

The Carbon Footprint of Multinational Production

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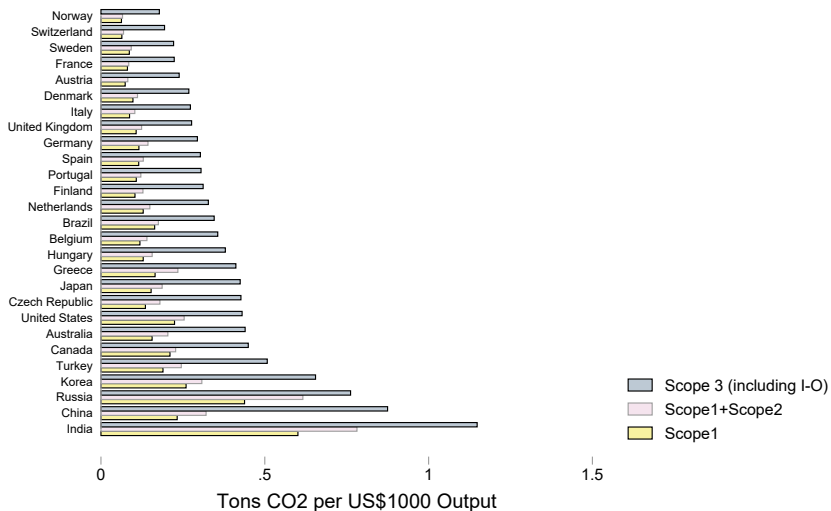
UC Berkeley & NBER

SED Annual Meeting 2025

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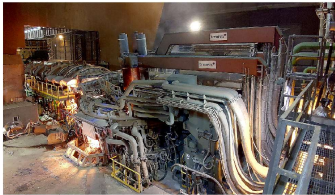
Emissions per Dollar Very Different Across Countries

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



Example: The Steel Industry in Vietnam

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



MP Italy->Vietnam



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



MP China->Vietnam



Vietnam steel corporation (Vietnam)



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 - Energy demand elasticities (nested CES): using US administrative micro data
 - **Methodology to uncover MP-specific energy cost-revenue shares**
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- **Quantitative Analysis**
 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
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- Preferences: Cobb-Douglas across sectors with share $\mu_{n,s}$

Model: Mining Sectors Exhibit Decreasing Returns to Scale

- Each $s \in \mathcal{K}^M$ produces a freely tradable **homogeneous** good
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- Production of $s \in \mathcal{K}^M$ requires sector-specific mines, labor, and intermediates
 - Labor share: $\alpha_{j,\ell s}$. Intermediates share: $\alpha_{j,ks}$
 - Decreasing returns: $\nu_{j,s} = 1 - \alpha_{j,\ell s} + \sum_{k \in \mathcal{K}} \alpha_{j,ks} \in (0, 1)$
 - MP is exogenous (owns mines) and has rents $\Pi_{h,j,s} = \nu_{j,s} Y_{h,j,s}$

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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

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

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

Model: Production Function for Non-mining Sector

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

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

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

Model: Technology Choice for Non-Mining Firms

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

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

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

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

\Rightarrow \mathbf{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

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

Demand for s in l

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

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

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

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

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

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

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- $\{\alpha_{l,ks}, \alpha_{l,ls}\}$, $s \in \mathcal{K}^M$, and $\{\beta_{l,ks}, \beta_{l,ls}\}$ 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 $\varepsilon, \tilde{\varepsilon}$, 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:

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

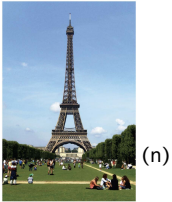
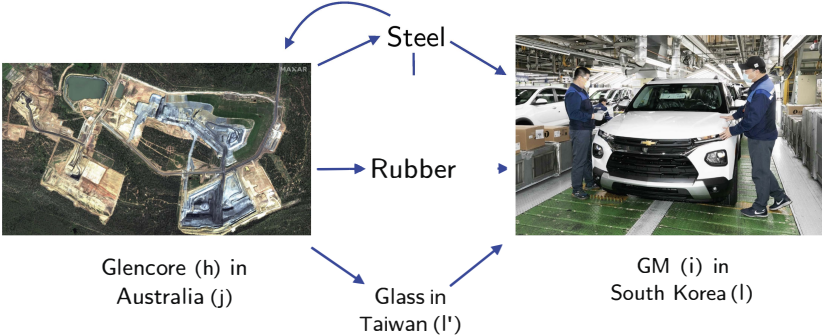
$$\alpha_{i,l} = \frac{1}{\tilde{\sigma}_s} \frac{(\tilde{p}_l/x_i)^{1-\varepsilon}}{(\tilde{p}_l/x_i)^{1-\varepsilon} + 1} \quad \forall i, l$$

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

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

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

- 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 $\alpha_{hi,jl,ks} \equiv \lambda_{h,jl,k}^{model} \alpha_{i,l,ks}^{model}$
- Final sales: $X_{i,ln,s}^C = \lambda_{i,ln,s}^{model} X_{n,s}^{C,WIOD}$
- Today: no technology choice so that $\alpha_{i,l,ks}^{model} = \alpha_{i,l,ks}^{data}$ for all i

Carbon Accounting: Allocating Emissions

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

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

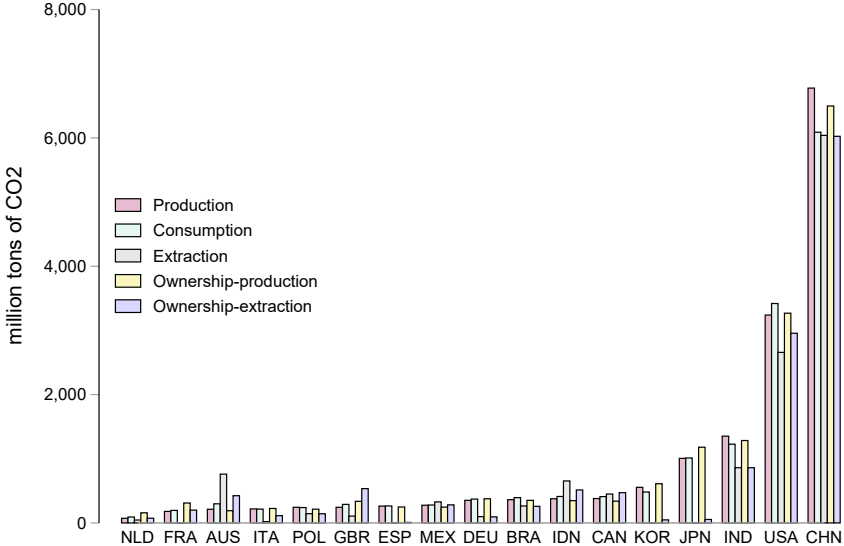
$$\mathcal{E}_j^M = \sum_{hi,ln,ks} \mathcal{E}_{hi,jln,ks} \quad \text{Mining}$$

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

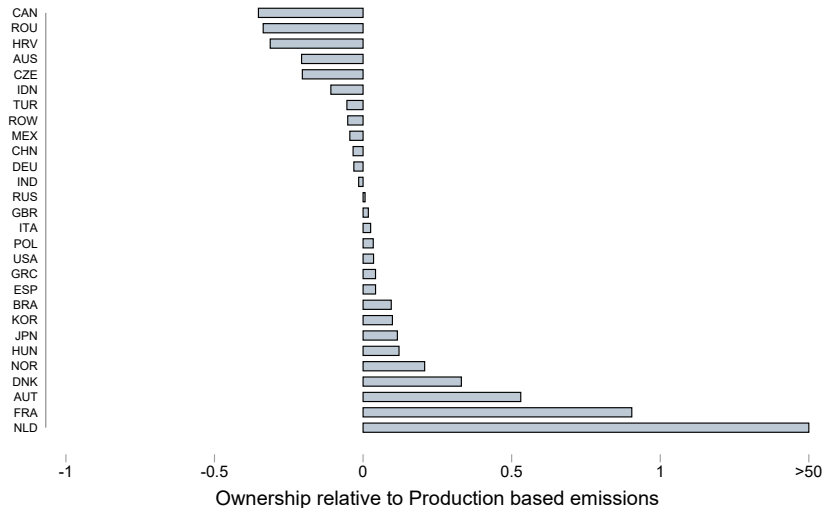
$$\mathcal{E}_l^{P1} = \sum_{hi,jn,ks} \frac{e_k}{p_k} \alpha_{hi,jl,ks} Y_{i,l,s} \quad \text{Production (S1)}$$

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 ($\mathbf{a}_{i,s}$); 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 $\mathbf{a}_{i,s} = \mathbf{a}_{j,s}$ 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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 - New estimates on key energy elasticities

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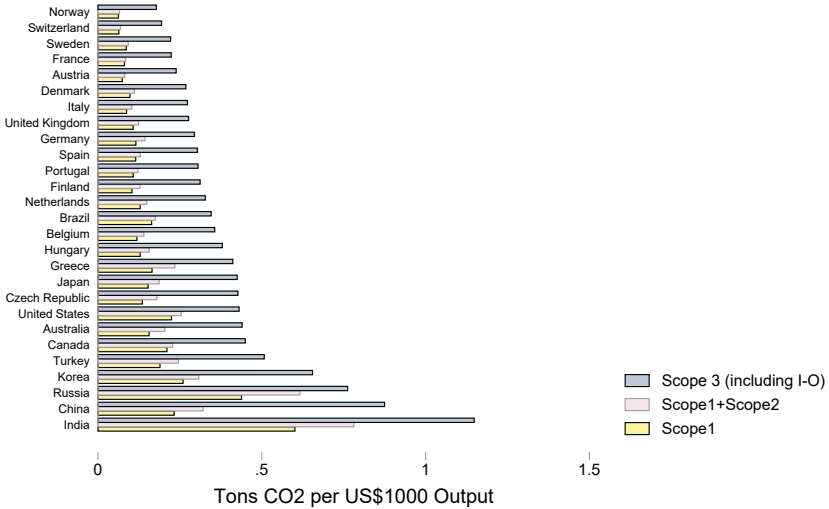
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- **What's next**

- Optimal carbon taxes and leakage through MP
- Responsible sourcing and supply-chain externalities

Appendix

Emissions per \$Output Very Different Across Countries

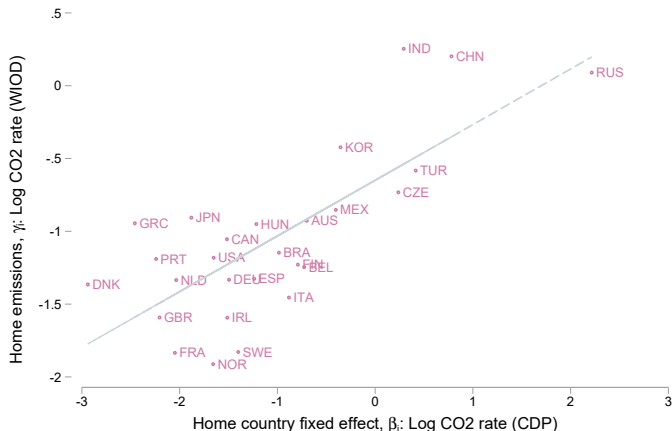


With electric grid

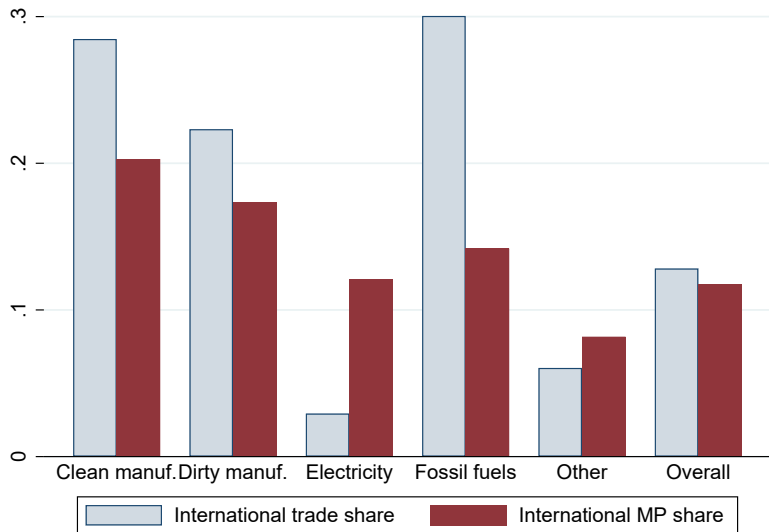
Affiliates from Cleaner Countries Are Cleaner Everywhere

Firm f , home country i , host country l , industry s . \mathcal{E} Emissions. Y Revenue [Back](#)

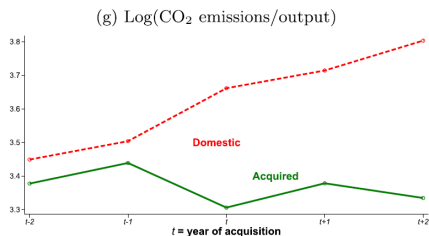
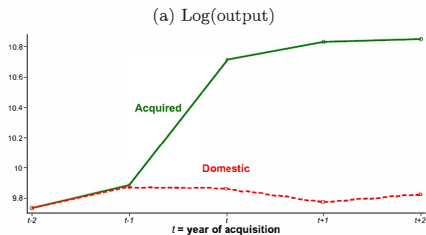
$$\log\left(\frac{\mathcal{E}_{i,s}}{Y_{i,s}}\right)^{WIOD} = \gamma_i + \delta_s + \varepsilon_{i,s} \quad \text{vs.} \quad \log\left(\frac{\mathcal{E}_{fi,l,s}}{Y_{fi,l,s}}\right)^{CDP} = \beta_i + \delta_{l,s} + \varepsilon_{fi,l,s}$$



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

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

$$\text{Vertex } v, \text{ energy type } k, \text{ region } j: v_k = \frac{\partial \ln p_k / \partial \ln E_k}{\partial \ln p_k / \partial \ln E_k + 1} \Rightarrow \ln p_{v_j,k} = \zeta_k \ln E_{v_j,k} + \mu_{j,k} + \zeta_{v_j,k}$$

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 \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** (0.159)	0.364** (0.177)	0.400** (0.155)	0.263** (0.105)	0.401** (0.162)	0.293** (0.124)	0.415* (0.245)	0.456** (0.184)
Plant level		X						
Industry FE			X					
Asinh				X		X		
Exclude coal					X	X		
Weighted 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*** (0.006)	0.404*** (0.007)	0.510*** (0.006)	0.791*** (0.047)	0.506*** (0.006)	0.421*** (0.007)	0.529*** (0.011)	0.526*** (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 Instrument							X	
								X
N	12,500	22,500	12,500	12,500	12,500	12,500	12,500	7,100
First stage F								3121

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 (v)

- Decreasing returns v_k in terms of inverse supply elasticity

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

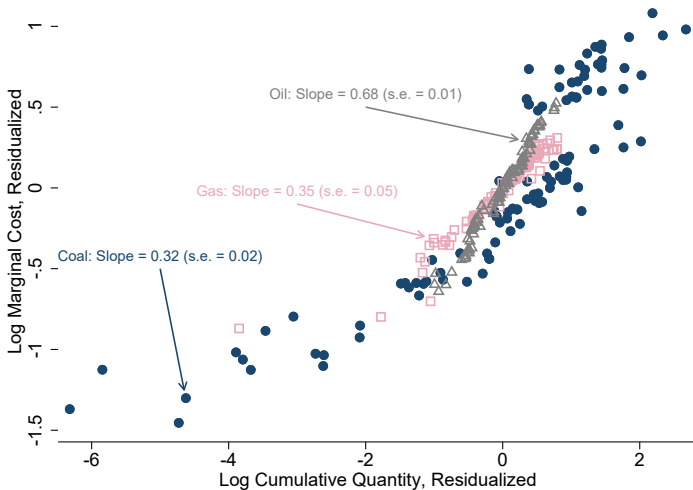
- Regression version: Vertex v , energy type k , region j

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

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

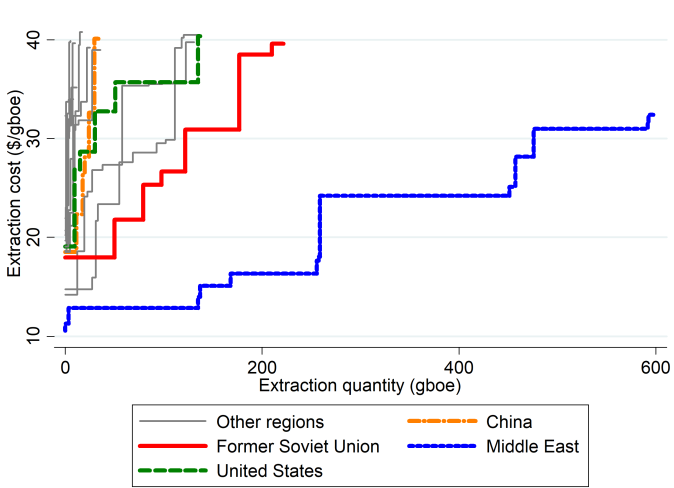
Parameters: Decreasing Returns in Mining (v Raw Data)

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



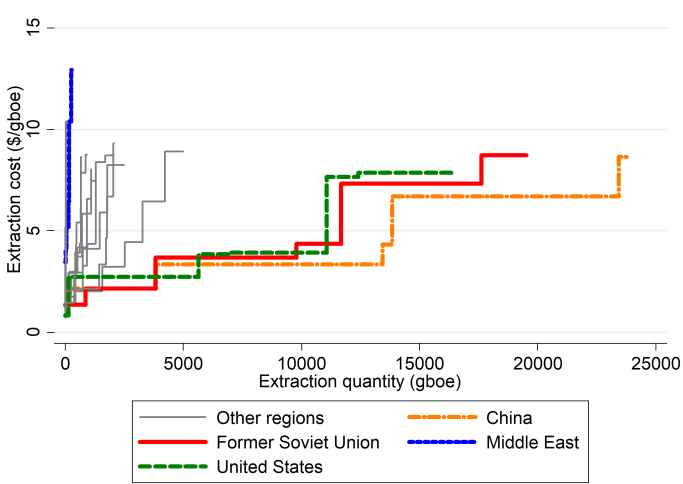
Parameters: Decreasing Returns in Mining (v Raw Data)

Oil



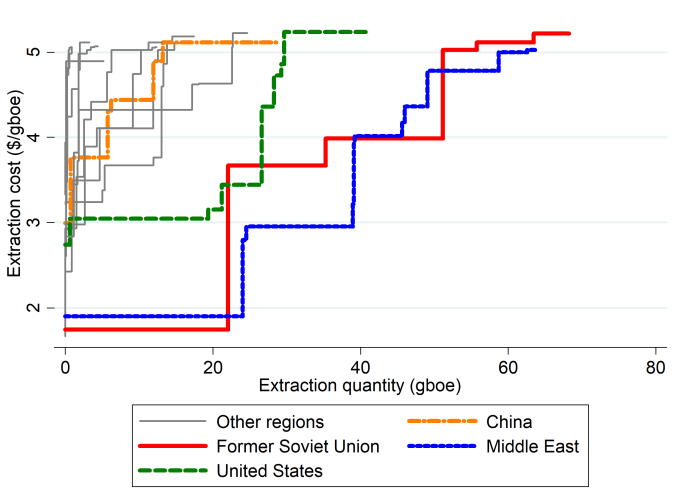
Parameters: Decreasing Returns in Mining (v Raw Data)

Coal



Parameters: Decreasing Returns in Mining (v Raw Data)

Gas

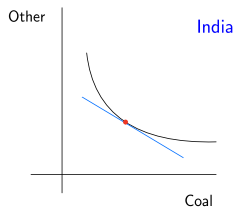


$$\alpha_{i,l,ks} = \frac{(\tilde{p}_{l,ks}/x_{i,ks})^{1-\gamma}}{\sum_{k' \in \mathcal{K}^E} (\tilde{p}_{l,k's}/x_{i,k's})^{1-\gamma}} \frac{(\sum_{k' \in \mathcal{K}^E} (\tilde{p}_{l,k's}/x_{i,k's})^{1-\gamma})^{\frac{1-\varepsilon}{1-\gamma}}}{(\sum_{k' \in \mathcal{K}^E} (\tilde{p}_{l,k's}/a_{i,k's})^{1-\gamma})^{\frac{1-\varepsilon}{1-\gamma}}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

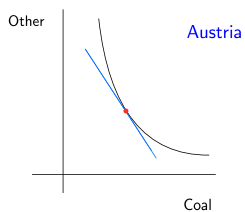
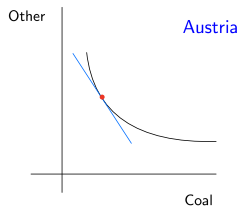
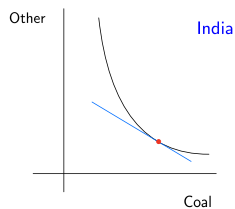
where $x_{i,ks} \equiv a_{i,ks}/a_{i,s}$ and $\tilde{p}_{l,ks} \equiv \delta_{l,ks}^{\frac{1}{1-\gamma}} (p_{l,k}/w_l)$

Technology Choice: Illustration

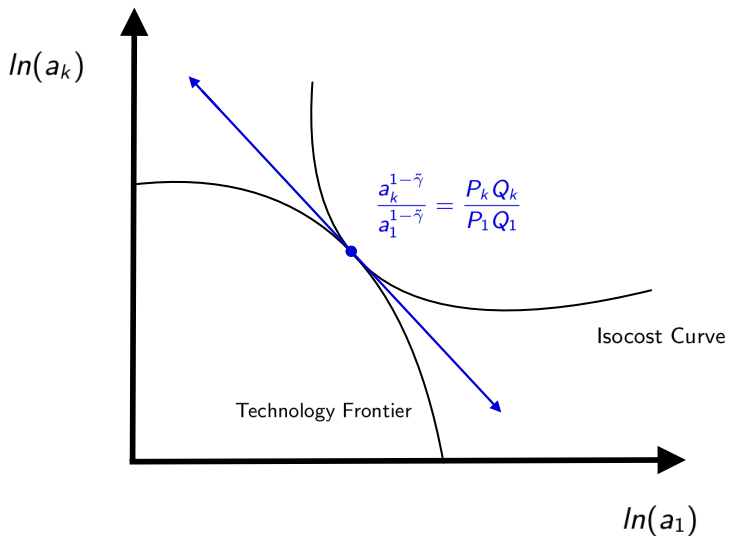
French firms



Chinese firms



Model: Optimal Technology Choice, Illustration



Model: Recovering Trilateral Expenditure Flows Back

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

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

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