How Firms Cut Carbon: Evidence from the European Emissions Market

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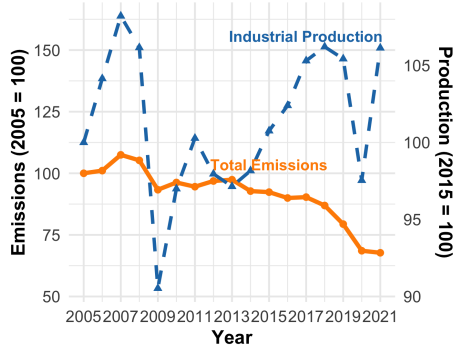
NBER The Economics of Decarbonizing Industrial Production

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The results and opinions expressed today are subject to change.

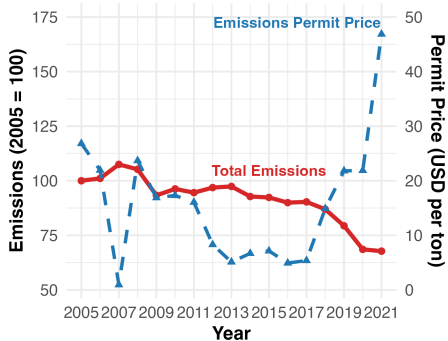
Understanding EU's Emissions Decline

- EU industrial CO_2 **emissions fell over 30%** from 2005–2021
- Despite EU industrial production **increasing 7.5%** over that period
  - (Colmer et al., 2024; Dechezlepretre, et. al., 2023; Marin et al., 2018; others)



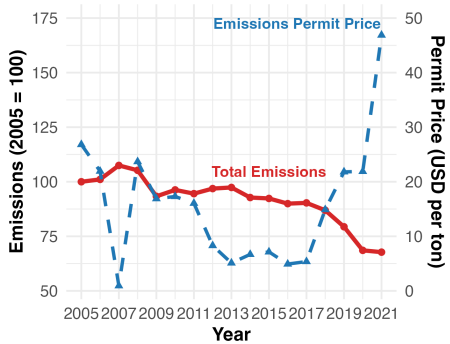
Requires an Account of the EU ETS

- Coincides with the launch of the **EU Emissions Trading System**
- And, subsequent **60% rise in the price** of emitting **CO_2** in the EU



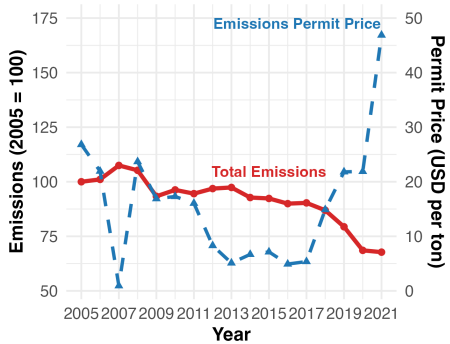
Begs the question(s): How did Firms Cut Carbon?

- What role did input substitution play?
- What role did changes in technology play?
- What role did re-allocation play?
  - Within industries
  - And, across industries.
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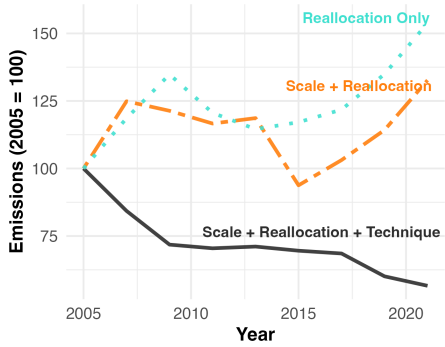
Begs the question(s): How Did Firms Cut Carbon?

- What role did input substitution play? **Within firm**
- What role did changes in technology play? **Within firm**
- What role did re-allocation play? **Across firm**
  - Within industries
  - And, across industries.
- *Crucial for understanding existing and proposed policies regarding pricing carbon.*



What we do in this paper

- **We investigate mechanisms** driving EU's emissions decline
- Develop **structural equilibrium model**
  - Provides microfoundation linking firm production decisions to aggregate effects of carbon pricing
  - Leverages firm-level data covering broad levels of emissions and production/input use
- **Counterfactuals**: quantify how changes in carbon price impacts emissions, output, inputs (e.g., labor)
  - Heterogeneity across industries?
  - How does clean technical change mitigate compliance costs?



Overview of the Results

What Do We Find?

- **Low elasticity of substitution between emissions and other inputs**:
  - Heterogeneity across sectors; but all **below 0.1**.
- **Sizeable role for clean technology**:
  - Cumulative growth in clean technology close to 50% over our time period.
- **Scope for reallocation both within and across sectors**:
  - Heterogeneous emissions cost shares + elastic demand lead to higher industry level elasticities; (e.g., Petroleum as high as 3)
- **Carbon price increase counterfactuals**:
  - Holding technology fixed; leaves limited scope for technique
  - Most emissions reductions come reallocation

Disclaimers

Key assumptions/weaknesses of our approach (thus far)

- **Assume technology–including "clean technology"–is exogenous**
- **Assume price taking behavior in input markets**
- **Limited role for dynamic effects (including entry/exit)**
- **Other relevant issues**
  - Data limitations create possible emissions leakage
  - Partial equilibrium approach to the labor market
  - Symmetric elasticity of substitution between emissions/other inputs

A Model of Firm Emissions

Model of Firm Production and Abatement

- **Firms choose:**
  - Composite input X (capital + labor + materials)
  - Abatement effort θ
- **Parameters:**
  - A: Total factor productivity
  - B: Clean technology
  - $\psi(\theta; B)$: Abatement function (emissions per unit input)
    - Monotonically decreasing in θ; more effort reduces emissions
    - Lower with higher B; cleaner technology lowers emissions at any θ
- **Outcomes:**
  - Output: $Y = (1 - \theta)AX$
  - Emissions: $E = \psi(\theta; B)AX$

Recast: CES Production Function with Emissions as Input

- We can invert abatement to embed emissions directly:

$$Y = A\left[\alpha_x X^{\frac{\sigma-1}{\sigma}} + \alpha_e (BE)^{\frac{\sigma-1}{\sigma}}\right]^{\frac{\sigma}{\sigma-1}}$$

Key Parameters:

- σ: **elasticity of substitution** between inputs and emissions
  - High σ: firms can abate by substituting toward other inputs
  - Low σ: limited scope for input substitution to reduce emissions
- B: **clean technical change:** emissions-biased productivity
  - High B: firms can produce more output per unit of emissions

Examples of Increase in B: Clean Technology

- Higher $B \Rightarrow$ more output per unit of emissions $\Rightarrow$ "cleaner" production
- **Example 1: Electric utility retires coal plant, builds solar farm**
  - Can produce same electricity output, holding other inputs fixed
  - Emissions fall $\Rightarrow$ higher B
- **Example 2: Steel firm switches to electric arc furnace**
  - Still uses same amount materials and labor and maintains output
  - New furnace cuts CO_2 per ton of steel $\Rightarrow$ higher B

Demand and Reallocation

- We assume there is a representative consumer with (two nests) CES preferences:

$$Q = \left(\sum_{n \in N} D_n^{\frac{1}{v}} Q_n^{\frac{v-1}{v}} \right)^{\frac{v}{v-1}}, \quad Q_n = \left(\sum_{i \in I_n} D_{ni}^{\frac{1}{\varepsilon_n}} Q_{ni}^{\frac{\varepsilon_n - 1}{\varepsilon_n}} \right)^{\frac{\varepsilon_n}{\varepsilon_n - 1}} \tag{1}$$

- **Two forces drive reallocation** toward cleaner firms:
  - **Heterogeneity in emissions cost shares** χ_n**:** if firms differ in emissions intensity, carbon pricing changes their *relative* costs
  - **Demand elasticity** ε_n**:** determines how much customers shift consumption across firms given a change in relative prices
  - With both forces strong, dirty firms shrink, clean firms expand
  - v contributes to the degree of across industry reallocation ▸ Estimation

- Model implies an **industry-level elasticity of substitution**
  - $=$ firm-level elasticity + reallocation of emissions across firms (Oberfield and Raval, 2021)

▸ Aggregate Elasticity

▸ Estimating Demand and Heterogeneity Index

Data

Data

- **Firm-level financial data** (BvD's Orbis):
  - Revenues, labor costs, employees, materials costs, capital assets
- **Firm-level emissions data** (EUETS.INFO):
  - Aggregated from installation-level emissions
- **Firm identifier crosswalk** (EU Joint Resource Centre):
  - Successfully match over 50% of EU ETS emissions to Orbis firms
- **Carbon price data** (Resources for the Future - RFF):
  - Annual average EU ETS permit prices
- **Sample coverage:** 2005–2021

Estimation

Estimation: Substitution Elasticities and Clean Technology

- Estimate model by NACE 2-digit sector

- Firms' FOC imply the following estimating equation :

$$\underbrace{\log\left(\frac{E_{it}}{X_{it}}\right)}_{\text{Emissions-to-input ratio}} = \beta_n \underbrace{\log\left(\frac{p_t^E}{p_{it}^X}\right)}_{\text{Emissions-to-input price ratio}} + h_n(t) + \lambda_i + \epsilon_{it}$$

  - $-\beta_n = \sigma_n$: sector-specific elasticity of substitution
  - $h_n(t)$: industry-specific time trend (clean tech)
  - λ_i: firm-level fixed effects
  - Not subject to identification challenges surrounding total factor productivity/demand

▸ Identification Assumptions

▸ Composite Input Construction

Intuition for Estimating Equation

$$\log\left(\frac{E_{it}}{X_{it}}\right) = \underbrace{\beta_n}_{\substack{-\sigma_n: \\ \text{Elasticity of} \\ \text{Substitution}}} \log\left(\frac{p_t^E}{p_{it}^X}\right) + h_n(t) + \lambda_i + \epsilon_{it}$$

Perfect Complements

- $\sigma_n = 0, \beta_n = 0$
- Emissions/input ratio constant when prices change

Cobb-Douglas

- $\sigma_n = 1, \beta_n = -1$
- Emissions/input ratio moves one-for-one with price ratio

- Trend $h_n(t)$: captures average clean tech improvement (B—change in emissions intensity over time, controlling for prices)

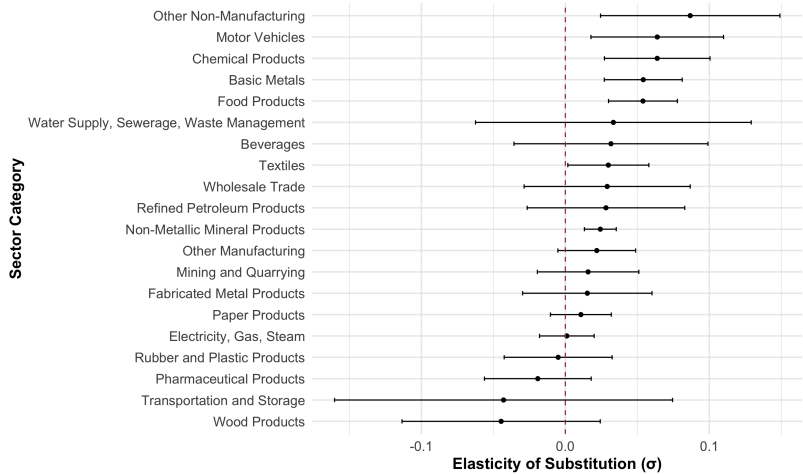
Results

Pooled Elasticity of Substitution Estimates

Dependent Variable:	Log(E/X)			
	(1)	(2)	(3)	(4)
Log(P_E/P_X)	-0.0261	-0.0395	-0.0573	-0.2699
	(0.0042)	(0.0047)	(0.0132)	(0.0263)
Elasticity of Substitution (σ)	0.026	0.039	0.057	0.270
Time trend	Log	Cubic	Log	Cubic
Model	OLS	OLS	IV	IV
Firm FE	Yes	Yes	Yes	Yes
Observations	38,841	38,841	38,841	38,841
R^2	0.91360	0.91403	0.91343	0.90715
Within R^2	0.01572	0.02062	0.01378	-0.05784

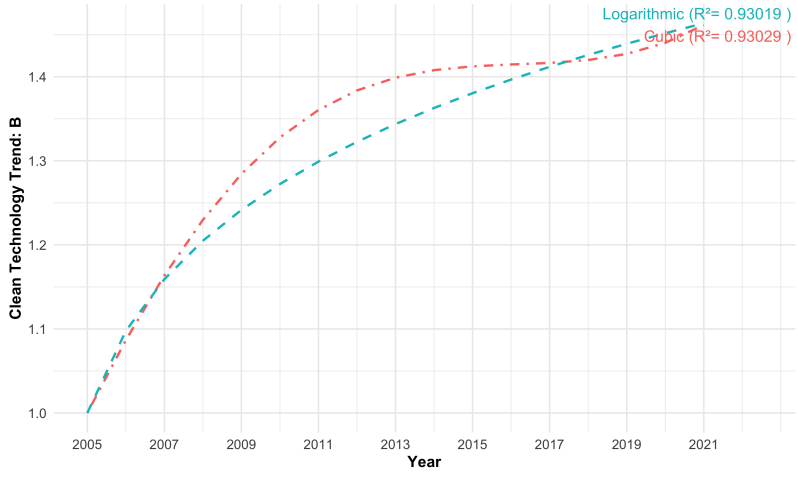
Notes: Firm FE included. Table reports OLS and IV estimates with log and cubic time trends. IV uses shocks Kanzig instruments for carbon prices.

Elasticity of Substitution: Emissions vs Composite Input



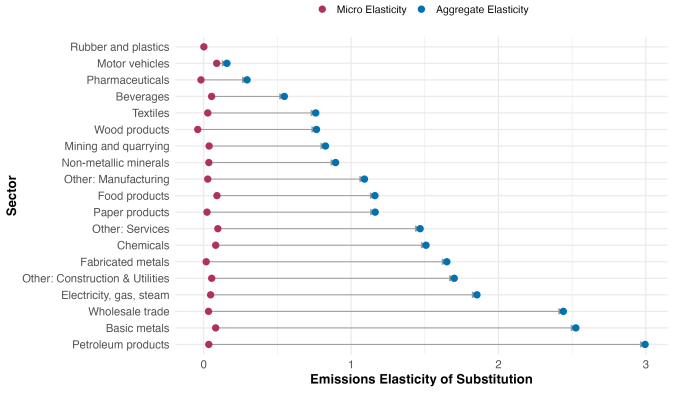
- All sectors exhibit low elasticity of substitution ($\sigma < 0.1$)
- Suggests limited abatement via input substitution

Avg. Clean Technical Change Trend



- +50% improvement in clean technology (B) ▸ By Sector Trends
- Rapid increase between 2005–2013, slower afterwards

Firm vs. Industry-Level Elasticity of Substitution



- At the industry level, most elasticities much higher than at firm level
  - Industry elasticity = firm-level substitution + output reallocation
- High values in petroleum and basic metals:
  - High emissions heterogeneity & elastic demand $\Rightarrow$ reallocation

▸ Industry Demand Elasticities ▸ Emissions Heterogeneity Index

Counterfactuals

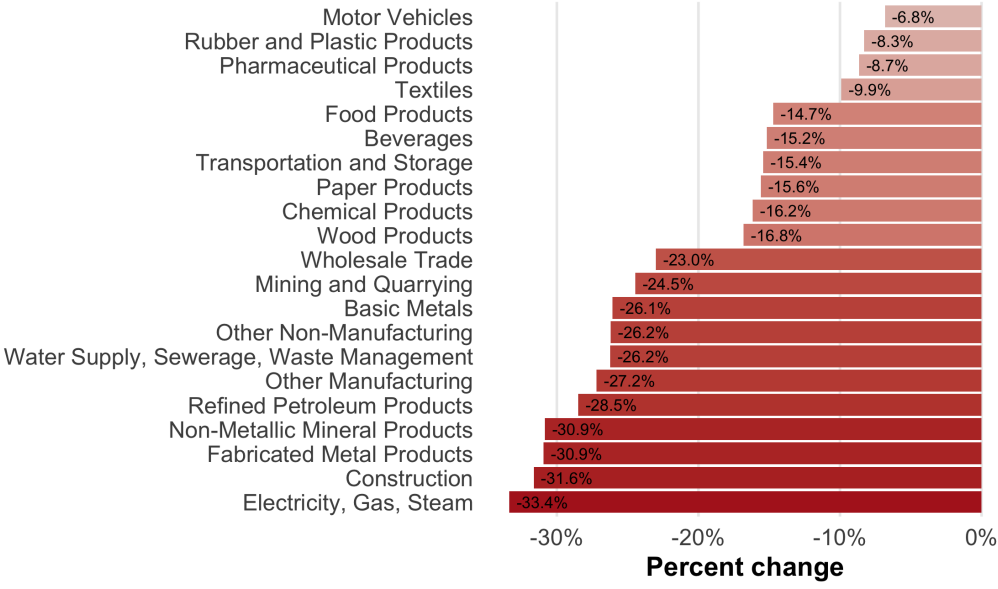
Counterfactual Simulations

- **We simulate three scenarios:**
  1. **Baseline:** Hold CO_2 prices and clean technology fixed at 2005 levels
  2. **CO_2 Price Increase, Fixed Technology:** Double carbon price in 2005 ($27 $\rightarrow$ $52), hold B fixed
  3. **Double CO_2 Price + Increase Clean Tech:** Apply both CO_2 price increase; and technology improvement (Raise B from 2005 to 2021 level)

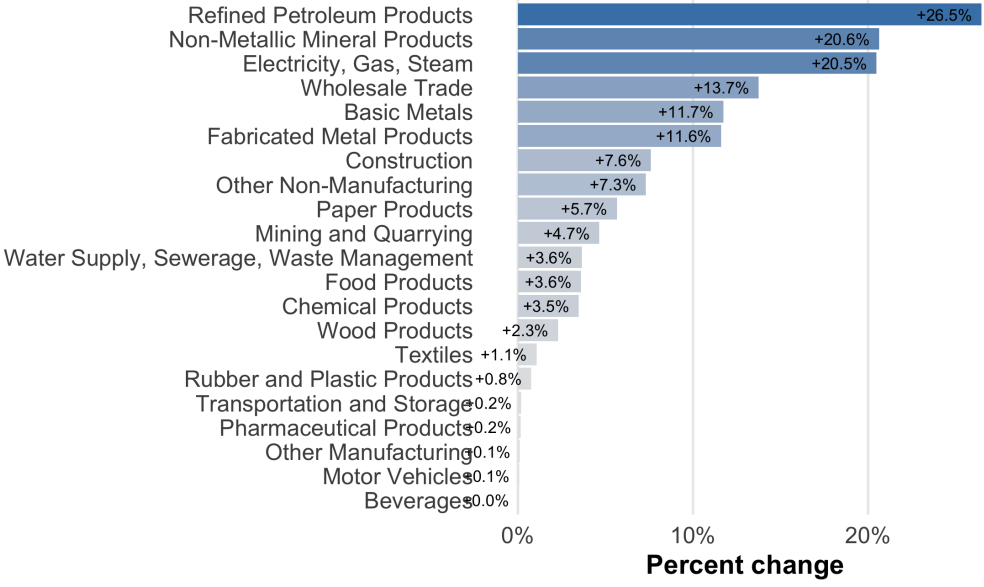
- Simulate equilibrium in emissions, output, and employment (composite input) across sectors

- Highlight scenario #2 and focus on breakdown across industries

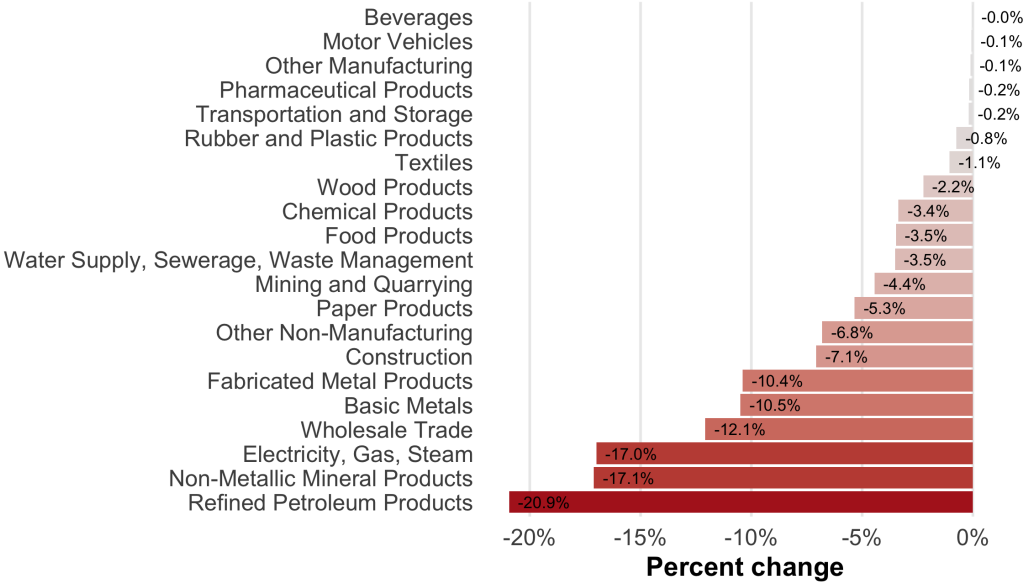
Impact of Doubling Carbon Price by Sector: Emissions



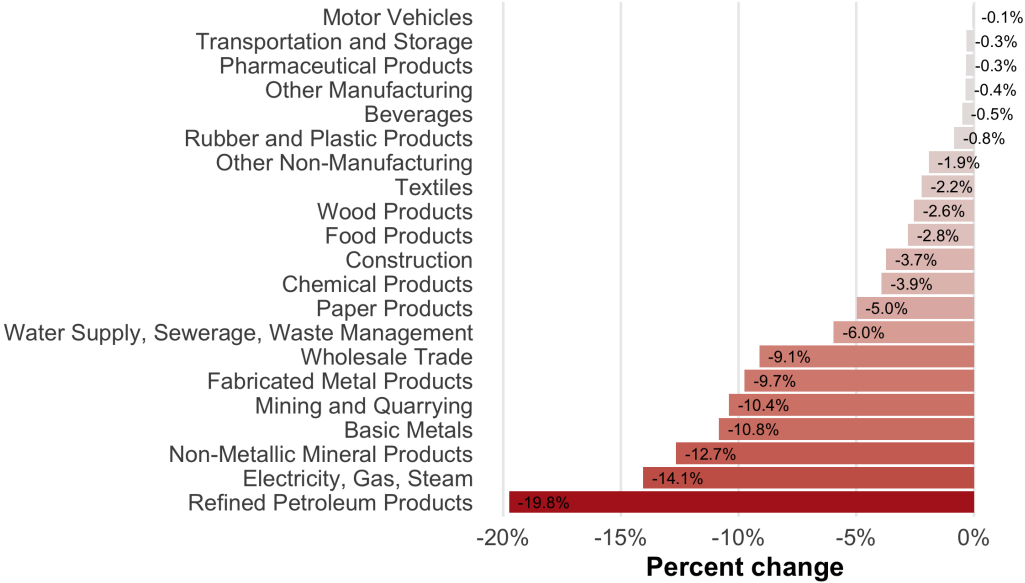
Impact of Doubling Carbon Price by Sector: Output Price



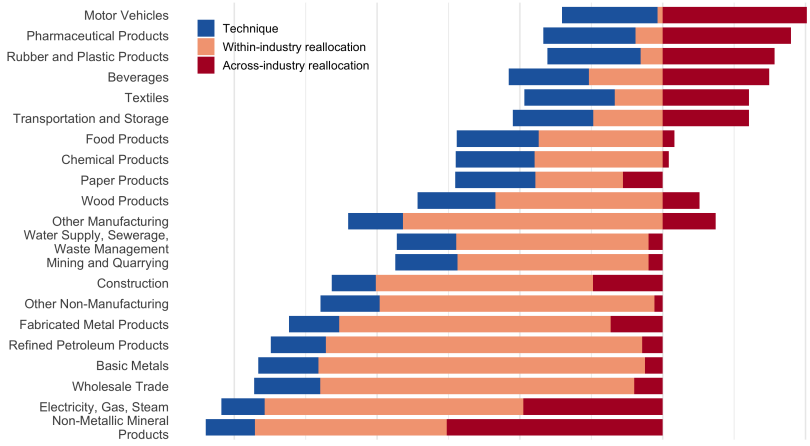
Impact of Doubling Carbon Price by Sector: Output



Impact of Doubling Carbon Price by Sector: Labor



Doubling Carbon Price: Emissions Decomposition



Conclusions

- We develop a new **model of production under CO_2 pricing**
  - Captures: input substitution, clean technology, and reallocation
  - Can be estimated using standard financial and emissions data

- Model estimates show:
  - **Low substitution elasticities** - firms can't abate via input mix
  - **50%+** factor-biased **clean tech improvement** since 2005
  - **Reallocation effects** matter where emissions intensity varies and demand is elastic

- Counterfactuals imply:
  - **Carbon pricing cuts emissions** but also output and inputs (labor)
  - **Clean tech mitigates these costs**, though firms likely bear higher fixed costs

Appendix: Identification Strategy

- **Intuition:**
  - If emissions cost share rises 1-for-1 with permit prices $\Rightarrow \sigma \sim 0$
    - Firms are not adjusting input mix to abate
  - If emissions cost share stays flat while permit prices rise $\Rightarrow \sigma \sim 1$
    - Firms use more composite inputs to substitute away from emitting
  - Time trend $h_n(t)$ captures clean technical change:
    - If cost share falls over time (holding prices fixed), clean tech must be improving

- **Key Identification Assumption:** Emissions (permit prices) and other input prices are uncorrelated with error term

- **Outline of Key Concerns:** ▸ See here

- ▸ Back to Estimating Equation

Appendix: Addressing Identification Concerns

- **Concern:** Permit prices rise over time with clean tech
  - *Solution:* Include flexible sector-specific time trends
- **Concern:** Permit prices move with energy prices
  - *Solution:* Instrument with regulatory shocks (Kanzig 2023)
- **Concern:** Multinational firms shift emissions out of EU
  - *Solution:* Restrict to EU-focused firms; interpret estimate as upper bound
- ▸ Back to Estimating Equation
- ▸ Back to Identification Strategy

Appendix: Constructing the Composite Input

- Composite input X is CES over capital K and labor L:

$$X_{it} = \left[\alpha_k K_{it}^{\frac{\xi-1}{\xi}} + \alpha_l (H_{it} L_{it})^{\frac{\xi-1}{\xi}} \right]^{\frac{\xi}{\xi-1}}$$

- Estimate ξ_n using variation in wages and capital-labor ratios
- ▸ Back to Estimating Equation

Appendix: Composite Price Index and Composite Quantities

- Composite input price index:

$$P_{it}^{X} = \left[(1-\delta_L)^{\xi} (P_{it}^{K})^{1-\xi} + \delta_L^{\xi} (P_{it}^{L})^{1-\xi} \right]^{\frac{1}{1-\xi}}$$

- Labor share:

$$\delta_L = \frac{P_{i0}^{L} L_{i0}}{P_{i0}^{K} K_{i0} + P_{i0}^{L} L_{i0}}$$

- Composite input level:

$$X_{it} = \frac{P_{it}^{K} K_{it} + P_{it}^{L} L_{it}}{P_{it}^{X}}$$

- ▸ Back to Estimating Equation

Appendix: Aggregate Elasticity of Substitution

- Industry-level emissions response includes reallocation across firms
- **Aggregate elasticity:** $\bar{\sigma} = (1 - \chi)\sigma + \chi\varepsilon$
  - σ: firm-level substitution elasticity (from production)
  - ε: elasticity of demand (from price sensitivity)
  - χ: heterogeneity index, increases with dispersion in emissions cost shares
- When χ and ε are high, carbon prices shift output toward cleaner firms

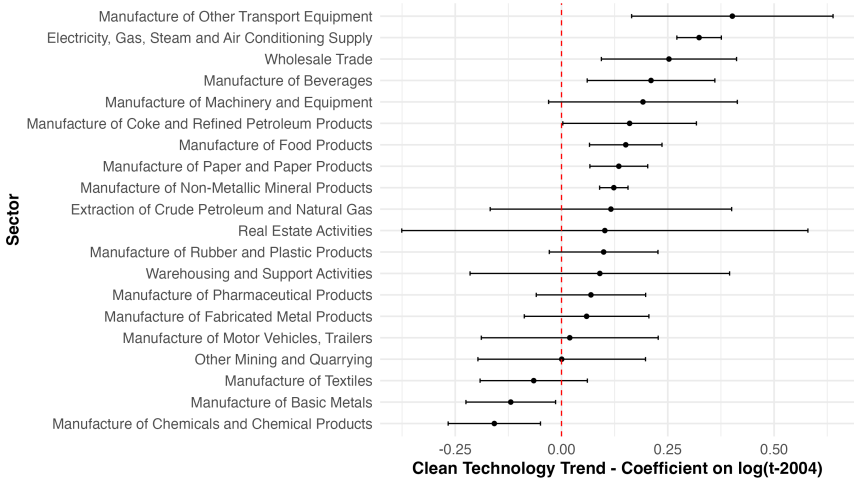
▸ Back to Demand and Reallocation

Appendix: Estimating Demand and Heterogeneity

- **Demand elasticity ε:** estimated from revenue and cost data under monopolistic competition
  - $\mu_i = \frac{P_i}{MC_i} = \frac{\varepsilon}{\varepsilon - 1} \Rightarrow$ back out ε from markup
  - Estimate markup as $\mu_i = \frac{R_i}{TC_i}$ under constant returns to scale
- **Heterogeneity index χ:** reflects dispersion in emissions cost shares
  - Computed as variance-weighted ratio of emissions cost shares across firms
  - High χ indicates large reallocation potential

▸ Back to Demand and Reallocation

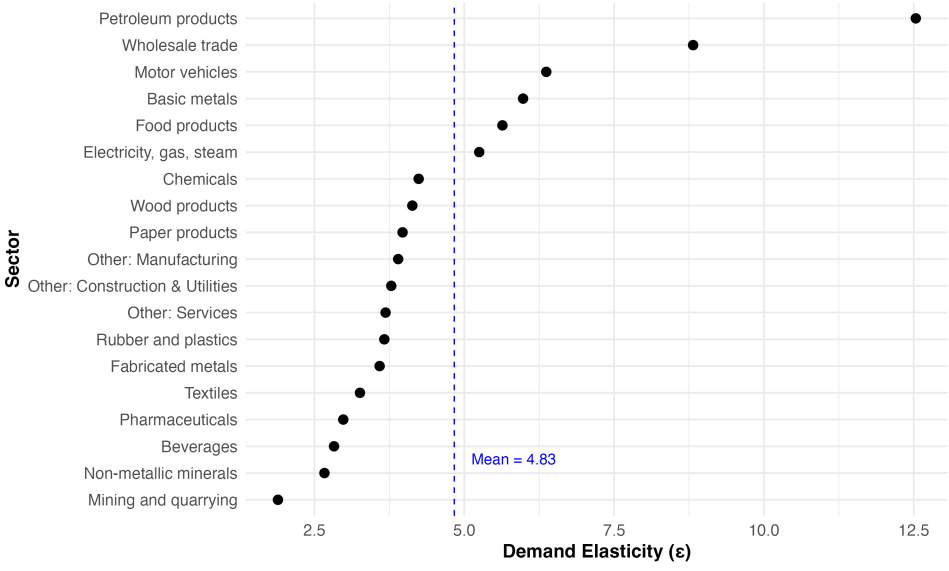
Appendix: Clean Technical Change Log Trend by Sector



- Electric/Gas utilities experienced large increase in B (renewables, etc.)

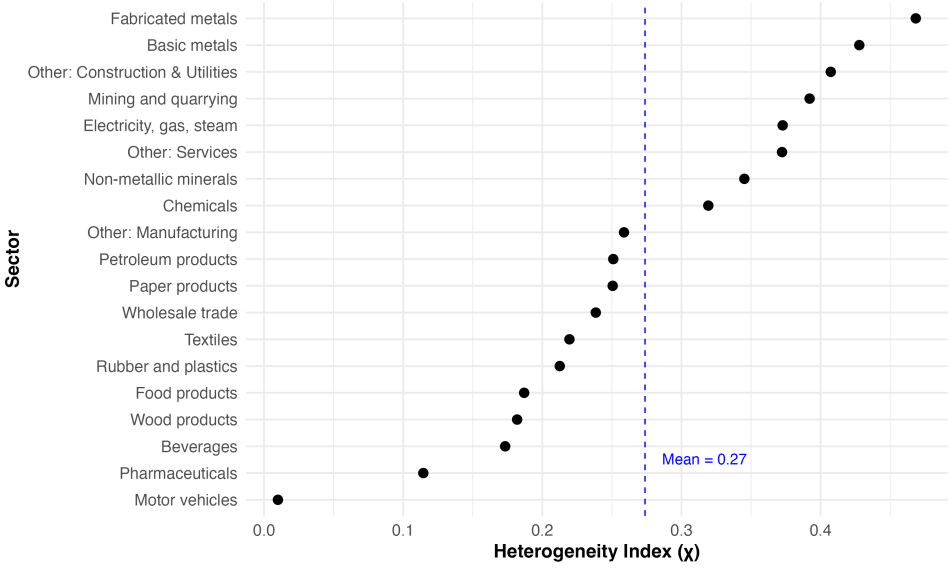
▸ Back to Aggregate Trend

Appendix: Industry Demand Elasticities



Back to Results

Appendix: Emissions Heterogeneity Index



Back to Results

Cross-Industry Elasticity

	Log(Q)			
	(1)	(2)	(3)	(4)
Log(P)	-0.4130	-0.4276	-2.764	-3.221
	(0.3452)	(0.3731)	(0.5788)	(0.4483)
Model	OLS	OLS	IV	IV
NACE Section by Year Trends	No	Yes	No	Yes
Observations	266	266	266	266
NACE 2-Digit fixed effects	Yes	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes	Yes

IV specifications use a sector's average product of labor as an instrument for price.

▸ Back to Demand and Reallocation