The Carbon Footprint of Multinational Production

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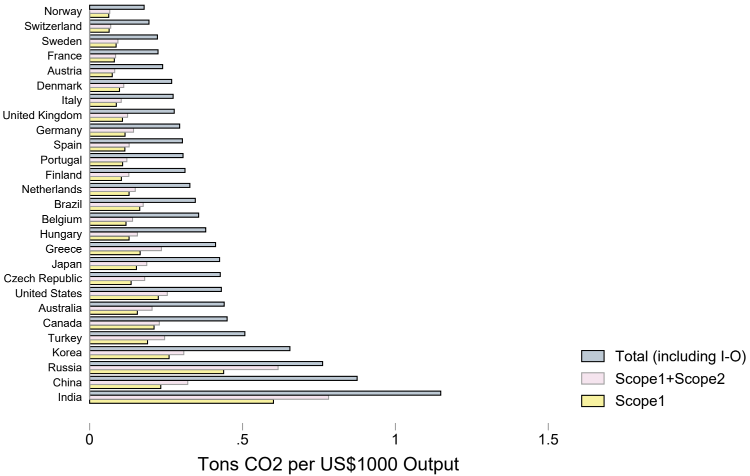
Emissions per Dollar Are Very Different Across Countries

$$\frac{\mathcal{E}_{I,s}}{Y_{I.s}} = \gamma_I + \delta_s + \varepsilon_{I,s}$$



Basic Research Questions

1. How does the activity of MNEs affect global emissions?

2. How do the effects of carbon taxes differ in the presence of MNEs?

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Related more basic questions

- How does trade affect carbon emissions globally and in each country?

- How does trade affect the impact of carbon taxes on global emissions?

Our Approach

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2. **Quantitative model of trade, multinational production (MP), and fossil fuels**

    - Multiple sectors including fossil fuels, IO links (Caliendo & Parro, 14)
    - Trade & MP (Arkolakis et al., 18): closed-form & aggregation, GE
    - Emissions are generated by the *use* of fossil fuels

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3. **Carbon accounting and counterfactual exercises (hat-algebra)**
    - Emissions based on consumption, production, extraction, and ownership

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3. **Carbon accounting and counterfactual exercises (hat-algebra)**
    - Emissions based on consumption, production, extraction, and ownership
    - Is a world without MP cleaner? Without trade?

What is New?

- **Trade & environment** Abatement approach: Grossman & Krueger 1995; Antweiler, Copeland, & Taylor 2001; Copeland & Taylor 2004; Nordhaus 2015; Shapiro & Walker 2018; Farrokhi & Lashkaripour 2022. Fossil-fuel approach: Egger & Nigai 2015; Larch & Wanner 2017; Kortum & Weisbach 2021; Caron & Fally 2022
  - GE quantitative approach for trade and multinational production
- **Multinational production** Helpman 1984; Markusen & Venables 2000; Helpman, Melitz, & Yeaple 2004; Ramondo & Rodriguez-Clare 2013; Arkolakis, Ramondo, Rodríguez-Clare, & Yeaple (ARRY) 2018; Sun 2020
  - Add energy-emissions link
- **Carbon accounting** Davis & Caldeira 2010; Peters et al. 2011; Zhang et al. 2020
  - Integrated approach grounded in theory
  - Add emissions accounting by ownership
- **Second-best climate policy** Goulder et al. 2012; Martin et al. 2014; Fowlie et al. 2016; Bohringer et al. 2016; Shapiro 2021
  - Policy for multinational production

Project Outline

- **Start with a multi-sector model of trade and fossil fuels (TODAY)**
  - Model-based carbon accounting with trade
  - Counterfactual to trade-autarky, trade liberalization, carbon taxes
- **Enrich the model with multinational production (MP) ... and more**
  - Model-based carbon accounting with MP
  - Counterfactual to MP-autarky, MP liberalization, carbon taxes

Model of Trade and Fossil Fuels

- k and s are sectors
  - 3 fossil-fuel sectors $s \in \mathcal{K}^M$ (coal, natural gas, crude oil)
  - 6 energy sectors (fossil fuels, electricity, refined oil, distributed gas)
- j, l are locations of production; n is destination of sales

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- j, l are locations of production; n is destination of sales
- Caliendo-Parro (2014): many sectors; intermediates; IO loop
  - Armington version with preferences
    - Cobb-Douglas across sectors, $\mu_{n,s} \in (0,1)$, $\sum_s \mu_{n,s} = 1$
    - CES within each sector, $\sigma_s > 1$
  - Perfect competition in all sectors
  - Trade costs are $\tau_{jl,s} \geq 1$ with $\tau_{jj,s} = 1$

Production In Non-Mining Sectors

- Production is constant-returns-to-scale Cobb-Douglas in $s \notin \mathcal{K}^M$
  - Labor share in (l, s): $\alpha_{l,\ell s}$
  - Intermediate input share k in (l, s): $\alpha_{l,ks}$

- Price of good s in l is

$$p_{l,s} = A_{l,s}^{-1} w_l^{\alpha_{l,\ell s}} \prod_k P_{l,k}^{\alpha_{l,ks}}$$

- Price index of sector s in n is

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

Production In Mining Sectors Uses Fixed Factor

- Fixed factor: sector-specific mines $M_{j,s}$ for $s \in \mathcal{K}^M$

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$$q = \ell^{\alpha_{j,\ell s}} \prod_{k \in \mathcal{K}} q_k^{\alpha_{j,ks}}$$

where

$$\nu_s = 1 - \alpha_{I,\ell s} + \sum_{k \in \mathcal{K}} \alpha_{I,ks} \in (0,1)$$

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where

$$\nu_s = 1 - \alpha_{l,\ell s} + \sum_{k \in \mathcal{K}} \alpha_{l,ks} \in (0,1)$$

- Upward-sloping supply curve for good s

$$Y_{j,s} \equiv p_{j,s} Q_{j,s} = M_{j,s} \left(p_{j,s} w_j^{-\alpha_{j,\ell s}} \prod_k P_{j,k}^{-\alpha_{j,ks}} \right)^{\frac{1}{\nu_s}}$$

Market Equilibrium for Good k Produced in j

$$
\begin{aligned}
Y_{j,k} &= \sum_n X^C_{jn,k} + \sum_l \lambda_{jl,k} \sum_s \alpha_{l,ks} Y_{l,s} \\
\implies Y_{j,k} &= \sum_{l,n,s} \chi_{jl,ks} X^C_{ln,s}
\end{aligned}
$$

where

$$
\chi_{jl,ks} \equiv \left(I - \{\alpha_{jl,ks}\}\right)^{-1} \quad \text{and} \quad \alpha_{jl,ks} \equiv \lambda_{jl,k}\alpha_{l,ks} \quad \text{and} \quad \lambda_{jl,k} \equiv \frac{X_{jl,k}}{X_{l,k}}
$$

Emissions and Fossil Fuels

- **Emissions are generated by using fossil fuels for production and consumption**

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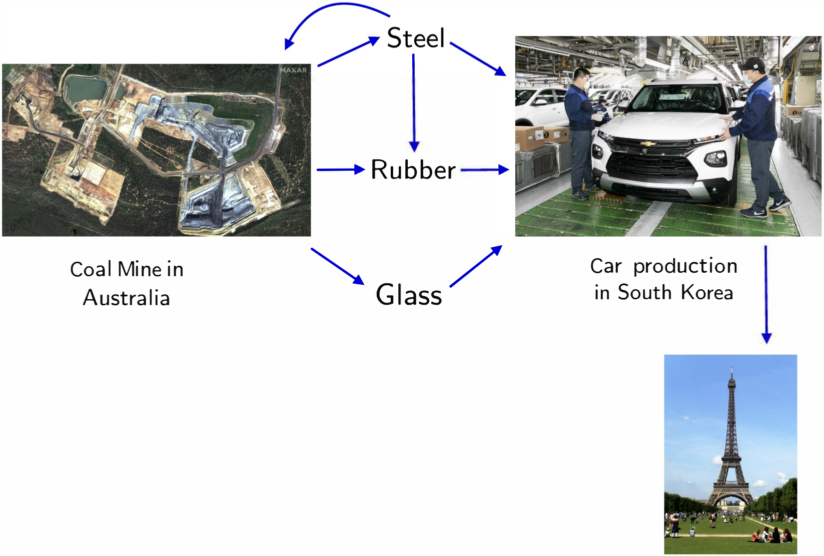
- Emissions from using a unit of good s are e_s, with $e_s > 0$ only for $s \in \mathcal{K}^M$

Emissions and Fossil Fuels

- **Emissions are generated by using fossil fuels for production and consumption**
- Emissions from using a unit of good s are e_s, with $e_s > 0$ only for $s \in \mathcal{K}^M$
- Emissions from fossil fuel s extracted in j to produce goods in l consumed in n are

$$\mathcal{E}_{j,ln,s} = e_s Q_{j,ln,s} = \frac{e_s}{p_{j,s}} \sum_k \chi_{jl,sk} X^C_{ln,k}$$

Carbon Accounting: Illustration



Carbon Accounting: Consumption, Production, Extraction

$$\mathcal{E}_{j,ln,s} = \frac{e_s}{p_{j,s}} \sum_k \chi_{jl,sk} X^C_{ln,k}$$

Consumption: $$\mathcal{E}^C_n = \sum_{j,l,s} \mathcal{E}_{j,ln,s}$$

Production (S3): $$\mathcal{E}^{P3}_l = \sum_{j,n,s} \mathcal{E}_{j,ln,s}$$

Extraction: $$\mathcal{E}^M_j = \sum_{l,n,s} \mathcal{E}_{j,ln,s}$$

Production (S1): $$\mathcal{E}^{P1}_l = \sum_{s,k,j} \frac{e_s}{p_{j,s}} \lambda_{jl,s} \alpha_{l,sk} Y_{l,k} + \sum_{s,j} \frac{e_s}{p_{j,s}} X^C_{jl,s}$$

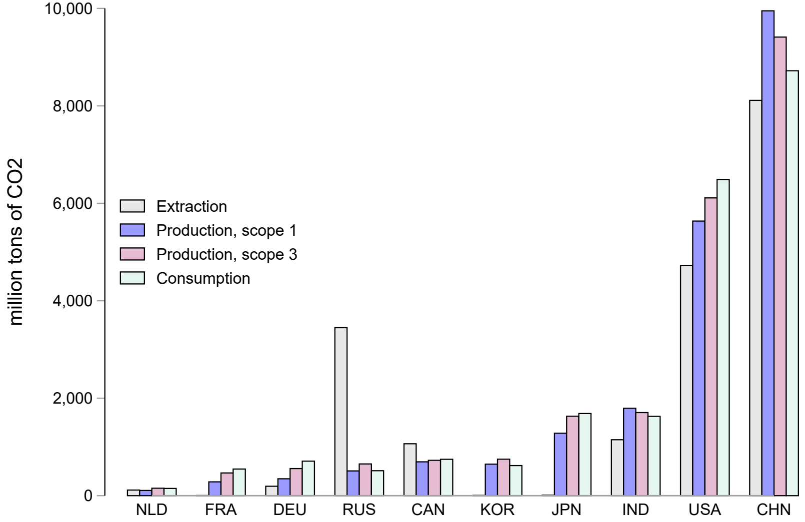
Carbon Accounting: Data

$$\mathcal{E}_{j,ln,s} = \frac{e_s}{p_{j,s}} \sum_k \chi_{jl,sk} X^C_{ln,k} \qquad \text{with} \qquad \chi_{jl,sk} \equiv \left(I - \{\alpha_{jl,sk}\}\right)^{-1}$$

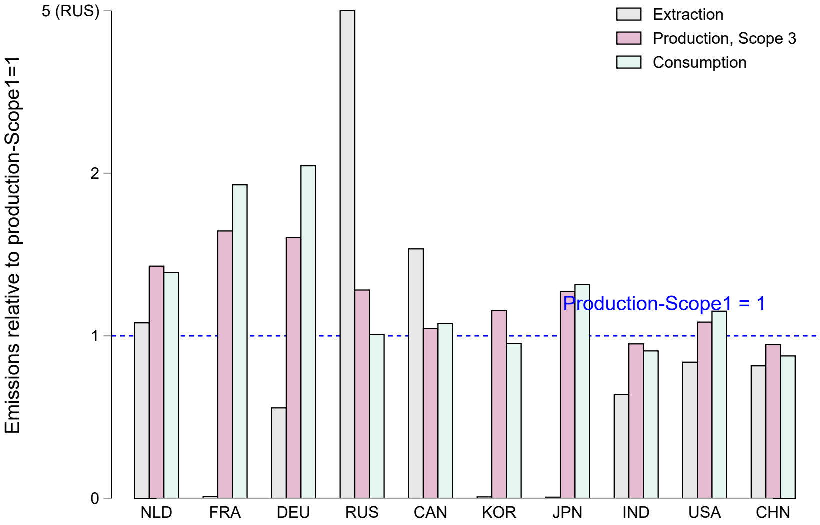
- **World I-O Dataset (WIOD), Exiobase/Eora, International Energy Agency (IEA)**
  - Year: 2014
  - 28 sectors: 3 fossil fuels (coal, crude oil, natural gas)
  - 27 countries + ROW
  - IO coefficients $\alpha^{WIOD}_{jl,sk}$, and final use, $X^{C,WIOD}_{ln,k}$
  - Emissions per dollar of extraction (tons CO_2 per \$)

$$\frac{e_s}{p_{j,s}} = e^{IEA}_s \frac{Q^{IEA}_{j,s}}{Y^{WIOD}_{j,s}}$$

Carbon Accounting, Selected Countries



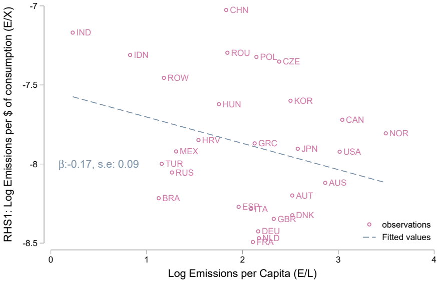
Carbon Accounting: Comparisons, Selected Countries



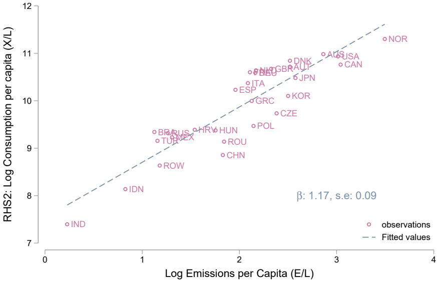
Carbon Accounting, Variance Decomposition

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

Emissions per $ of consumption: -0.17



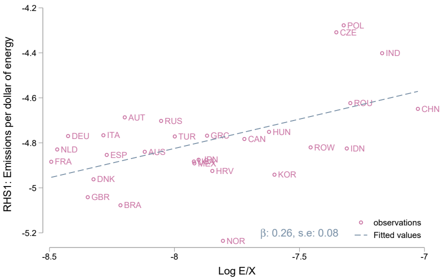
Consumption per capita: 1.17



Carbon Accounting, Variance Decomposition

$$\underbrace{\ln \frac{\mathcal{E}_n^C}{X_n^C}}_{\text{emissions per \$ of consumption}} = \underbrace{\ln \sum_s \frac{\sum_{j,l,k} \frac{e_s}{p_{j,s}} \chi_{jl,sk} X_{ln,k}^C}{\sum_{s\in\mathcal{K}^M} \sum_{j,l,k} \chi_{jl,sk} X_{ln,k}^C}}_{\text{emissions per \$ of energy}} + \underbrace{\ln \frac{\sum_{s\in\mathcal{K}^M} \sum_{j,l,k} \chi_{jl,sk} X_{ln,k}^C}{X_n^C}}_{\text{energy expenditure per \$ of consumption}}$$

Emissions per $ of energy: 0.26



Energy expenditure per $ of consumption: 0.74

Problematic Fossil-Fuel Prices

- Implicit prices of fossil fuels

$$p_{j,s} = \frac{Y_{j,s}^{WIOD}}{Q_{j,s}^{IEA}} \qquad s \in \mathcal{K}^M$$

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- Advantages: match country-level extraction-based emissions and global emissions

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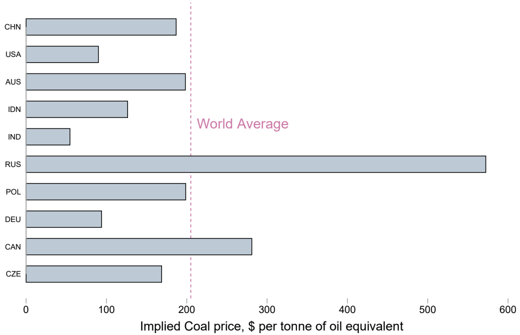
- Advantages: match country-level extraction-based emissions and global emissions
- Disadvantages: extreme values of $p_{j,s}$ might have large effects on counterfactuals

Coal prices for top producers



Removing Heterogeneity in Fossil-Fuel Prices

- Frictionless trade in *homogeneous* fossil fuels: $p_{j,s} = p_s$ for $s \in \mathcal{K}^M$

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$\implies$ World emissions are unchanged (match IEA data)

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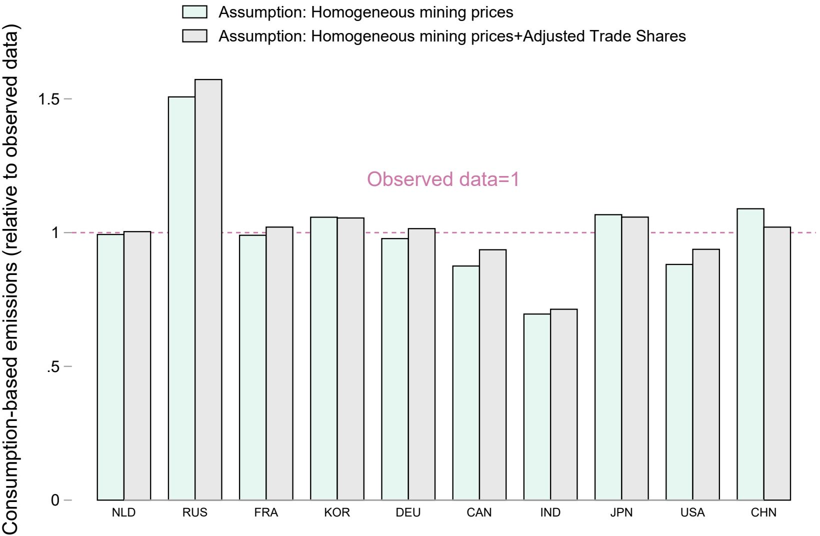
$\Longrightarrow$ World emissions are unchanged (match IEA data)

- Adjustment of trade shares in mining: $\lambda_{jl,s} = \frac{Y_{j,s}}{\sum_j Y_{j,s}}$ for $s \in \mathcal{K}^M$

  - Extraction-based emissions by country unchanged by λ's adjustment

  - Production(S1)- based emissions by country unchanged by λ's adjustment

Consumption-Based Emissions With Adjustments



Autarky Counterfactual: Changes in Emissions

$$\mathcal{E}_{n,s}^{A} - \mathcal{E}_{n,s}^{C} \quad = \quad \frac{e_s}{p_{n,s}^{A}} \sum_{k} \chi_{n,sk} X_{n,k}^{C,A} - \frac{e_s}{p_s} \sum_{j,l,k} \chi_{jl,sk} \lambda_{ln,k} X_{n,k}^{C}$$

Autarky Counterfactual: Changes in Emissions

$$\mathcal{E}^A_{n,s} - \mathcal{E}^C_{n,s} \quad = \quad \frac{e_s}{p^A_{n,s}} \sum_k \chi_{n,sk} X^{C,A}_{n,k} - \frac{e_s}{p_s} \sum_{j,l,k} \chi_{jl,sk} \lambda_{ln,k} X^C_{n,k}$$

Calibration

- WIOD data for expenditure, trade, and IO coefficients (with Cobb-Douglas $\chi^A_{n,sk} = \chi_{n,sk}$)
- IEA and WIOD data for $e_s/p_s = e^{IEA}_s Q^{IEA}_s / Y^{WIOD}_s$ (tons CO_2 per \$)
  - coal: 0.019; natural gas: 0.007; crude oil: 0.005
- Solve for autarky equilibrium: Need parameter ν (elasticity of supply for fossil fuels)

Fossil-Fuel Supply Curve Elasticity ν: Estimation

- Decreasing returns ν_s in terms of inverse supply elasticity

$$\nu_s = \frac{\partial \ln p_s / \partial \ln Q_s}{\partial \ln p_s / \partial \ln Q_s + 1}$$

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- Data for energy cost schedules for each fossil fuel and region (Welsby et al., 2021) data

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- Regression version, pooled: Vertex v, energy type s, region j

$$\ln p_{vj,s} = \beta \ln Q_{vj,s} + \mu_{j,s} + \zeta_{vj,s}$$

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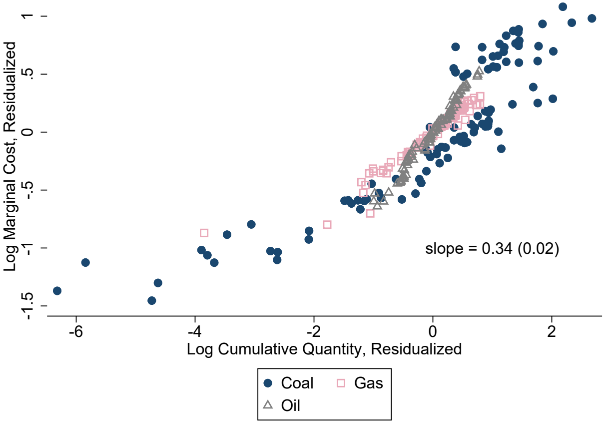
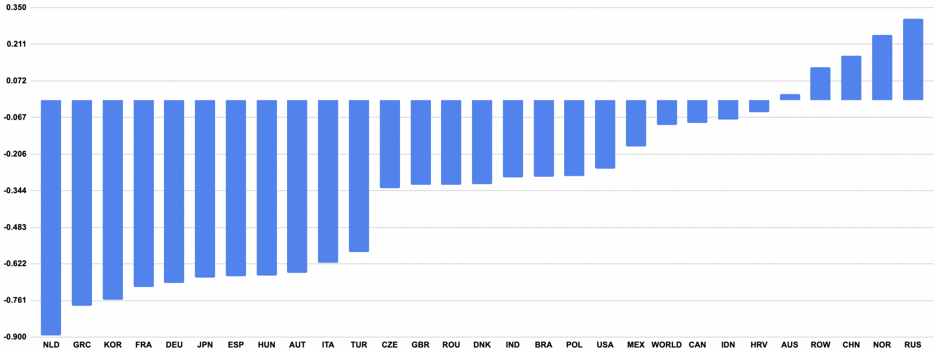


Inverse elasticity $\beta = 0.342 \implies \nu = \beta/(\mathbf{1} + \beta) = \mathbf{0.25}$

Moving To Autarky Decreases Global Emissions By 9.5%



Autarky emissions, relative to observed consumption-based emissions, $\frac{\mathcal{E}_n^A - \mathcal{E}_n^C}{\mathcal{E}_n^C}$.

Counterfactual Change in Emissions, Decomposition

$$\mathcal{E}^{A}_{n,s} - \mathcal{E}^{C}_{n,s} \quad = \quad \frac{e_s}{p^{A}_{n,s}} \sum_{k} \chi_{n,sk} X^{C,A}_{n,k} - \frac{e_s}{p_s} \sum_{j,l,k} \chi_{jl,sk} \lambda_{ln,k} X^{C}_{n,k}$$

Counterfactual Change in Emissions, Decomposition

$$\mathcal{E}_{n,s}^{A} - \mathcal{E}_{n,s}^{C} = \frac{e_s}{p_{n,s}^{A}} \sum_{k} \chi_{n,sk} X_{n,k}^{C,A} - \frac{e_s}{p_s} \sum_{j,l,k} \chi_{jl,sk} \lambda_{ln,k} X_{n,k}^{C}$$

$$\mathcal{E}_{n}^{A} - \mathcal{E}_{n}^{C} = \sum_{s \in \mathcal{K}^M} \mathcal{E}_{n,s}^{A} - \mathcal{E}_{n,s}^{C}$$

$$= \underbrace{\sum_{s \in \mathcal{K}^M} e_s \sum_{k} \chi_{n,sk} \left(\frac{X_{n,k}^{C,A}}{p_{n,s}^{A}} - \frac{X_{n,k}^{C}}{p_s} \right)}_{\Delta_n^1 \equiv \text{ Price channel}}$$

$$+ \underbrace{\sum_{s \in \mathcal{K}^M} \frac{e_s}{p_s} \sum_{k} \left(\chi_{n,sk} - \sum_{j,l} \chi_{jl,sk} \lambda_{ln,k} \right) X_{n,k}^{C}}_{\Delta_n^2 \equiv \text{ Demand channel}}$$

Counterfactual Change in Emissions, Decomposition

$$
\begin{aligned}
\mathcal{E}_s^A - \mathcal{E}_s^C &= \sum_n \mathcal{E}_{n,s}^A - \mathcal{E}_{n,s}^C \\
&= \underbrace{e_s \sum_{k,n} \chi_{n,sk} \left(\frac{X_{n,k}^{C,A}}{p_{n,s}^A} - \frac{X_{n,k}^C}{p_s} \right)}_{\Delta_s^1 \equiv \text{ Price channel}} + \underbrace{\frac{e_s}{p_s} \sum_{k,n} \left(\chi_{n,sk} - \sum_{j,l} \chi_{jl,sk} \lambda_{ln,k} \right) X_{n,k}^C}_{\Delta_s^2 \equiv \text{ Demand channel}}
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\end{aligned}
$$

- Price channel $\Delta_s^1 < 0$ (i.e. trade increases emissions)?
  - With flat supply curves for mining goods, $\Delta_s^1 = 0$ for all s
  - With no intermediates and $\mu_{n,s} = \mu_s$, $\Delta_s^1 < 0$ for all s

Counterfactual Change in Emissions, Decomposition

$$\begin{aligned}
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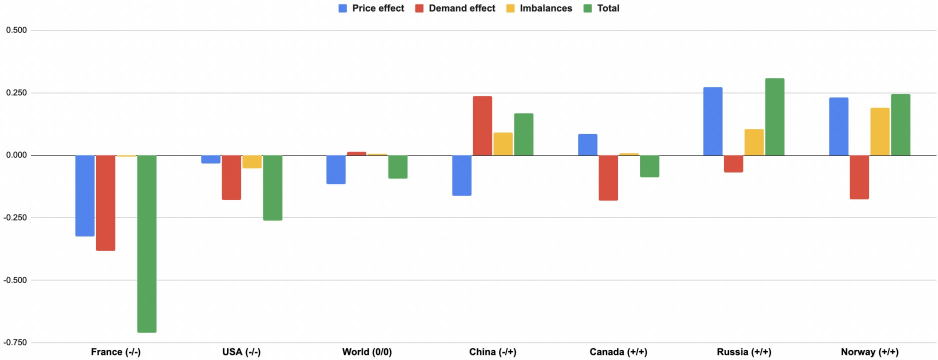
\end{aligned}$$

- Demand channel Δ_s^2: All about technology reflected in differences in IO matrices
  - If $\alpha_{n,sk} = \alpha_{sk} \implies \sum_j \chi_{jn,sk} = \chi_{sk} \implies \Delta_s^2 = 0$ for all s
  - If $\alpha_{j,sk} = 0$ for $k \in \mathcal{K}^M$ and $\alpha_{j,sk} = 0$ for $s \notin \mathcal{K}^M \implies \Delta_s^2 < 0$ if countries that use fossil fuels intensively in the production of non-mining goods have positive net export of those goods Data

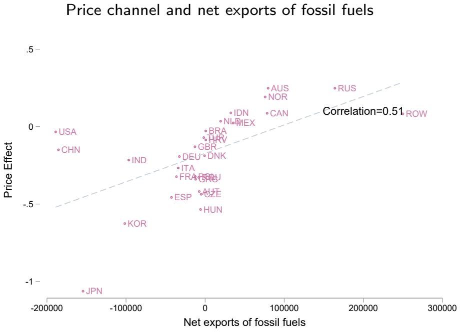
Moving To Autarky Decreases Global Emissions By 9.5%

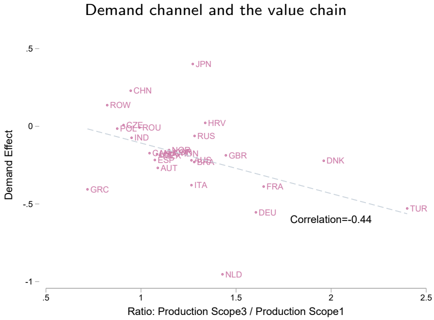
$$\mathcal{E}_n^A - \mathcal{E}_n^C = \underbrace{\sum_{s \in \mathcal{K}^M} e_s \sum_k \chi_{n,sk} \left(\frac{X_{n,k}^{C,A}}{p_{n,s}^A} - \frac{X_{n,k}^C}{p_s} \right)}_{\Delta_n^1 \equiv \text{ Price channel}} + \underbrace{\sum_{s \in \mathcal{K}^M} \frac{e_s}{p_s} \sum_k \left(\chi_{n,sk} - \sum_{j,l} \chi_{jl,sk} \lambda_{ln,k} \right) X_{n,k}^C}_{\Delta_n^2 \equiv \text{ Demand channel}} + \Delta_n^{TB}$$



Relative to observed consumption-based emissions, $\mathcal{E}_n^C$. (Net exports of fossil fuels/Net exports of all goods).

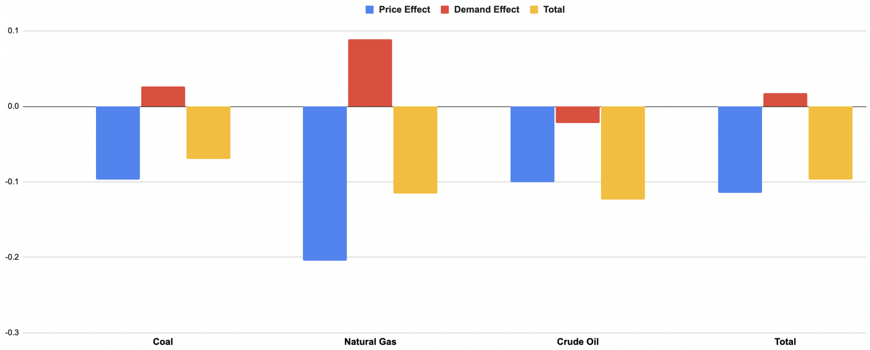
Understanding the Price and Demand Channels





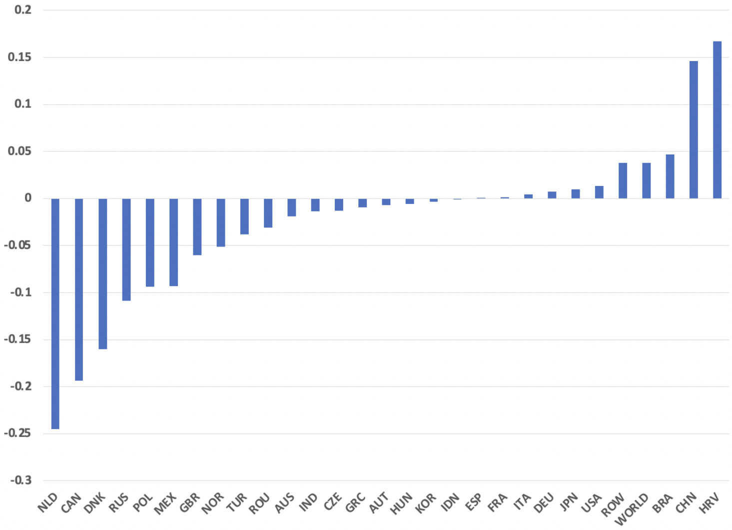
Moving To Autarky Decreases Global Emissions By 9.5%

$$\mathcal{E}_s^A - \mathcal{E}_s^C = \underbrace{e_s \sum_{k,n} \chi_{n,sk} \left(\frac{X_{n,k}^{C,A}}{p_{n,s}^A} - \frac{X_{n,k}^C}{p_s} \right)}_{\Delta_s^1 \equiv \text{ Price channel}} + \underbrace{\frac{e_s}{p_s} \sum_{k,n} \left(\chi_{n,sk} - \sum_{j,l} \chi_{jl,sk} \lambda_{ln,k} \right) X_{n,k}^C}_{\Delta_s^2 \equiv \text{ Demand channel}}$$



Relative to observed emissions, $\mathcal{E}_s^C$

Trade liberalization of 20% Increases Emissions By 3.8%



Trade-liberalization emissions, relative to observed consumption-based emissions, $\frac{\mathcal{E}_n' - \mathcal{E}_n^C}{\mathcal{E}_n^C}$.

Key Extensions

2. Adding carbon taxes to the trade model

    - Quantifying the effects of production vs consumption taxes, leakage

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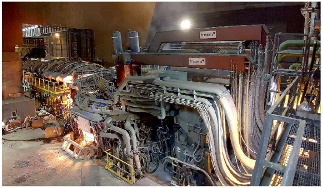
   - i home country of firms, l location of production, n destination of sales
4. Ex-ante choice of energy intensity that affects firm emissions worldwide
   - Algorithm to uncover trilateral flows $X_{i,ln,s}$ and cost-revenue shares $\alpha_{i,l,ks}$

MNEs and the Steel Industry in Vietnam

Tenova (Italy): mini mill (electric arc furnace)

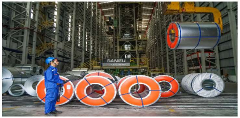


Kunming Iron & Steel (China): integrated mill (blast furnace)

MP Italy->Vietnam

MP China->Vietnam

Vietnam steel corporation (Vietnam)



Data Sources

- **Aggregate data**
  - World Input Output Dataset (WIOD) and Exiobase/Eora

    Emissions and energy consumption by industry-country-energy type
  - Activity of Multinational Enterprises (AMNE)

    Revenues by industry-origin country-host country

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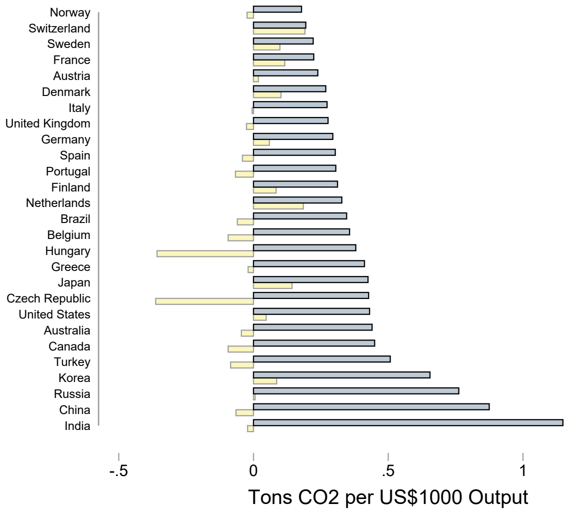
- **Firm and affiliate data**
  - Carbon Disclosure Project (CDP) and ORBIS

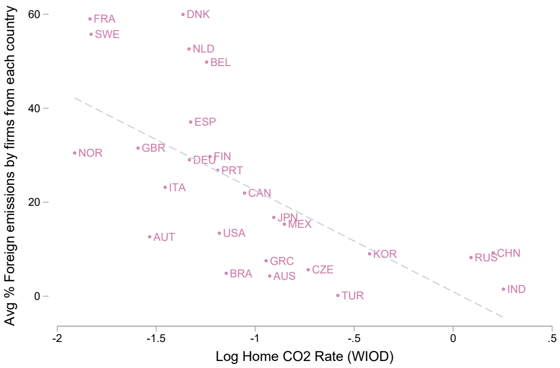
    Emissions per dollar for each parent and country of production
  - US Census of Manufactures and Manufacturing Energy Consumption Survey

MNEs Are Headquartered in Cleaner Countries



Yellow bar: net multinational production (affiliate sales abroad - foreign affiliate sales) as share of gross output.

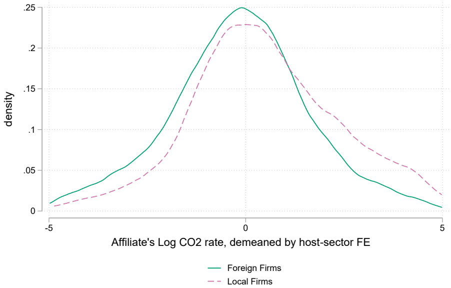
MNE Affiliates Are Dirtier Abroad ("Leakage")



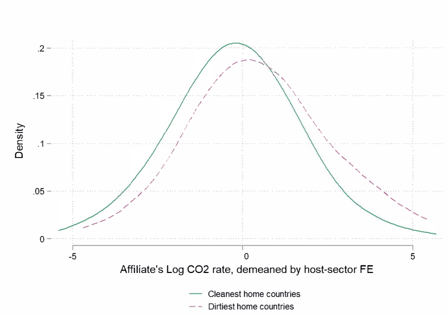
Foreign emissions of Home firms as share of total emissions at Home and Abroad. Average across firms in each home country.

… But MNE Affiliates Are Cleaner Everywhere

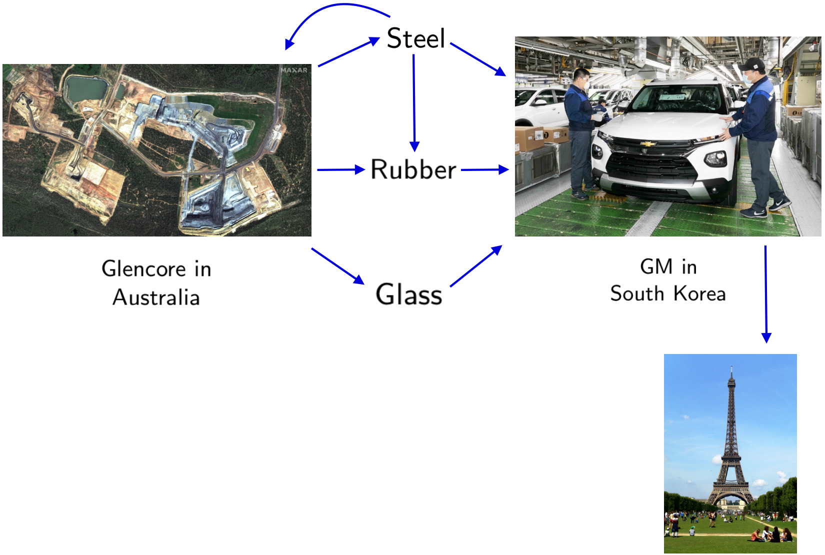
MNE affiliates are the cleanest firms in their Host country



MNE affiliates with clean Homes are cleaner everywhere



Trade and MP Model: Overview



Final Remarks

- **Multinational production (MP) and the environment**
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  - New estimates on key demand & supply energy elasticities

Final Remarks

- **Multinational production (MP) and the environment**
  - Important, distinct issues from trade
- **What we will offer**
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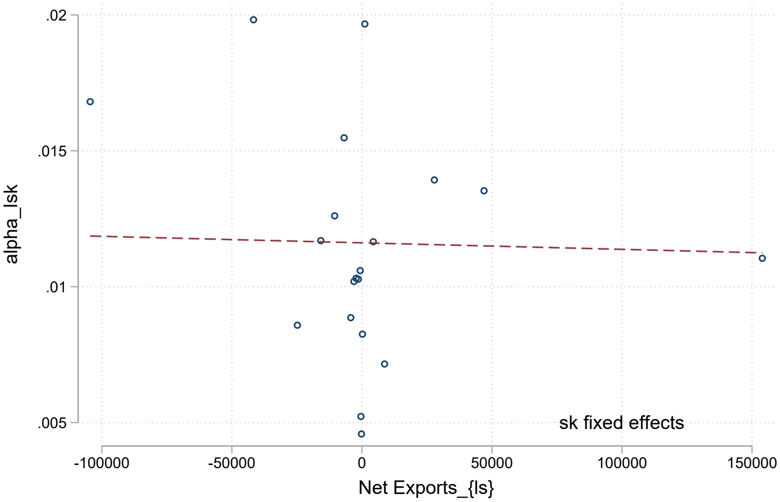
  - Flexible GE model of trade, MP, and energy, to study climate change issues
  - New estimates on key demand & supply energy elasticities
- **What's next**
  - Optimal carbon taxes with trade and MP
  - Leakage
  - Responsible sourcing and supply-chain externalities

Appendix

Correlation: Net exports v. Fossil-fuel Expenditure Back



Equilibrium Back

- Final expenditure

$$X_l^C = w_l L_l + \nu \sum_{s \in \mathcal{K}^M} Y_{l,s} + \Delta_l$$

- Gross output

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

- Total expenditure

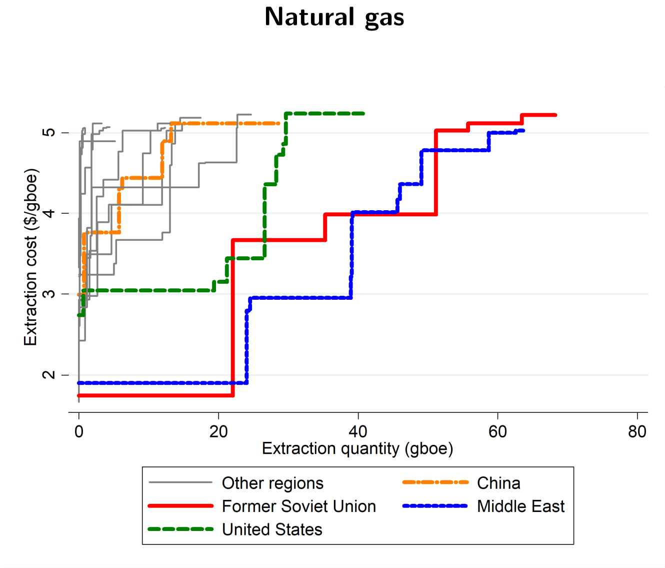
$$X_{l,s} = \mu_{l,s} X_l^C + \sum_k \alpha_{l,sk} Y_{l,k}$$

- Labor market clearing condition

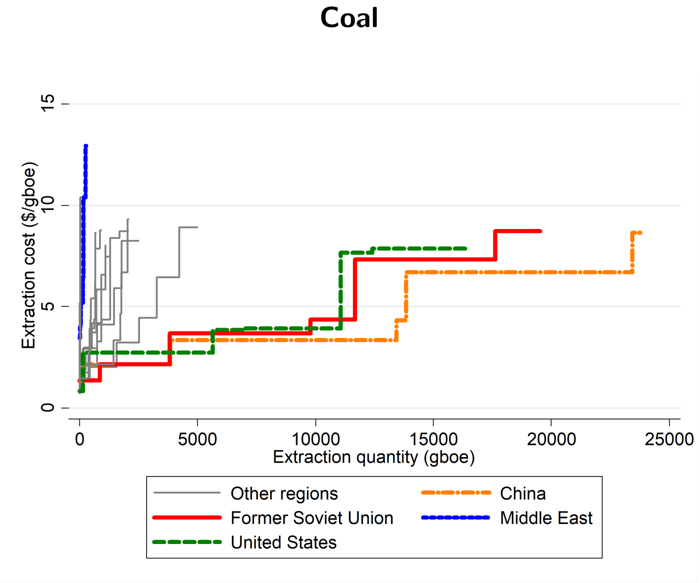
$$w_l L_l = \sum_s \alpha_{l,\ell s} Y_{l,s}$$

Fossil-Fuel Supply Curve Elasticity: Raw Data

Back



Fossil-Fuel Supply Curve Elasticity: Raw Data



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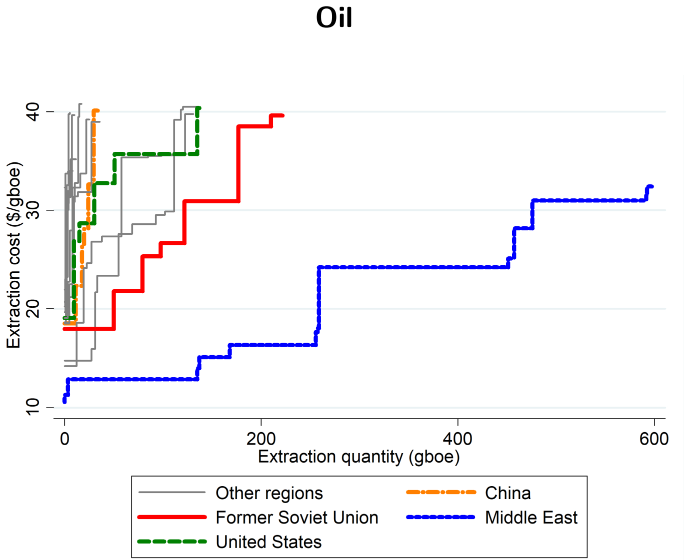


Model: Production Function for Non-mining Sector

A firm has productivity vector $\boldsymbol{z} \equiv (z_1, z_2, ..., z_N)$ and technology $\boldsymbol{a} \equiv (a_1, a_2, ..., a_{K^E}, a)$

$$q = z_l \left(\left(\sum_{k \in \mathcal{K}^E} \delta_{l,ks}^{\frac{1}{\gamma}} (a_k q_k)^{\frac{\gamma-1}{\gamma}} \right)^{\frac{\gamma}{\gamma-1} \frac{\varepsilon-1}{\varepsilon}} + \left(a \; \ell^{\beta_{l,\ell s}} \prod_{k \notin \mathcal{K}^E} q_k^{\beta_{l,ks}} \right)^{\frac{\varepsilon-1}{\varepsilon}} \right)^{\frac{\varepsilon}{\varepsilon-1}}$$

$$\gamma \neq 1 \qquad \varepsilon \neq 1 \qquad \beta_{l,\ell s} + \sum_{k \notin \mathcal{K}^E} \beta_{l,ks} = 1 \quad \text{for all } s$$

Back

Model: Productivity for Non-Mining Firms

- A firm from i draws productivity z from multivariate Pareto

  $\theta_s > \max\{1, 1/(\sigma_s - 1)\}$ and $\rho_s \in [0, 1)$

$$\Pr(Z_1 \leq z_1, ..., Z_N \leq z_n) = 1 - \left(\sum_{l=1}^{N} \left(T_{i,l,s} z_l^{-\theta_s} \right)^{\frac{1}{1-\rho_s}} \right)^{1-\rho_s}$$

$\Rightarrow$ Closed-form for aggregate expenditure, prices, profits

- "Head-to-head" comparison (unit costs) $C_{i,n,s} = \min_l \tau_{i,ln,s} \frac{c_{i,l,s}}{z_l}$
- Selection (marketing fixed costs) $Profits(C_{i,n,s}) - P_{n,s} F_{n,s} \geq 0$

Back

Model: Technology Choice for Non-Mining Firms

- A firm chooses its technology $\boldsymbol{a}$ from the set

$\tilde{\varepsilon} \neq 1 \qquad \tilde{\gamma} \neq 1 \qquad \varepsilon + \tilde{\varepsilon} < 2 \qquad \gamma + \tilde{\gamma} < 2$

$$\left(\sum_{k \in \mathcal{K}^E} a_k^{1-\tilde{\gamma}} \right)^{\frac{1-\tilde{\varepsilon}}{1-\tilde{\gamma}}} + a^{1-\tilde{\varepsilon}} \leq 1$$

- A firm chooses $\boldsymbol{a}$ before knowing $\boldsymbol{z}$ to maximize expected global profits

$\Rightarrow$ $\boldsymbol{a}$ is common across all (i, s) firms

Back

Model: Optimal Technology Choice Across Energy Types

$$\text{Slope of technology frontier (lhs)} \quad = \quad \text{Slope of iso-profit curve (rhs)}$$

$$x_{i,ks}^{1-\tilde{\gamma}} \equiv \left(\frac{a_{i,ks}}{a_{i,s}}\right)^{1-\tilde{\gamma}} \quad = \quad \frac{\sum_l \alpha_{i,l,ks} Y_{i,l,s}}{\sum_l \left(Y_{i,l,s} - \sum_k \alpha_{i,l,ks} Y_{i,l,s}\right)} \quad \forall k \in \mathcal{K}^E$$

- $Y_{i,l,s} \equiv$ output of (i,l,s) firms
- $\alpha_{i,l,ks} \equiv$ revenue share of k input for (i,l,s) firms

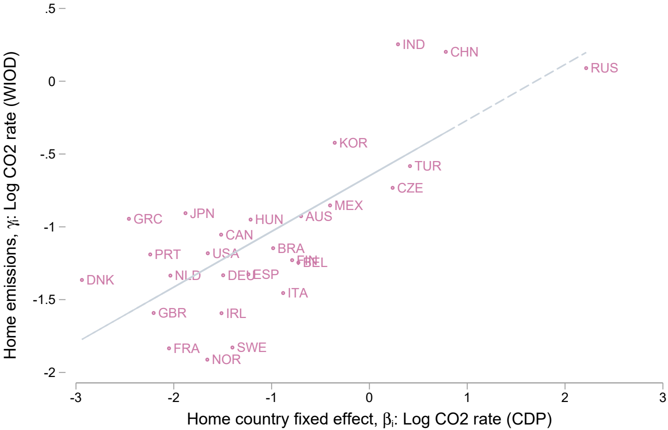
$$\alpha_{i,l,ks} = \frac{(\tilde{p}_{l,ks}/x_{i,ks})^{1-\gamma}}{\sum_{k' \in \mathcal{K}^E} (\tilde{p}_{l,k's}/x_{i,k's})^{1-\gamma}} \frac{\left(\sum_{k' \in \mathcal{K}^E} (\tilde{p}_{l,k's}/x_{i,k's})^{1-\gamma}\right)^{\frac{1-\varepsilon}{1-\gamma}}}{\left(\sum_{k' \in \mathcal{K}^E} (\tilde{p}_{l,k's}/x_{i,k's})^{1-\gamma}\right)^{\frac{1-\varepsilon}{1-\gamma}} + 1}$$

where $\tilde{p}_{l,ks} \equiv \left(\delta_{l,ks}^{1/(1-\gamma)} w_l^{-\eta_{l,\ell s}} \prod_{k \in \mathcal{K}} P_{l,k}^{-\eta_{l,ks}}\right) P_{l,k}$

Affiliates from Cleaner Countries Are Cleaner Everywhere

Firm f, home country i, host country l, industry s. $\mathcal{E}$ Emissions. Y Revenue Back

$$\log\left(\frac{\mathcal{E}_{i,s}}{Y_{i,s}}\right)^{WIOD} = \gamma_i + \delta_s + \varepsilon_{i,s} \qquad \text{vs.} \qquad \log\left(\frac{\mathcal{E}_{fi,l,s}}{Y_{fi,l,s}}\right)^{CDP} = \beta_i + \delta_{l,s} + \varepsilon_{fi,l,s}$$



Affiliates with Cleaner Homes Are Cleaner Everywhere

Firm f, home country i, host country l, industry s. $\mathcal{E}$ Emissions. Y Revenue

$$\log\left(\frac{\mathcal{E}_{fi,l,s}}{Y_{fi,l,s}}\right)^{CDP} = \beta_1 \log\left(\frac{\mathcal{E}_i}{Y_i}\right)^{WIOD} + X'_{f,l}\gamma + \delta_{l,s} + \epsilon_{fi,l,s}$$

Dependent variable:	Log firm CO_2 rate					
Home log CO_2 rate	0.96***	1.07***	0.56*	0.63**	0.63**	0.60**
	(0.24)	(0.22)	(0.30)	(0.25)	(0.23)	(0.29)
Host log CO_2 rate	0.89***	0.86***				
	(0.09)	(0.09)				
Firm log revenues						-0.48***
						(0.08)
Observations	4,833	4,833	4,833	4,833	4,833	4,833
R-squared	0.05	0.24	0.28	0.48	0.63	0.70
# host countries	42	42	42	42	42	42
# home countries	32	32	32	32	32	32
Industry FE	no	yes	no	yes	-	-
Host country FE	no	no	yes	yes	-	-
Industry x host country FE	no	no	no	no	yes	yes

Estimation Using Micro Data Back

1. Energy-Type Substitution $\gamma \approx 0.45$: Energy quantities, prices, across states within firm
    - Data: US Mfg Energy Consumption Survey 2014; State Energy Database System

$$\ln\left(\frac{Q_{f,l,k}}{Q_{f,l,1}}\right) = -\gamma \ln\left(\frac{P_{l,k}}{P_{l,1}}\right) + \phi_{f,k} + \xi_{f,l,k}$$

Estimation Using Micro Data

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2. Energy/Non-Energy Substitution $\varepsilon \approx 0.45$: Energy exp, prices across states within firm
   - Data: US State Energy Database System; US Census of Manufactures 2012

$$\ln\left(\frac{\alpha_{f,l}}{1-\alpha_{f,l}}\right) = (1-\varepsilon)\ln\left(\frac{P_{l,1}}{P_l^{NE}}\left(\frac{\alpha_{f,l,1}}{\alpha_{f,l}}\right)^{-\frac{1}{1-\gamma}}\right) + \phi_f + \xi_{f,l}$$

Parameters: Energy Type Substitution γ

- Extended to firms & states, model implies

$$\ln\left(\frac{Q_{f,l,k}}{Q_{f,l,1}}\right) = -\gamma \ln\left(\frac{P_{l,k}}{P_{l,1}}\right) + \phi_{f,k} + \xi_{f,l,k}$$

  - Energy quantities $Q_{f,l,k}$: Manufacturing Energy Consumption Survey 2014
  - Energy prices $P_{l,k}$: State Energy Database System
  - Firm$\times$energy type fixed effects $\phi_{f,k}$
  - Electricity as reference energy type ($k = 1$)

- Notes
  - Arbitrary autocorrelation (two-way cluster) within state and firm
  - Excluded observations: administrative records, imputed values, zero electricity
  - Basic observation is firm$\times$state (aggregate across establishments w/in state)

- Baseline estimate $\gamma \approx 0.45$

Parameters: Energy Type Substitution γ

$$\ln\left(\frac{Q_{f,l,k}}{Q_{f,l,1}}\right) = -\gamma \ln\left(\frac{P_{l,k}}{P_{l,1}}\right) + \phi_{f,k} + \xi_{f,l,k}$$

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Price ratio term (γ)	0.409**	0.364**	0.400**	0.263**	0.401**	0.293**	0.415*	0.456**
	(0.159)	(0.177)	(0.155)	(0.105)	(0.162)	(0.124)	(0.245)	(0.184)
Plant level		X						
Industry FE			X					
Asinh				X		X		
Exclude coal					X	X		
Weighted							X	
Instrument								X
N	4,600	7,000	4,600	9,000	4,400	6,000	4,600	4,600
First stage F								651

Parameters: Energy Type Substitution γ

- Model-based analysis uses $\gamma = 0.45$

- Existing estimates?

  - Vermetten and Plantinga (1953) cross-section of US states: $\gamma \approx 2.1$ to 2.4

  - Serletis et al. (2010) translog with US time series: $\gamma = 0.25$ to 0.60

    - Cross-industry mean: 0.40

    - Standard value for CGE models (EPA, MIT EPPA model)

    - But time series confounding: inflation, growth, OPEC crisis, etc.

Parameters: Energy vs Non-Energy Substitution ε

- Extended to firms, $l =$ US state, our model implies

$$\ln\left(\frac{\alpha_{f,l}}{1-\alpha_{f,l}}\right) = (1-\varepsilon)\ln\left(\frac{P_{l,1}}{P_l^{NE}}\left(\frac{\alpha_{f,l,1}}{\alpha_{f,l}}\right)^{-\frac{1}{1-\gamma}}\right) + \phi_f + \xi_{f,l}$$

  - Census of Manufactures 2012 administrative/confidential micro-data
  - $\alpha_{f,l}, \alpha_{f,l,1}$ Energy-cost shares. Establishment-level spending on electricity, fuels, materials, value added
  - $P_{l,1}$ Price of energy type 1 (electricity). State Energy Data System (US Energy Information Agency)
  - P_l^{NE} Price of non-energy. We use w_l for now
    - Microdata from 2012 Current Population Survey-ASEC
    - Mincer regression with state fixed effects
    - w_l^L are state fixed effects evaluated at reference category
  - γ: from earlier estimates
- Baseline estimate $\varepsilon \approx 0.45$

Parameters: Energy vs Non-Energy Substitution ε

$$\ln\left(\frac{\alpha_{f,l}}{1-\alpha_{f,l}}\right) = (1-\varepsilon)\ln\left(\frac{P_{l,1}}{P_l^{NE}}\left(\frac{\alpha_{f,l,1}}{\alpha_{f,l}}\right)^{-\frac{1}{1-\gamma}}\right) + \phi_f + \xi_{f,l}$$

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Price ratio term	0.513***	0.404***	0.510***	0.791***	0.506***	0.421***	0.529***	0.526***
	(0.006)	(0.007)	(0.006)	(0.047)	(0.006)	(0.007)	(0.011)	(0.007)
Bootstrap S.E.	(0.129)	(0.160)	(0.125)	(0.081)	(0.129)	(0.096)	(0.192)	(0.129)
Plant level		X						
Industry FE			X					
Asinh				X		X		
Exclude coal					X	X		
Weighted							X	
Instrument								X
N	12,500	22,500	12,500	12,500	12,500	12,500	12,500	7,100
First stage F								3121

Details

Parameters: Energy vs Non-Energy Substitution ε

$$\ln\left(\frac{\alpha_{f,l}}{1-\alpha_{f,l}}\right) = (1-\varepsilon)\ln\left(\frac{P_{l,1}}{P_l^{NE}}\left(\frac{\alpha_{f,l,1}}{\alpha_{f,l}}\right)^{-\frac{1}{1-\gamma}}\right) + \phi_f + \xi_{f,l}$$

- $\alpha_{f,l}$ on left and right-hand side: simultaneity bias if measurement error
  - Solution: instrument $\alpha_{f,l}$ with lag from 2011 Annual Survey of Manufacturers
- γ is a generated regressor
  - Solution: bootstrap over 200 estimates of γ
- Other variations:
  - Firm v. establishment
  - Zero values for energy share: inverse hyperbolic sine
  - Coal often missing, some estimates exclude

Model: Recovering Trilateral Expenditure Flows

Data, Model

$$X_{ln} = \sum_i X_{i,ln} \qquad Y_{i,l} = \sum_n X_{i,ln}$$

$$X_{i,ln} = \frac{\phi_{i,l}\phi_{ln}}{\sum_{l'} \phi_{i,l'}\phi_{l'n}} \frac{\left(\sum_{l'} \phi_{i,l'}\phi_{l'n}\right)^{1-\rho}}{\sum_{i'} \left(\sum_{l'} \phi_{i',l'}\phi_{l'n}\right)^{1-\rho}} X_n$$

$$\phi_{i,l} \equiv \left(M_i T_{i,l} (\tau_{i,l} c_{i,l})^{-\theta}\right)^{1-\rho} \qquad \phi_{ln} \equiv \left(\tau_{ln}^{-\theta}\right)^{\frac{1}{1-\rho}}$$

Model: Recovering Energy Cost Shares, Illustration

- Two inputs (energy, labor), one sector, $\varepsilon = \gamma$, $\tilde{\varepsilon} = \tilde{\gamma}$. Equilibrium:

$$x_i^{1-\tilde{\varepsilon}} = \frac{\sum_l \alpha_{i,l} Y_{i,l}}{\sum_l (1-\alpha_{i,l}) Y_{i,l}} \qquad \forall i$$

$$\alpha_{i,l} = \frac{1}{\tilde{\sigma}_s} \frac{(\tilde{p}_l / x_i)^{1-\varepsilon}}{(\tilde{p}_l / x_i)^{1-\varepsilon} + 1} \qquad \forall i, l$$

$$\alpha_l = \sum_i \alpha_{i,l} \frac{Y_{i,l}}{\sum_{i'} Y_{i',l}} \qquad \forall l$$

where $x_i \equiv a_i^E / a_i^L$ and $\tilde{p}_l \equiv \delta_l^{\frac{1}{1-\varepsilon}} (p_l / w_l)$

- System of equations to solve for $\{x_i\}$, $\{\alpha_{i,l}\}$ and $\{\tilde{p}_l\}$ given data, $\tilde{\varepsilon}$, ε

Carbon Accounting with Multinational Production

For $k \in \mathcal{K}^M$

$$\mathcal{E}_{hi,jln,ks} = \frac{e_{l,k}}{p_{l,k}} \ \chi_{hi,jl,ks} \ X^C_{i,ln,s}$$

- Emission rate (tons/$): $\frac{e_{l,k}}{p_{l,k}} = \frac{e^{IEA}_k Q^{IEA}_{l,k}}{Y^{WIOD}_{l,k}}$
- Leontief inverse: $\{\chi_{hi,jl,ks}\} = (I - \{\alpha_{hi,jl,ks}\})^{-1}$ where $\alpha_{hi,jl,ks} \equiv \lambda^{model}_{h,jl,s} \alpha^{model}_{i,l,ks}$
- Final sales: $X^C_{i,ln,s} = \lambda^{model}_{i,ln,s} X^{C,WIOD}_{n,s}$