The Carbon Footprint of Multinational Production

Ezequiel Garcia-Lembergman
Universidad Católica de Chile

Natalia Ramondo
Boston University, CEPR & NBER

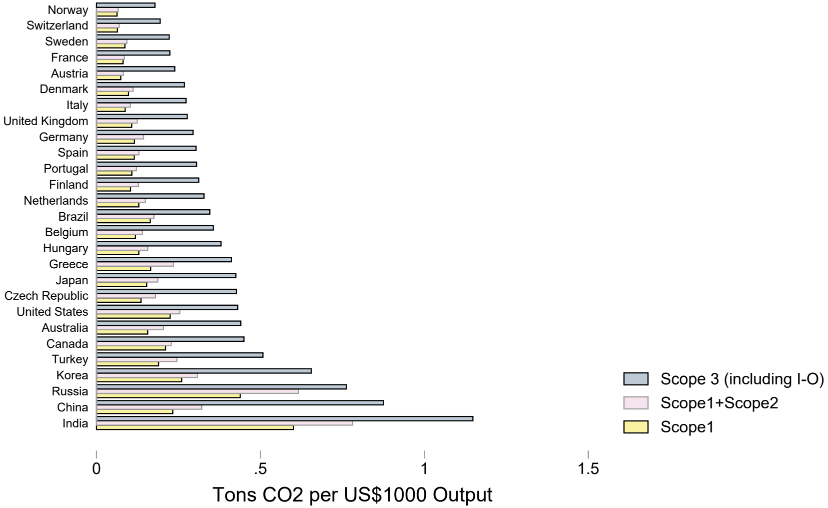
Andrés Rodríguez-Clare
UC Berkeley, CEPR & NBER

Joseph S. Shapiro
UC Berkeley & NBER

SED Annual Meeting 2025

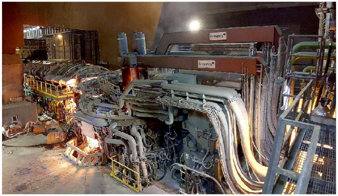
Emissions per Dollar Very Different Across Countries

$$\frac{\mathcal{E}_{l,s}}{Y_{l,s}} = \gamma_l + \delta_s + \varepsilon_{l,s}$$



Example: 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)

Our Approach

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  - Trade & MP with MV Pareto: closed-form & aggregation, GE
  - Multiple sectors & IO links: energy, mining, other inputs
  - Energy-intensity technology choice: affects firm red emissions worldwide

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  - Methodology to uncover MP-specific energy cost-revenue shares
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    1. Carbon accounting: Consumption, Production, Extraction, Ownership
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- **Companion paper: "Carbon Emission in the Global Economy"**

Data Sources

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

    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

MP Facts: Pollution Heaven and Pollution Halo

- MNE Affiliates Are Dirtier Abroad

- MNE Affiliates Are Cleaner than Domestic Firms in Host Country

- MNE Affiliates with Cleaner Home Are Cleaner Everywhere **[New]**

Model: Notation and Preliminaries

- Many countries
  - i home country of firms. l location of production. n destination of sales

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  - Six energy sectors $s \in \mathcal{K}^E$

    Mining sectors: coal, natural gas, crude oil (fossil fuels) $s \in \mathcal{K}^M$

    Non-mining sectors: electricity, refined oil, gas distribution
  - Non-energy sectors $s \notin \mathcal{K}^E$

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- Preferences: Cobb-Douglas across sectors with share $\mu_{n,s}$

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  - Labor share: $\alpha_{j,\ell s}$. Intermediates share: $\alpha_{j,ks}$
  - Decreasing returns: $\nu_{j,s} = 1 - \alpha_{j,\ell s} + \sum_{k \in \mathcal{K}} \alpha_{j,ks} \in (0,1)$
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- **Emissions are generated exclusively by using fossil fuels**

$$e_s \equiv \frac{\mathcal{E}_s}{q_s} \begin{cases} > 0 & \text{for } s \in \mathcal{K}^M \\ = 0 & \text{for } s \notin \mathcal{K}^M \end{cases}$$

Model: Non-Mining Sectors

- Production (ε, γ): energy, non-energy inputs, labor
- Trade and MP: MV Pareto productivity (θ, ρ_s), monopolistic competition (ν_s)
- Energy-intensity technology choice ($\tilde{\gamma}$, $\tilde{\varepsilon}$): firms have same technology everywhere

Model: Production Function for Non-mining Sector

Energy inputs: coal, crude oil, natural gas, electricity, refined oil, gas distribution

Non-energy inputs: labor and other inputs

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

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

Model: Production Function for Non-mining Sector

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

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

- Productivity $\boldsymbol{z}$ is MV Pareto $(T_{i,l,s}, \theta, \rho_s)$
- Technology choice is of $\boldsymbol{a}$ (next slide)

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 $\mathbf{z}$ to maximize expected global profits

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

Model: Optimal Technology Choice Across Energy Types

Slope of technology frontier = Slope of iso-profit curve

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

- $\alpha_{i,l,ks} \equiv$ revenue share of k input for (i,l,s) firms nested CES
- $Y_{i,l,s} \equiv$ output of (i,l,s) firms
- $\sum_l \alpha_{i,l,ks} Y_{i,l,s} \equiv$ expected global costs of input k for (i,l,s) firms

Model: Equilibrium

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

Demand for s in l

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

Market clearing for $i, l, s \notin \mathcal{K}^M$

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

Supply curve for $s \in \mathcal{K}^M$

$$\sum_{h,j} Y_{h,j,s} = \sum_{i,l,n} \lambda_{i,ln,s} X_{n,s}$$

Market clearing for $s \in \mathcal{K}^M$

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

Labor market clearing in l

$$X_i^C = w_i L_i + \sum_{l,s} \Pi_{i,l,s} + \xi_i$$

Final expenditure in i

Exact Hat-Algebra: Parameters

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- $\{\alpha_{l,ks}, \alpha_{l,\ell s}\}$, $s \in \mathcal{K}^M$, and $\{\beta_{l,ks}, \beta_{l,\ell s}\}$ from WIOD
- $\theta = 5$, $\rho = 0.6$, $\nu_s = 0.2$ for $s \notin \mathcal{K}^M$ from literature

Exact Hat-Algebra: Model-Based Variables

Non-mining sectors $s \notin \mathcal{K}^M$

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$\Rightarrow$ *Given ρ, trade and MP shares $\{\lambda_{ln,s}, \lambda_{i,l,s}\}$, and $\tau_{i,ln,s} = \tau_{i,l,s}\tau_{ln,s}$*

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$\Rightarrow$ *Given* $\varepsilon, \tilde{\varepsilon}$*, MP and energy shares* $\{\lambda_{i,l,s}, \alpha_{l,ks}\}$*, and world-wide technology choice*

Model: Recovering Energy Cost Shares, Illustration

- Two inputs (energy, labor), one sector. Equilibrium:

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

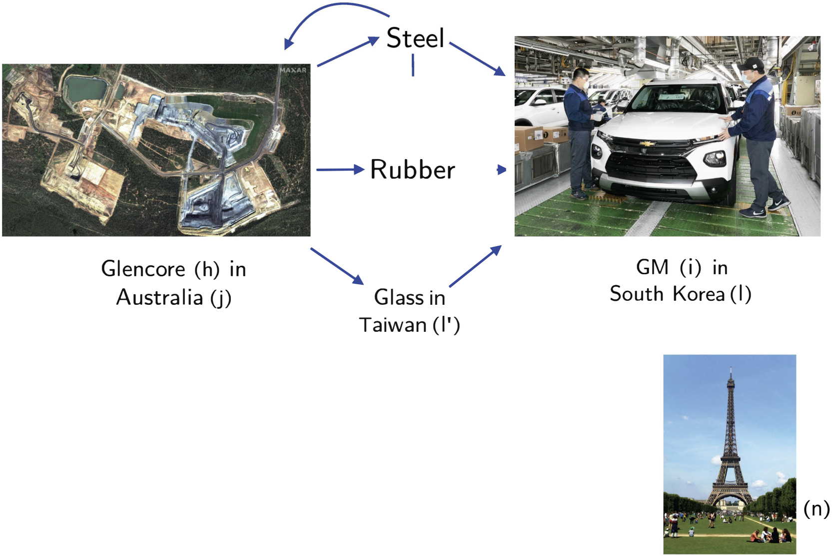
$$\alpha_{i,l} = \frac{1}{\tilde{\sigma}_s} \frac{(\tilde{p}_l / x_i)^{1-\varepsilon}}{(\tilde{p}_l / x_i)^{1-\varepsilon} + 1} \qquad \forall i, l$$

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

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



Carbon Accounting with Multinational Production

$$\mathcal{E}_{hi,jln,ks} = \frac{e_k}{p_k} \; \chi_{hi,jl,ks} \; X^C_{i,ln,s}$$

- Emission rate (tons/$): $\frac{e_k}{p_k} = \frac{e_k^{IEA}}{Y_K^{WIOD}/Q_k^{IEA}}$
- Leontief inverse: $\{\chi_{hi,jl,ks}\} = (I - \{\alpha_{hi,jl,ks}\})^{-1}$ where $\alpha_{hi,jl,ks} \equiv \lambda^{model}_{h,jl,k} \alpha^{model}_{i,l,ks}$
- Final sales: $X^C_{i,ln,s} = \lambda^{model}_{i,ln,s} X^{C,WIOD}_{n,s}$
- Today: no technology choice so that $\alpha^{model}_{i,l,ks} = \alpha^{data}_{l,ks}$ for all i

Carbon Accounting: Allocating Emissions

$$\mathcal{E}_l{}^{P3} = \sum_{hi,jn,ks} \mathcal{E}_{hi,jln,ks} \qquad \text{Production (S3)}$$

$$\mathcal{E}_n{}^{C} = \sum_{hi,jl,ks} \mathcal{E}_{hi,jln,ks} \qquad \text{Consumption}$$

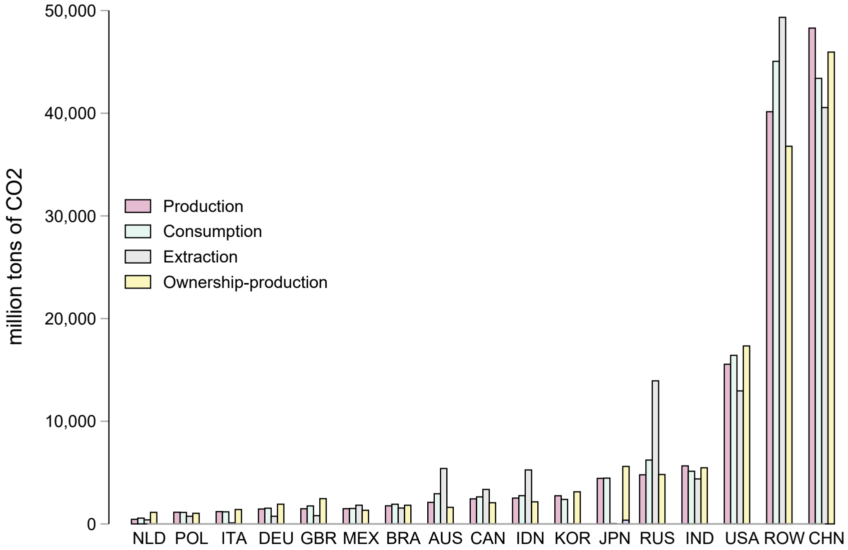
$$\mathcal{E}_j{}^{M} = \sum_{hi,ln,ks} \mathcal{E}_{hi,jln,ks} \qquad \text{Mining}$$

$$\mathcal{E}_i{}^{O} = \sum_{h,jln,ks} \mathcal{E}_{hi,jln,ks} \qquad \text{Ownership}$$

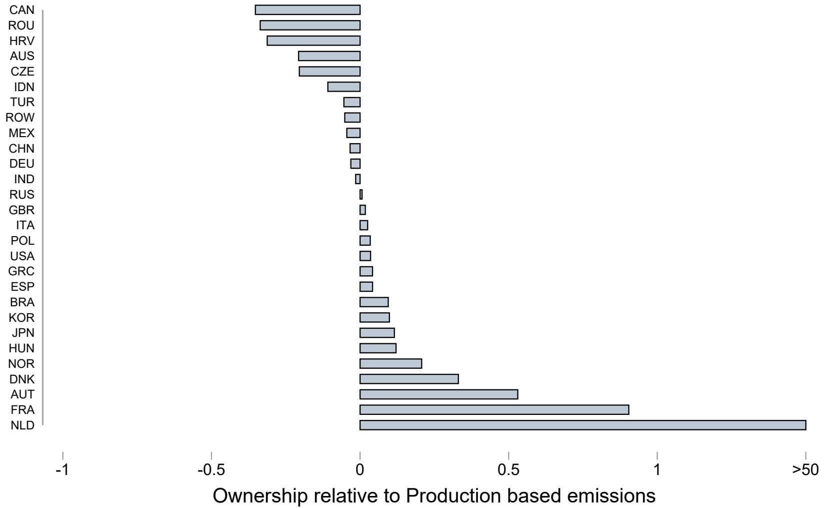
$$\mathcal{E}_l{}^{P1} = \sum_{hi,jn,ks} \frac{e_k}{p_k} \alpha_{hi,jl,ks} Y_{i,l,s} \qquad \text{Production (S1)}$$

h, i = Country of ownership for inputs, outputs; j, l = Country of production for inputs, outputs
n = Country of consumption; k, s = Industry for inputs, outputs

Carbon Accounting: Results



Carbon Accounting: Ownership vs Production (S1)



Model: MP Autarky—Analytical Counterfactual

- No IO loop; exogenous technologies ($\boldsymbol{a}_{i,s}$); no trade in energy; CRS in mining ($\nu_s = 0$)

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- Shutting down MP affects sectoral emissions per worker by

$$\frac{\mathcal{E}'_{l,s}/L'_{l,s}}{\mathcal{E}_{l,s}/L_{l,s}} = \frac{\mathcal{E}_{l,l,s}/L_{l,l,s}}{\mathcal{E}_{l,s}/L_{l,s}}$$

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- If $\boldsymbol{a}_{i,s} = \boldsymbol{a}_{j,s}$ for all i, j, turning off MP has no effect on sector-level emissions

- If clean country has MP in dirty country, turning off MP increases sector-level emissions
  - Clean country: emissions unchanged
  - Dirty country: resources move from clean foreign to dirty domestic firms

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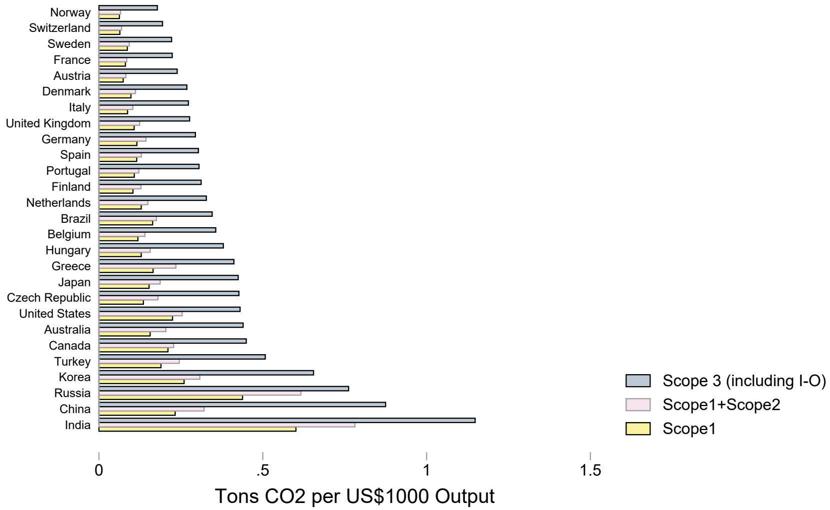
- **What's next**
  - Optimal carbon taxes and leakage through MP
  - Responsible sourcing and supply-chain externalities

Appendix

Emissions per $Output Very Different Across Countries

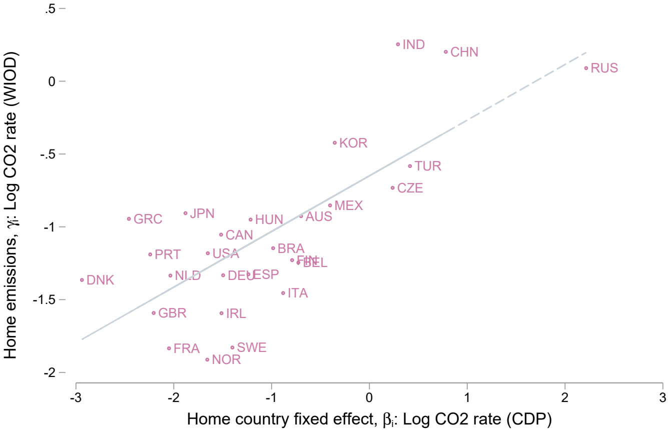


With electric grid

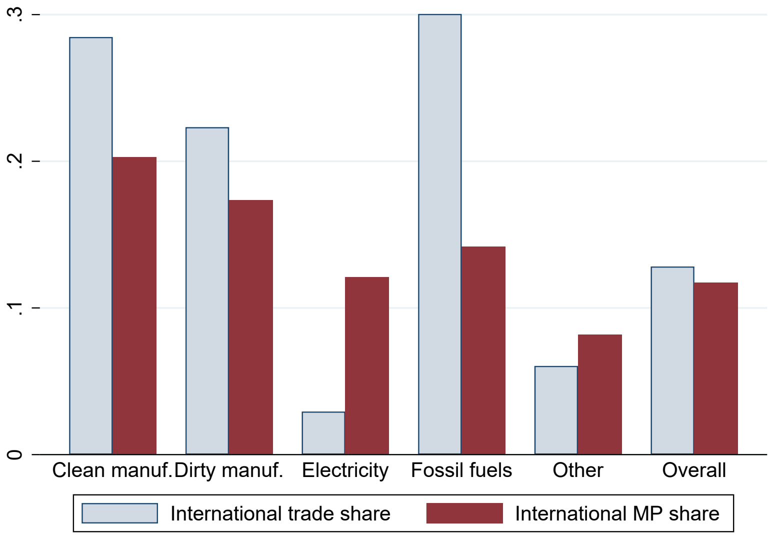
Affiliates from Cleaner Countries Are Cleaner Everywhere

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

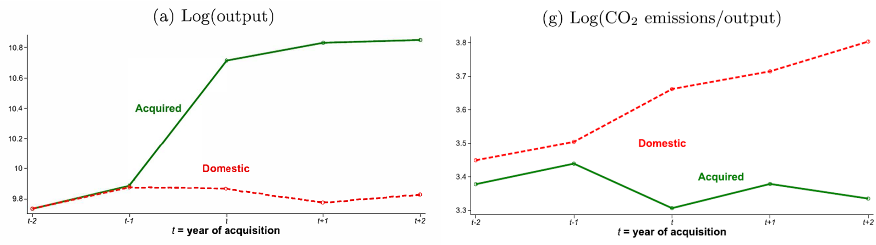
$$\log\left(\frac{\mathcal{E}_{i,s}}{Y_{i,s}}\right)^{WIOD} = \gamma_i + \delta_s + \varepsilon_{i,s} \quad \text{vs.} \quad \log\left(\frac{\mathcal{E}_{fi,l,s}}{Y_{fi,l,s}}\right)^{CDP} = \beta_i + \delta_{l,s} + \varepsilon_{fi,l,s}$$



Importance of Trade v. Multinational Production



Brucal, Javorcik, and Love (JIE 2019)



Parameters: Estimation 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

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

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

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3. Decreasing returns in mining $\upsilon = 0.25$: Extraction costs, quantities by energy & region
   - Data: Welsby et al. (Nature 2021)

Vertex v, energy type k, region j: $\upsilon_k = \dfrac{\partial \ln p_k / \partial \ln E_k}{\partial \ln p_k / \partial \ln E_k + 1} \quad \Rightarrow \quad \ln p_{vj,k} = \zeta_k \ln E_{vj,k} + \mu_{j,k} + \zeta_{vj,k}$

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×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×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/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/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/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

Parameters: Decreasing Returns in Mining (υ)

- Decreasing returns υ_k in terms of inverse supply elasticity

$$\upsilon_k = \frac{\partial \ln p_k / \partial \ln E_k}{\partial \ln p_k / \partial \ln E_k + 1}$$

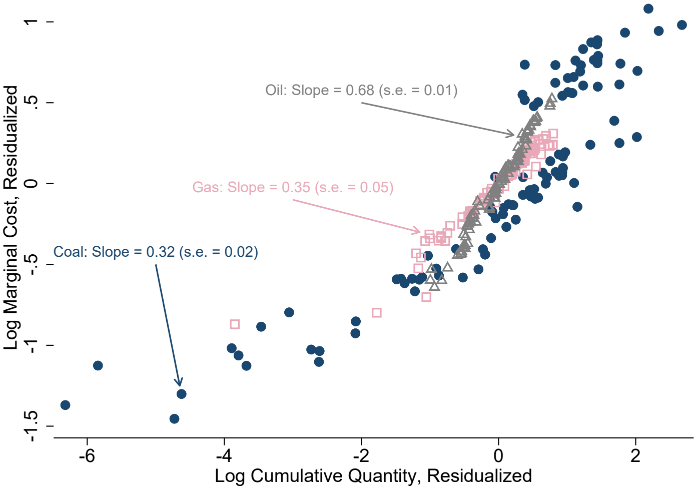
- Regression version: Vertex v, energy type k, region j

$$\ln p_{vj,k} = \zeta_k \ln E_{vj,k} + \mu_{j,k} + \zeta_{vj,k}$$

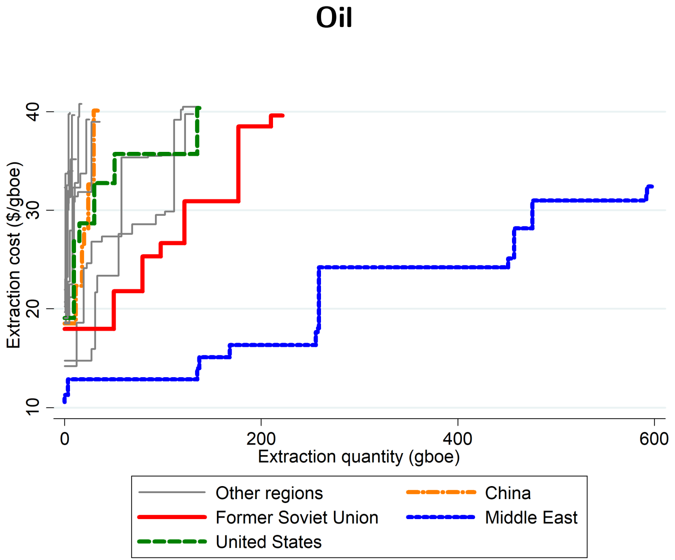
- Data source: Welsby et al. (*Nature* 2021)
- Decreasing returns (=resource cost share, rents): $\upsilon = 0.25$
  - Source: pooled inverse elasticity $\zeta = 0.342$ (0.025)

Parameters: Decreasing Returns in Mining (υ Raw Data)

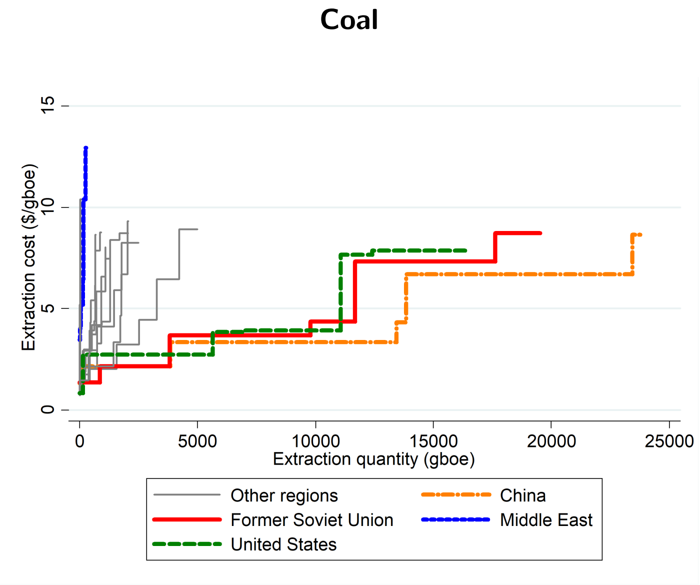
$$\ln p^E_{vj,k} = \zeta_k \ln E_{vj,k} + \mu_{j,k} + \zeta_{vj,k}$$



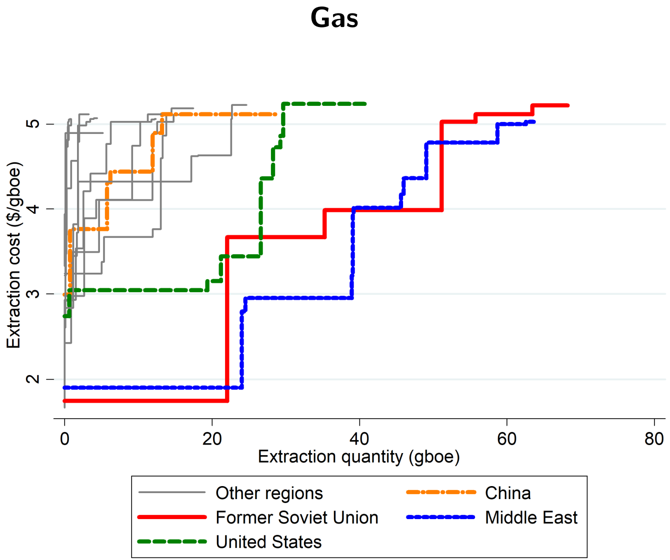
Parameters: Decreasing Returns in Mining (υ Raw Data)



Parameters: Decreasing Returns in Mining (υ Raw Data)



Parameters: Decreasing Returns in Mining (υ Raw Data)

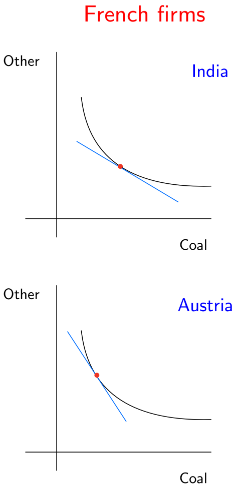


Model: Revenue Energy Cost Shares Back

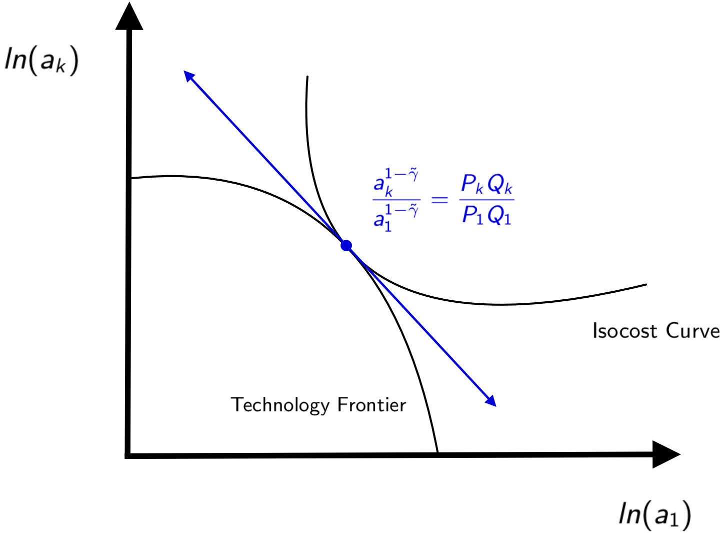
$$\alpha_{i,l,ks} = \frac{\left(\tilde{p}_{l,ks}/x_{i,ks}\right)^{1-\gamma}}{\sum_{k'\in\mathcal{K}^E}\left(\tilde{p}_{l,k's}/x_{i,k's}\right)^{1-\gamma}} \frac{\left(\sum_{k'\in\mathcal{K}^E}\left(\tilde{p}_{l,k's}/x_{i,k's}\right)^{1-\gamma}\right)^{\frac{1-\varepsilon}{1-\gamma}}}{\left(\sum_{k'\in\mathcal{K}^E}\left(\tilde{p}_{l,k's}/a_{i,k's}\right)^{1-\gam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

where $x_{i,ks} \equiv a_{i,ks}/a_{i,s}$ and $\tilde{p}_{l,ks} \equiv \delta_{l,ks}^{\frac{1}{1-\gamma}}\left(p_{l,k}/w_l\right)$

Technology Choice: Illustration



Model: Optimal Technology Choice, Illustration



Model: Recovering Trilateral Expenditure Flows Back

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

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

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