

Carbon Taxes in the Global Economy: A Quantitative Analysis*

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Abstract

We develop a quantitative model of trade, sectoral linkages, and carbon emissions, with fossil fuel markets playing a central role. These goods, produced from natural resources and traded globally, exhibit upward-sloping supply. We use the model to account for carbon emissions, quantify the impact of trade shocks on emissions and welfare, and to derive and evaluate optimal carbon tax instruments implemented at different stages of the global value chain. We compare, alone and in combination, an extraction tax on fossil fuel mining, a production tax on the direct use of fossil fuels, and consumption and export taxes on the use of fossil fuels in intermediate and final goods. We show how each tax instrument affects direct and indirect emissions and how global value chains reorganize endogenously in response. We estimate fossil fuel supply elasticity using mine-level data across world regions, and show that a \$100 per ton CO₂ global carbon tax would cut emissions by nearly half and raise welfare by 1.4 percent. Unilateral optimal production taxes induce substantial leakage. A unilateral optimal consumption tax that affect direct and indirect emissions along the global value chains can reduce leakage and yield greater global welfare gains. Pairing unilateral consumption and extraction taxes yields larger welfare gains than implementing either tax in isolation, whereas adding export taxes to the mix produces only modest additional benefits—except when imposed by China, where the effects are substantial.

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Introduction

Trade, carbon, and energy policy are increasingly intertwined. Europe has introduced the first carbon-based import tariff (the Carbon Border Adjustment Mechanism, or CBAM). In response, many other countries are debating implementation of their own CBAMs. More broadly, global climate negotiations fiercely debate each country’s contribution to and responsibility for carbon emissions. Fragmented national policies raise concerns about “leakage,” as production shifts to less regulated regions.

A central issue in these debates is how to measure and account for the fossil fuels embodied in intermediate goods circulating through global value chains (GVCs). This issue arises both from the wide cross-country variation in the fossil-fuel intensity of producing final and intermediate goods and from concerns about carbon leakage when unilateral carbon policies are implemented. Consequently, there is growing interest in carbon taxes designed to affect the indirect use of fossil fuels along GVCs. A country able to impose such a tax could potentially reduce leakage and achieve larger reductions in global emissions. At the same time, general-equilibrium responses in fossil fuel markets may critically shape the magnitude of carbon leakage.

Although recent work has begun adopting quantitative models to study the interactions between trade and the environment, fossil fuel markets and their role on GVCs are often absent. This paper contributes by developing a quantitative trade model that explicitly incorporates fossil fuel markets and sectoral linkages to examine how international trade and GVCs shape the design and effectiveness of optimal climate policies. With fossil fuels and input–output linkages at its core, the model enables the design and quantification of optimal carbon taxes that target both the direct and indirect use of fossil fuels along GVCs.

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 moving to autarky on carbon emissions. Third, we derive optimal carbon taxes at different stages of the GVC and quantify their effects on emissions, real income, and welfare.

Our framework is based on a quantitative model of trade and carbon emissions. Three mining sectors – coal, natural gas, and crude oil – use natural resources for production, generating upward-sloping supply curves. Unlike most trade-energy frameworks, which assume that fossil fuels are differentiated, we assume that fuels are homogeneous and freely tradable. 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, and we allow for carbon taxes applied at the point of extraction, production, or consumption, as well as taxes on the carbon content of imports and exports, which play a critical role in carbon border adjustment mechanisms. These assumptions provide a transparent framework for tracking emissions through GVCs and yield counterfactual results that are straightforward to interpret.

Our approach contrasts with most of the literature, which typically models pollution as a reduced-form byproduct of production (Copeland and Taylor, 1994). Instead, we treat emissions as the outcome of explicit decisions about fossil fuels use in production. Consistent with the science of carbon emissions

from homogeneous Earth elements, we assume that emissions per physical unit of fossil fuel are constant across counterfactuals. At the same time, emissions per unit of output can vary depending on inputs choices in production, reflecting substitution between fossil fuels and other factors. In this framework, fossil fuel prices adjust endogenously to clear global supply and demand.

Additionally, our approach allows for the implementation of carbon tax instruments at multiple stages of the GVC, enabling us to study their optimal design and effects. Specifically, we consider taxes on fossil fuel extraction—made possible by explicitly modeling fossil fuel markets—, taxes on direct fossil fuel use in production, and consumption taxes that target both the direct and indirect use of fossil fuels embedded in goods. These last taxes can transmit upstream across the GVC, rendering prices and trade shares specific to the GVC end point destination—a feature we build into the framework. We derive conditions under which these tax instruments, individually or in combination, maximize global efficiency in the presence of environmental externalities, both under globally coordinated taxation and when a single country or coalition acts unilaterally.

We quantify the model by compiling a wide array of existing data and estimating one key parameter. We combine data from the World Input Output Database (WIOD) (Timmer et al. 2015) and Exiobase (Lenzen et al. 2012) 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 mine-level cost schedules across several world regions from Welsby et al. (2021) to estimate the global supply elasticity of coal, natural gas, and crude oil. The average supply elasticity across the three fossil fuels is of around 3. This elasticity is an important parameter for our quantitative analysis as it governs general equilibrium price responses of fossil fuels.

We begin the analysis by presenting model-based carbon accounting calculations that allocate emissions responsibilities to countries according to extraction of fossil fuels, the direct use of fossil fuels in consumption or production, or the direct and indirect use of fossil fuels in consumption. We use these accounting measures to measure leakage and to compute optimal taxes; they are also directly relevant to climate negotiations.

Following research on the gains from trade, we quantify the impact of international trade on emissions by comparing observed emission levels with those under an autarky counterfactual. We find that international trade increases global emissions relative to autarky by 5.7 percent. While autarky represents an extreme scenario, it helps clarify channels through which trade affects emissions. Our results depend on the fossil fuel supply elasticity: With flat supply curves, trade increases emissions by only 0.34 percent. This result suggests that changes in the price of fossil fuels are a key mechanism through which trade affects emissions: trade decreases fossil fuel prices in fuel importing countries, increasing their emissions, while higher prices exporting countries do not balance out this shift.

We then use the model to derive optimal carbon taxes. We consider three tax instruments that parallel the three emission-accounting metrics mentioned above: extraction, production, and consumption taxes.

An extraction tax targets fossil fuel producers; a production tax applies to fossil fuels used directly in production and consumption; and a consumption tax covers fossil fuels used throughout the global value chain ending in final consumption. We also consider taxes on the carbon emissions associated with imports and exports, as these are necessary for a CBAM, as well as optimal combinations of carbon taxes.¹

We first characterize the taxes that achieve global efficiency. If a global tax is available, then an extraction, production or consumption tax at a rate equal to the global social cost of carbon (SCC) achieves the first best, since this is a Pigouvian tax. If instead only a single country or a subset of countries implements carbon taxes, we show that the globally efficient rate for each tax is the SCC scaled by one minus the leakage rate.² Intuitively, higher leakage decreases environmental benefits while preserving economic distortions, reducing the optimal tax rate. Using an intuition similar to [Kortum et al. \(2023\)](#), a combination of extraction, consumption, and export carbon taxes can reduce leakage, increasing welfare.

We quantify the effects of both optimal global and optimal single-country carbon taxes, assuming a global SCC of \$100 per ton of CO₂. A global tax on extraction, production or consumption reduces emissions by around 45 percent, and increases welfare by 1.4 percent relative to baseline global GDP. Consumption decreases by around one percent on average, with heterogeneous effects across countries. For example, due to terms-of-trade effects, net exporters of fossil fuels gain from a global extraction tax, but lose from a global production or consumption tax. Net fossil fuel importers have opposite patterns. The upward-sloping supply curve for fossil fuels shapes the effects of a global carbon tax. A decomposition of the aggregate effects shows that the reduction in emissions would be 50 percent larger with perfectly elastic supply of fossil fuels, compared to our baseline estimates. With either a production or consumption tax, this difference arises because, in response to the global decline in fossil fuel demand, world fossil fuel prices fall, which weakens the tax incentive to reduce fossil fuel use. With extraction tax, the difference arises because, in response to the global decline in fossil fuel supply, world fossil fuel prices increase, which weakens the tax incentive to reduce fossil fuel production.

When only one or a subset of countries imposes the taxes, the optimal tax rate and its effectiveness vary significantly by tax type and country. By taxing emissions along the entire global value chain, a consumption tax most effectively limits leakage, which is twice as large under extraction or production taxes. As a result, when considering the optimal tax that each country in isolation would impose (assuming other countries set taxes to zero), the average optimal policy is most stringent for consumption taxes,

¹A consumption tax is close to CBAM as it is equivalent to a production tax and an import tax of the same magnitude, supplemented by an export subsidy to undo the production tax on exports.

²Global efficiency is the obvious goal for a global tax, but it is also a natural objective to consider for a tax imposed by a single country. Countries' climate policies are often guided by global considerations. Many countries reference the global social cost of carbon (SCC) when setting carbon taxes, as documented by [OECD \(2021\)](#). This feature aligns with evidence that carbon taxes often exceed country-specific damage estimates. [Kotchen 2018](#) rationalize this policy through a repeated game framework, where countries internalize the global SCC expecting future cooperation. Focusing on global efficiency also allows the planner abstracting from terms-of-trade effects and focusing exclusively on solving the environmental externality, which is the main goal of most environmental policies.

with \$70 per ton of CO₂, followed by \$42 for production, and \$35 for extraction taxes. Taxes applied to a single country are more effective when large economies impose them. For example, a production tax levied in China, which accounts for over 30 percent of global production emissions, results in a leakage rate of 32 percent, while the same policy in France leads to substantially higher leakage. In general, production taxes are more effective when applied by major producers, and extraction taxes are most effective when implemented by large fossil fuel exporters.

When consumption taxes are applied to one country in isolation, they decrease global emissions and increase global welfare more than other taxes do. A consumption tax in China cuts global emissions by 11.5 percent and generates welfare gains of 0.43 percent relative to initial GDP, while the same policy by the EU reduces emissions by 2.4 percent and generates welfare gains of 0.07 percent relative to initial GDP. In contrast, a production tax in the EU yields only a one percent emissions reduction and a global welfare gain of 0.04 percent. Since the consumption tax closely resembles a CBAM, these results highlight the potential gains from shifting toward such policies.

Finally, we examine carbon taxes that combine demand- and supply-side instruments, specifically, a consumption, export, and extraction taxes applied to one country at the time. The combined approach consistently delivers higher global welfare gains than any single instrument alone. While a consumption tax applied to any single country generally yields better global welfare outcomes than a production tax, combining it with an extraction tax further enhances gains. For example, the combined US taxes generate global welfare gains that are 40 percent higher than the gains from a consumption tax alone. Further adding an optimal export tax does not deliver a large quantitative difference, except if the three taxes were applied to a large exporter like China. Taken together, these results suggest that as countries move toward consumption-based climate policies, they may achieve additional gains by also incorporating supply-side measures targeting fossil fuel extraction.

We build on the growing literature on quantitative models of trade and the environment. Like much of that literature, our model allows for many sectors and for a sectoral input-output structure, as in [Costinot and Rodríguez-Clare \(2014\)](#) and [Caliendo and Parro \(2015\)](#). A few papers include mining sectors using natural resources in fixed supply, as we do. [Farrokhi and Lashkaripour \(2023\)](#), [Bourany 2024](#), and [Farrokhi et al. \(2025\)](#) allow for a freely-tradable energy resource produced under decreasing returns to scale. They follow the standard approach of assuming differentiated (Armington) energy varieties, while we assume that each fossil fuel is homogenous, an approach with easily interpretable implications. [Egger and Nigai \(2014\)](#) model energy markets explicitly, but their analysis is restricted to flat supply curves for fossil fuels, and does not distinguish among the different fossil fuels (e.g., coal versus gas), or among different non-mining sectors, which misses the heterogeneity embedded in the world input-output table. [Larch and Wanner \(2017\)](#), [Caliendo et al. \(2024\)](#), and [Moigne et al. \(2024\)](#) adopt an abatement approach, as originally proposed by [Copeland and Taylor \(1994\)](#), and assume constant sectoral emission intensity. This framework abstracts from explicit modeling of fossil fuel markets, and therefore does not directly link responses in these markets to changes in emissions. As discussed above, this omission overlooks the price channel and prevents endogenous adjustments in sectoral emission intensity in response to

shocks—channels that are quantitatively important for assessing the impact of trade shocks and carbon policies. Since the supply elasticity for fossil fuels turns out to be critical in these models, our contribution is to provide estimates for coal, natural gas, and crude oil, separately, and to show quantitatively that this is a key parameter when evaluating the effect of trade shocks and environmental policies.

Our design of optimal carbon taxes using a model based on fossil fuel markets is related to [Kortum et al. \(2023\)](#). While they present analytical results for optimal taxes in a stylized model, we use a quantitative trade model and exact hat algebra methods to compute optimal taxes and quantify their effects on emissions and welfare. [Farrokhi and Lashkaripour \(2023\)](#) and [Bourany 2024](#) also evaluate quantitatively different carbon policies. Their analysis centers on climate clubs, carbon taxes, terms-of-trade effects, and the associated political economy. In contrast, our focus is on globally efficient carbon tax schemes that can affect the direct and indirect use of fossil fuel along GVCs. By incorporating intermediate goods and input–output linkages, our model can capture how endogenous GVC responses affect the effectiveness of climate policies.

An industrial ecology literature, distant from international trade research, measures 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,” and 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. Unlike this literature, we provide theory-grounded aggregate measures and decompositions of carbon emissions according to where energy is extracted, used in production, and consumed.³

The paper proceeds as follows. Section 1 presents the model, and Section 2 presents the analysis of optimal carbon taxes. Section 3 describes the data. Section 4 discusses carbon accounting. Section 5 presents the estimation of fossil fuel supply elasticities. Section 6 analyzes the autarky counterfactual. Section 7 analyzes optimal carbon taxes. Section 8 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). Only these fossil fuels generate CO₂ emissions, reflecting the fact that together they are responsible for about 75% of global greenhouse gas emissions ([Ge et al. 2024](#)).

Non-mining goods are differentiated by origin (*à la* Armington), and traded internationally incurring iceberg-trade costs. Fossil fuels, in contrast, are homogeneous and freely traded internationally, but may face *per-unit* carbon taxes. Mining goods are produced using labor and a natural resource (“mines”)

³Because ours is a general equilibrium model, counterfactual exercises account for all adjustments in prices and quantities. This approach differs from accounting analyses, such as [Davis and Caldeira \(2010\)](#), which use the Leontief inverse of a global multi-region input-output table to learn about the emissions embodied in traded goods, but they do not study the equilibrium outcome under a specific counterfactual.

specific to each mining sector, and non-mining goods are produced with labor and intermediate goods as in [Caliendo and Parro \(2015\)](#).⁴ All markets are perfectly competitive.

Our assumption that fossil fuels are homogeneous departs from most of the literature, which assumes Armington differentiation (e.g. [Caliendo and Parro, 2022](#); [Moigne et al., 2024](#)). The homogeneity assumption is convenient and matches several realistic features of fossil fuel markets. First, fossil fuels are relatively undifferentiated—many are traded on spot markets, and estimated demand elasticities are high, ranging from 25 to 45 ([Fontagne et al. 2022](#)). Second, differentiation leads to implausible implications: high-priced varieties would bear lower ad valorem carbon taxes despite emitting the same CO₂ per unit, inducing sharp and unrealistic reallocations. Third, the homogeneity assumption yields more transparent tax incidence and counterfactual results. Finally, there are data reasons to assume homogeneous prices for fossil fuels—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 (see [Appendix D](#)). However, when analyzing the effects on emissions, it is important to model separately the three fossil fuels since the quantity of CO₂ emissions they each produce are very different—coal is the dirtiest while natural gas is the cleanest.

1.1 Setup

The economy is composed of multiple countries indexed by $i, j, l, n = 1, \dots, N$ and multiple sectors indexed by $k, s, r \in \mathcal{K} \equiv \{1, \dots, K\}$. 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, indices i and l represent the countries where production of non-mining goods takes place, and n is mostly reserved to denote the country of final consumption. Country j is endowed with L_j units of labor and $M_{j,s}$ mines that can only be used for $s \in \mathcal{K}^M$.

Each country has a representative agent with indirect utility function

$$V_n(P_n, X_n^C, \mathcal{E}) = \frac{X_n^C - \gamma_n \mathcal{E}}{P_n}, \quad (1)$$

where X_n^C and P_n are final expenditure and the consumer price index in n , and γ_n denotes the dollar-valued damages to country n from worldwide emissions \mathcal{E} (i.e., the national social cost of carbon in terms of the numeraire), with $\gamma \equiv \sum_l \gamma_l$, the global social cost of carbon. Letting $P_{n,s}$ denote the price or price index of good s in country n , the consumer price index in n reflects Cobb-Douglas preferences and is given by $P_n = \prod_s P_{n,s}^{\mu_{n,s}}$, with $\mu_{n,s} \in [0, 1]$ and $\sum_s \mu_{n,s} = 1$.

Mining sectors and emissions. The production of mining good $s \in \mathcal{K}^M$ uses mines m and labor ℓ according to

$$q = m^{\alpha_{j,s}} \left(\frac{\ell}{1 - \alpha_{j,s}} \right)^{1 - \alpha_{j,s}}, \quad (2)$$

⁴We use the terms mining goods and fossil fuels interchangeably.

with $\alpha_{j,s} \in [0, 1]$. 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.⁵

Carbon emissions result exclusively from the use of mining goods in production and consumption. Emissions from the use of one unit of mining good s equal an “engineering” constant $e_s > 0$. Letting $q_{j,s}$ denote output (in quantities) of mining good s in country j , global carbon emissions are then

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

Non-mining sectors. Within each non-mining sector $s \notin \mathcal{K}^M$, Armington varieties are aggregated assuming a constant elasticity of substitution (CES) $\sigma_s > 1$. This aggregate good is then consumed or used as an input to produce 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 according to

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

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 and $s \notin \mathcal{K}^M$.

Varieties of non-mining goods are subject to iceberg trade costs: $\tau_{ln,s} \geq 1$ units of $s \notin \mathcal{K}^M$ need to be shipped from l so that one arrives in n . The triangular inequality holds, $\tau_{jn,s} \leq \tau_{jl,s} \tau_{ln,s}$, for all j, l, n and $s \notin \mathcal{K}^M$, and we assume that $\tau_{nn,s} = 1$ for all n and $s \notin \mathcal{K}^M$.

Carbon Taxes. We allow for several types of *per-unit* carbon taxes. Specifically, we allow for *mining taxes*, which are levied directly on carbon emissions associated with mining goods extracted; *production taxes*, which are levied directly on carbon emissions from the use of fossil fuels in domestic production and consumption; *consumption taxes*, which are levied on the carbon emissions in the whole global value chain (GVC) ending with domestic final consumption; *import taxes*, which are levied on the carbon emissions in foreign links of GVCs ending with domestic consumption; and *export taxes*, which are levied on the carbon emissions in the domestic links of GVCs ending with final consumption abroad. These per-unit taxes on carbon are in dollars per metric ton of carbon emitted multiplied by the factor e_s introduced above.

We denote mining, production, consumption, import and export taxes by $t_j^M, t_l^P, t_n^C, t_n^I$, and t_l^X . In the presence of these taxes, producers of good s in country j are paid the price $p_s - e_s t_j^M$, where p_s is the international price of mining good s . The purchase price in country l for a good used in the GVC ending

⁵Although 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 and use a static model. This choice allows us to capture rich geographic and input-output linkages while abstracting from the long-run dynamics of climate change. 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 upward-sloping supply curve for resources. Our calibration of γ_n uses independent estimates of the social cost of carbon derived from integrated assessment models that also incorporate long-term effects.

in destination n is $p_s + e_s (t_l^P + t_n^C + \mathbb{I}_{l \neq n} t_n^I + \mathbb{I}_{n \neq l} t_l^X)$, where \mathbb{I} is the indicator function (i.e., $\mathbb{I}_{l \neq n} = 1$ if $l \neq n$ and $\mathbb{I}_{l \neq n} = 0$ otherwise). Importantly, prices of mining goods used as inputs in production now depend both on the country where production takes place as well as the GVC endpoint.

1.2 Model Equilibrium

Letting w_j denote the wage in country j and recalling that the endowment of mines for s in j is $M_{j,s}$, the supply curve of s in country j is

$$Y_{j,s} \equiv (p_s - e_s t_j^M) q_{j,s} = M_{j,s} (p_s - e_s t_j^M)^{\frac{1}{\alpha_{j,s}}} w_j^{-\frac{1-\alpha_{j,s}}{\alpha_{j,s}}}. \quad (5)$$

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

$$\Pi_{j,s} = \alpha_{j,s} Y_{j,s}. \quad (6)$$

For non-mining goods $s \notin \mathcal{K}^M$, the supply curve in country l for GVCs ending in country n is perfectly elastic at unit cost

$$p_{l,n,s} = A_{l,s}^{-1} w_l^{\alpha_{l,s}} \prod_{k \in \mathcal{K}^M} (p_k + e_k \bar{t}_{l,n})^{\alpha_{l,ks}} \prod_{k \notin \mathcal{K}^M} P_{l,n,k}^{\alpha_{l,ks}},$$

where $\bar{t}_{l,n} \equiv t_l^P + t_n^C + \mathbb{I}_{l \neq n} t_n^I + \mathbb{I}_{n \neq l} t_l^X$, and $P_{l,n,k}$ denotes the price index of non-mining input $k \notin \mathcal{K}^M$ faced by producers in l who are part of GVCs ending in n .⁶ Crucially, when consumption, import or export carbon taxes are in place, these price indices depend on the GVC endpoint n , since the prices producers face for their intermediate goods vary with the destination of the GVC.⁷

Given our CES assumption for varieties of non-mining goods, these price indices satisfy

$$P_{l,n,k}^{1-\sigma_k} = \sum_i [\tau_{il,k} p_{i,n,k}]^{1-\sigma_k}, \quad (7)$$

where $\tau_{il,k}$ are trade costs to ship non-mining good k from i to l . Trade shares also depend on the point of final consumption. Specifically, the share of expenditure by country l on non-mining good k for GVCs ending in n that is allocated to origin i is

$$\lambda_{il,n,k} = \frac{(\tau_{il,k} p_{i,n,k})^{1-\sigma_k}}{P_{l,n,k}^{1-\sigma_k}}. \quad (8)$$

Expenditure on any good s in country l comes from both final consumption and demand for intermediate goods used in production. Recalling that X_l^C denotes final expenditure in country l , gross

⁶The consumption price index in n for non-mining good k is $P_{n,k} \equiv P_{n,n,k}$.

⁷Without consumption, import and export taxes the previous equation takes the more standard form $p_{l,s} = A_{l,s}^{-1} w_l^{\alpha_{l,s}} \prod_{k \in \mathcal{K}^M} (p_k + e_k t_l^P)^{\alpha_{l,ks}} \prod_{k \notin \mathcal{K}^M} P_{l,k}^{\alpha_{l,ks}}$.

expenditure in sector s by country l for GVCs ending in country n is

$$X_{l,n,s} = \mathbb{I}_{l=n} \mu_{l,s} X_l^C + \sum_{k \notin \mathcal{K}^M} \alpha_{l,sk} Y_{l,n,k}, \quad (9)$$

where $Y_{l,n,k}$ denotes gross output (in value) of non-mining good k produced in country l for GVCs ending in n . While the first term on the right-hand side of equation (9) captures final expenditure in s by l and is non-zero only for GVCs ending in l (i.e., for $l = n$), the second term captures demand in l for s as an input in production of non-mining goods k for GVCs ending in n .

Final expenditure equals the sum of wages, rents, carbon taxes revenues, and international transfers,

$$X_l^C = w_l L_l + \sum_{s \in \mathcal{K}^M} \alpha_{j,s} Y_{l,s} + \Upsilon_l + \Lambda_l. \quad (10)$$

As in [Dekle et al. \(2008\)](#), exogenous transfers Λ_l are needed in our static model to account for trade imbalances, while transfers Υ_l are endogenous and funded from the revenues collected from carbon taxes. These revenues are given by

$$T_l = \sum_{s \in \mathcal{K}^M} e_s \left(t_l^M q_{l,s} + \sum_n t_l^P q_{l,n,s} + \sum_i t_l^C q_{i,l,s} + \sum_{i \neq l} t_l^I q_{i,l,s} + \sum_{n \neq l} t_l^X q_{l,n,s} \right),$$

where

$$q_{l,s} = \frac{Y_{l,s}}{p_s - e_s t_l^M} \quad (11)$$

is the *quantity produced* of $s \in \mathcal{K}^M$ in l and

$$q_{l,n,s} = \frac{X_{l,n,s}}{p_s + e_s \bar{t}_{l,n}} \quad (12)$$

is the *quantity used* of $s \in \mathcal{K}^M$ in l for GVCs ending in n .

The standard assumption has these tax revenues rebated to consumers in the same country, $\Upsilon_l = T_l$. While our model can accommodate essentially any system of transferring carbon tax revenues across countries, we also consider a simple rule in which global carbon tax revenues are distributed in proportion to the damages from carbon emissions across countries, $\Upsilon_l = (\gamma_l / \gamma) \sum_l T_l$.

A competitive equilibrium satisfies three sets of market-clearing conditions. The market clearing condition for non-mining good $s \notin \mathcal{K}^M$ produced in country l for GVCs ending in country n is

$$Y_{i,n,s} = \sum_l \lambda_{il,n,s} X_{l,n,s}. \quad (13)$$

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

$$\sum_j q_{j,s} = \sum_{l,n} q_{l,n,s}. \quad (14)$$

Finally, labor market clearing in each country l entails

$$w_l L_l = \sum_s \alpha_{l,\ell s} Y_{l,s}, \quad (15)$$

where $\alpha_{l,\ell s} = 1 - \alpha_{l,s}$ for $s \in \mathcal{K}^M$ and $Y_{l,s} = \sum_n Y_{l,n,s}$ for $s \notin \mathcal{K}^M$.

A competitive equilibrium given taxes is a set of good prices, sectoral price indices, gross expenditures and revenues, and trade shares for non-mining goods, $\{p_{l,n,s}, P_{l,n,s}, \lambda_{j,l,n,s}, X_{l,n,s}, Y_{l,n,s}\}_{s \notin \mathcal{K}^M}$, world mining-good prices, $\{p_s\}_{s \in \mathcal{K}^M}$, quantities and revenues for mining goods, $\{q_{j,s}, q_{l,n,s}\}$, final expenditure and wages, $\{X_n^C, w_l\}$, such that equations (5)-(15) are satisfied.

1.3 Emissions

We allocate global emissions across countries according to extraction, production, and consumption. We first calculate global emissions by substituting mining output in equation (11) into equation (3). Extraction-based emissions reflect the fossil fuels each country extracts,

$$\mathcal{E}_j^M = \sum_{s \in \mathcal{K}^M} e_s q_{j,s}. \quad (16)$$

Production-based emissions reflect where fossil fuels are used in production,

$$\mathcal{E}_l^P = \sum_{s \in \mathcal{K}^M} \sum_n e_s q_{l,n,s}. \quad (17)$$

Also called ‘‘Scope 1’’ emissions, the expression in (17) is the most common measure of emissions used in research and policy. For example, widely-used datasets like WIOD or the Global Trade and Analysis Project (GTAP) report $\mathcal{E}_{l,s}^P$ by sector.⁸

Equation (23) helps relate our modeling of emissions to that of the abatement approach in the literature, which assumes that pollution is an input to production. We can rewrite equation (23) using that

$$q_{l,n,s} = \frac{X_{l,n,s}}{p_s + e_s \bar{t}_{l,n}} = \frac{\mathbb{I}_{l=n} \mu_{l,s} X_l^C}{p_s + e_s \bar{t}_{l,n}} + \sum_{k \notin \mathcal{K}^M} \frac{\alpha_{l,sk} Y_{l,n,k}}{p_s + e_s \bar{t}_{l,n}}.$$

Hence,

$$\mathcal{E}_l^P = \sum_{s \in \mathcal{K}^M} e_s \frac{\mu_{l,s} X_l^C}{p_s + e_s (t_l^P + t_l^C)} + \sum_{s \notin \mathcal{K}^M} \mathcal{E}_{l,k}^P, \quad (18)$$

⁸Final consumption of mining good $s \in \mathcal{K}^M$ in country l are included in $q_{l,l,s}$. Equation (9) implies that $q_{l,l,s} = \frac{X_{l,l,s}}{p_s + e_s (t_l^P + t_l^C)} = \frac{\mu_{l,s} X_l^C}{p_s + e_s (t_l^P + t_l^C)} + \frac{\sum_{k \notin \mathcal{K}^M} \alpha_{l,sk} Y_{l,l,k}}{p_s + e_s (t_l^P + t_l^C)}$. The first term on the right-hand side is final consumption of mining good s , while the second term is the use of s as an intermediate good for non-mining production for domestic GVCs.

where the first term refers to emissions produced by household, and the second term are emissions related to the use of fossil fuels in non-mining sector k ,

$$\mathcal{E}_{l,k}^P \equiv \sum_{s \in \mathcal{K}^M} e_s \sum_n \frac{\alpha_{l,sk} Y_{l,n,k}}{p_s + e_s \bar{t}_{l,n}}.$$

Papers such as [Caliendo et al. \(2024\)](#) and [Moigne et al. \(2024\)](#) use data on scope 1 production emissions and output value in industry k and country l to calculate sectoral emissions per unit of output at baseline, which are directly observed in the data. Equation (18) reveals that sectoral emission intensities change with the price of fossil fuels as well as with carbon taxes. For example, with only production carbon taxes, this intensity would be given by $\tilde{e}_{l,k} \equiv \mathcal{E}_{l,k}^P / (Y_{l,k} / p_{l,k}) = \frac{1}{p_{l,k}} \sum_{s \in \mathcal{K}^M} \frac{e_s}{p_s + e_s \bar{t}_{l,n}^P} \alpha_{l,sk}$. Our approach, consistent with the scientific properties of homogeneous Earth elements, fixes emissions per physical unit of each fossil fuel, e_s , while allowing sectoral emissions intensities $\tilde{e}_{l,k}$ to adjust endogenously in response to shocks.⁹ In this way, we capture within-sector “technique effects,” whereby a sector’s emission intensity declines in response to a carbon tax—effects that are absent under the fixed-intensity approach, where changes occur solely through the reallocation of production across sectors and countries.

Consumption-based emissions reflect final consumption responsible for fossil fuels used along the GVC. As an intermediate step to compute consumption-based emissions, we first solve for gross output levels in terms of final consumption. Substituting equation (9) into (13) yields

$$Y_{i,n,k} = \sum_l \lambda_{in,n,k} \mu_{l,k} X_l^C + \sum_l \sum_{r \notin \mathcal{K}^M} \alpha_{il,n,kr} Y_{l,n,r} \quad \text{for } k \notin \mathcal{K}^M. \quad (19)$$

This is a standard accounting identity—all of country i ’s sales of non-mining good k to GVCs ending in country n either go to final demand or to intermediates. Here, $\alpha_{il,n,kr} \equiv \lambda_{il,n,k} \alpha_{l,kr}$ represents world input-output coefficients for non-mining goods, valued at producer prices, for GVCs ending in country n . Importantly, in the presence of consumption, import or export taxes, input-output coefficients $\alpha_{il,n,kr}$ vary by the country where the GVC ends. Solving for gross output levels yields

$$Y_{i,n,k} = \sum_l \underbrace{\sum_{r \notin \mathcal{K}^M} \chi_{il,n,kr} \lambda_{ln,n,r} \mu_{n,r}}_{\Xi_{il,n,k}} X_n^C \quad \text{for } k \notin \mathcal{K}^M, \quad (20)$$

where $\chi_{il,n,kr} \equiv (I - \{\alpha_{il,n,kr}\})^{-1}$.¹⁰ The term $\Xi_{il,n,k}$ captures the value at producer prices of non-mining good k from i used as an intermediate in the GVCs ending with non-mining goods produced in l for final consumption in n . Emissions associated with mining good s used as an intermediate for GVCs ending

⁹At the observed equilibrium, both approaches should, in principle, yield the same emission intensity (pinned down by the data), with any difference attributable solely to measurement error.

¹⁰The matrix $\{\alpha_{il,n,kr}\}$ is for the non-mining sectors only, so it is a $(K - 3) \times (K - 3)$ matrix.

with non-mining goods produced in l and consumed in n are therefore

$$\mathcal{E}_{ln,s} = e_s \sum_i \frac{1}{p_s + e_s \bar{t}_{i,n}} \sum_{k \notin \mathcal{K}^M} \alpha_{i,sk} \Xi_{il,n,k}, \quad \text{for } s \in \mathcal{K}^M. \quad (21)$$

Multiplying $\Xi_{il,n,k}$ by $\alpha_{i,sk}$ yields the value at user prices of mining good s used for that production. To get to $\mathcal{E}_{ln,s}$ we divide by the user price of s in i , sum over i , and multiply by emissions e_s per unit of mining good s .¹¹ We arrive at consumption-based emissions in country n by summing $\mathcal{E}_{ln,s}$ over all l and all $s \in \mathcal{K}^M$, and then adding the emissions associated with final consumption of fossil fuels,

$$\mathcal{E}_n^C = \sum_{s \in \mathcal{K}^M} \frac{e_s}{p_s + e_s (t_n^P + t_n^C)} \mu_{n,s} X_n^C + \sum_{s \in \mathcal{K}^M} \sum_l \mathcal{E}_{ln,s}. \quad (22)$$

If instead we sum over all n , we arrive at “scope 3” production-based emissions,

$$\mathcal{E}_l^{P3} = \sum_{s \in \mathcal{K}^M} \frac{e_s}{p_s + e_s (t_l^P + t_l^C)} \mu_{l,s} X_l^C + \sum_{s \in \mathcal{K}^M} \sum_n \mathcal{E}_{ln,s}. \quad (23)$$

Consumption-based carbon accounting, \mathcal{E}_n^C , measures the emissions from the fossil fuels embodied in both mining and non-mining final goods *consumed* in country n . In contrast, scope 3 production-based carbon accounting, \mathcal{E}_l^{P3} , measures emissions from fossil fuels embodied in non-mining final goods *produced* in country l plus mining goods directly consumed in l . Both measures account for emissions in the entire GVC of the final goods that a country consumes or produces.

The analysis of optimal taxes also requires measures of import-based and export-based emissions:

$$\mathcal{E}_n^I = \sum_{s \in \mathcal{K}^M} \sum_{l \neq n} e_s q_{l,n,s} \quad (24)$$

$$\mathcal{E}_l^X = \sum_{s \in \mathcal{K}^M} \sum_{n \neq l} e_s q_{l,n,s}. \quad (25)$$

Import-based emissions are associated with fossil fuels used as intermediates in foreign production of non-mining goods for GVCs ending domestically. Export-based emissions are associated with fossil fuels used as intermediates in the production of non-mining goods for GVCs ending abroad. Unlike the other four metrics, import and export-based emissions are not part of the emissions accounting, since they do not sum to global emissions.

To illustrate the difference between the four measures of country-level emissions, consider cars that are purchased by US consumers and produced in Mexico using coal extracted in Canada and steel produced in Brazil. Emissions generated along the whole GVC leading to those cars would be attributed to the US according consumption-based accounting, to Mexico according to production-based accounting (scope 3), and to Canada according to extraction-based accounting. Scope 1 production-based emissions would be

¹¹ $\mathcal{E}_{ln,s}$ refers to emissions generated in value chains ending in final production in l and exported for consumption in n ; the lack of comma is intentional. By contrast, $Y_{i,n,k}$ does not require direct trade between i and n .

attributed both to Mexico and to Brazil—Mexico would be responsible for carbon emitted from burning coal to produce cars, while Brazil would be responsible for the carbon emitted from the fossil fuels used in making the steel used as an input by Mexico to make the cars.

2 Optimal Carbon Taxes

We derive formulas for optimal carbon taxes building on [Costinot and Werning \(2023\)](#) and [Adão et al. \(2024\)](#), who provide necessary conditions for taxes to support a Pareto-efficient allocation in the presence of externalities. Like [Kortum and Weisbach \(2024\)](#), we abstract from terms-of-trade considerations, which are zero-sum globally; [Farrokhi et al. \(2025\)](#) provide analyses incorporating such effects.

Appendix [B.2](#) shows that globally efficient carbon taxes must satisfy

$$\sum_j t_j^M d\mathcal{E}_j^M + \sum_l t_l^P d\mathcal{E}_l^P + \sum_n t_n^C d\mathcal{E}_n^C + \sum_n t_n^I d\mathcal{E}_n^I + \sum_l t_l^X d\mathcal{E}_l^X = \gamma d\mathcal{E}. \quad (26)$$

For global efficiency, emissions must be such that fiscal externalities from carbon taxes, on the left, equal global externalities from carbon emissions, on the right. If taxes fail to satisfy this condition, then a small adjustment would raise global money-equivalent utility.¹²

A carbon tax system may include one or several types of carbon taxes. Let $Z \in \mathcal{T} \equiv \{M, P, C, I, X\}$ index different types of carbon taxes. Equation (26) implies that if the planner can freely choose tax t_l^Z , it must satisfy

$$\sum_{Z' \in \mathcal{T}} \sum_j t_j^{Z'} \frac{\partial \mathcal{E}_j^{Z'}}{\partial t_l^Z} = \gamma \frac{\partial \mathcal{E}}{\partial t_l^Z}. \quad (27)$$

Because extraction, production, and consumption taxes satisfy $\sum_j \mathcal{E}_j^Z = \mathcal{E}$, the preceding formula shows that global efficiency is achieved by setting any one of those taxes equal to the social cost of carbon, $t_j^Z = \gamma$ for all j and $Z \in \{M, P, C\}$. We refer to these taxes as optimal *global* carbon taxes.

Setting carbon taxes in a single country represents the other extreme. In this case, equation (26) implies a simple optimal tax formula in terms of leakage, which is defined as

$$\mathcal{L}_j^Z \equiv 1 - \frac{\partial \mathcal{E} / \partial t_j^Z}{\partial \mathcal{E}_j^Z / \partial t_j^Z}, \quad (28)$$

i.e., one minus the marginal change in global emissions relative to the change in the country imposing the tax. Combined with equation (26), the optimal tax t_j^Z then satisfies

$$t_j^Z = \gamma(1 - \mathcal{L}_j^Z). \quad (29)$$

¹²If international transfers are available, such an adjustment combined with appropriate transfers would make all countries strictly better off. In the absence of transfers its desirability can still be assessed under a specific global welfare criterion – such as the sum of money-equivalent welfare across countries – which again implies that the adjustment is welfare-enhancing.

With zero leakage, the optimal tax equals the global social cost of carbon. Because trade generates leakage, Equation (29) shows that trade decreases optimal taxes. In the extreme of complete leakage, any emissions decrease in the region imposing the tax would be exactly offset by an equivalent increase in emissions in the rest of the world, so that the optimal tax is zero.

For $Z \in \{M, P, C\}$, we can use $\mathcal{E} = \sum_j \mathcal{E}_j^Z$ to rewrite leakage as $\mathcal{L}_j^Z = -\frac{\sum_{i \neq j} \partial \mathcal{E}_i^Z / \partial t_j^Z}{\partial \mathcal{E}_j^Z / \partial t_j^Z}$. An increase in t_j^Z leads to a fall in \mathcal{E}_j^Z , and the leakage captures the offsetting increase in foreign emissions. In the case of $Z \in \{I, X\}$, one can use $\mathcal{E} = \sum_j \mathcal{E}_j^P$ and $\mathcal{E}_j^P + \mathcal{E}_j^I = \mathcal{E}_j^C + \mathcal{E}_j^X$ to rewrite the leakage as $\mathcal{L}_j^Z = -\frac{(\partial \mathcal{E}_i^C / \partial t_i^X - \partial \mathcal{E}_i^I / \partial t_i^X) + \sum_{i \neq j} \partial \mathcal{E}_i^P / \partial t_i^X}{\partial \mathcal{E}_i^X / \partial t_i^X}$. An increase in t_i^X leads to a decline in \mathcal{E}_i^X , but this is offset by the increase in foreign production emissions *and* by emissions generated by domestic production for domestic consumption.

Equation (29) can be easily adjusted to compute the globally efficient tax in j allowing for arbitrary (i.e., not necessarily efficient) taxes in other countries. In this case, equation (26) must still hold, but only for changes in taxes that can be freely chosen. Thus, for example, the globally efficient production tax in country j given arbitrary production taxes in other countries satisfies

$$\sum_l t_l^P \frac{\partial \mathcal{E}_l^P}{\partial t_j^P} = \gamma \frac{\partial \mathcal{E}}{\partial t_j^P}.$$

Equation (29) must still hold, with leakage given by

$$\mathcal{L}_j^Z = -\frac{\sum_{l \neq j} (1 - t_l^P / \gamma) \partial \mathcal{E}_l^P / \partial t_j^P}{\partial \mathcal{E}_j^P / \partial t_j^P}.$$

As in the case of global optimal taxes, some taxes are redundant. Starting from a production tax, adding an import tax and an export subsidy to undo the production tax on exports can replicate an equivalent consumption tax—a carbon-border adjustment tax reflects this idea. Without loss of generality, we focus on optimal carbon tax schemes that combine extraction, consumption, and export taxes. We can again express optimal taxes in terms of leakage. When extraction, consumption, and export taxes are available, we define the leakage from a consumption tax as

$$\mathcal{L}_{j, d\mathcal{E}_j^M = d\mathcal{E}_j^X = 0}^C \equiv 1 - \frac{d\mathcal{E} / dt_j^C |_{d\mathcal{E}_j^M = d\mathcal{E}_j^X = 0}}{d\mathcal{E}_j^C / dt_j^C |_{d\mathcal{E}_j^M = d\mathcal{E}_j^X = 0}}.$$

This expression entails a variation dt_j^M, dt_j^C, dt_j^X such that

$$\sum_{Z \in \{M, C, X\}} \frac{\partial \mathcal{E}_j^M}{\partial t_j^Z} dt_j^Z = \sum_{Z \in \{M, C, X\}} \frac{\partial \mathcal{E}_j^X}{\partial t_j^Z} dt_j^Z = 0,$$

and the optimal consumption tax is then

$$t_j^C = \gamma \left(1 - \mathcal{L}_{j, d\mathcal{E}_j^M = d\mathcal{E}_j^X = 0}^C \right).$$

We can similarly conclude that optimal extraction and export taxes satisfy

$$t_j^M = \gamma \left(1 - \mathcal{L}_{j,d\mathcal{E}_j^C=d\mathcal{E}_j^X=0}^M \right) \quad \text{and} \quad t_j^X = \left(1 - \mathcal{L}_{j,d\mathcal{E}_j^M=d\mathcal{E}_j^C=0}^X \right).$$

In the case in which a coalition of countries, rather than only one country, coordinates on carbon taxes, equation (26) can again be used to characterize optimality. Consider a coalition of countries $\Omega \subset \{1, \dots, N\}$ that agrees to impose uniform carbon taxes to pursue global efficiency, understanding that leakage will occur since countries outside the coalition set zero taxes. If the coalition has access to only one tax, the optimality condition is analogous to equation (29): $t_\Omega^Z = \gamma (1 - \mathcal{L}_\Omega^Z)$, with $\mathcal{L}_\Omega^Z \equiv 1 - \frac{\partial \mathcal{E} / \partial t_\Omega^Z}{\partial \mathcal{E}_\Omega^Z / \partial t_\Omega^Z}$, and $\mathcal{E}_\Omega^Z \equiv \sum_{j \in \Omega} \mathcal{E}_j^Z$, for $Z \in M, P, C$. For a combination of taxes, optimality conditions for a coalition of countries is analogous to the conditions for an individual country.

We do not claim that these taxes implement what a planner with full control of the allocation in country j , or among the coalition Ω , would do. First, we assume a uniform carbon tax across fuels, but heterogeneity in leakage across different fuel types may recommend a deviation from $t^M + t^C \neq \gamma$ —with only one fuel, [Kortum and Weisbach \(2024\)](#) show that $t^M + t^C = \gamma$. Second, while besides the two previous restrictions we have allowed for fully general carbon taxes, full efficiency may require other taxes and subsidies, as [Kortum and Weisbach \(2024\)](#) show. Finally, when a coalition is considered, we restrict taxes to be uniform across members, but leakage may differ across countries, and hence, different taxes may improve efficiency.

3 Data

We combine data from global multi-region input-output tables to build a sample of 28 countries, including a category for the Rest of the World (ROW), and 28 sectors. Appendix Table ?? lists sectors and Appendix Table D3 lists countries.

Our primary data is from the World Input Output Database (WIOD), 2016 release ([Timmer et al. 2015](#)). This dataset includes 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.

Appendix C.1 provides details on how we combine data from WIOD and Exiobase ([Lenzen et al. 2012](#)) to include three mining sectors: coal; natural gas; crude oil. We separate crude from refined oil, and gas mining from gas processing and distribution, to distinguish extraction from processing and distribution activities. To match the structure of the model, we reallocate the intermediate inputs used by the mining sectors in a country to value added, with a corresponding adjustment to final consumption. The procedure is detailed in Appendix C.1.

WIOD also provides Energy Tables with data on the quantities of each fossil fuel used, by country and sector. We aggregate these data to obtain world quantities of each fossil fuel. We use these world quantitative together with the dollar value of world gross output from WIOD to compute the global price for each mining good $s \in \mathcal{K}^M$,

$$p_s = \frac{\sum_j Y_{j,s}^{WIOD}}{\sum_{l,k} q_{l,sk}^{WIOD}}. \quad (30)$$

We obtain $p_{coal} = 204$, $p_{gas} = 314$, and $p_{oil} = 564$ dollars per ton of oil equivalent.¹³

We obtain emissions per physical unit of each fossil fuels, e_s , from the U.S. Energy Information Administration, which reports $e_{coal} = 3.81$, $e_{gas} = 2.06$, and $e_{oil} = 2.94$ tons of CO₂ per tonne of oil equivalent.

The indirect utility in our model incorporates country-specific damages from carbon emissions. We set the global Social Cost of Carbon (SCC) to \$100 per ton of CO₂—our parameter γ .¹⁴ To reflect the heterogeneous distribution of climate damages across countries, we use the country-level SCC estimates, SSC_j , from [Ricke et al. \(2018\)](#), to allocate the global SCC to countries proportionally. Specifically, the country-specific damage parameter is calculated as $\gamma_j = \frac{SSC_j}{\sum_{j'} SSC_{j'}} \gamma$. Appendix Figure A3 shows γ_j for each country.

Finally, to estimate the mining supply elasticity, we use data from [Welsby et al. \(2021\)](#), who provide marginal extraction cost curves for each fossil fuel separately, for 16 regions around the world.¹⁵ The data combine mine- and field-level fossil fuel quantities with estimates of extraction costs by resource type and region—and they do not include transportation costs or taxes.

4 Carbon Emissions Accounting

In this section we use the data described in Section 3 to compute the emissions measures introduced in Section 1.3. Importantly, there were no destination-specific carbon taxes in place in 2014 (i.e., no consumption, import or export carbon taxes), so that $\lambda_{il,n,s} = \lambda_{il,s}$ and $\alpha_{il,n,sk} \equiv \lambda_{il,s} \alpha_{l,sk}$ for all i, l, n and all s, k . Moreover, since carbon taxes were low at this time, we assume that they are equal to zero in our analysis.¹⁶

Figure 1 reports carbon emissions according to our four measures of country emissions in equations (17)-(23), in million tons of CO₂, for selected countries in our sample. We sort countries according to

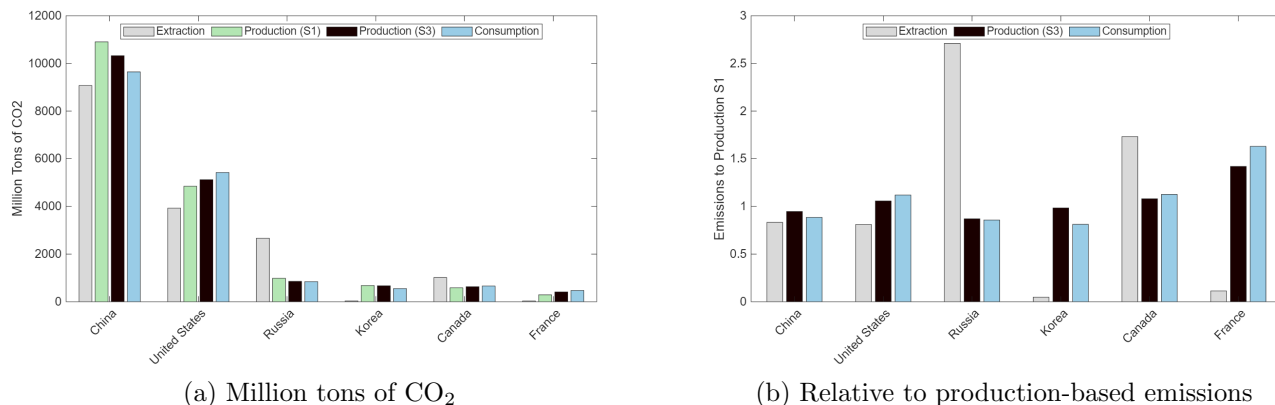
¹³Using a global price for each fossil fuel computed as in equation (30) would match world emissions as reported in the WIOD data, but it will not match production emissions reported for each country individually. Discrepancies, however, are not large. Appendix Figure A2 shows country-level emissions calculated with our methodology and emissions calculated using implied country-level prices. Appendix Figure A1 shows the country-level production prices implied by the WIOD and International Energy Agency (IEA) quantity data ($p_{j,s} = Y_{j,s}^{WIOD}/Q_{j,s}^{IEA}$): there is large variation across countries that we would attribute to measurement error rather than to true differences in prices of a mostly homogeneous good.

¹⁴Recent estimates of the SCC concentrate around \$200, though earlier estimates were concentrated around \$50, with some estimates on a much higher range. Given that our data are for the year 2014, we choose \$100, which is in the middle range of those estimates.

¹⁵[McCollum and Khourdjie \(2021\)](#) 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. \(2016\)](#).

¹⁶According to World Bank Carbon Pricing Database ([World Bank 2015](#)) in 2014 only five countries—Australia, Canada, Korea, Spain, and Norway—had carbon prices exceeding \$30 per ton in 2014. The carbon price under the EU Emissions Trading System was just \$9.50 per ton.

Figure 1: Carbon Accounting, Selected Countries



Notes: Calculations using data from WIOD and equations (16), (17), (22), and (23).

their production emissions, \mathcal{E}_I^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 that echoes previous work (Davis and Caldeira, 2010), and which reflects trade imbalances. Additionally, scope 1 production emissions are lower than scope 3 for the US, while the opposite is true for China, reflecting differences between direct emissions from using fossil fuels, which matter for scope 1 emissions, and emissions embodied in inputs used along the GVC, which matter for scope 3 emissions.

To ease the comparison across measures for each country, the right panel of Figure 1 shows the various measures of emissions relative to scope 1 production emissions. Appendix Table D3, which describes all countries in our sample, confirms several well-known patterns. Net exporters of fossil fuels (e.g., Canada and Russia) 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. In general, the opposite is true for less developed countries.¹⁷

5 Estimation of the Supply Elasticity for Fossil Fuels

The quantitative version of the model requires an estimate of decreasing returns in mining. We assume that $\alpha_{j,s}$ varies across fossil fuel type, but not across countries, $\nu_s \equiv \alpha_{j,s}$. This parameter is isomorphic to the share of natural resources in mining, and is directly related to the supply elasticity of fossil fuels. Estimates are therefore useful not only for our model's calibration, but also for macroeconomic research on energy and climate change more broadly.

¹⁷Appendix E.4 presents two decompositions of consumption-based emissions. The first decomposes the cross-country variance in emissions per capita into differences in emissions per dollar of consumption and in consumption per capita. The second decomposition splits emissions into emissions per dollar of fossil fuel and energy expenditure per dollar of consumption.

Rewriting the mining supply curve in equation (5) in terms of the quantity of mining good s , and inverting it yield

$$\tilde{p}_{j,s} = (q_{j,s})^{\frac{\nu_s}{1-\nu_s}} M_{j,s}^{-\frac{\nu_s}{1-\nu_s}} \left(w_j^{-\alpha_{j,\ell s}} \right)^{-\frac{1}{1-\nu_s}}, \quad (31)$$

where $\tilde{p}_{j,s} \equiv p_s - e_s t_j^M$ is the extraction price of s in country j . Conditional on the wage and the amount of natural resources, $M_{j,s}$, the inverse supply elasticity for fossil fuel s is

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

and hence,

$$\nu_s = \frac{\beta_s}{\beta_s + 1}. \quad (32)$$

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 to estimate the inverse supply elasticity for each fossil fuel s separately, by OLS, using the following equation:

$$\ln \tilde{p}_{vj,s} = \beta_s \ln q_{vj,s} + \mu_{j,s} + \zeta_{vj,s}. \quad (33)$$

Each observation in this regression represents a vertex v describing a region j extracting mining good s . The dependent variable $\ln \tilde{p}_{vj,s}$ 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 the marginal cost of the first unit of fossil fuel s in region j . The error term $\zeta_{vj,s}$ contains any measurement error in the prices of mining goods.

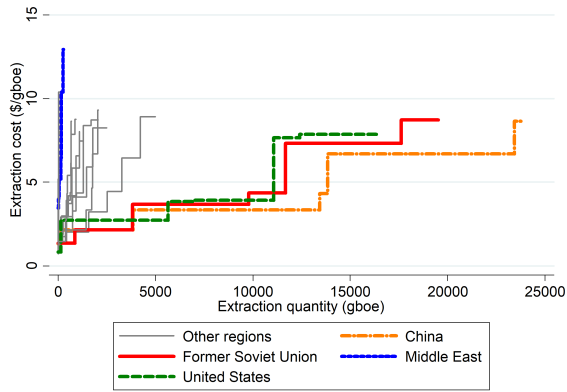
Figure 2 shows the raw data from [Welsby \(2021\)](#). Each panel describes one of the three fossil fuels, and each line describes a region's supply curve.

The supply curves consist of horizontal segments. The left of each curve shows the cheapest sources for each fossil fuel. Moving to the right along each curve progressively adds more expensive sources. The regression in equation (33) interprets flat segments as a data point $(\ln \tilde{p}_{vj,k}, \ln q_{vj,k})$. 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.

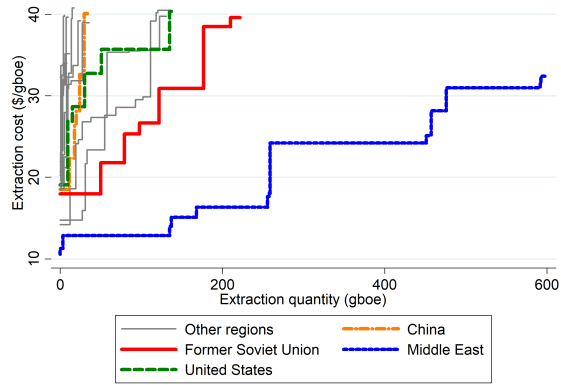
Figure 3 shows the vertex of each line segment from Figure 2, residualized by region and fossil fuel type fixed effects, as well as the estimates of the coefficient β_s .

Our estimates range from 0.32 (0.02) for coal and 0.35 (0.05) for natural gas, to 0.68 (0.01) for oil. Equation (32) implies decreasing returns parameters of $\nu_{Coal} = 0.24$, $\nu_{NGas} = 0.26$, and $\nu_{Oil} = 0.41$. Economically, these estimates imply that natural resources account for a fourth of the cost of fossil fuel extraction for coal and natural gas, and 40 percent for oil. In turn, these estimates of β_s imply supply

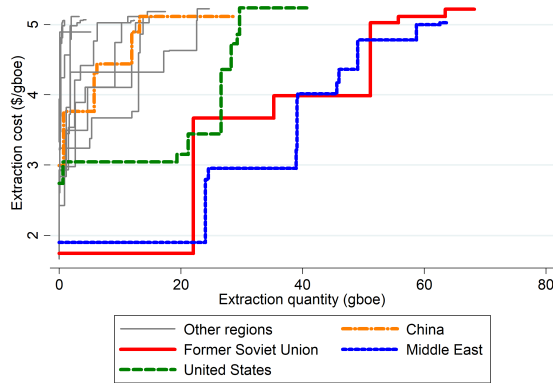
Figure 2: Fossil Fuel Extraction Costs and Quantities



(a) Coal



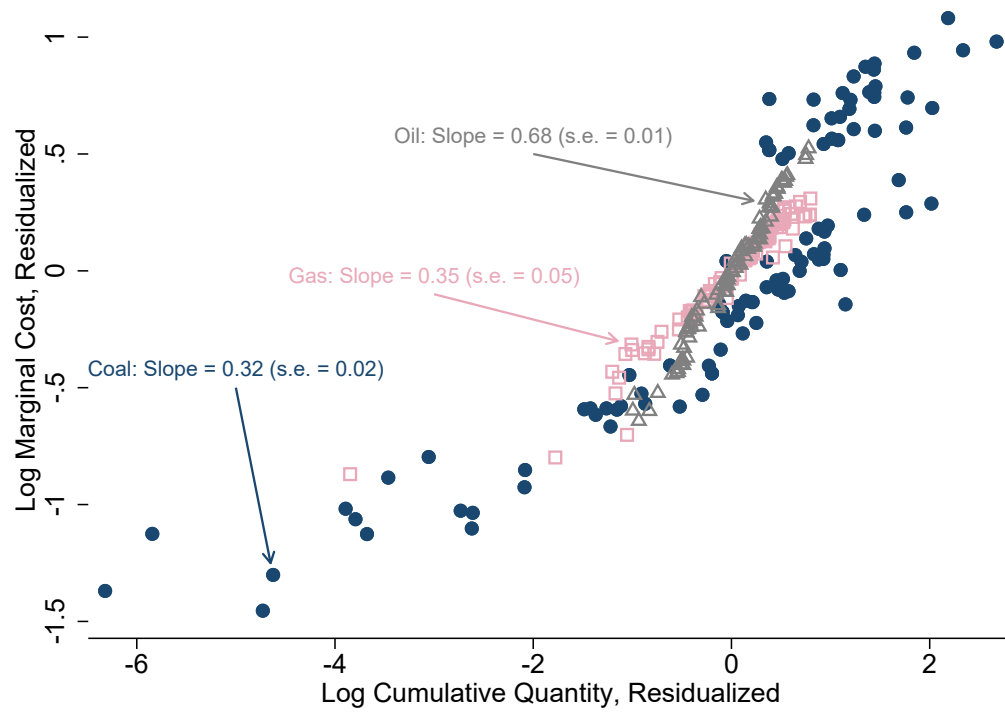
(b) Oil



(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 (31) 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. Standard errors are in parentheses.

elasticities of 3.1 for coal, 2.9 for natural gas, and 1.5 for crude oil. Given these magnitudes—and the estimates in the literature reviewed below—we interpret them as pertaining to long-run elasticities.

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 the effectiveness of a carbon tax in reducing carbon emissions, the literature is scarce and US-focused. [Arora \(2014\)](#) reviews the elasticity assumed in computable general equilibrium 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 \(2012\)](#) review the literature and conclude with estimates of the supply elasticity of 1 for gas and 4 for coal, which are in a similar overall range as our estimates. In recent work, [Farrokhi and Lashkaripour \(2023\)](#) calibrate the cost share of carbon reserves from the value added share of natural resources in the primary energy sectors, from GTAP, with a range of 0.31 to 0.49, similar to ours. [Abuin \(2024\)](#) recovers supply elasticities for gas and coal from IV regressions that exploit shifts in prices coming from changes in electricity demand conditions. Her estimates are around 0.24 for gas and 0.77 for coal. Overall, we view as the most reliable approach in the energy and climate macro literatures to estimate these elasticities using physical estimates of extraction costs across fossil fuel deposits (e.g., [Bornstein et al., 2019](#); [Cruz and Rossi-Hansberg, 2024](#)).

6 Effects of Moving to Autarky

Much of the quantitative trade literature studies the effects of moving to autarky (e.g., [Arkolakis et al., 2012](#)). While this case represents an extreme experiment, we begin by analyzing its effects on emissions, real GDP, and welfare, because it provides a simple way to highlight key mechanisms in the model.¹⁸

We compute the effect of autarky by applying exact hat algebra to the model’s equilibrium conditions ([Dekle et al., 2008](#); [Costinot and Rodríguez-Clare, 2014](#)), as shown in Appendix B.1. As in Section 4, we assume that carbon taxes are zero, avoiding differentiation in trade shares or input shares across GVCs ending in different countries, and, hence, making the exact hat algebra analysis standard.

Appendix B.1 shows how to express emissions under autarky as a function of variables in the observed equilibrium (and the supply elasticity of fossil fuels,

$$\mathcal{E}_n^A = \sum_{s \in \mathcal{K}^M} \mathcal{E}_{n,s}^M \left(\frac{\psi_{n,s} w_n L_n / (1 - \psi_n^M)}{Y_{n,s}} \right)^{1-\nu_s},$$

where $\psi_{n,s} \equiv \mu_{n,s} + \sum_{k,r \notin \mathcal{K}^M} \alpha_{n,sk} \chi_{n,kr} \mu_{n,r}$ is the Domar weight of sector s in autarky, $\{\chi_{n,sk}\} = (I - \{\alpha_{n,sk}\})^{-1}$ is the standard Leontief inverse matrix for non-mining sectors, and $\psi_n^M \equiv \sum_{s \in \mathcal{K}^M} \nu_s \psi_{n,s}$.

We compute the change in consumption-based observed emissions and autarky emissions.¹⁹ Appendix

¹⁸Real GDP and consumption differ due to exogenous international transfers, Λ_n . We report changes in real GDP to avoid having trade imbalances substantially affecting results ([Costinot and Rodríguez-Clare, 2014](#)).

¹⁹The different accounting measures of emissions are all equivalent in autarky. Because baseline emissions differ at the country level depending on the accounting method adopted, changes in emissions due to a move to autarky also differ across accounting

B.1 also shows the expressions for changes in real GDP, $\mathcal{Y}_n \equiv (w_n L_n + \sum_{s \in \mathcal{K}^M} \nu_s Y_{n,s}) / P_n$, from the observed equilibrium to autarky.

Finally, we need a measure of welfare, which adjusts consumption by carbon damages. Applying hat algebra to equation (1) yields

$$\hat{V}_n = \frac{\hat{X}_n^C - \hat{\mathcal{E}}(\gamma_n \mathcal{E} / X_n)}{1 - (\gamma_n \mathcal{E} / X_n)} \frac{1}{\hat{P}_n}. \quad (34)$$

Without trade imbalances ($\Lambda_n = 0$) or carbon damages ($\gamma_n = 0$), the change in real GDP equals the change in welfare, $\hat{V}_n = \hat{\mathcal{Y}}_n$.²⁰

We combine the expressions above with values for $\{\alpha_{l,sk}, \alpha_{l,ls}, \lambda_{ln,s}, p_s, Y_{l,s}, X_l^C, \mu_{l,s}, \Lambda_l\}$ and $\{e_s\}_{s \in \mathcal{K}^M}$, from the data. We use the estimates of ν_s from each $s \in \mathcal{K}^M$ from Section 5, set $\sigma_s = 6$ for all $s \notin \mathcal{K}^M$, from Head and Mayer (2014), and use the estimates of country-level carbon damages, γ_n , described in Section 3.

6.1 Autarky Results

Figure 4 shows the change in each country's consumption-based emissions from moving to autarky, $(\mathcal{E}_n^A / \mathcal{E}_n^C - 1) \times 100$. Appendix Table D4 shows the corresponding numbers.

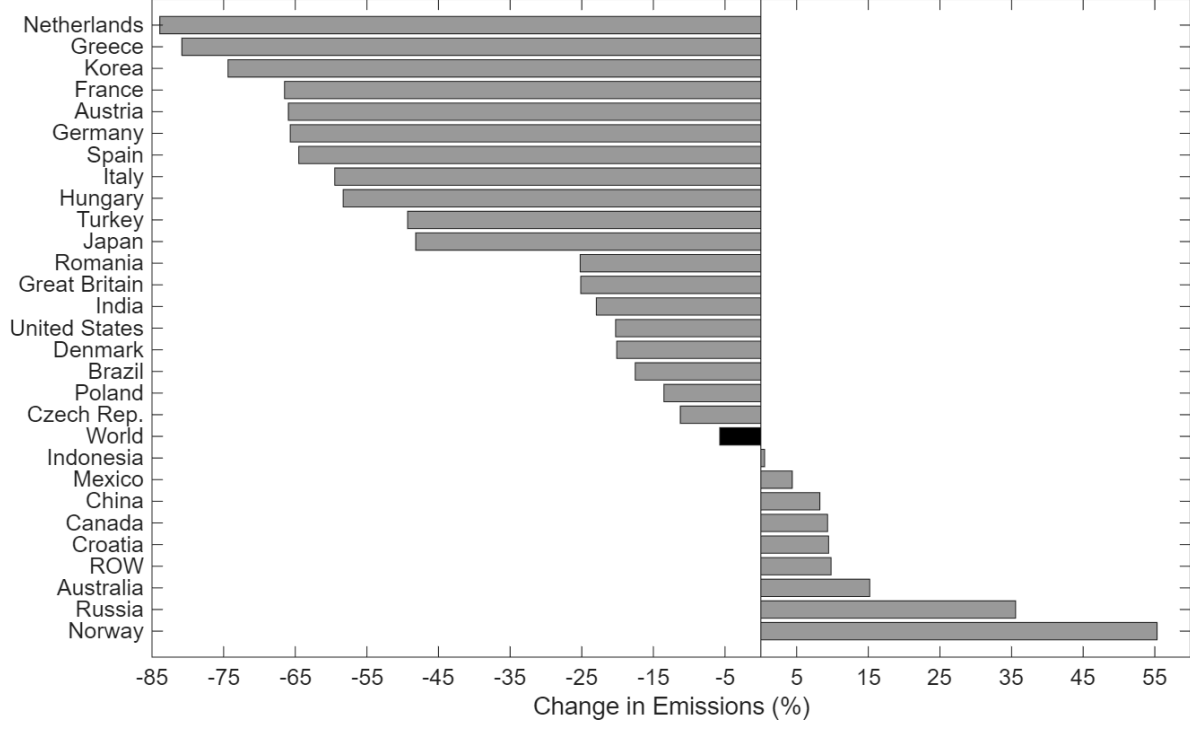
The effect of autarky on consumption-based emissions varies widely across countries. Autarky decreases consumption-based emissions the most in the Netherlands, a small open economy with few domestic fossil resources, by nearly 90 percent. Autarky decreases consumption-based emissions in South Korea, another small open economy with few domestic fuel resources, by nearly 70 percent. At the other extreme, autarky increases consumption-based emissions the most in Norway, a fuel abundant country, by almost 50 percent. Since Norway is a net exporter of mining goods, moving to autarky increases the domestic consumption of its fuel production.

Globally, autarky decreases emissions by five percent, or two billion tons. Autarky increases energy prices in many large countries, leaving energy exporters like Russia and Norway unable to arbitrage high fuel prices abroad. Higher prices lead to lower use of fossil fuels and lower global emissions.

methods.

²⁰Computing \hat{V}_n uses the fact that final expenditure equals GDP in autarky, hence $\hat{X}_n^C = X_n^{C,A} / X_n^C = Y_n^A / X_n^C$. We also use this observation when we compute changes in consumption, \hat{X}_n^C / \hat{P}_n .

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



Notes: Autarky to observed consumption-based emissions, $(\mathcal{E}_n^A/\mathcal{E}_n^C - 1) \times 100$. ROW is rest of world.

To generalize beyond such qualitative explanations, we decompose the effect of autarky on each country's consumption-based emissions:

$$\begin{aligned}
 \mathcal{E}_n^A - \mathcal{E}_n^C &= \underbrace{\sum_{s \in \mathcal{K}^M} e_s \psi_{n,s} \left(\frac{X_n^{C,A}}{p_{n,s}^A} - \frac{X_n^{C,B}}{p_s^B} \right)}_{\Delta_n^{A,1} \equiv \text{Price channel}} \\
 &+ \underbrace{\sum_{s \in \mathcal{K}^M} \frac{e_s}{p_s^B} \sum_{r \notin \mathcal{K}^M} \left(\sum_{k \notin \mathcal{K}^M} \alpha_{n,sk} \chi_{n,kr} - \sum_{i,l} \alpha_{i,sk} \chi_{il,kr}^B \lambda_{ln,r}^B \right) \mu_{n,r} X_n^{C,B}}_{\Delta_n^{A,2} \equiv \text{Sourcing channel}} \\
 &+ \underbrace{\left(\mathcal{E}_n^{C,B} - \mathcal{E}_n^C \right)}_{\Delta_n^{A,3} \equiv \text{Imbalances channel}}.
 \end{aligned} \tag{35}$$

Equation (35) expresses the change in emissions in each country as the sum of three terms.

The imbalances channel $\Delta_n^{A,3}$ measures the change in consumption-based emissions for country n due to shutting down trade imbalances ($\Lambda'_n = 0$ for all n).

The sourcing channel $\Delta_n^{A,2}$ reflects the effect of autarky on sourcing of intermediates, evaluated at final expenditure $X_{n,k}^{C,B}$ and fossil fuel prices p_s^B after removing trade imbalances. The sourcing channel entirely reflects differences in input-output coefficients $\alpha_{n,sk}$ across countries. If $\alpha_{n,sk} = \alpha_{sk}$ for all n , then $\sum_n \Delta_n^{A,2} = 0$. Trade shares $\lambda_{ln,r}^B$ reflect the counterfactual equilibrium after removing trade imbalances, and $\{\chi_{il,kr}^B\} \equiv \{1 - \{\alpha_{i,kr} \lambda_{il,r}^B\}\}^{-1}$.

The price channel $\Delta_n^{A,1}$ reflects effects of autarky on fossil fuel prices. These price changes reflect shifts in fuel demand intersecting upward-sloping fuel supply. Thus, they closely reflect the supply parameter ν . Additionally, fuel price changes affect mining rents and therefore final expenditure, which changes from $X_n^{C,B}$ to $X_n^{C,A}$. Multiplying by the closed-economy Domar weight of each fossil fuel and dividing by the corresponding price gives the implied change in the quantity of each fossil fuel.

Table 1 reports $\Delta_n^{A,1}$, $\Delta_n^{A,2}$, and $\Delta_n^{A,3}$ from equation (35) as a percent of baseline consumption-based emissions for selected countries; Appendix Table D4 shows all countries. The table also reports the implied change in welfare and real GDP.

Table 1 shows that the price channel accounts for most of autarky’s effects on global emissions. The price change decreases global emissions by 5.11 percent, accounting for 95 percent of the total effect of autarky on emissions. The sourcing channel decreases emissions by 0.34 percent, or a six percent decrease relative to baseline. Perhaps unsurprisingly, trade imbalances do not affect global emissions much.²¹ Key to the price channel is the supply elasticity of fossil fuels. If the fuel supply curves were flat ($\nu_s = 0$, for all s), autarky would barely decrease emissions; the sourcing channel would completely account for the autarky’s effects, and the price channel would vanish. Concretely, emissions would decrease by -0.31 percent rather than -5.75 (-5.44-0.31) percent. The sharp contrast between results highlights the importance of allowing for upward-sloping fuel supply curves in understanding how trade affects emissions.

The relative importance of the price and sourcing channels varies by country. Autarky decreases emissions for net fuel importers, like France and Korea, by increasing fuel prices. Although China is a net importer of fuels, autarky increases China’s emissions by nine percent due to a large positive sourcing effect—China’s domestic value chain has greater carbon intensity than the Chinese GVC observed in the data. In contrast, autarky increases emissions for net exporters of fossil fuels, like Canada and Russia, with the sourcing channel offsetting the increase in the case of Canada, but reinforcing it in the case of Russia. Appendix Figure A6 plots systematic versions of these relationships. Panel (a) plots the price channel $\Delta_n^{A,1}$ from equation (35) against net fuel exports, by country. Panel (b) plots the sourcing channel $\Delta_n^{A,2}$ from equation (35) against the ratio of production-based scope 3 to scope 1 emissions, a ratio that captures the relative dirtiness of GVCs due to imported inputs.

Finally, Table 1 shows the effects of autarky on real GDP and welfare; Appendix Table D4 shows all countries. Unsurprisingly, autarky decreases real GDP in all countries, by more than three percent in the US and around 19 percent in France. The decline in emissions makes the autarky welfare loss only slightly smaller globally than the decline in real GDP. This echoes the idea that benefits from international trade

²¹Our analysis of the change in emissions under autarky uses consumption-based emissions. 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 D3 and D4 provide the numbers to perform these calculations.

Table 1: Effect of Global Autarky

Country	Price channel $\% \Delta_n^{A,1}/\mathcal{E}_n^C$ (1)	Sourcing channel $\% \Delta_n^{A,2}/\mathcal{E}_n^C$ (2)	Imbalances channel $\% \Delta_n^{A,3}/\mathcal{E}_n^C$ (3)	% change in emissions (4)	% change in real GDP (5)	% change in welfare (6)
Canada	17.1	-7.72	-0.04	9.32	-10.9	-10.2
China	-8.21	9.19	7.25	8.23	-3.2	2.85
France	-36.7	-30.2	0.32	-66.5	-18.7	-19.2
Korea	-82.8	-6.86	15.2	-74.4	-17.1	-7.93
Russia	26.2	0.19	9.16	35.6	-9.79	-4.72
USA	-4.64	-9.83	-5.81	-20.3	-3.05	-5.54
World	-5.44	-0.31	0.02	-5.73	-6.91	-6.91

Notes: % change in emissions refers to autarky relative to observed consumption-based emissions, $(\mathcal{E}_n^A/\mathcal{E}_n^C - 1) \times 100$. $\Delta_n^{A,1}$ is the price channel, $\Delta_n^{A,2}$ is the sourcing channel, and $\Delta_n^{A,3}$ is the trade imbalance channel, in equation (35), all relative to observed consumption-based emissions. Welfare changes are given by equation (34). World change in real GDP and welfare are calculated using equation (36).

dramatically exceed climate damages due to trade (Shapiro, 2016).

7 Effects of Optimal Carbon Taxes

7.1 Carbon Taxes: Overview and Methodology

This section evaluates how carbon taxes on extraction, production, consumption, imports, and exports affect emissions, real income, and welfare. In a closed economy, these taxes have identical effects on national emissions—with import and export taxes not operative. In an open economy, taxes applied to a single country may produce different levels of leakage, and hence different impacts on emissions and real income. We consider single-country taxes and global taxes. For global taxes, we consider two transfer rules: a national system that distributes tax revenues in the country where they originate, and a global system that redistributes tax revenue across countries according to each country’s losses from climate change (γ_n). We compare all tax counterfactuals to a baseline calibration that matches the observed data, assumes zero baseline carbon taxes, and assumes a global social cost of carbon of $\gamma = 100$, in dollars per metric ton.

Analysis of counterfactual scenarios must recognize that variables like trade shares and input shares become specific to GVC endpoints when import or consumption taxes are implemented. We derive expressions for the counterfactual changes in equilibrium variables as functions of observable data, model parameters, and the analyzed shocks. Where possible, we define proportional changes using standard hat algebra notation, $\hat{x} \equiv x'/x$. For variables that become GVC endpoint-specific only after the shock, we define the proportional change relative to the initial non-GVC-specific value, $\hat{x}_n \equiv x'_n/x$, where the subscript n refers

to the GVC endpoint.²² Appendix B.1 shows the conversion of equilibrium equations (5)-(15) in levels to analogous equations (39)-(46) in changes. Given baseline values $\{\alpha_{l,sk}, \alpha_{l,\ell s}, \lambda_{il,s}, p_s, Y_{l,s}, X_l^C, \mu_{l,s}, \Lambda_l\}$ from data, and given the shocks of interest, we use these equations to compute counterfactual changes:

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

The rest of the calibration mirrors the one in Section 6.

We measure utility changes for each country using equation (34). To assess the impact of policy changes on global welfare, we first compute the compensating variation associated with the tax for each country, then sum across countries and divide by the initial world GDP,

$$\Delta = \sum_n \frac{X_n^C}{\sum_n X_n^C} \left[\left(\hat{X}_n^C - \hat{P}_n \right) + \left(\gamma_n \mathcal{E} / X_n^C \right) \left(\hat{P}_n - \hat{\mathcal{E}} \right) \right]. \quad (36)$$

Appendix B.3 shows the derivation. The first term on the right-hand side of equation (36) is the aggregate effect of the tax on consumption—without environmental losses, that term would measure the policy’s welfare impact. The second term measures the aggregate carbon damages.

In what follows, we first consider global extraction, production, and consumption taxes separately, and set the tax rate equal to the global social cost of carbon, $\gamma = 100$. As Section 1 demonstrates, this case corresponds to the optimal global tax. And second, we consider optimal taxes, both in isolation and combined, applied to each country in our sample, one at the time.

7.2 Global Carbon Tax Results

When the planner implements a global tax, it is optimal to do so through either an extraction, production, or consumption tax equivalent to the SCC. Table 2 shows estimates of the effects of global carbon taxes on emissions, consumption, and welfare, for selected countries and the entire globe; Appendix Table D8 shows results for all countries. We present results under the assumptions that taxes are redistributed domestically and globally, alternately.

A global carbon tax of \$100 per ton of CO₂, either to extraction, production, or consumption, would reduce global emissions by around 43.5 percent. For comparison, the Dynamic Integrated Climate-Economy model (DICE) estimates a decrease in global CO₂ emissions of around a third (Barrage and Nordhaus, 2024).²³ Despite that our model differs considerably from DICE, and the scenarios considered

²²If we departed from a baseline with carbon taxes that differentiated according to the GVC endpoint, we would need a global input-output table capturing this variation, i.e., we would need $\{\alpha_{il,n,ks}\}$ rather than just $\{\alpha_{il,ks}\}$. The European Union is introducing a carbon border adjustment mechanism, which may add GVC endpoint considerations into carbon taxes, but this is not in place in 2014, the year of our data. The counterfactual data that we derive from the exact hat algebra with consumption taxes has the differentiation by GVC endpoint, $\{\alpha_{il,n,ks}\}$.

²³The Optimal Cost/Benefit scenario in Barrage and Nordhaus (2024) has the global carbon price rise steadily to \$115 per ton of CO₂ in the year 2050. Their baseline begins with a carbon price of \$6 per ton of CO₂ in 2022, growing at 2.5 percent per year. By 2050, their baseline has a carbon tax of \$12.59 per ton of CO₂. 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 CO₂.

are not identical, we estimate emissions effects of a similar order of magnitude.

Table 2 also shows that the different tax instruments have heterogeneous effects across countries. For example, a global extraction tax decreases Korea emissions by 62.3 percent, which is much higher than the effects of a global production or consumption tax. For US, Russia, and China, the three global taxes have similar effects on emissions.

Columns (4) through (6) of Table 2 show that the effects on consumption depend on the type of tax applied. An extraction tax benefits a fossil fuel exporter, like Russia, when tax revenues are rebated domestically because the tax increases global energy prices and improves the terms of trade, and hence, it acts encouraging the exercise of market power. Correspondingly, an extraction tax decreases consumption for fossil fuel importers when revenue is rebated domestically. If tax revenues were instead rebated internationally according to each country's environmental damages, fossil fuel exporters, like Russia, would experience very large consumption losses, of around 15 percent. Column (5) shows that when revenues are rebated domestically, a production tax decreases consumption in countries with carbon-intensive technology, like China and Russia, while increasing consumption in countries with cleaner technology, like South Korea. These patterns change considerably when revenues are rebated globally. Effects of production and consumption taxes are more similar partly because most goods are produced and consumed domestically, and hence, taxing either production or consumption has somewhat similar effects. With global transfers, the tax base is irrelevant for global emissions or country-level changes in consumption and welfare.

Overall, Table 2 shows that while an optimal global tax reduces global consumption by 0.7 percent, by also reducing emissions by almost half, it increases global welfare by around 1.5 percent. Welfare increases the most in the US, India, and Brazil (see Appendix Table D8), and decreases the most in Russia. The contrast between Russia and India is striking: Russia gains from higher emissions due to potential agricultural benefits in a warming climate, while India gains from lower emissions, given its disutility from climate change.

To understand the mechanisms driving the changes in emissions, globally and in each country, we decompose the effect of a global production tax on emissions. We emphasize channels that are present in our model, but are typically absent in papers that follow an abatement or constant emissions intensity approach. We perform two decompositions: the first one emphasizes the price channel that arises from allowing for an upward-sloping mining supply curve, while the second emphasizes the technique effect that arises from endogenous changes in sectoral emission intensity.

We first show that the percentage change in production-based emissions after a global tax can be decomposed into the following terms (see Appendix E.2):

$$\mathcal{E}_l^{P'} - \mathcal{E}_l^P = \underbrace{\sum_s \left(\frac{e_s}{p'_s} - \frac{e_s}{p_s} \right) \sum_n X_{l,n,s}}_{\text{Price Effect}} + \underbrace{\sum_s \left(\frac{e_s}{p'_s + e_s t_l^P} - \frac{e_s}{p'_s} \right) \sum_n X'_{l,n,s}}_{\text{Direct Tax Effect}} + \underbrace{\sum_s \frac{e_s}{p'_s} \left(\sum_n X'_{l,n,s} - \sum_n X_{l,n,s} \right)}_{\text{Expenditure Effect}}. \quad (37)$$

Table 2: Optimal Global Carbon Taxes

% change Tax	Emissions			Consumption			Welfare		
	Extr. (1)	Prod. (2)	Cons. (3)	Extr. (4)	Prod. (5)	Cons. (6)	Extr. (7)	Prod. (8)	Cons. (9)
Canada	-34.0	-37.9	-39.3	0.31	-1.61	-1.39	-1.61	-3.42	-3.20
China	-49.8	-52.0	-50.5	-2.14	-1.54	-2.02	-0.09	0.52	0.02
France	-41.5	-32.3	-39.5	-0.69	0.02	0.38	-0.44	0.27	0.63
Korea	-62.3	-31.9	-38.1	-1.92	1.84	0.77	-1.72	2.06	0.99
Russia	-53.8	-58.7	-58.7	2.47	-2.88	-3.26	-3.59	-8.06	-8.38
USA	-36.8	-30.2	-33.8	-0.76	-0.2	-0.08	0.35	0.91	1.03
World	-43.2	-43.5	-43.5	-0.79	-0.79	-0.79	1.41	1.37	1.37

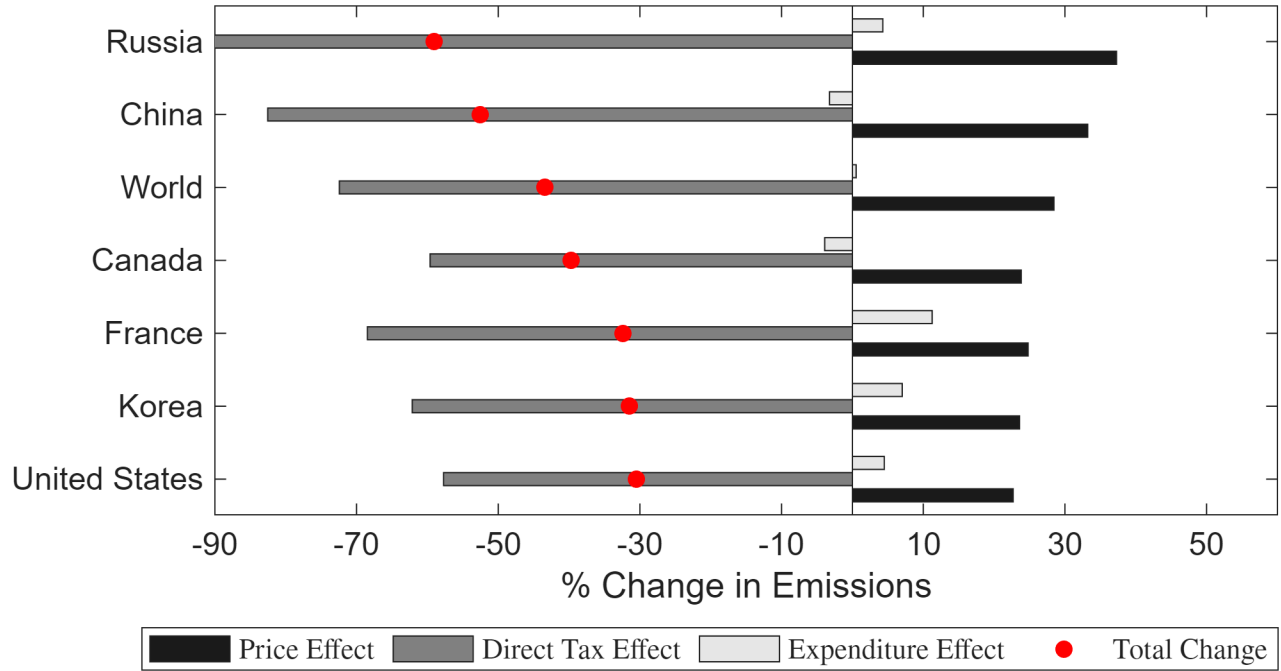
(a) National Transfers

% change Tax	Emissions			Consumption	Welfare
	Extr. (10)	Prod. (11)	Cons. (12)	Either (13)	Either (14)
Canada	-30.7	-39.7	-43.6	-6.50	-8.06
China	-49.8	-52.6	-51.9	-4.28	-2.38
France	-42.4	-32.4	-40.5	-0.41	-0.16
Korea	-63.8	-31.5	-40.2	-1.92	-1.72
Russia	-45.1	-59.1	-65.0	-14.7	-18.1
USA	-37.4	-30.5	-34.7	-0.73	0.36
World	-43.5	-43.5	-43.5	-0.74	1.59

(b) Global Transfers

Note: Tax is $t_s = scc \times e_s$ where $scc = 100\$/\text{ton CO}_2$, for $s \in \mathcal{K}^M$, applied to all countries. For the extraction tax, we report extraction-based emissions calculated using equation (16). For the production tax, we report production-based emissions (scope 1) calculated using equation (17). For the consumption tax, we report consumption-based emissions calculated using equation (22). Welfare changes for each country are calculated using equation (34). Global welfare gains and changes in consumption are expressed relative to initial GDP, calculated using equation (36). Columns (1)-(9) report results assuming that tax revenues are rebated to local consumers, while columns (10)-(14) report results for tax revenues redistributed globally according to the country's share of the social cost of carbon (in US dollars).

Figure 5: Global Carbon Tax, Decomposition: Price effect



Notes: Decomposition of the total change in production-based (scope 1) emissions (red circle) relative to baseline emissions due to a global production tax of 100\$ per ton of CO₂. Each bar corresponds to a term of equation (37).

The first term represents the price channel, which captures the change in energy demand in country l resulting from shifts in fossil-fuel prices. Since a global production tax lowers aggregate demand, the tax decreases fossil fuel prices, increasing the incentives to use them in production, and resulting in increases of global emissions. The second term captures the direct effect of the tax on households and industry fossil fuel use, while holding prices constant. Finally, the last term reflects changes in expenditure of fossil fuels.

Figure 5 presents results for selected countries and the entire world; Appendix Table D6 shows results for all countries. Each term of the decomposition, represented by the bars, is calculated as percentages of baseline production-based emissions. Their sum corresponds to the total change in emissions, represented by the red circle. The direct tax channel accounts for most of the tax’s impact on global emissions. This channel captures declines in the demand for fossil fuels from direct consumption (households) and for intermediate goods (firms). The expenditure channel plays a small role. Importantly, the price channel dampens the effectiveness of the tax, raising global emissions by 30 percent relative to the baseline; without this channel, the reduction in emissions would be substantially larger.

Our second decomposition shows the contribution of technique, composition, and household expenditure in reducing production-based (scope 1) emissions when a global production tax is applied (see Appendix E.3):

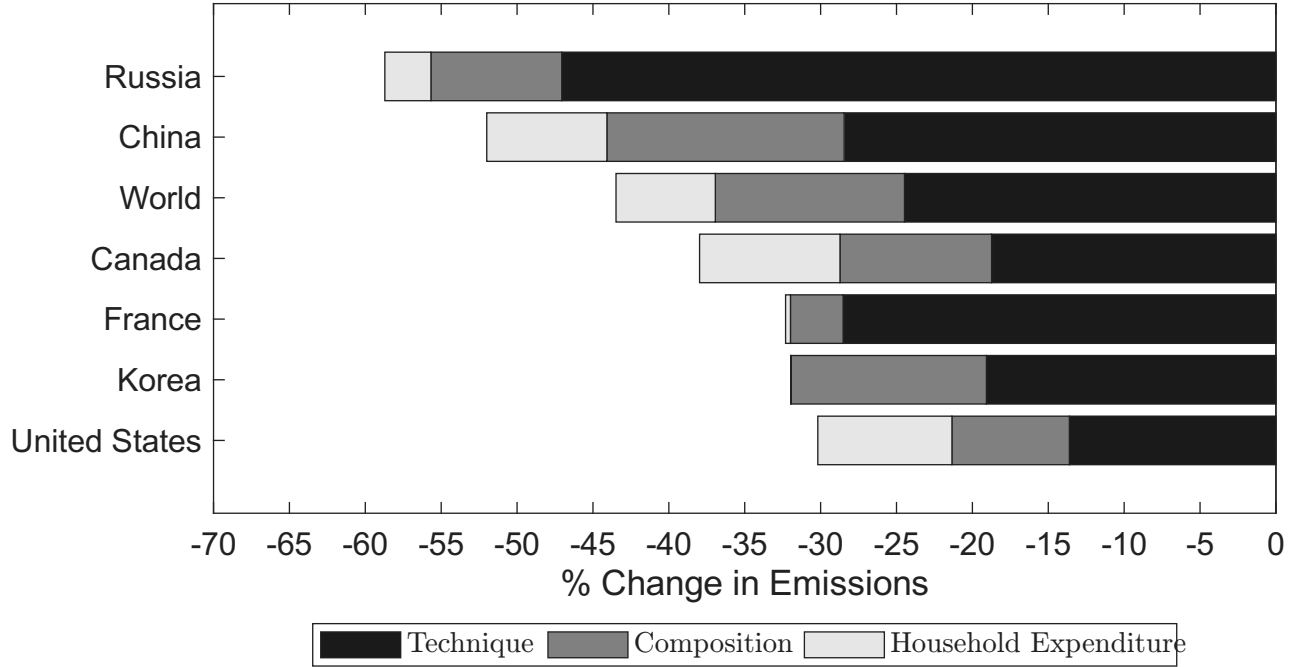
$$\mathcal{E}_l^{P'} - \mathcal{E}_l^P = \underbrace{\left(\sum_{k \notin \mathcal{K}^M} (\tilde{e}'_{l,k} - \tilde{e}_{l,k}) \frac{Y'_{l,k}}{p'_{l,k}} \right)}_{\text{Technique}} + \underbrace{\sum_{k \notin \mathcal{K}^M} \tilde{e}_{l,k} \left(\frac{Y'_{l,k}}{p'_{l,k}} - \frac{Y_{l,k}}{p_{l,k}} \right)}_{\text{Composition}} + \underbrace{\sum_s e_s \left(\frac{\mu_{l,s}}{p'_s + e_s t_l^P} X_l^{C'} - \frac{\mu_{l,s}}{p_s} X_l^C \right)}_{\text{Household expenditure}}, \quad (38)$$

where sectoral emission intensity is defined as

$$\tilde{e}_{l,k} \equiv \frac{\mathcal{E}_{l,k}^P}{Y_{l,k}/p_{l,k}} = \frac{\sum_{s \in \mathcal{K}^M} \frac{e_s}{p_s + e_s t_l^P} \alpha_{l,sk} Y_{l,k}}{Y_{l,k}/p_{l,k}}.$$

The technique effect captures changes in emissions resulting from adjustments in production techniques within each sector, so that emissions per unit of output decrease. This channel is absent in papers that assume a fixed sectoral emission intensity. The second term reflects effects arising from the reallocation of activity across sectors with different emission intensities. The third term captures changes in emissions due to shifts in household expenditure. Figure (6) shows the results for selected countries and the world. The technique effect accounts for a substantial share of the emission reduction in all countries. For instance, of the 45 percent decline in global emissions, changes in emission intensity within sectors explain 25 percentage points, changes across sectors account for 12 percentage points, and changes in household expenditures contribute to the remaining 7 percentage points.

Figure 6: Global Carbon Tax, Decomposition: Technique effect



Notes: Decomposition of the change in production-based (scope 1) emissions relative to baseline emissions due to a global production tax of 100\$ per ton of CO₂. Each bar corresponds to a term of equation (38).

7.3 Single-Country Carbon Tax Results

This section quantifies the effects of a carbon tax applied to a single country by a planner that maximizes global welfare. First, we consider the case where a single country has access to only one tax instrument (extraction, production, or consumption). We compute the optimal tax level using equation (29), and evaluate its effects on global emissions, global consumption, and global welfare.

Figure 7 summarizes the results for selected countries and the EU. The first panel reports the optimal tax rate applied to each country (one at the time), based on extraction, production, or consumption; Appendix Table D7 reports results for all countries. Because the optimal tax is given by equation (29), $t_j^Z = \gamma(1 - \mathcal{L}_j^Z)$, leakage \mathcal{L}_j^Z can be inferred from the tax rates shown in the figure. Consumption taxes most effectively limit carbon leakage, since they affect both the use of fossil fuels domestically and along the GVC ending in the country. The optimal consumption tax therefore exceeds the optimal extraction or production tax level, and averages about \$70 per ton of CO₂. Notably, we find little cross-country heterogeneity in optimal consumption tax rates, as their broad coverage across GVCs reduces country-specific leakage. Optimal extraction and production taxes are lower, and average \$37 and \$42 per ton of CO₂, respectively. The optimal production tax is the most heterogeneous across countries due to its associated leakage. Larger economies, like the US, Russia, and China, have higher optimal production tax levels, as their market size dampens leakage.

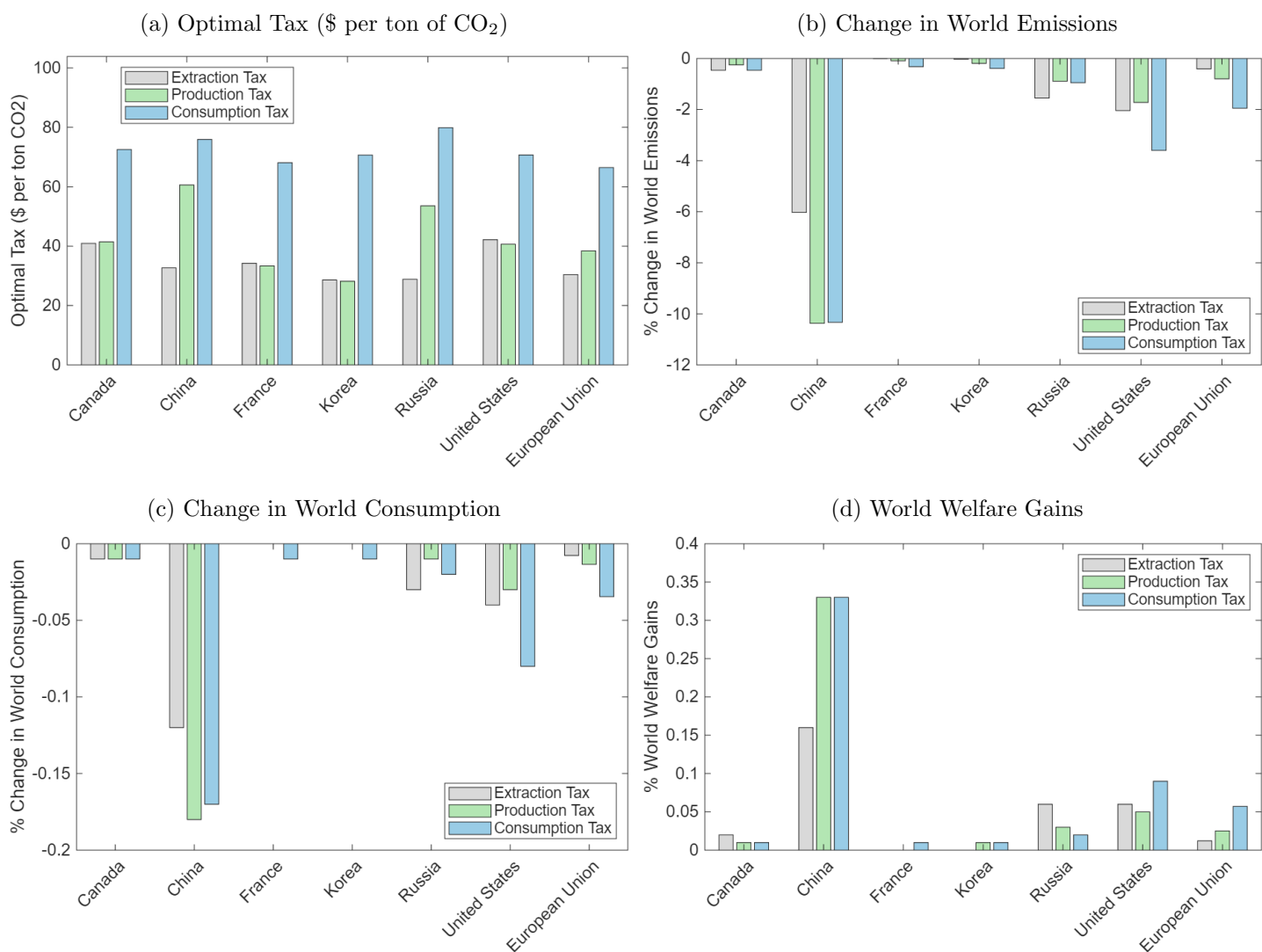
The remaining panels of Figure 7 show the effects on world emissions, world consumption and world welfare, resulting from each single country implementing one of these taxes; Appendix Table D8 presents results for all countries. Overall, consumption taxes are more efficient than production taxes at reducing global emissions and improving global welfare. They also increase global welfare more than extraction taxes, except in the case of large fossil fuel producers such as Russia. For example, the optimal US production tax reduces global emissions by two percent, whereas the optimal US consumption tax reduces them by 3.9 percent. This reduction in emissions results in a 66 percent higher welfare gain under the consumption tax. If the European Union applied these taxes, the effects are even more pronounced, with a consumption tax doubling global welfare gains compared to a production tax. This result suggests that shifting from production taxes—which primarily target the direct use of fossil fuels and are the most commonly used—to consumption taxes, which also account for their indirect use through GVCs, can significantly improve global efficiency.

To highlight the importance of the curvature of the fossil fuel supply, we examine the sensitivity of optimal taxes to the parameter ν_s . Table 3 reports results for our benchmark values of ν_s and alternative scenarios where the values of ν_s are scaled by 80 percent and 120 percent, respectively. A lower supply elasticity (i.e., higher ν_s) implies lower leakage from an extraction tax, but higher leakage from a production or consumption tax. Hence, optimal consumption and production taxes decrease with ν_s , while optimal extraction taxes increase with ν_s . Averaging across countries, when we increase ν_s by 20 percent, for all s , with respect to the baseline estimates, the average optimal extraction tax increases from 33 to 38 dollars per ton of CO₂, while the optimal consumption tax decreases from 68 to 62 dollars. Average optimal production tax also decreases from 38 to 36 dollars. Intuitively, when the supply elasticity is low (high ν_s), it becomes more difficult for the rest of the world to boost production and offset the supply lost due to the country’s extraction tax, resulting in lower leakage and a higher optimal tax. Conversely, when a country imposes a production tax, domestic demand falls, pushing prices down. A more inelastic supply for fossil fuels (high ν_s) causes a larger price drop, which in turn leads to a greater increase in demand elsewhere, increasing leakage—and hence, decreasing the optimal tax. Appendix Table D11 explore the sensitivity of optimal taxes to the trade elasticity $\sigma - 1$ and shows that a lower trade elasticity is associated with higher optimal taxes.

7.4 Single-Country Carbon Tax Combination Results

This subsection considers a scenario where a single country or coalition implements the optimal combination of extraction, consumption, and export taxes. We also present results for the intermediate case of combining extraction and consumption taxes. Combining tax instruments can improve global efficiency relative to using one tax in isolation. An extraction tax raises the global price of fossil fuels by reducing supply, while both a consumption and export tax—acting on the carbon emissions of the GVC ending domestically and abroad, respectively—lowers global demand and decreases fossil fuel prices. As these pressures on prices offset each other, the joint implementation of these taxes can stabilize the world price and reduce carbon leakage ((Markusen, 1975; Kortum and Weisbach, 2021; Kortum et al., 2023)).

Figure 7: Single-Country Optimal Carbon Tax



Note: In each panel, the x-axis represents the country or coalition applying the optimal tax while the the bars indicate the tax type. Panel (a) shows the optimal tax t_j^Z in dollars per ton of CO₂ according to equation (27). Panel (b) reports the corresponding percentage change in world emissions. Panel (c) shows the percentage change in world real consumption, calculated using equation (36). Panel (d) presents the world welfare gains relative to initial GDP, calculated using equation (36).

Table 3: Optimal Tax and the Supply Elasticity of Fossil Fuels

	Extraction Tax			Production Tax			Consumption Tax		
	$0.8 \times \nu_s$ (1)	ν_s (2)	$1.2 \times \nu_s$ (3)	$0.8 \times \nu_s$ (4)	ν_s (5)	$1.2 \times \nu_s$ (6)	$0.8 \times \nu_s$ (7)	ν_s (8)	$1.2 \times \nu_s$ (9)
Canada	35.61	40.95	45.99	43.62	41.44	39.04	80.60	72.55	65.12
China	27.62	32.68	37.55	63.35	60.60	57.71	80.74	75.93	71.13
France	28.56	34.24	38.31	35.08	33.37	31.51	75.16	68.09	63.37
Korea	23.89	28.60	32.16	30.13	28.20	26.22	78.35	70.67	65.52
Russia	24.13	28.83	33.49	56.28	53.57	51.33	82.71	79.90	73.38
United States	37.06	42.19	47.03	43.70	40.66	37.69	76.49	70.71	65.01
World Average	28.55	33.63	38.41	40.98	38.48	36.08	73.99	68.21	62.71

Note: Optimal tax for different values of ν_s . Tax is $t_{j,s}^Z = t_j^Z \times e_s$ where t_j^Z is the optimal tax per ton of CO₂, for $s \in \mathcal{K}^M$, and applied by each country shown, one at the time.

Table 4 presents the results for a tax scheme that combines optimal extraction and consumption taxes in selected countries, one country at a time. Appendix Table D9 report results for all countries. We report the effects on world emissions, world consumption, and global welfare. Optimally combining carbon taxes with a different base leads to greater welfare gains, compared to each tax alone. The largest global emissions reduction occurs when China implements the policy (15 percent), accompanied by a 0.41 percent increase in welfare. Taxes by US or Russia are also important as they reduce global emissions 5.2 and 2.7 percent, respectively. Taxes by the EU can reduce global emissions by 2.29 percent, leading to less than a 0.1 percent welfare gain.

Next, we consider the full set of optimal taxes that is characterized by a consumption, an extraction, and an export tax. Table 5 summarizes the results for selected countries and Appendix Table D10 report results for all countries. This tax combination allows for a country like China to achieve a higher reduction in global emissions and global welfare gains. As China is a large exporter, adding an export tax to the optimal tax scheme allows for a reduction of more than 15 percent in global emissions, leading to half a point increase in global welfare.

Finally, Figure 8 compares the global welfare gains, measured according to equation (36), resulting from the five tax schemes previously analyzed. For fossil fuel exporters, such as Canada and Russia, extraction taxes deliver greater welfare gains than either unilateral production or consumption taxes. For large consumers, like China, the US, and the EU, consumption taxes outperform both alternatives in terms of global welfare. For instance, when the EU adopts a consumption tax, global welfare rises by 200 percent more than under a production tax. While production carbon taxes remain the most common policy instrument, this result highlights the potential of measures that target the indirect use of fossil fuels along GVC—such as certain proposals for the Carbon Border Adjustment Mechanism (CBAM), which approximates our consumption tax. An optimal combination of consumption and extraction taxes delivers even larger, quantitatively significant gains. Relative to a consumption tax alone, combining

Table 4: Single-Country Optimal Carbon Taxes: Consumption and Extraction

	Change in world emissions (%)	Change in world consumption (%)	World welfare gains (%)	Extraction tax	Consumption tax
	(1)	(2)	(3)	(4)	(5)
Canada	-0.88	-0.02	0.02	36.7	65.4
China	-13.8	-0.25	0.41	23.3	73.6
France	-0.35	-0.01	0.01	33.2	62.9
Korea	-0.42	-0.01	0.01	25.4	67.0
Russia	-2.35	-0.04	0.07	25.9	72.5
United States	-4.95	-0.10	0.13	31.8	65.9
European Union	-2.29	-0.04	0.07	27.3	65.7

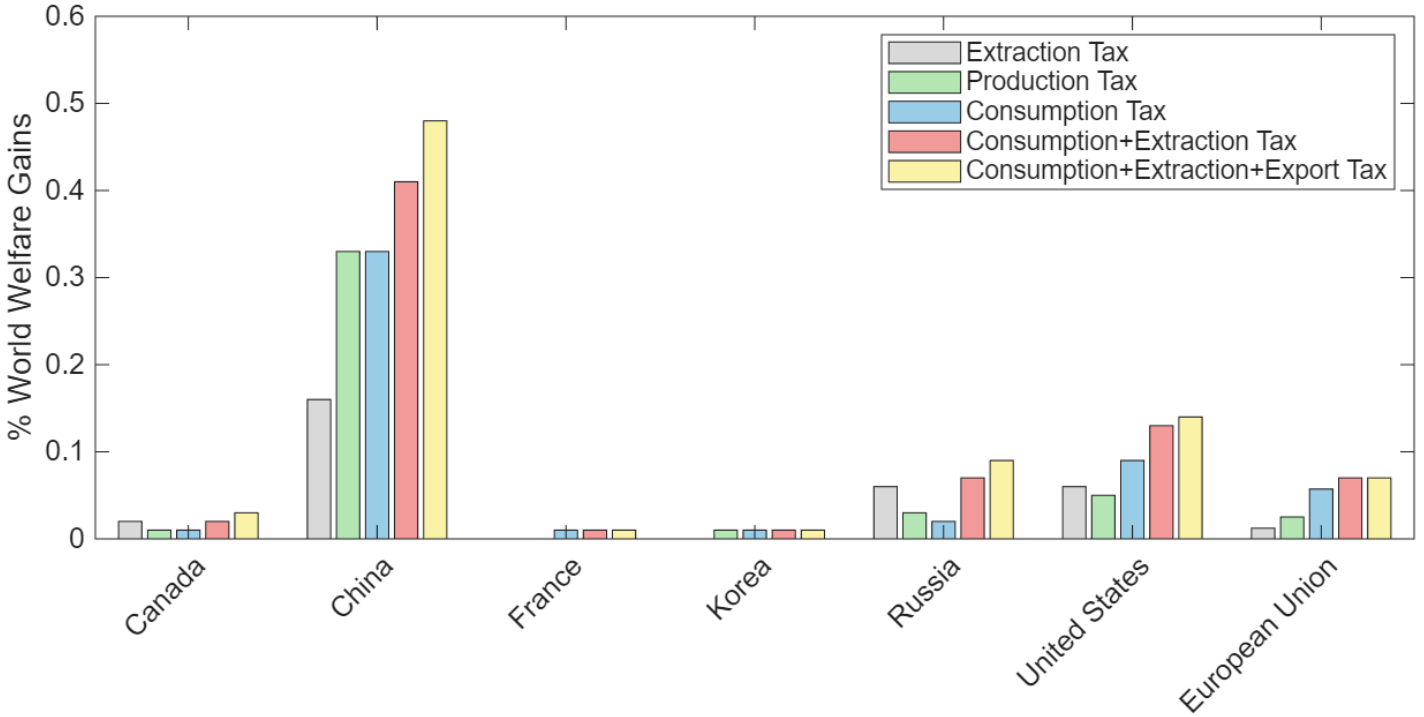
Note: Tax is $t_{j,s}^Z = t_j^Z \times e_s$ $Z \in \{E, C\}$, t_j^Z is the optimal tax combination of extraction and consumption tax per ton of CO₂, for $s \in \mathcal{K}^M$, applied by each country shown, one at the time. Global welfare gains and changes in consumption are expressed relative to initial GDP, calculated using equation (36).

Table 5: Single-Country Optimal Carbon Taxes: Consumption, Extraction, and Export

	Change in world emissions (%)	Change in world consumption (%)	World welfare gains (%)	Extraction tax	Consumption tax	Export tax
	(1)	(2)	(3)	(4)	(5)	(6)
Canada	-0.92	-0.02	0.03	37.7	64.9	25.1
China	-15.8	-0.28	0.48	24.3	73.8	52.8
France	-0.36	-0.01	0.01	33.3	62.6	17.2
Korea	-0.48	-0.01	0.01	25.7	66.5	18.8
Russia	-2.68	-0.05	0.09	27.9	71.2	44.6
United States	-5.01	-0.10	0.14	31.9	65.7	15.3
European Union	-2.37	-0.04	0.07	27.6	67.3	23.6

Note: Tax is $t_{j,s}^Z = t_j^Z \times e_s$ $Z \in \{E, C\}$, t_j^Z is the optimal tax combination of extraction, consumption, and export tax per ton of CO₂, for $s \in \mathcal{K}^M$, applied by each country shown, one at the time. Global welfare gains and changes in consumption are expressed relative to initial GDP, calculated using equation (36).

Figure 8: World Welfare Gains, Different Tax Combinations



Notes: World welfare gains of different optimal taxes and tax combinations, applied to each of the countries shown, one at the time. Global welfare gains are expressed relative to initial GDP, calculated using equation (36).

both instruments increases global welfare by 39 percent for the EU, 100 percent for Canada, 19 percent for China, and 40 percent for the US.

These results indicate that while shifting from production to consumption-based taxation improves efficiency considerably, further gains can be achieved by a country complementing demand-side taxes with supply-side taxes on fossil fuel extraction. Finally, incorporating export taxes into the policy mix amplifies efficiency for major (non-mining) goods exporters. For example, China’s welfare gain rises from 0.42 to 0.49 when an export tax is added to the consumption–extraction tax scheme. For the remaining regions and countries, the quantitative effects of adding an optimal export tax are small.

8 Conclusions

We develop a quantitative trade model with fossil fuel markets and global value chains (GVCs). We use the model to quantitatively evaluate the welfare and emissions effects of a range of optimal carbon taxes applied at different points of the GVC. We also use the model to illustrate the effects of moving to trade autarky. By modeling the production of fossil fuels with decreasing returns to scale, we capture the endogenous price adjustments that are central to understanding the effects of climate policy.

We analyze optimal policy design through extraction, production, and consumption carbon taxes, implemented either globally or unilaterally, and alone or in combination. When applied globally at the social cost of carbon, all three taxes yield similar aggregate outcomes—reducing global emissions by 45 percent and raising welfare by around 1.5 percent.

Unilateral policies, however, differ sharply in their effectiveness. Consumption taxes deliver the highest global welfare gains by targeting emissions along GVCs and limiting carbon leakage. Pairing a consumption tax with an extraction tax further increases efficiency: applied to the US, this combined approach raises welfare by up to 40 percent relative to a consumption tax alone. Further adding an export carbon tax improves outcomes only slightly, except when the taxes are applied to a large exporter like China.

These results underscore the importance of targeting emissions comprehensively along the GVC—an approach central to current policy debates, such as the EU’s CBAM and the Foreign Pollution Fee Act 2025 under discussion in the US Congress. Combining demand- and supply-side instruments further enhances the effectiveness of unilateral climate policy in bolstering global welfare.

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A Summary of Main Model Variables

Table A1: Main Variables

Variable	Description
$\{i, j, l, n\}$	Country indices
$\{k, s, r\}$	Sector indices; $s \in \mathcal{K}^M$ for mining, $s \notin \mathcal{K}^M$ for non-mining
$M_{j,s}$	Number of mines in country j for mining sector s
$V_n(P_n, X_n^C, \mathcal{E})$	Indirect utility in country n
X_n	Total expenditure in country n
X_n^C	Final expenditure in country n
\hat{Y}_n	Real GDP in country n
P_n	Consumer price index in country n
γ_n	Damage cost (dollars) in n from emissions global emissions
\mathcal{E}	Global carbon emissions
$P_{n,s}$	Price index of good s in country n
$\mu_{n,s}$	Cobb-Douglas expenditure share on good s in country n
$\alpha_{j,s}$	Output elasticity of mines in mining sector s in country j
$q_{j,s}$	Quantity of mining good s produced in country j
e_s	Emissions per unit of mining good s
σ_s	Elasticity of substitution in sector s
$A_{l,s}$	Productivity in non-mining sector s in country l
$\alpha_{l,\ell s}$	Labor shares in non-mining production in country l sector s
$\alpha_{l,ks}$	Share of input k in non-mining production in country l sector s
$\tau_{ln,s}$	Iceberg trade cost from l to n for good s
t_j^M	Extraction carbon tax in country j
t_l^P	Production carbon tax in country l
t_n^C	Consumption carbon tax in country n
t_n^I	Import carbon tax in country n
t_l^X	Export carbon tax in country l
p_s	International price of mining good s
$Y_{j,s}$	Value of mining good s produced in j
$p_{l,n,k}$	unit cost of good k in l for GVCs ending in n
$P_{l,n,k}$	Price index of non-mining input k in l for GVCs ending in n
$X_{l,n,s}$	Gross expenditure by l on good s for GVCs ending in n
$Y_{l,n,k}$	Output of non-mining good k in l for GVCs ending in n
$\lambda_{il,n,s}$	Expenditure share by l on good s from i for GVCs ending in n
$\Pi_{j,s}$	Rents from mines in country j , sector s
w_j	Wage in country j
Λ_l	Exogenous transfers to country l
Υ_l	Carbon tax transfers to country l
T_l	Carbon tax revenues collected by l
$q_{l,n,s}$	Quantity of good s used in l for GVCs ending in n
\mathcal{E}_j^M	Extraction-based emissions from j
\mathcal{E}_l^P	Production-based (Scope 1) emissions from l
\mathcal{E}_n^C	Consumption-based emissions in n
\mathcal{E}_l^{P3}	Scope 3 production-based emissions in l
\mathcal{E}_n^I	Import-based emissions in n
\mathcal{E}_l^X	Export-based emissions from l
\mathcal{L}_j^n	Leakage of country j

B Model

B.1 Hat Algebra

The hat change in the unit cost of good $s \notin \mathcal{K}^M$ in i in a GVC ending at n is

$$\hat{p}_{i,n,s} = \hat{A}_{i,s}^{-1} \hat{w}_i^{\alpha_{i,\ell s}} \prod_{k \in \mathcal{K}^M} \left(\frac{p_k \hat{p}_k + e_k (t_i^P + t_n^C + \mathbb{I}_{i \neq n} t_n^I + \mathbb{I}_{n \neq i} t_i^X)}{p_k} \right)^{\alpha_{i,ks}} \prod_{k \notin \mathcal{K}^M} \hat{P}_{i,n,k}^{\alpha_{i,ks}},$$

the change in the price index is

$$\hat{P}_{i,n,s}^{1-\sigma_s} = \sum_l \lambda_{li,s} \hat{A}_{l,s}^{\sigma_s-1} \left(\hat{\tau}_{li,s} \hat{w}_l^{\alpha_{l,\ell s}} \prod_{h \in \mathcal{K}^M} \left(\frac{\hat{p}_h p_h + e_h (t_l^P + t_n^C + \mathbb{I}_{l \neq n} t_n^I + \mathbb{I}_{n \neq l} t_l^X)}{p_h} \right)^{\alpha_{l,hs}} \prod_{h \notin \mathcal{K}^M} \hat{P}_{l,n,h}^{\alpha_{l,hs}} \right)^{1-\sigma_s}, \quad (39)$$

and the change in trade shares is

$$\hat{\lambda}_{il,n,s} = \frac{\hat{A}_{i,s}^{\sigma_s-1} \left(\hat{\tau}_{il,s} \hat{w}_i^{\alpha_{i,\ell s}} \prod_{h \in \mathcal{K}^M} \left(\frac{\hat{p}_h p_h + e_h (t_i^P + t_n^C + \mathbb{I}_{i \neq n} t_n^I + \mathbb{I}_{n \neq i} t_i^X)}{p_h} \right)^{\alpha_{i,hs}} \prod_{h \notin \mathcal{K}^M} \hat{P}_{i,n,h}^{\alpha_{i,hs}} \right)^{1-\sigma_s}}{\hat{P}_{l,n,s}^{1-\sigma_s}}. \quad (40)$$

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

$$\hat{Y}_{j,s} = \hat{M}_{j,s} \left(\frac{\hat{p}_s p_s - e_s t_j^{M'}}{p_s} \hat{w}_j^{-\alpha_{j,\ell s}} \right)^{\frac{1}{\nu_s}}. \quad (41)$$

Changes in final expenditure are given by

$$\hat{X}_l^C X_l^C = w_l L_l \hat{w}_l \hat{L}_l + \sum_{s \in \mathcal{K}^M} \nu_s Y_{l,s} \hat{Y}_{l,s} + \hat{T}_l T_l + \hat{\Lambda}_l \Lambda_l, \quad (42)$$

where

$$\hat{T}_l T_l = \sum_{s \in \mathcal{K}^M} e_s \left(t_l^M q'_{l,s} + \sum_n t_l^P q'_{l,n,s} + \sum_i t_l^C q'_{i,l,s} + \sum_{i \neq l} t_l^I q'_{i,l,s} + \sum_{n \neq l} t_l^X q'_{l,n,s} \right),$$

while changes in total sectoral expenditure are

$$\hat{X}_{l,n,k} X_{l,k} = \mathbb{I}_{(l=n)} \mu_{n,k} \hat{X}_n^C X_n^C + \sum_{s \notin \mathcal{K}^M} \alpha_{l,ks} \sum_h \hat{\lambda}_{lh,n,s} \lambda_{lh,s} \hat{X}_{h,n,s} X_{h,s}. \quad (43)$$

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

$$\hat{Y}_{l,n,s} Y_{l,s} = \sum_h \hat{\lambda}_{lh,n,s} \lambda_{lh,s} \hat{X}_{h,n,s} X_{h,s}, \quad (44)$$

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

$$\sum_j q'_{j,s} = \sum_{l,n} q'_{l,n,s}. \quad (45)$$

Finally, labor market clearing in country l entails

$$w_l L_l \hat{w}_l \hat{L}_l = \sum_s \alpha_{l,ls} Y_{l,s} \hat{Y}_{l,s}. \quad (46)$$

Autarky. Emissions under autarky are

$$\mathcal{E}_n^A = \sum_{s \in \mathcal{K}^M} e_s \frac{Y_{n,s}^A}{p_{n,s}^A} = \sum_{s \in \mathcal{K}^M} \mathcal{E}_{n,s}^M \frac{\hat{Y}_{n,s}}{\hat{p}_{n,s}}, \quad (47)$$

where the second equality follows from the definition $\mathcal{E}_{n,s}^M \equiv e_s Y_{n,s} / p_s$, variables in changes are $\hat{p}_{n,s} \equiv p_{n,s}^A / p_s$ and $\hat{Y}_{n,s} \equiv Y_{n,s}^A / Y_{n,s}$, and under autarky, mining good prices are specific to each country, $p_{n,s}^A$.

To compute $\hat{Y}_{n,s}$ in equation (47), we start from the equilibrium equation $Y_{n,s}^A = \psi_{n,s} X_n^{C,A}$, where $\psi_{n,s} \equiv \mu_{n,s} + \sum_{k,r \notin \mathcal{K}^M} \alpha_{n,sk} \chi_{n,kr} \mu_{n,r}$ is the Domar weight of sector s in autarky, and $\{\chi_{n,sk}\} = (I - \{\alpha_{n,sk}\})^{-1}$ the standard Leontief inverse matrix for non-mining sectors. Final expenditure in autarky equals wages plus rents, $X_n^{C,A} = w_n^A L_n + \sum_{s \in \mathcal{K}^M} \nu_s Y_{n,s}^A$. Combining these equations and letting $\psi_n^M \equiv \sum_{s \in \mathcal{K}^M} \nu_s \psi_{n,s}$ denote the Domar weight of the whole mining sector in autarky, we have $X_n^{C,A} = \frac{w_n^A L_n}{1 - \psi_n^M}$. Setting $w_n^A = w_n$ by choice of numeraire yields

$$\hat{Y}_{n,s} = \frac{\psi_{n,s} w_n L_n / (1 - \psi_n^M)}{Y_{n,s}}.$$

The proportional change in the price of mining good $s \in \mathcal{K}^M$ is $\hat{p}_{j,s} = \hat{Y}_{j,s}^{\nu_s}$, which captures the change in the domestic price of mining good k resulting from moving along its supply curve as the country shuts down trade.

Autarky emissions in equation (47) can therefore be rewritten as

$$\mathcal{E}_n^A = \sum_{s \in \mathcal{K}^M} \mathcal{E}_{n,s}^M \left(\frac{\psi_{n,s} w_n L_n / (1 - \psi_n^M)}{Y_{n,s}} \right)^{1 - \nu_s}. \quad (48)$$

Changes in real GDP, $\mathcal{Y}_n \equiv (w_n L_n + \nu \sum_{k \in \mathcal{K}^M} Y_{n,k}) / P_n$, from the observed equilibrium to autarky, are given by

$$\hat{\mathcal{Y}}_n = \frac{w_n L_n / (1 - \psi_n^M)}{w_n L_n + \sum_{k \in \mathcal{K}^M} \nu_k Y_{n,k}} \frac{1}{\hat{P}_n}, \quad (49)$$

with

$$\hat{P}_n = \prod_{s \in \mathcal{K}^M} \left(\frac{\psi_{n,s} w_n L_n / (1 - \psi_n^M)}{Y_{n,s}} \right)^{\nu_s \psi_{n,s}} \prod_{s \notin \mathcal{K}^M} \lambda_{nn,s}^{-\frac{\psi_{n,s}}{\sigma_s - 1}}. \quad (50)$$

The first term on the right-hand side of equation (49) captures the change in GDP, which we divide by

the change in the consumer price index to obtain the change in real GDP. The change in the consumer price index in equation (50) reflects both changes in the price of mining and non-mining goods (first and second terms). If $\nu_s = 0$, for all s , and noting that $\sigma_s = \infty$ for $s \in \mathcal{K}^M$, then $\hat{\mathcal{Y}}_n = \prod_s \lambda_{nn,s}^{\frac{\psi_{n,s}}{\sigma_s - 1}}$, which is the standard expression for the gains from trade in a model with input-output links (Arkolakis et al., 2012; Caliendo and Parro, 2015).

B.2 Optimal taxes

Letting e_i and r_i denote the expenditure and revenue functions in country i , an equilibrium satisfies

$$e_i(\mathbf{p}, u_i, \mathcal{E}) = r_i(\mathbf{p}, \boldsymbol{\pi}, \mathbf{t}) + \Lambda_i + \Upsilon_i, \quad (51)$$

where \mathbf{p} and $\boldsymbol{\pi}$ denote the vector of consumer and producer prices, respectively, \mathbf{t} is the vector of carbon taxes. Consumer prices in country n for $s \in \mathcal{K}^M$ are $p_{n,s}$ and for variety j of $s \notin \mathcal{K}^M$ are $p_{jn,n,s}$. Producer prices in country i are $\pi_{i,s}$ for $s \in \mathcal{K}^M$ and $\pi_{i,n,s}$ for sales of $s \notin \mathcal{K}^M$ for GVCs ending in n . Producers pay the same prices as consumers for intermediate goods, hence the dependence of the revenue function on \mathbf{p} . The vector of prices also includes $p_{ji,n,s}$, which is the price of variety j of $s \notin \mathcal{K}^M$ for use as inputs in producing non-mining goods in i for GVCs ending in n . Producers are also affected by carbon taxes directly in their use of fossil fuels.

Fiscal transfers satisfy

$$\sum_i \Upsilon_i = \sum_{s \in \mathcal{K}^M} e_s \left[\sum_i t_i^M q_{i,s} + \sum_n \left(t_n^C c_{n,s} + \sum_i \bar{t}_{i,n} q_{i,n,s} \right) \right],$$

where $q_{i,s}$ is quantity of s extracted in i , $c_{n,s}$ is quantity of s consumed in n , $q_{i,n,s}$ is quantity of s used by i to produce non-mining goods for GVCs ending in n .

The expenditure function satisfies

$$e_i(\mathbf{p}, u_i, E) = \tilde{e}_i \left(\left\{ p_{n,s} \right\}_{s \in \mathcal{K}^M}, \left\{ \min_{\{c_{j,i}\}_i} \left\{ \sum_j p_{ji,i,s} c_{ji,s} | h_{i,s}(c_{1i,s}, \dots, c_{Ni,s}) \geq 1 \right\} \right\}_{s \notin \mathcal{K}^M}, u_i \right) + \gamma_i \mathcal{E},$$

where $c_{ji,s}$ denotes consumption of variety j of $s \notin \mathcal{K}^M$ in country i , and h_i is some CRS function (in our

case CES).²⁴ The revenue function satisfies

$$r_i(\mathbf{p}, \boldsymbol{\pi}, \mathbf{t}) = \max_{\{\ell_{i,s}\}_{s \in \mathcal{K}^M}, \{\ell_{i,n,s}, q_{i,n,sk}\}_{s \notin \mathcal{K}^M}} \left\{ \begin{array}{l} \sum_{s \in \mathcal{K}^M} \pi_{i,s} f_{i,s}(\ell_{i,s}) \\ + \sum_{s \notin \mathcal{K}^M} \sum_n \pi_{i,n,s} g_{i,s}(\ell_{i,n,s}, \{q_{i,n,ks}\}_{k \in \mathcal{K}^M}, \{q_{ji,n,ks}\}_{k \notin \mathcal{K}^M}) \\ - \sum_{s \notin \mathcal{K}^M} \sum_{k \in \mathcal{K}^M} \sum_n (p_{n,k} + e_k (\bar{t}_{i,n} - t_n^C)) q_{i,n,ks} \\ - \sum_{s \notin \mathcal{K}^M} \sum_{k \notin \mathcal{K}^M} \sum_{j,n} p_{j,n,k} q_{ji,n,ks} \end{array} \right\},$$

where $\ell_{i,s}$ for $s \in \mathcal{K}^M$ is the quantity of labor used for mining s in i , and $\ell_{i,n,s}$, $q_{i,n,ks}$ and $q_{ji,n,ks}$ denote the quantities of labor, mining good $k \in \mathcal{K}^M$ and variety j of non-mining good $k \notin \mathcal{K}^M$ used to produce variety i of good $s \notin \mathcal{K}^M$ for GVCs ending in n .

Market clearing conditions are

$$\begin{aligned} f_{i,s}(\ell_{i,s}) &= q_{i,s}, \quad s \in \mathcal{K}^M, \\ \sum_i q_{i,k} &= \sum_n c_{n,k} + \sum_{i,n} q_{i,n,k}, \quad s \in \mathcal{K}^M, \\ q_{i,n,s} &\equiv \sum_{k \neq \mathcal{K}^M} q_{i,n,sk}, \quad s \in \mathcal{K}^M \\ g_{i,s}(\ell_{i,n,s}, \{q_{i,n,ks}\}_{k \in \mathcal{K}^M}, \{q_{ji,n,ks}\}_{k \notin \mathcal{K}^M}) &= x_{i,n,s}, \quad s \notin \mathcal{K}^M, \\ x_{i,n,s} &= \sum_l \sum_{k \notin \mathcal{K}^M} \tau_{il,s} q_{il,n,sk} + \tau_{in,s} c_{in,s}, \quad s \notin \mathcal{K}^M, \end{aligned}$$

where $x_{i,n,s}$ is the quantity of non-mining good s produced by i for GVCs ending in n . No-arbitrage conditions are

$$\begin{aligned} p_{n,s} &= p_s + e_s t_n^C, \quad s \in \mathcal{K}^M, \\ \pi_{i,s} &= p_s - e_s t_i^M, \quad s \in \mathcal{K}^M, \\ p_{il,n,s} &= \tau_{il,s} \pi_{i,n,s}, \quad s \notin \mathcal{K}^M. \end{aligned}$$

Differentiating equation 51 yields the total differential

$$e_i(\mathbf{p}, u_i, \mathcal{E}) = r_i(\mathbf{p}, \boldsymbol{\pi}, \mathbf{t})$$

²⁴The consumer price index in i for $s \notin \mathcal{K}^M$ is

$$P_{i,s} = \min_{\{c_{1i,s}, \dots, c_{Ni,s}\}} \left\{ \sum_j p_{ji,i,s} c_{ji,s} | h_{i,s}(c_{1i,s}, \dots, c_{Ni,s}) \geq 1 \right\}.$$

$$\begin{aligned}
& \sum_{s \in \mathcal{K}^M} e_{i,p_{i,s}} dp_{i,s} + \sum_{s \notin \mathcal{K}^M} \sum_j e_{i,p_{j,i,s}} dp_{j,i,s} + e_{i,u} du_i + e_{i,\mathcal{E}} d\mathcal{E} = \\
& \quad \sum_{k \in \mathcal{K}^M} r_{i,p_{n,k}} dp_{n,k} + \sum_{k \notin \mathcal{K}^M} \sum_{j,n} r_{i,p_{j,i,n,k}} dp_{j,i,n,k} \\
& + \sum_{s \in \mathcal{K}^M} r_{i,\pi_{i,s}} d\pi_{i,s} + \sum_{s \notin \mathcal{K}^M} \sum_n r_{i,\pi_{i,n,s}} d\pi_{i,n,s} + \sum_{s \notin \mathcal{K}^M} \sum_Z \sum_n r_{i,t_n^Z} dt_n^Z + d\Upsilon_i.
\end{aligned}$$

Applying the envelope theorem yields

$$\begin{aligned}
& \sum_{s \in \mathcal{K}^M} c_{i,s} dp_{i,s} + \sum_{s \notin \mathcal{K}^M} \sum_j c_{j,i,s} dp_{j,i,s} + e_{i,u} du_i + e_{i,E} d\mathcal{E} \\
& = - \sum_{s \notin \mathcal{K}^M} \sum_{k \in \mathcal{K}^M} \sum_n q_{i,n,ks} dp_{n,k} - \sum_{s \notin \mathcal{K}^M} \sum_{k \notin \mathcal{K}^M} \sum_{j,n} q_{j,i,n,ks} dp_{j,i,n,k} \\
& + \sum_{s \in \mathcal{K}^M} q_{i,s} d\pi_{i,s} + \sum_{s \notin \mathcal{K}^M} \sum_n q_{i,n,s} d\pi_{i,n,s} - \sum_{s \notin \mathcal{K}^M} \sum_{k \in \mathcal{K}^M} \sum_n e_k (d\bar{t}_{i,n} - dt_n^C) q_{i,n,ks} + d\Upsilon_i.
\end{aligned}$$

Adding up over i and using the no-arbitrage conditions yields

$$\begin{aligned}
& \sum_{s \in \mathcal{K}^M} \sum_i c_{i,s} (dp_s + e_s dt_i^C) + \sum_{s \notin \mathcal{K}^M} \sum_{i,j} c_{j,i,s} \tau_{j,i,s} d\pi_{j,i,s} + dW + \gamma d\mathcal{E} \\
& = - \sum_{s \notin \mathcal{K}^M} \sum_{k \in \mathcal{K}^M} \sum_{i,n} q_{i,n,ks} (dp_k + e_k d\bar{t}_{i,n}) - \sum_{s \notin \mathcal{K}^M} \sum_{k \notin \mathcal{K}^M} \sum_{j,i,n} q_{j,i,n,ks} \tau_{j,i,k} d\pi_{j,i,n,k} \\
& \quad + \sum_{s \in \mathcal{K}^M} \sum_i q_{i,s} (dp_s - e_s dt_i^M) + \sum_{s \notin \mathcal{K}^M} \sum_{i,n} q_{i,n,s} d\pi_{i,n,s} + \sum_i d\Upsilon_i,
\end{aligned}$$

where $dW \equiv \sum_i e_{i,u} du_i$ and we have used $e_{i,E} = \gamma_i$ and $\gamma \equiv \sum_i \gamma_i$. Using

$$\begin{aligned}
\sum_i d\Upsilon_i &= \sum_{s \in \mathcal{K}^M} e_s \left[\sum_i t_i^M dq_{i,s} + \sum_i q_{i,s} dt_i^M \right] \\
& + \sum_{s \in \mathcal{K}^M} e_s \sum_n (t_n^C dc_{n,s} + c_{n,s} dt_n^C) \\
& + \sum_{k \in \mathcal{K}^M} e_k \sum_n \left(\sum_i (\bar{t}_{i,n} dq_{i,n,k} + q_{i,n,k} d\bar{t}_{i,n}) \right),
\end{aligned}$$

market clearing conditions $q_{i,n,s} \equiv \sum_{k \neq \mathcal{K}^M} q_{i,n,sk}$ for $s \in \mathcal{K}^M$, and cancelling terms we have

$$\begin{aligned}
& \sum_{s \in \mathcal{K}^M} \sum_i c_{i,s} dp_s + \sum_{s \notin \mathcal{K}^M} \sum_{i,j} c_{ji,s} \tau_{ji,s} d\pi_{j,i,s} + dW + \gamma d\mathcal{E} \\
&= - \sum_{k \in \mathcal{K}^M} \sum_{i,n} q_{i,n,k} dp_k - \sum_{s \notin \mathcal{K}^M} \sum_{k \notin \mathcal{K}^M} \sum_{j,i,n} q_{ji,n,ks} \tau_{ji,k} d\pi_{j,n,k} \\
&\quad + \sum_{s \in \mathcal{K}^M} \sum_i q_{i,s} dp_s + \sum_{s \notin \mathcal{K}^M} \sum_{i,n} q_{i,n,s} d\pi_{i,n,s} \\
&+ \sum_{s \in \mathcal{K}^M} \sum_i e_s t_i^M dq_{i,s} + \sum_{s \in \mathcal{K}^M} \sum_n e_s t_n^C dc_{n,s} + \sum_{s \in \mathcal{K}^M} \sum_{i,n} (e_s \bar{t}_{i,n} dq_{i,n,s})
\end{aligned}$$

Collecting terms yields

$$\begin{aligned}
& \sum_{s \in \mathcal{K}^M} \left(\sum_i c_{i,s} + \sum_{i,n} q_{i,n,s} - \sum_i q_{i,s} \right) dp_s + dW + \gamma d\mathcal{E} \\
&= \sum_{s \notin \mathcal{K}^M} \sum_{j,n} \left[q_{j,n,s} - \tau_{jn,k} c_{jn,s} - \sum_{k \notin \mathcal{K}^M} \sum_i \tau_{ji,s} q_{ji,n,sk} \right] d\pi_{j,n,s} \\
&+ \sum_{s \in \mathcal{K}^M} \sum_i e_s t_i^M dq_{i,s} + \sum_{s \in \mathcal{K}^M} \sum_n e_s t_n^C dc_{n,s} + \sum_{k \in \mathcal{K}^M} \sum_{i,n} (e_k \bar{t}_{i,n} dq_{i,n,k})
\end{aligned}$$

Using the market clearing conditions and the definition of $\bar{t}_{i,n}$ then implies

$$\begin{aligned}
dW + \gamma d\mathcal{E} &= \sum_i t_i^M \sum_{s \in \mathcal{K}^M} e_s dq_{i,s} \\
&+ \sum_n \sum_{s \in \mathcal{K}^M} t_n^C e_s \left(dc_{n,s} + \sum_i dq_{i,n,s} \right) \\
&+ \sum_i t_i^P \sum_{s \in \mathcal{K}^M} \sum_n e_s dq_{i,n,s} \\
&+ \sum_n t_n^I \sum_{s \in \mathcal{K}^M} \sum_{i \neq n} e_s dq_{i,n,s} \\
&+ \sum_i t_i^X \sum_{s \in \mathcal{K}^M} \sum_{n \neq i} e_s dq_{i,n,s}.
\end{aligned}$$

Using

$$c_{n,s} = \frac{e_s}{p_s + e_s (t_n^P + t_n^C)} \mu_{n,s} X_n^C,$$

and

$$q_{i,n,s} = \sum_i \frac{1}{p_s + e_s \bar{t}_{i,n}} \sum_{k \notin \mathcal{K}^M} \alpha_{i,sk} \sum_l \sum_{r \notin \mathcal{K}^M} \chi_{il,n,kr} \lambda_{ln,n,r} \mu_{n,r} X_n^C,$$

and the definitions of \mathcal{E}^Z for $Z = M, P, C, I, X$, we finally get

$$dW + \gamma dE = \sum_i t_j^M d\mathcal{E}_j^M + \sum_i t_i^P d\mathcal{E}_i^P + \sum_n t_n^C d\mathcal{E}_n^C + \sum_n t_n^X d\mathcal{E}_n^X + \sum_i t_i^X d\mathcal{E}_i^X.$$

Setting $dW = 0$ we then have the equation in the text.

B.3 Aggregation for World Consumption and Welfare

We have that

$$V_n = \frac{X_n^C - \gamma_n \mathcal{E}}{P_n}.$$

Simple algebra shows that

$$\hat{V}_n = \frac{1}{\hat{P}_n} \frac{X_n^C \hat{X}_n^C - \gamma_n \mathcal{E} \hat{\mathcal{E}}}{X_n^C - \gamma_n \mathcal{E}} = \frac{1}{\hat{P}_n} \frac{\hat{X}_n^C - (\gamma_n \mathcal{E} / X_n^C) \hat{\mathcal{E}}}{1 - \gamma_n \mathcal{E} / X_n^C}.$$

The compensating variation (CV) is obtained by solving for \hat{X}_n for $\hat{V}_n = 1$,

$$\hat{X}_n^{CV} = \hat{P}_n [1 - (\gamma_n \mathcal{E} / X_n^C)] + (\gamma_n \mathcal{E} / X_n^C) \hat{\mathcal{E}}.$$

The CV is then

$$CV_n = X_n^C \hat{X}_n^{CV} - X_n^C = X_n^C [\hat{P}_n [1 - (\gamma_n \mathcal{E} / X_n^C)] + (\gamma_n \mathcal{E} / X_n^C) \hat{\mathcal{E}} - 1],$$

or

$$CV_n = X_n^C [\hat{P}_n - 1 + (\gamma_n \mathcal{E} / X_n^C) (\hat{\mathcal{E}} - \hat{P}_n)].$$

A measure of the welfare gain for n is

$$\Delta_n \equiv (X_n^C \hat{X}_n^C - X_n^C) - CV_n = X_n^C [\hat{X}_n^C - \hat{P}_n - (\gamma_n \mathcal{E} / X_n^C) (\hat{\mathcal{E}} - \hat{P}_n)].$$

Adding across countries, dividing by world's GDP $X^C \equiv \sum_n X_n^C$ and using $\omega_n \equiv X_n^C / X^C$ yield

$$\Delta / X^C = \sum_n \Delta_n / X^C = \sum_n \omega_n [\hat{X}_n^C - \hat{P}_n - (\gamma_n \mathcal{E} / X_n^C) (\hat{\mathcal{E}} - \hat{P}_n)].$$

This is a measure of the gains as a share of pre-policy GDP.

We can further decompose the welfare changes into changes in real expenditure gains and changes in emissions.

$$\Delta / X^C = \sum_n \omega_n (\hat{X}_n^C - \hat{P}_n) + \sum_n \omega_n (\gamma_n \mathcal{E} / X_n^C) (\hat{P}_n - \hat{\mathcal{E}}).$$

C Data Appendix

C.1 Constructing Energy Sectors in WIOD

WIOD describes three main sectors that cover energy: mining; utilities; and refining of petroleum and coke. 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 input cost shares between the Electricity and Gas Utility sectors are the same. 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.

Finally, to be consistent with the model production function in mining, we re-allocate inputs used by country l in mining sector $k \in \mathcal{K}^M$ to value added of that country-sector. To maintain the accounting identities unchanged we reallocate the flows of inputs s from country j purchased by mining sectors $k \in \mathcal{K}^M$ in country l into final demand of country l for good s from country j . This maintains country-level Scope 1 emissions and extraction-based emissions unchanged, while changes country-level consumption-based emissions. World emissions are also unchanged.

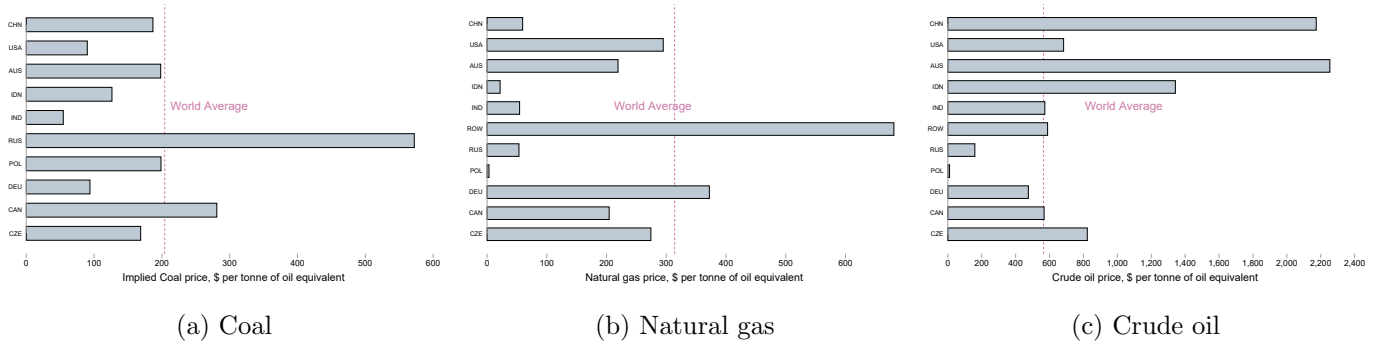
C.2 Additional Data Details

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 Fed-

Table C2: List of Sectors

Codes	Sector
A	Agriculture
B10	Coal*
B11	Natural Gas*
B12	Crude Petroleum*
B13	Non-energy mining and quarrying
C10T12	Food, beverages & tobacco
C13T15	Textiles, apparel & leather
C16	Wood & cork products (excl. furniture)
C17T18	Paper, media & printing
C19	Coke & petroleum products
C20T21	Chemicals & pharmaceuticals
C22	Rubber & plastics
C23	Non-metallic minerals
C24	Basic metals
C25	Fabricated metals (excl. machinery)
C26T28	Electronics, machinery & equipment
C29T30	Motor vehicles & transport equipment
C31T33	Furniture, other manuf. & repairs
D35A	Electricity
D35B	Gas distribution
F	Construction
G	Trade (wholesale & retail)
H	Transport & storage
I	Accommodation & food services
J	Information & communication
KL	Real estate & insurance
MTN	Professional & administrative services
PQRSTUOTE	Education, health, public & other services

Figure A1: Implied prices for fossil fuels, by country



Notes: The bars are implied producer 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 global price calculated in the paper as $p_s = Y_s/Q_s$.

eral 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.

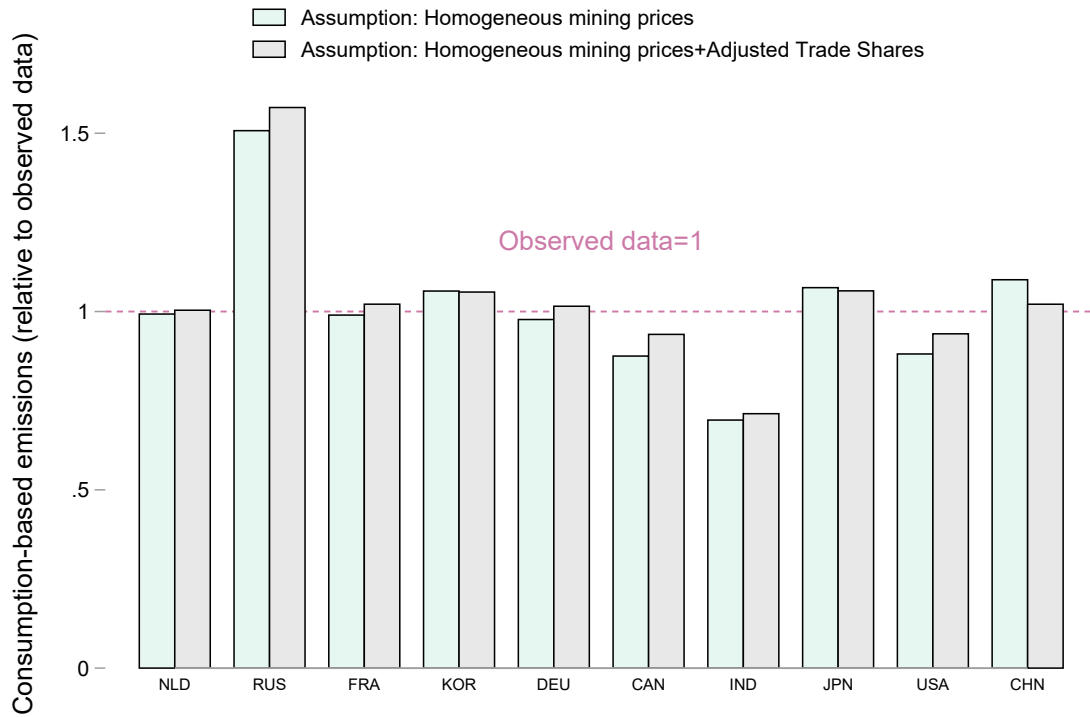
D Additional Results

Table D3: Accounting for carbon emissions, by country and measure

Country name	Country code	Extraction	Production (S1)	Production (S3)	Consumption
Australia	AUS	1,399	287	494	409
Austria	AUT	8	59	75	84
Brazil	BRA	493	487	561	599
Canada	CAN	1,019	582	630	659
China	CHN	8,519	11,189	10,433	10,340
Czech Republic	CZE	51	82	89	84
Germany	DEU	92	342	555	743
Denmark	DNK	36	48	71	74
Spain	ESP	29	306	298	293
France	FRA	33	291	418	474
Great Britain	GBR	405	533	641	720
Greece	GRC	8	75	46	55
Croatia	HRV	55	32	30	34
Hungary	HUN	3	44	48	51
Indonesia	IDN	924	398	550	516
India	IND	405	1,122	1,081	1,001
Italy	ITA	45	262	328	382
Japan	JPN	202	1,445	1,497	1,529
Korea	KOR	29	681	723	636
Mexico	MEX	426	243	355	344
Netherlands	NLD	111	10	154	161
Norway	NOR	600	221	217	241
Poland	POL	192	263	251	245
Romania	ROU	42	96	98	94
Rest of the World	ROW	13,327	10,285	9,811	9,173
Russia	RUS	2,472	989	1,217	919
Turkey	TUR	101	123	216	249
United States	USA	4,198	4,730	4,338	5,116
World	WORLD	35,225	35,225	35,225	35,225

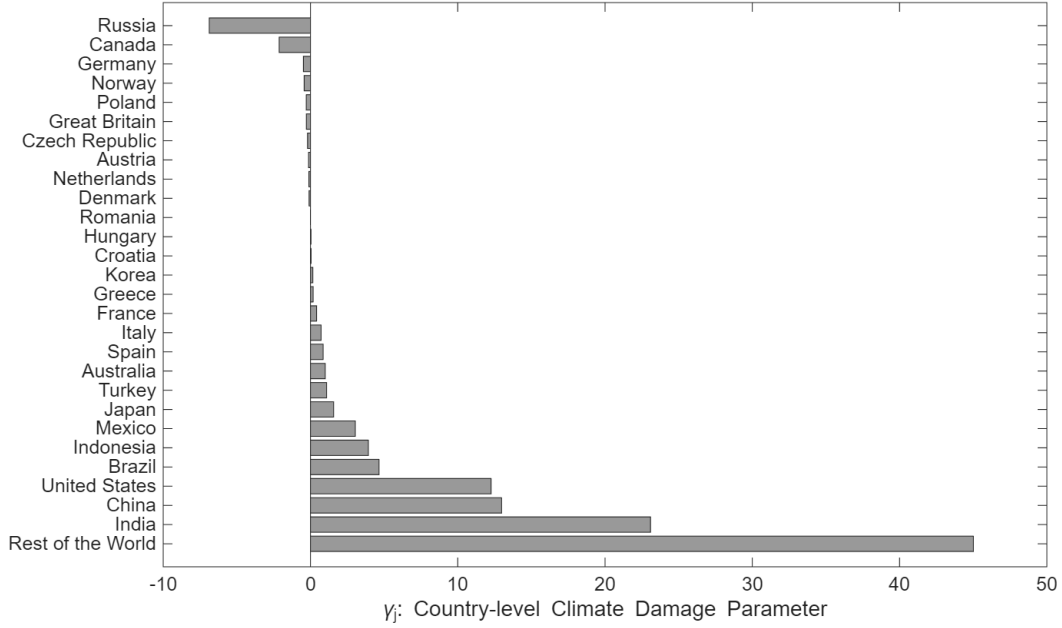
Notes: Emissions are in million tons of CO₂. Extraction-, production (S1)-, production (S3), and consumption-based emissions.

Figure A2: 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.

Figure A3: Country-level Climate Damage Parameter, by Country



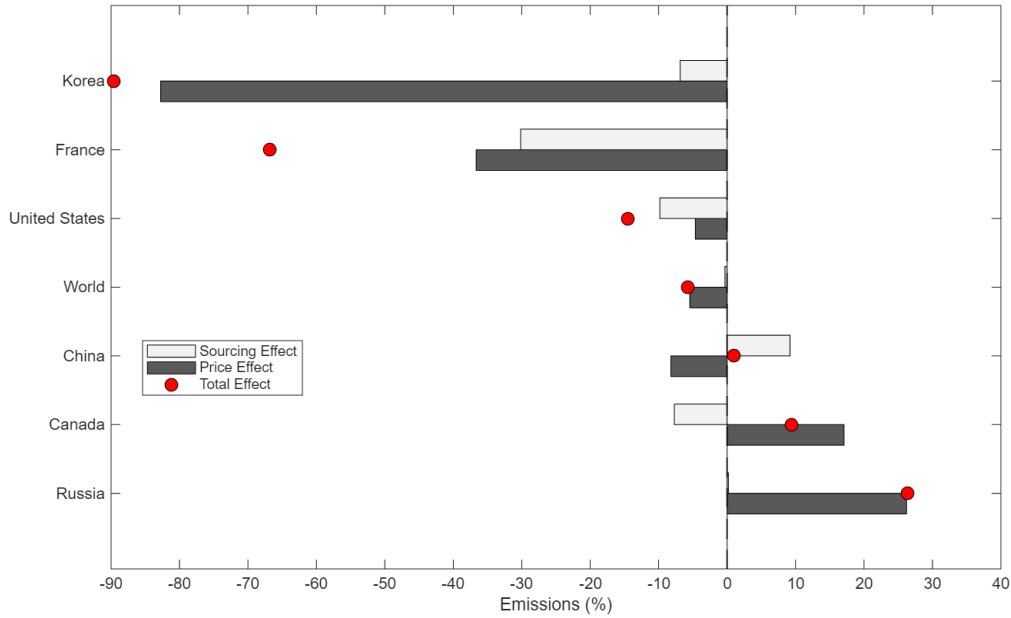
Notes: Country-specific damage parameter is calculated as $\gamma_j = \frac{SSC_j}{\sum_{j'} SSC_{j'}} \gamma$, where SSC_j denotes country-level damage from [Ricke et al. \(2018\)](#), and γ is the global social cost of carbon set at \$100 per ton of CO₂.

E Counterfactual Emissions Decompositions

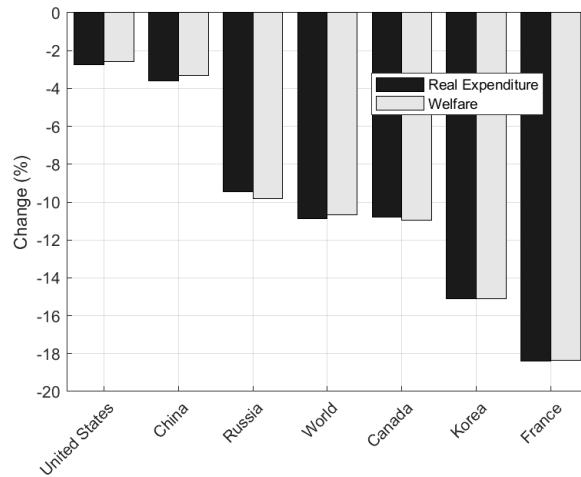
E.1 Autarky: Decomposition

$$\begin{aligned} \mathcal{E}_n^C &= \sum_{s \in \mathcal{K}^M} \frac{e_s}{p_s} \mu_{n,s} X_n^C + \sum_{s \in \mathcal{K}^M} \sum_l \mathcal{E}_{ln,s} \\ \mathcal{E}_{ln,s} &= \frac{e_s}{p_s} \sum_i \sum_{k \notin \mathcal{K}^M} \alpha_{i,sk} \Xi_{il,n,k} \\ \Xi_{il,n,k} &= \sum_{r \notin \mathcal{K}^M} \chi_{il,kr} \lambda_{ln,r} \mu_{n,r} X_n^C \\ \mathcal{E}_n^C &= \sum_{s \in \mathcal{K}^M} \frac{e_s}{p_s} \left[\mu_{n,s} + \sum_{i,l} \sum_{k \notin \mathcal{K}^M} \alpha_{i,sk} \sum_{r \notin \mathcal{K}^M} \chi_{il,kr} \lambda_{ln,r} \mu_{n,r} \right] X_n^C \end{aligned}$$

Figure A4: Effect of Global Autarky, Selected Countries



(a) Change in Emissions



(b) Change in Real GDP and Welfare

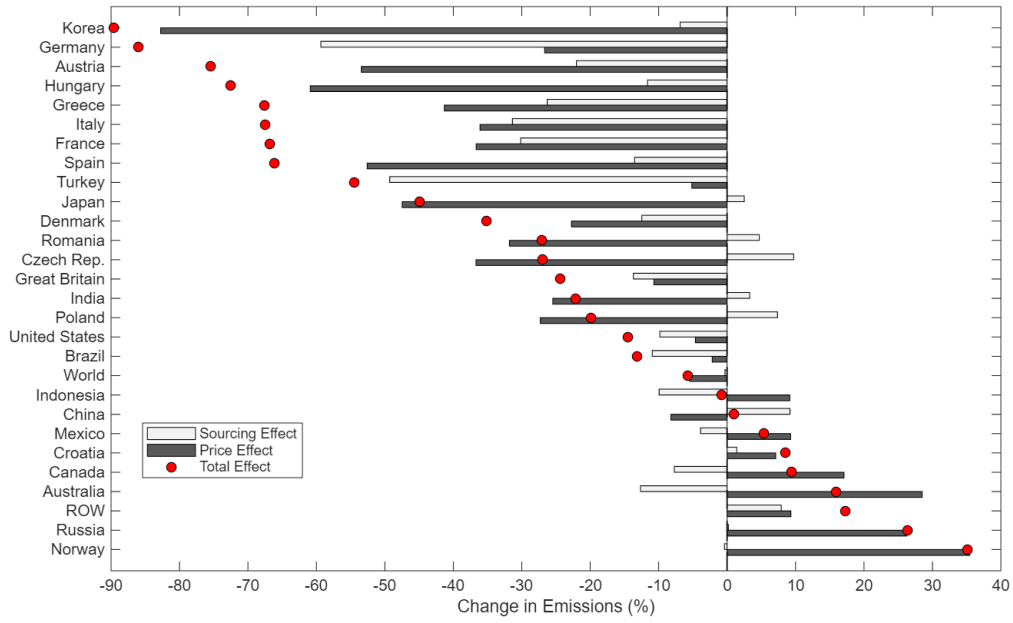
Notes: % change in autarky to observed consumption-based emissions, $(\mathcal{E}_n^A/\mathcal{E}_n^C - 1) \times 100$. $\Delta_n^{A,1}$ is the price channel, $\Delta_n^{A,2}$ is the sourcing channel, and $\Delta_n^{A,3}$ is the trade imbalance channel, in equation (35). Welfare changes are calculated using equation (34), for each country. Global change in real GDP and welfare calculated using equation (36).

Table D4: Effects of Global Autarky, by Country

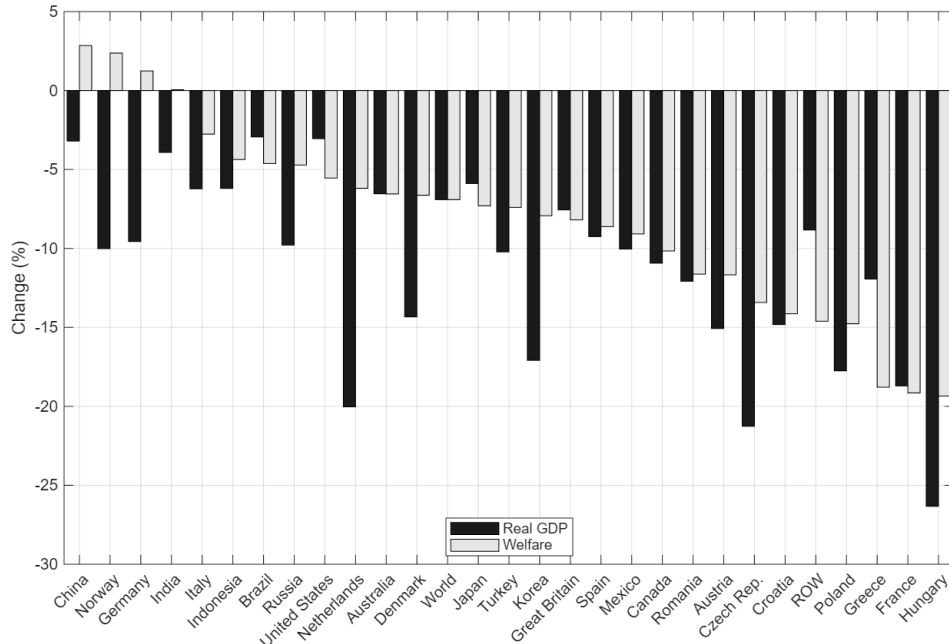
	$\Delta_n^{A,1}$	$\Delta_n^{A,2}$	$\Delta_n^{A,3}$	Observed emissions	% change in emissions	Net exports Fossil fuels	Net exports All sectors	% change in real GDP	% change in welfare	γ_n
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
Australia	28.51	-12.65	-0.66	412	15.2	79632	-1741	-6.54	-6.55	1.00
Austria	-53.44	-22.01	9.49	77	-65.96	-7434	16126	-15.07	-11.67	-0.13
Brazil	-2.18	-10.94	-4.42	626	-17.54	752	-47223	-2.94	-4.62	4.65
Canada	17.08	-7.72	-0.04	659	9.32	78399	18792	-10.93	-10.16	-2.13
China	-8.21	9.19	7.25	9646	8.23	-185439	583854	-3.2	2.85	12.98
Czech Rep.	-36.69	9.73	15.72	73	-11.24	-5043	19169	-21.26	-13.42	-0.20
Germany	-26.65	-59.35	20.3	617	-65.7	-32567	389853	-9.56	1.24	-0.48
Denmark	-22.73	-12.46	15.07	64	-20.12	-738	26674	-14.33	-6.63	-0.10
Spain	-52.58	-13.52	1.6	288	-64.51	-42545	6778	-9.25	-8.62	0.86
France	-36.66	-30.16	0.32	472	-66.5	-36269	-15446	-18.71	-19.15	0.41
Great Britain	-10.7	-13.69	-0.77	725	-25.15	-12913	-18828	-7.56	-8.19	-0.28
Greece	-41.32	-26.28	-13.23	63	-80.83	-12043	-18225	-11.94	-18.79	0.18
Croatia	7.11	1.41	0.94	34	9.46	864	321	-14.82	-14.14	0.04
Hungary	-60.9	-11.63	14.21	44	-58.31	-5829	10769	-26.33	-19.35	0.04
Indonesia	9.17	-9.94	1.28	510	0.52	32464	7630	-6.2	-4.37	3.93
India	-25.47	3.31	-0.81	1008	-22.97	-96595	-2184	-3.92	0.05	23.09
Italy	-36.09	-31.36	7.97	354	-59.49	-34016	68703	-6.22	-2.76	0.72
Japan	-47.46	2.51	-3.23	1579	-48.18	-154366	-71612	-5.89	-7.3	1.57
Korea	-82.75	-6.86	15.22	552	-74.39	-101567	135150	-17.09	-7.93	0.16
Mexico	9.28	-3.87	-1.03	347	4.38	35624	6632	-10.04	-9.08	3.04
Netherlands	9.04	-119.5	26.55	128	-83.91	19540	123667	-20.03	-6.19	-0.11
Norway	35.47	-0.39	20.23	201	55.31	75897	62348	-10.01	2.37	-0.43
Poland	-27.3	7.37	6.41	230	-13.53	-12419	19041	-17.75	-14.77	-0.29
Romania	-31.8	4.71	1.88	92	-25.22	-8074	990	-12.08	-11.63	-0.01
ROW	9.32	7.91	-7.43	9900	9.8	451361	-975407	-8.83	-14.61	45.01
Russia	26.22	0.19	9.16	843	35.57	164058	114886	-9.79	-4.72	-6.88
Turkey	-5.15	-49.28	5.13	237	-49.31	-1772	19607	-10.22	-7.4	1.09
USA	-4.64	-9.83	-5.81	5423	-20.28	-188963	-480322	-3.05	-5.54	12.26
World	-5.44	-0.31	0.02	35204	-5.73	0	0	-6.91	-6.91	100.00

Notes: % change in autarky to observed consumption-based emissions, $(\mathcal{E}_n^A/\mathcal{E}_n^C - 1) \times 100$. $\Delta_n^{A,1}$ is the price channel, $\Delta_n^{A,2}$ is the sourcing channel, and $\Delta_n^{A,3}$ is the trade imbalance channel, in equation (35). Net exports are in US dollars. Welfare changes are calculated using equation (34), for each country, and γ_n is the disutility of global emissions ($\$/tCO_2$). Global change in real GDP and welfare calculated using equation (36).

Figure A5: Effect of Global Autarky: Emissions, Real GDP, and Welfare



(a) Change in Emissions



(b) Change in Real GDP and Welfare

Notes: % change in autarky to observed consumption-based emissions, $(\mathcal{E}_n^A/\mathcal{E}_n^C - 1) \times 100$. $\Delta_n^{A,1}$ is the price channel, $\Delta_n^{A,2}$ is the sourcing channel, and $\Delta_n^{A,3}$ is the trade imbalance channel, in equation (35). Welfare changes are calculated using equation (34), for each country. Global change in real GDP and welfare are calculated using equation (36).

Table D5: The Effects of a Global Carbon Tax

% change Tax	National Transfers						Global Transfers														
	Emissions			Consumption			Welfare			Emissions			Consumption			Welfare					
	Extr.	Prod.	Cons.	Extr.	Prod.	Cons.	Extr.	Prod.	Cons.	Extr.	Prod.	Cons.	Extr.	Prod.	Cons.	Extr.	Prod.	Cons.	Extr.	Prod.	Cons.
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)	(17)	(18)	(19)	(20)	(21)
Australia	-55.04	-43.71	-44.04	1.43	-1.94	-1.42	2.61	-0.88	-0.34	-53.99	-43.45	-44.17	-1.61	-0.55							
Austria	-33.73	-39.04	-40.69	-0.43	0.28	0.58	-0.97	-0.27	0.03	-33.78	-39.41	-42.61	-1.38	-1.91							
Brazil	-33.25	-32.16	-34.75	-0.59	-0.47	-0.14	2.81	2.90	3.26	-36.34	-30.87	-31.75	2.17	5.82							
Canada	-34.02	-37.98	-39.25	0.31	-1.61	-1.39	-1.61	-3.42	-3.20	-30.68	-39.71	-43.58	-6.5	-8.06							
China	-49.77	-52.00	-50.49	-2.14	-1.54	-2.02	-0.09	0.52	0.02	-49.83	-52.56	-51.94	-4.28	-2.38							
Czech Rep.	-62.43	-53.05	-47.28	-0.91	-0.12	-0.06	-2.62	-1.85	-1.79	-62.59	-53.56	-50.37	-4.77	-6.29							
Germany	-57.54	-33.37	-44.34	0.15	0.55	0.94	-0.09	0.31	0.70	-58.43	-33.69	-45.75	-0.53	-0.76							
Denmark	-28.70	-41.43	-38.64	0.01	-0.21	0.23	-0.52	-0.73	-0.29	-28.21	-41.65	-40.65	-1.93	-2.43							
Spain	-61.27	-37.74	-40.66	-0.91	0.55	0.38	0.16	1.65	1.48	-63.3	-37.82	-40.87	0.41	1.5							
France	-41.52	-32.31	-39.51	-0.69	0.02	0.38	-0.44	0.27	0.63	-42.43	-32.41	-40.53	-0.41	-0.16							
Great Britain	-35.57	-36.30	-38.70	-0.72	-0.43	-0.04	-0.88	-0.59	-0.20	-35.52	-36.8	-40.45	-1.89	-2.04							
Greece	-62.73	-24.43	-36.51	1.28	1.13	0.47	-0.03	2.44	1.77	-64.92	-24.11	-36.82	0.38	1.67							
Croatia	-61.56	-59.15	-53.86	-0.79	-2.28	-1.82	0.52	-1.03	-0.56	-62.17	-59.24	-54.76	-3.2	-1.98							
Hungary	-44.68	-33.73	-40.22	-1.45	0.86	0.68	-0.96	1.37	1.18	-45.62	-34.41	-41.86	-1.12	-0.64							
Indonesia	-50.70	-31.15	-38.87	0.34	-1.78	-1.33	8.82	6.14	6.69	-54.61	-30.2	-33.44	4.21	13.49							
India	-49.22	-45.49	-43.98	-1.89	0.19	-0.06	25.25	28.70	28.25	-65.92	-42.42	-25.47	18.46	62.24							
Italy	-35.15	-26.29	-36.64	-0.47	0.35	0.53	0.13	0.96	1.14	-36.2	-26.34	-37.4	0.08	0.69							
Japan	-51.32	-43.66	-41.26	-1.62	0.10	0.36	-1.08	0.66	0.92	-52.7	-43.77	-42.72	-1.07	-0.53							
Korea	-62.30	-31.97	-38.09	-1.92	1.84	0.77	-1.72	2.06	0.99	-63.8	-31.52	-40.21	-1.92	-1.72							
Mexico	-27.60	-30.80	-32.39	0.00	-1.20	-0.63	4.32	2.94	3.58	-29.33	-30.22	-29.58	2.58	7.14							
Netherlands	-35.39	-3.92	-43.78	1.24	-0.21	0.75	0.98	-0.45	0.50	-35.5	-3.95	-45.17	-0.69	-0.93							
Norway	-34.07	-32.09	-36.29	4.46	-3.57	-3.80	2.78	-4.93	-5.15	-27.28	-34.52	-40.78	-9.07	-10.21							
Poland	-62.84	-54.32	-50.06	-1.27	-0.42	-0.49	-2.17	-1.33	-1.40	-62.89	-54.87	-52.53	-4.23	-5.04							
Romania	-50.83	-41.49	-40.77	-1.97	-0.08	-0.14	-2.03	-0.15	-0.20	-51.41	-42.24	-43.2	-3.22	-3.28							
ROW	-37.78	-43.01	-43.53	-0.57	-1.78	-2.03	4.47	3.06	2.78	-38.9	-42.39	-42.18	0.24	5.31							
Russia	-53.78	-58.71	-58.67	2.47	-2.88	-3.26	-3.59	-8.06	-8.38	-45.09	-59.05	-65.01	-14.65	-18.05							
Turkey	-62.36	-53.53	-48.90	-0.72	-0.54	0.40	1.80	1.96	2.96	-64.68	-53.12	-48.12	1.82	4.48							
USA	-36.76	-30.18	-33.81	-0.76	-0.20	-0.08	0.35	0.91	1.03	-37.37	-30.54	-34.71	-0.73	0.36							
World	-43.18	-43.48	-43.50	-0.79	-0.79	-0.79	1.41	1.37	1.37	-43.45	-43.45	-43.45	-0.74	1.59							

Note: Tax is $t_s = scc \times e_s$ where $scc = 100\$/\text{ton CO}_2$, for $s \in \mathcal{K}^M$, and applied to all countries. For the extraction tax, we report extraction-based emissions calculated using equation (16). For the production tax, we report production-based emissions (scope 1) calculated using equation (17). For the consumption tax, we report consumption-based emissions calculated using equation (22). Welfare changes are given by equation (34). Global welfare gains and changes in consumption are expressed relative to initial GDP, calculated using equation (36).

Table D6: Optimal Global Carbon Tax, Decomposition 1: Price effect

	% change in emissions (1)	Price effect (2)	Direct tax effect (3)	Expenditure effect (4)
Australia	-43.5	29.2	-78.1	5.40
Austria	-39.4	24.8	-55.6	-8.60
Brazil	-30.9	24.7	-62.4	6.85
Canada	-39.7	23.8	-59.6	-3.92
China	-52.6	33.2	-82.5	-3.23
Czech Rep.	-53.6	29.5	-70.4	-12.6
Germany	-33.7	28.9	-82.0	19.4
Denmark	-41.6	20.9	-43.6	-18.9
Spain	-37.8	25.4	-63.5	0.30
France	-32.4	24.8	-68.5	11.3
Great Britain	-36.8	24.9	-63.9	2.17
Greece	-24.1	23.7	-59.4	11.6
Croatia	-59.2	36.5	-93.8	-1.92
Hungary	-34.4	24.2	-64.2	5.61
Indonesia	-30.2	26.6	-70.4	13.6
India	-42.4	29.6	-72.5	0.48
Italy	-26.3	21.3	-58.9	11.3
Japan	-43.8	27.9	-72.5	0.77
Korea	-31.5	23.6	-62.1	7.03
Mexico	-30.2	22.6	-52.2	-0.58
Netherlands	-3.95	21.7	-74.1	48.5
Norway	-34.5	21.7	-51.5	-4.72
Poland	-54.9	33.6	-81.1	-7.38
Romania	-42.2	27.8	-69.3	-0.79
ROW	-42.4	26.7	-69.3	0.19
Russia	-59.1	37.3	-100.6	4.29
Turkey	-53.1	35.7	-99.8	10.9
USA	-30.5	22.7	-57.7	4.49
World	-43.5	28.5	-72.4	0.52

Note: Decomposition of total change in emissions after a global production tax of 100\$ per ton of CO₂ calculated using equation (37).

Table D7: Single-Country Optimal Tax, All countries

	Extraction Tax (1)	Production Tax (2)	Consumption Tax (3)
Australia	29.20	38.56	77.45
Austria	35.82	28.95	58.05
Brazil	44.76	36.20	65.77
Canada	40.95	41.45	72.55
China	32.68	60.60	75.93
Czech Rep.	27.06	46.85	66.34
Germany	28.15	33.89	67.42
Denmark	42.43	24.61	60.79
Spain	28.64	32.42	64.09
France	34.24	33.37	68.09
Great Britain	40.00	42.96	67.35
Greece	27.49	18.97	60.10
Croatia	27.09	62.11	71.86
Hungary	30.99	29.20	62.63
Indonesia	32.47	30.93	72.00
India	29.84	43.54	70.30
Italy	34.96	32.06	66.87
Japan	29.97	47.38	69.57
Korea	28.60	28.20	70.67
Mexico	47.08	29.51	67.24
Netherlands	34.32	13.78	59.50
Norway	35.39	42.34	72.31
Poland	26.87	50.47	68.56
Romania	28.55	44.04	65.29
ROW	45.02	50.40	73.00
Russia	28.83	53.57	79.90
Turkey	28.03	60.09	65.61
United States	42.19	40.66	70.71
European Union	30.11	38.22	66.97

Notes: Optimal tax per ton of CO₂ for selected countries calculated using equation (29).

Table D8: Optimal Single-Country Carbon Tax, All Countries

Tax	% change in world emissions			% change in word consumption			% world welfare gains			% share of world emissions		
	Extr. (1)	Prod. (2)	Cons. (3)	Extr. (4)	Prod. (5)	Cons. (6)	Extr. (7)	Prod. (8)	Cons. (9)	Extr. (10)	Prod. (11)	Cons. (12)
Australia	-0.82	-0.15	-0.34	-0.02	0.00	-0.01	0.02	0.01	0.01	3.88	0.81	1.17
Austria	0.00	-0.02	-0.05	0.00	0.00	0.00	0.00	0.00	0.00	0.03	0.16	0.22
Brazil	-0.23	-0.16	-0.39	0.00	0.00	-0.01	0.01	0.01	0.01	1.34	1.40	1.78
Canada	-0.46	-0.25	-0.46	-0.01	-0.01	-0.01	0.02	0.01	0.01	2.88	1.66	1.87
China	-6.03	-10.37	-10.33	-0.12	-0.18	-0.17	0.16	0.33	0.33	25.8	30.9	27.4
Czech Rep.	-0.04	-0.06	-0.06	0.00	0.00	0.00	0.00	0.00	0.00	0.16	0.23	0.21
Germany	-0.08	-0.12	-0.48	0.00	0.00	-0.01	0.00	0.00	0.01	0.29	0.95	1.75
Denmark	-0.02	-0.01	-0.04	0.00	0.00	0.00	0.00	0.00	0.00	0.11	0.13	0.18
Spain	-0.02	-0.11	-0.22	0.00	0.00	0.00	0.00	0.00	0.01	0.08	0.87	0.82
France	-0.01	-0.09	-0.32	0.00	0.00	-0.01	0.00	0.00	0.01	0.09	0.82	1.34
Great Britain	-0.19	-0.23	-0.49	0.00	0.00	-0.01	0.01	0.01	0.01	1.14	1.51	2.06
Greece	-0.01	-0.01	-0.04	0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.21	0.18
Croatia	-0.04	-0.03	-0.04	0.00	0.00	0.00	0.00	0.00	0.00	0.15	0.09	0.10
Hungary	0.00	-0.01	-0.03	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.12	0.13
Indonesia	-0.54	-0.12	-0.40	-0.01	0.00	-0.01	0.01	0.01	0.02	2.61	1.13	1.45
India	-0.22	-0.69	-0.87	0.00	-0.01	-0.02	0.00	0.03	0.06	1.12	3.20	2.86
Italy	-0.02	-0.06	-0.22	0.00	0.00	0.00	0.00	0.00	0.01	0.14	0.74	1.00
Japan	-0.13	-0.91	-1.27	0.00	-0.01	-0.02	0.00	0.03	0.03	0.55	4.11	4.48
Korea	-0.03	-0.19	-0.39	0.00	0.00	-0.01	0.00	0.01	0.01	0.09	1.93	1.57
Mexico	-0.19	-0.06	-0.19	0.00	0.00	0.00	0.00	0.00	0.01	1.20	0.70	0.99
Netherlands	-0.05	0.00	-0.10	0.00	0.00	0.00	0.00	0.00	0.00	0.37	0.03	0.36
Norway	-0.27	-0.07	-0.13	-0.01	0.00	0.00	0.01	0.00	0.00	1.98	0.57	0.57
Poland	-0.13	-0.21	-0.22	0.00	0.00	0.00	0.00	0.01	0.01	0.57	0.74	0.65
Romania	-0.02	-0.05	-0.07	0.00	0.00	0.00	0.00	0.00	0.00	0.12	0.27	0.26
ROW	-6.99	-6.64	-8.66	-0.15	-0.12	-0.16	0.17	0.23	0.30	36.3	29.7	28.1
Russia	-1.55	-0.89	-0.95	-0.03	-0.01	-0.02	0.06	0.03	0.02	7.57	2.79	2.39
Turkey	-0.07	-0.11	-0.22	0.00	0.00	0.00	0.00	0.00	0.01	0.29	0.35	0.67
USA	-2.04	-1.72	-3.60	-0.04	-0.03	-0.08	0.06	0.05	0.09	11.2	13.8	15.4

Note: Optimal tax for each country is $t_{j,k}^Z = t_j^Z \times e_s$ where t_j^Z is the optimal tax and is applied to one country at the time. For the extraction tax, we report extraction-based emissions calculated using equation (16). For the production tax, we report production-based emissions (scope 1) calculated using equation (17). For the consumption tax, we report consumption-based emissions calculated using equation (22). Global welfare gains and changes in consumption are expressed relative to initial GDP, calculated using equation (36)

Table D9: Optimal Single-Country Carbon Tax Combination: Extraction and Consumption

	Tax Combination		% change in	% change in word	% world welfare
	Extr.	Cons.	world emissions	consumption	gains
	(1)	(2)	(3)	(4)	(5)
Australia	27.06	65.78	-1.09	-0.02	0.03
Austria	33.14	59.91	-0.06	0.00	0.00
Brazil	39.01	63.06	-0.58	-0.01	0.02
Canada	36.73	65.40	-0.88	-0.02	0.02
China	23.34	73.61	-13.80	-0.25	0.41
Czech Rep.	25.86	66.53	-0.10	0.00	0.00
Germany	27.54	62.48	-0.55	-0.01	0.02
Denmark	40.64	60.94	-0.06	0.00	0.00
Spain	26.40	63.97	-0.23	0.00	0.01
France	33.23	62.86	-0.35	-0.01	0.01
Great Britain	36.58	64.50	-0.68	-0.01	0.02
Greece	26.52	60.78	-0.04	0.00	0.00
Croatia	25.24	70.44	-0.07	0.00	0.00
Hungary	28.04	64.17	-0.03	0.00	0.00
Indonesia	28.18	65.65	-0.84	-0.02	0.03
India	27.53	69.33	-1.06	-0.02	0.06
Italy	31.79	62.24	-0.25	-0.01	0.01
Japan	27.56	69.13	-1.37	-0.02	0.04
Korea	25.41	67.04	-0.42	-0.01	0.01
Mexico	43.09	59.70	-0.35	-0.01	0.01
Netherlands	33.07	59.00	-0.15	0.00	0.00
Norway	31.50	63.66	-0.36	-0.01	0.01
Poland	25.38	68.12	-0.35	-0.01	0.01
Romania	26.87	65.74	-0.09	0.00	0.00
ROW	31.45	67.96	-13.12	-0.25	0.40
Russia	25.93	72.52	-2.35	-0.04	0.07
Turkey	26.62	64.76	-0.28	-0.01	0.01
USA	31.77	65.92	-4.95	-0.10	0.13
European Union	27.30	65.70	-2.29	-0.04	0.07

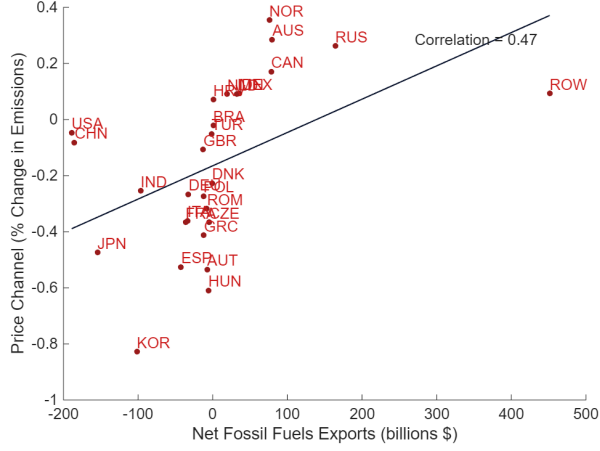
Note: Optimal tax columns present the optimal tax combination of an extraction and a consumption tax applied to one country at the time. Global welfare gains and changes in consumption are expressed relative to initial GDP, calculated using equation (36)

Table D10: Optimal Single-Country Carbon Tax Combination: Extraction and Consumption

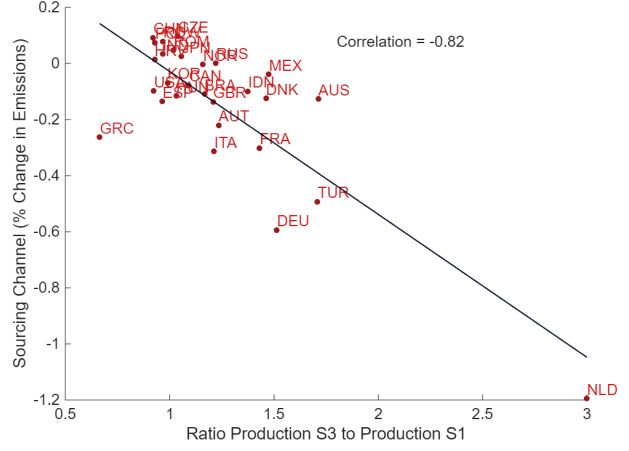
	Tax Combination			% change in	% change in word	% world welfare
	Extr.	Cons.	Export.	world emissions	consumption	gains
	(1)	(2)	(3)	(4)	(5)	(6)
Australia	27.66	65.13	31.71	-1.13	-0.02	0.03
Austria	33.81	60.36	23.10	-0.07	0.00	0.00
Brazil	39.64	62.50	21.36	-0.60	-0.01	0.02
Canada	37.63	64.90	26.47	-0.92	-0.02	0.03
China	24.27	73.77	52.75	-15.75	-0.28	0.48
Czech Rep.	26.36	66.35	38.44	-0.13	0.00	0.00
Germany	27.57	62.21	20.11	-0.58	-0.01	0.02
Denmark	42.13	61.27	23.08	-0.07	0.00	0.00
Spain	26.59	63.89	19.43	-0.26	-0.01	0.01
France	33.05	62.66	17.18	-0.36	-0.01	0.01
Great Britain	36.88	64.18	25.84	-0.71	-0.01	0.02
Greece	26.68	60.79	9.25	-0.05	0.00	0.00
Croatia	26.09	69.88	53.78	-0.08	0.00	0.00
Hungary	28.72	64.22	20.97	-0.04	0.00	0.00
Indonesia	28.87	64.78	17.65	-0.86	-0.02	0.03
India	28.91	68.39	29.28	-1.21	-0.02	0.06
Italy	31.99	61.89	16.12	-0.26	-0.01	0.01
Japan	28.63	67.93	36.93	-1.54	-0.03	0.04
Korea	25.73	66.54	18.78	-0.48	-0.01	0.01
Mexico	43.73	59.28	24.22	-0.37	-0.01	0.01
Netherlands	33.13	59.49	-2.70	-0.15	0.00	0.00
Norway	33.02	62.52	29.12	-0.39	-0.01	0.01
Poland	26.03	67.78	40.02	-0.42	-0.01	0.01
Romania	28.01	65.36	36.72	-0.11	0.00	0.00
ROW	31.31	68.77	35.77	-14.45	-0.27	0.44
Russia	27.86	71.16	44.63	-2.68	-0.05	0.09
Turkey	26.89	64.46	39.84	-0.30	-0.01	0.01
USA	31.93	65.72	15.31	-5.01	-0.10	0.14
European Union	27.60	67.30	23.61	-2.37	-0.04	0.07

Note: Optimal tax columns present the optimal tax combination of an extraction, a consumption, and an export tax applied to one country at the time. Global welfare gains and changes in consumption are expressed relative to initial GDP, calculated using equation (36)

Figure A6: Effect of Global Autarky, Price and Sourcing Channels



(a) Price channel and net exports of fossil fuels



(b) Sourcing channel and the value chain

Notes: % change in emissions refers to autarky relative to observed consumption-based emissions, $(\mathcal{E}_n^A/\mathcal{E}_n^C - 1) \times 100$. Price channel is $\Delta_n^{A,1}/\mathcal{E}_n^C \times 100$, and sourcing channel is $\Delta_n^{A,2}/\mathcal{E}_n^C \times 100$ in equation (35). Net exports of fossil fuels is exports of fossil fuels minus imports, expressed in million dollars. Ratio Production S3 to Production S1 is the ratio of production scope 3 emissions to production scope 1 emissions.

Table D11: Optimal Tax and the Trade Elasticity

	Extraction Tax		Production Tax		Consumption Tax	
	$\sigma = 3$	$\sigma = 6$	$\sigma = 3$	$\sigma = 6$	$\sigma = 3$	$\sigma = 6$
	(1)	(2)	(3)	(4)	(5)	(6)
Canada	43.56	40.95	52.93	41.44	73.46	72.55
China	37.13	32.68	69.22	60.60	78.43	75.93
France	34.24	34.24	48.74	33.37	69.61	68.09
Korea	28.64	28.60	41.07	28.20	70.90	70.67
Russia	30.26	28.83	63.83	53.57	80.24	79.90
United States	46.43	42.19	54.01	40.66	72.93	70.71
World Average	34.91	33.63	51.59	38.48	71.22	68.21

Note: Tax is $t_{j,s}^Z = t_j^Z \times e_s$ where t_j^Z is the optimal tax per ton of CO₂, 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 calculated using equation (16). For the production tax, we report production-based emissions (scope 1) calculated using equation (17). For the consumption tax, we report consumption-based emissions calculated using equation (22). Leakage is calculated using equation (28).

$$\begin{aligned}
\mathcal{E}_n^A - \mathcal{E}_n^C &= \sum_{s \in \mathcal{K}^M} e_s \psi_{n,s} \left(\frac{X_n^{C,A}}{p_{n,s}^A} - \frac{X_n^{C,B}}{p_s^B} \right) \\
&+ \sum_{s \in \mathcal{K}^M} \frac{e_s}{p_s^B} \left[\sum_{k,r \notin \mathcal{K}^M} \alpha_{n,sk} \chi_{n,kr} \mu_{n,r} - \sum_{i,l} \sum_{k,r \notin \mathcal{K}^M} \alpha_{i,sk} \chi_{il,kr} \lambda_{ln,r} \mu_{n,r} \right] X_n^{C,B} \\
&+ \mathcal{E}_n^{C,B} - \mathcal{E}_n^C
\end{aligned}$$

E.2 Global Production Tax Decomposition: Price Channel

$$\mathcal{E}_l^{P'} - \mathcal{E}_l^P = \sum_s \frac{e_s}{p'_s + e_s t_l^P} \sum_n X'_{l,n,s} - \sum_s \frac{e_s}{p_s} \sum_n X_{l,n,s}$$

$$\mathcal{E}_l^{P'} - \mathcal{E}_l^P = \sum_s \left(\frac{e_s}{p'_s} - \frac{e_s}{p_s} \right) \sum_n X_{l,n,s} + \sum_s \frac{e_s}{p'_s + e_s t_l^P} \sum_n X'_{l,n,s} - \sum_s \frac{e_s}{p'_s} \sum_n X_{l,n,s}$$

$$\mathcal{E}_l^{P'} - \mathcal{E}_l^P = \sum_s \left(\frac{e_s}{p'_s} - \frac{e_s}{p_s} \right) \sum_n X_{l,n,s} + \frac{1}{\mathcal{E}_l^P} \sum_s \left(\frac{e_s}{p'_s + e_s t_l^P} - \frac{e_s}{p'_s} \right) \sum_n X'_{l,n,s} + \sum_s \frac{e_s}{p'_s} \left(\sum_n X'_{l,n,s} - \sum_n X_{l,n,s} \right)$$

$$\begin{aligned}
\mathcal{E}_l^{P'} - \mathcal{E}_l^P &= \underbrace{\sum_s \left(\frac{e_s}{p'_s} - \frac{e_s}{p_s} \right) \sum_n X_{l,n,s}}_{\text{Price Effect}} + \underbrace{\sum_s \left(\frac{e_s}{p'_s + e_s t_l^P} - \frac{e_s}{p'_s} \right) \sum_n X'_{l,n,s}}_{\text{Direct Tax Effect}} + \underbrace{\sum_s \frac{e_s}{p'_s} \left(\sum_n X'_{l,n,s} - \sum_n X_{l,n,s} \right)}_{\text{Expenditure Effect}}.
\end{aligned}$$

E.3 Global Production Tax Decomposition: Technique, Composition, Household Expenditure

The effect of a global production tax on production scope 1 emissions is

$$\mathcal{E}_l^{P'} - \mathcal{E}_l^P = \left(\sum_{k \notin \mathcal{K}^M} \sum_s e_s \frac{\alpha_{l,sk}}{p'_s + e_s t_l^P} Y'_{l,k} + \sum_s \frac{\mu_{l,s}}{p'_s + e_s t_l^P} X_l^{C'} \right) - \left(\sum_{k \notin \mathcal{K}^M} \sum_s \frac{e_s}{p_s} \alpha_{l,sk} Y_{l,k} + \mu_{l,s} X_l^C \right).$$

Using the definition of $\tilde{e}_{l,k}$ and $\tilde{e}'_{l,k}$,

$$\mathcal{E}_l^{P'} - \mathcal{E}_l^P = \left(\sum_{k \notin \mathcal{K}^M} \tilde{e}'_{l,k} \frac{Y'_{l,k}}{P'_{l,k}} \right) + \sum_{k \notin \mathcal{K}^M} \tilde{e}_{l,k} \frac{Y_{l,k}}{P_{l,k}} + \sum_s e_s \left(\frac{\mu_{l,s}}{p'_s + e_s t_l^P} X_l^{C'} - \frac{\mu_{l,s}}{p_s} X_l^C \right).$$

Then,

$$\mathcal{E}_l^{P'} - \mathcal{E}_l^P = \left(\sum_{k \notin \mathcal{K}^M} (\tilde{e}'_{l,k} - \tilde{e}_{l,k}) \frac{Y'_{l,k}}{P'_{l,k}} \right) + \sum_{k \notin \mathcal{K}^M} \tilde{e}_{l,k} \left(\frac{Y'_{l,k}}{P'_{l,k}} - \frac{Y_{l,k}}{P_{l,k}} \right) + \sum_s e_s \left(\frac{\mu_{l,s}}{p'_s + e_s t_l^P} X_l^{C'} - \frac{\mu_{l,s}}{p_s} X_l^C \right).$$

E.4 Observed Emissions Decomposition

We 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,

$$\underbrace{\ln \frac{\mathcal{E}_n^C}{L_n}}_{\text{emissions per capita}} = \underbrace{\ln \frac{\mathcal{E}_n^C}{X_n^C}}_{\text{emissions per \$ of consumption}} + \underbrace{\ln \frac{X_n^C}{L_n}}_{\text{\$ consumption per capita}}. \quad (52)$$

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 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 A7 reports results.

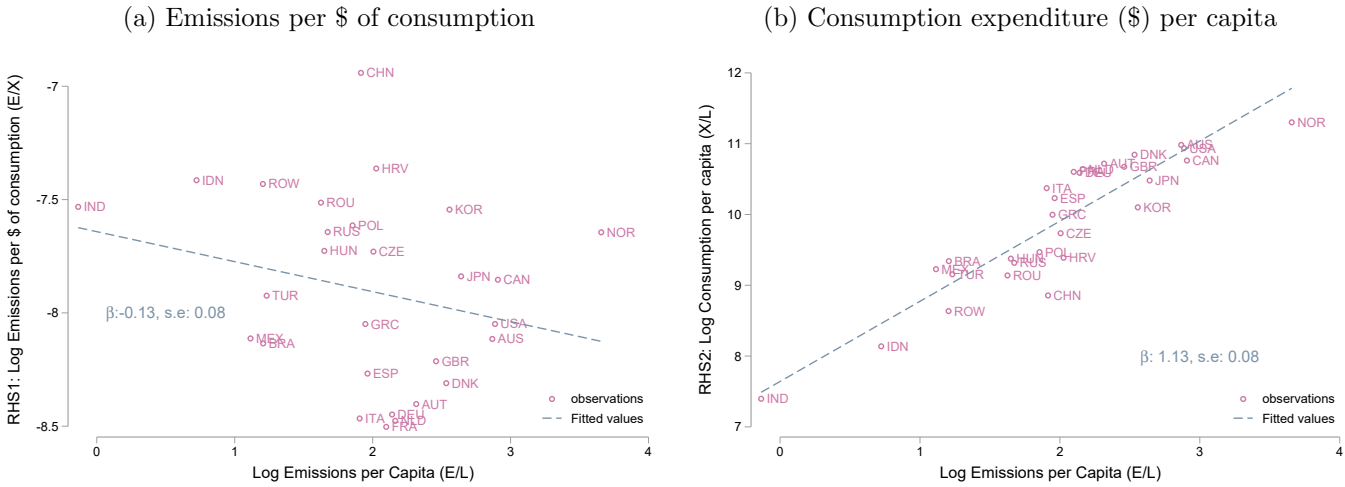
Emissions per dollar of consumption account for -13% of the variance in overall emissions per capita (left panel). while consumption per capita explains 113% of the variance (right panel). This comparison suggests that countries with lower emissions intensity per unit of consumption tend to have higher 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 equation (52)) into two components: emissions per dollar of fossil fuels used; and emissions coming from fossil fuel expenditure per dollar of consumption,

$$\underbrace{\ln \frac{\mathcal{E}_n^C}{X_n^C}}_{\text{emissions per \$ of consumption}} = \underbrace{\ln \sum_s \frac{\sum_{j,l,k} \frac{e_s}{p_s} \chi_{jl,sk} \lambda_{ln,k} X_{n,k}^C}{\sum_{s \in \mathcal{K}^M} \sum_{j,l,k} \chi_{jl,sk} \lambda_{ln,k} X_{n,k}^C}}_{\text{emissions per \$ of fossil fuel}} + \underbrace{\ln \frac{\sum_{s \in \mathcal{K}^M} \sum_{j,l,k} \chi_{jl,sk} \lambda_{ln,k} X_{n,k}^C}{X_n^C}}_{\text{fossil fuel expenditure per \$ of consumption}}. \quad (53)$$

The first term is reflects a country's the fossil fuel mix. The second term reflects a country's overall

Figure A7: Consumption-based emissions: variance decomposition



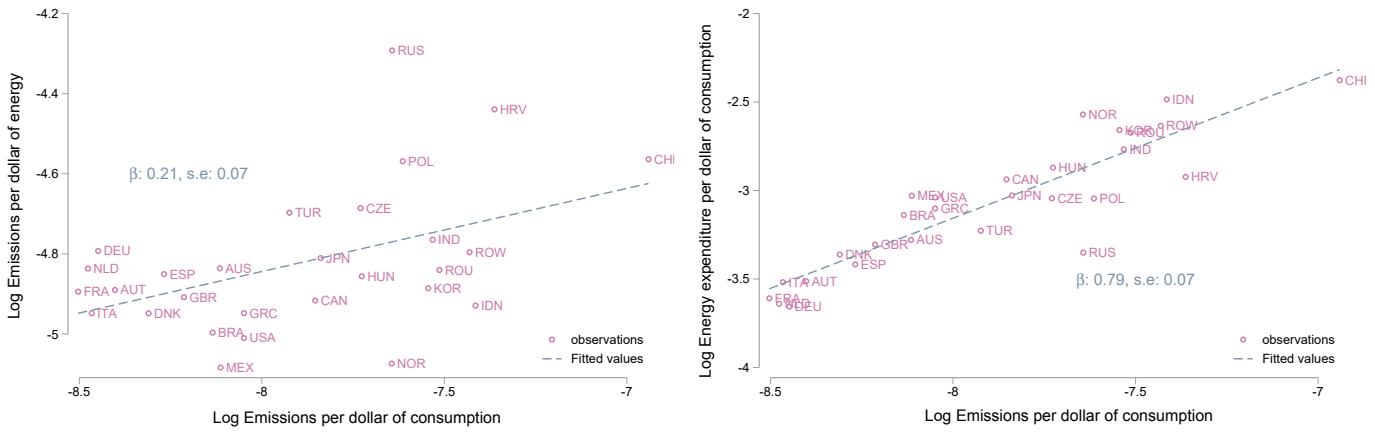
Notes: Graphs show a decomposition of consumption-based emissions. The left panel shows the first term in equation (52), while the right panel shows the second term in equation (52).

expenditure on fossil fuels. Figure A8 shows the results. The first term in equation (53) 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 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 6 uses the model, which accounts for equilibrium effects, to study counterfactual scenarios.

Figure A8: Consumption-based emissions: variance decomposition



(a) Emissions per \$ of fossil fuel used

(b) Energy expenditure per \$ of consumption

Notes: Consumption-based emissions. Left panel shows the first term in equation (53), while the right panel shows the second term in equation (53).