. Countries like France and Germany have low emissions per dollar of consumption both because they use cleaner types of energy and send a lower share of expenditure on fossil fuels. The types of fossil fuels matter more in coal-dependent countries like China, India, and Indonesia.

Summing up, richer countries have higher emissions per capita. However, they have lower emissions per dollar of consumption because fossil fuels account for a lower share of their expenditure and because they use cleaner fossil fuels.

Although these decompositions provide informative measures on how to allocate emissions responsibilities across countries, and speak to the sources of variation across countries, they do not take into account how equilibrium variables, such as fossil fuel prices, would respond to a change in policy, such as a reduction of trade costs. Section 5 uses the model, which accounts for equilibrium effects, to study counterfactual scenarios.