Delaying the Coal Twilight:
Local Mines, Regulators, and the Energy Transition

14th Toulouse Conference on the Economics of Energy and Climate

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CEMFI

June 7th, 2024

Outline

1. Introduction
2. Descriptive Evidence
3. Model
4. Estimation
5. Counterfactuals
6. Conclusion

Coal in the US

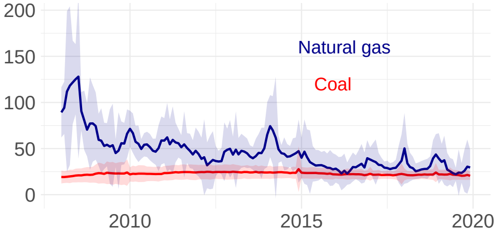

Figure 1: Unit cost ($/MWh)

- In the last decade, coal **alternatives became more affordable**.
- In the same period, coal plant owners (utilities) invested **$29 billion** in upgrades.

Why?

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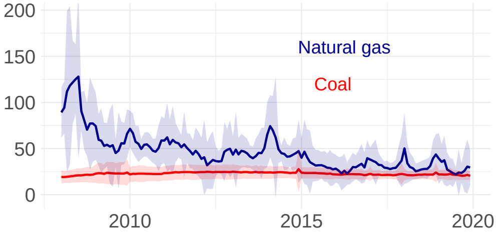

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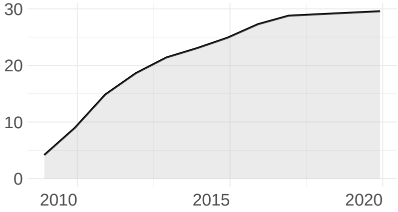

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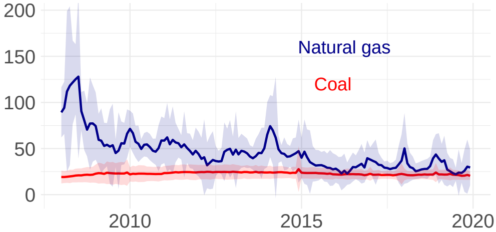

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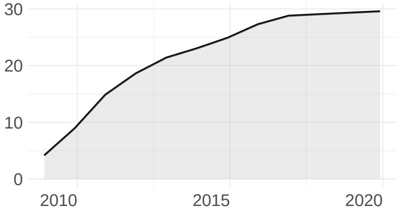

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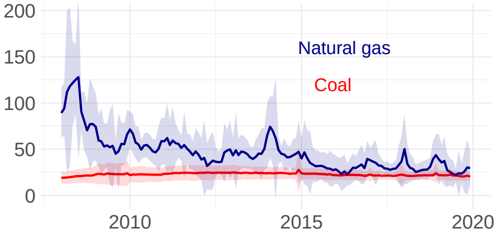

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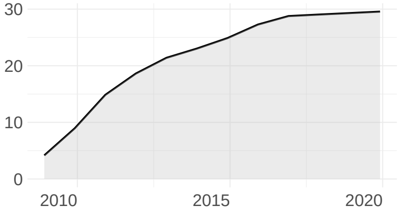

Figure 2: Upgrade investment, cumulative ($Bn)

This Paper

Studies the drivers of upgrade and closure decisions on US coal power plants in the 2008-2019 period.

The Setup

1. Coal **mining** is a major sector in some US states. +
    - Most mines extract **high-sulfur** coal.
    - Wyoming extracts **low-sulfur** coal.
2. Coal power plant **owners** (utilities).
    - By 2016 had to invest in **sulfur filters**, or **close**. MATS
    - Two filter types: standard and expensive Cost
        - Standard filters require low-sulfur coal.
        - Expensive filters are compatible with local coal.
3. State electricity **regulators**. +
    - Set the electricity price that plant owners charge.
    - **Influence** filter investment through the regulated price.

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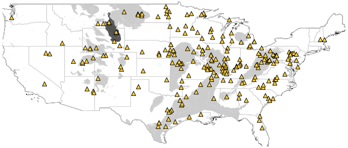

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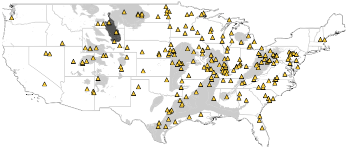

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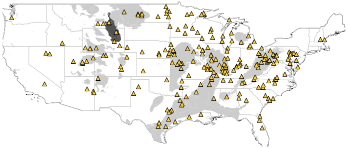

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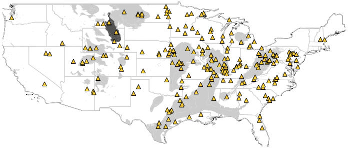

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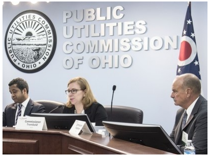

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The Setup

OG&E power plant upgrades could raise rates 15-20%

Published June 12, 2014

Figure 3: Oklahoma, 2014

State regulators approve $430M upgrade to coal plant in Cohasset

Minnesota Power's Cohasset unit will be retrofitted to sharply reduce mercury emissions. Customers can expect a rate increase.

Figure 4: Minnesota, 2012

NEWS

PSC gives OK to millions of dollars in upgrades to keep coal-fired power plants open

Figure 5: West Virginia, 2011

New Hampshire utility defends Merrimack scrubber project

August 14, 2014 Barry Cassell Generation

The executive director of the New Hampshire Public Utilities Commission on Aug. 12 issued a schedule covering the next few weeks of activity in a long-running case at the commission

Figure 6: New Hampshire, 2014

→ **The regulator tradeoff**: Expensive filters increase prices but may help the state mining sector.

Descriptive Exercise

Test whether state regulators promoted expensive filter investment to protect local mines.

My specification exploits two sources of variation:

1. Whether the plant charges a regulated price.
   → Non-regulated plants do not charge a regulated price.
2. Whether the regulator is from a mining state.

→ Regulated plants in mining states are more likely to install expensive filters.

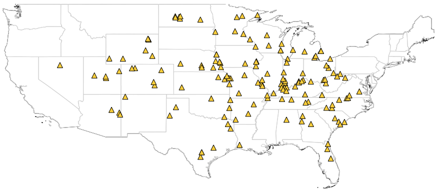

Figure 7: US coal plants, regulated 2008

Literature Liberalization ISO map Data Sources Balance Table Suggestive Evidence

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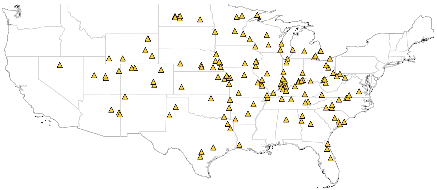

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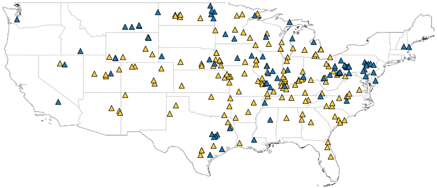

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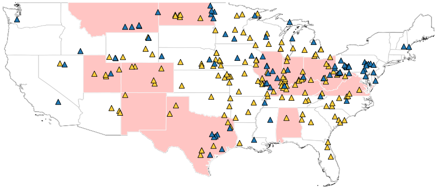

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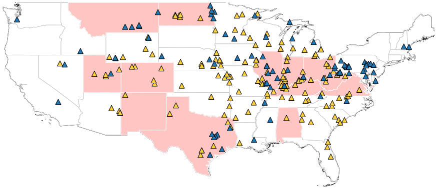

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- Multinomial logit with **four** outcomes $j \in \{\text{ Standard},\ \text{Expensive},\ \text{Close}\}$, $J = \text{No Filter}$

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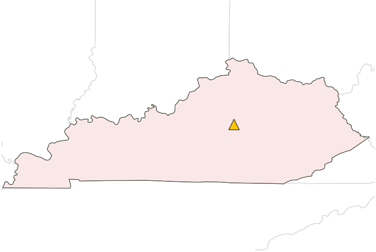

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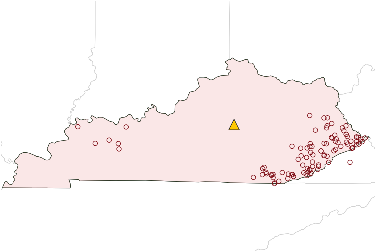

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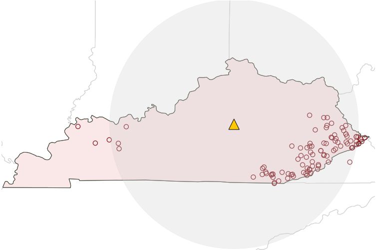

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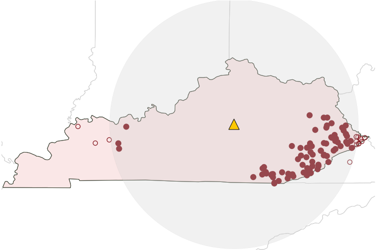

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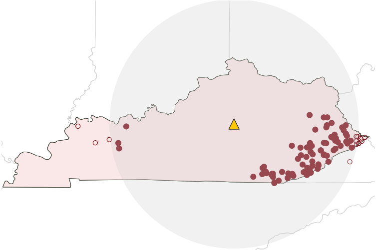

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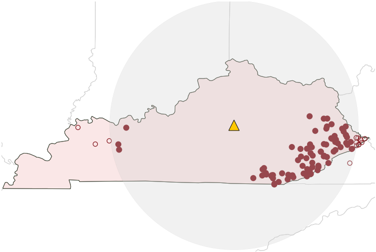

Results

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	Dependent variable		
	j = retire	j = standard	j = expensive
Regulated	0.243	1.034^{*}	1.122^{***}
	(0.349)	(0.590)	(0.372)
Mine Size (Million Ton, 2008)	0.024	0.008	-0.004
	(0.017)	(0.027)	(0.020)
Regulated x Mine Size	0.044	0.005	0.075^{**}
	(0.030)	(0.045)	(0.033)
		McFadden R2	0.218
		N	707

→ +1 million Ton in mining sector increases expensive filter adoption relative probability by 7.7%.

Mine State Indicator Mine Share Miners

Why Do I Need a Model?

So far...

Regulated plants from mining states are **more likely** to invest in expensive filters.

1. Establish a **link** between filter investment and plant retirement decisions.
2. **Quantify** the importance of the local mine protection mechanism.
3. Perform **counterfactual** exercises.

Closure Specification

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Closure Specification

Model Summary

- Dynamic model, infinite horizon. Two state variables:
  - Cost of natural gas, falling over time.
  - Countdown to 2016, filter becomes compulsory.
- Discrete-choice model
  - Remain open or retire.
  - Standard filter or expensive.
- Principal-agent model
  - The regulator (principal) cares about welfare and state mining revenue.
  - The coal plant owner (agent) is a profit maximizer.
- Estimation:
  - As in Rust 1987.

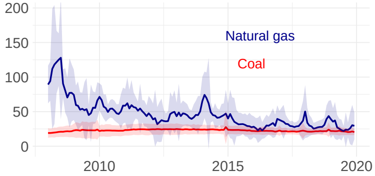

Figure 8: Unit cost ($/MWh)

Model Summary

- Dynamic model, infinite horizon. Two state variables:
  - Cost of natural gas, falling over time.
  - Countdown to 2016, filter becomes compulsory.
- Discrete-choice model
  - Remain open or retire.
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Figure 8: Decomissioning

Figure 9: Filter

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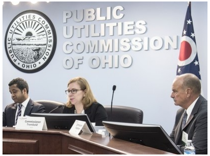

Figure 8: Regulator

OhioEdison®
A FirstEnergy Company

Figure 9: Plant-owner

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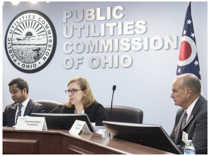

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Timing

The **regulator** offers a menu of **four** prices $p(\omega_t)$, depending on filter $\omega_t \in \{expensive, standard, none\}$.

$$p(expensive), \quad p(standard), \quad p(none)$$

The coal plant **owner** (agent): chooses a filter $\omega \in \{expensive, standard, none\}$ to maximize profits:

$$\pi(\omega_t) = q(\omega_t) \cdot (p(\omega_t) - \overline{c}(\omega_t)) - F_{\omega_t}$$

Regulator
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1. Cost of service regulation $\pi = 0$
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Mechanisms and Estimation Result

Regulator Utility Function

$$\textit{Welfare} \quad + \quad \alpha_1 \cdot \textit{Revenue}$$

- Parameter α_1 weights the importance of local mine revenue for the regulator.

	Standard Filter	Expensive filter
Low-sulfur Coal	↓ Fixed Cost → ↑ Welfare ↑ Unit Costs → ↓ Welfare ↓ Local mine Revenue	
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→ The average regulator from a mining state values mining revenue twice as much as welfare.

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- Exploit the **distance** *d* between the plant and Wyoming.

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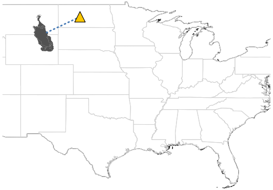

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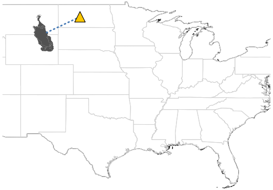

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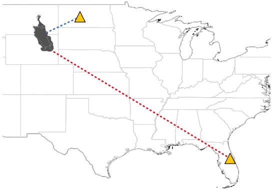

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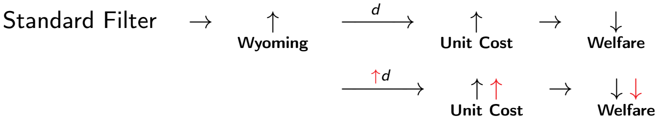

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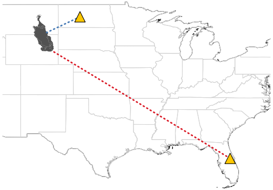

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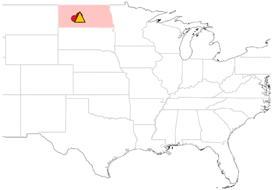

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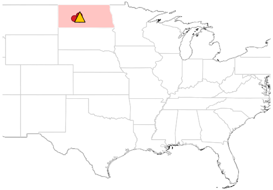

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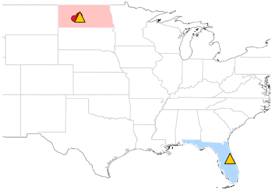

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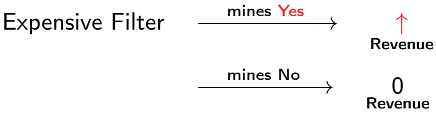

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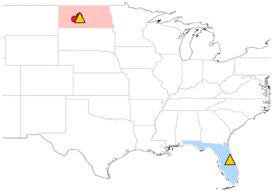

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Local Mine Protection

How many coal plants would have closed, absent local mine protection?

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$$\alpha_1 = 0$$

3. Results:
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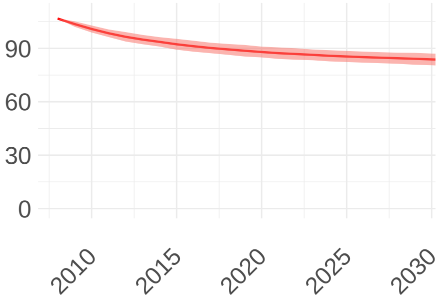

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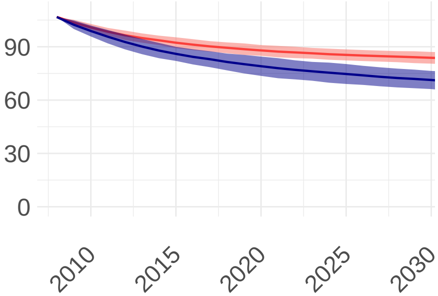

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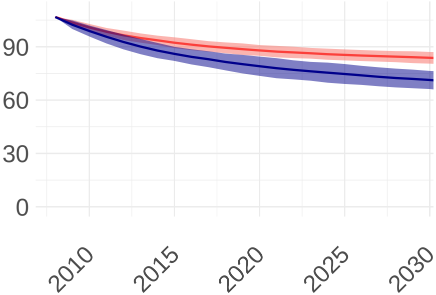

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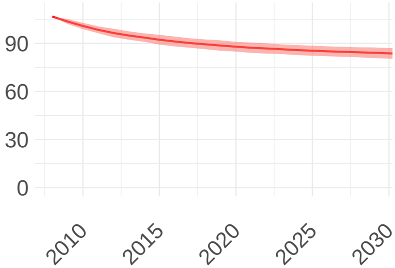

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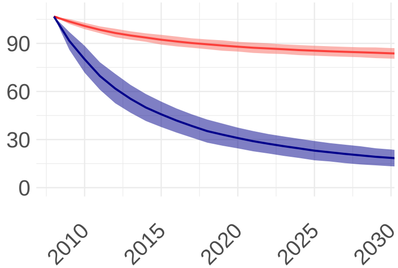

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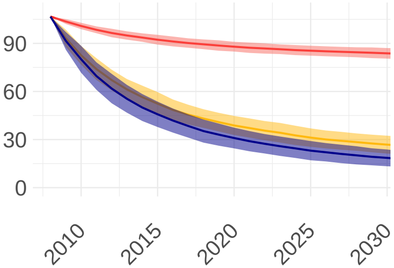

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Thank You!

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- Introduced in 2011, enforced since 2016.
- Establishes sulfur emission threshold S per output unit.

$$\underbrace{\bar{s} \cdot (1 - \omega)}_{\textbf{Sulfur Emissions}} \quad \leq \quad S$$

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Coal Mining in the US

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- Plant owners purchase coal from two sources, which determine $\bar{s}$.
    1. Local coal, with high sulfur concentration and little transport cost: $\uparrow \bar{s}$.
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→ **Tradeoff** between low-sulfur Wyoming coal and transportation cost.

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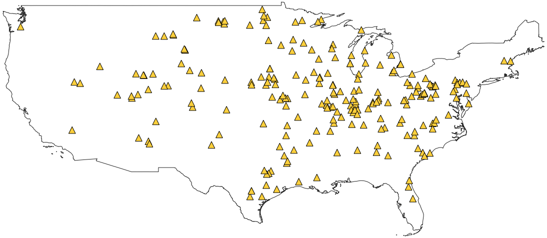

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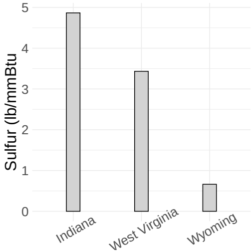

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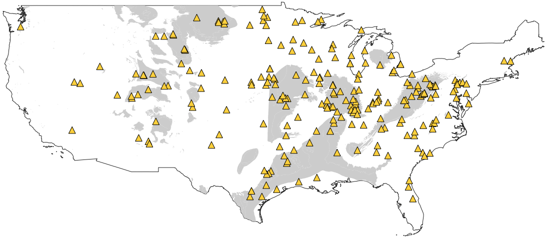

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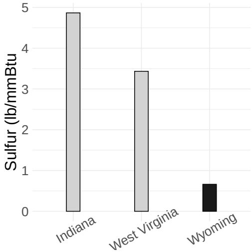

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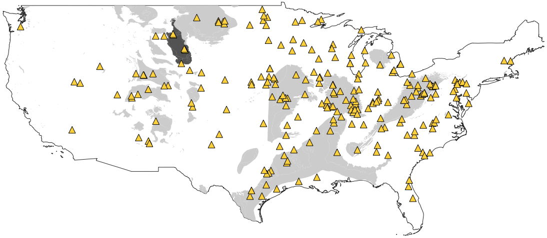

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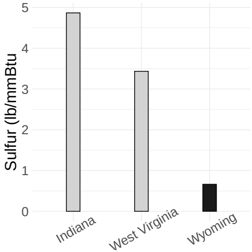

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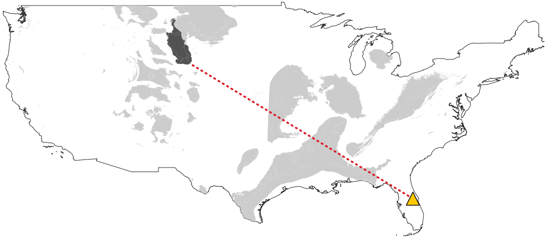

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Coal Blend and Filter Efficiency

$$\bar{s} \cdot (1 - \omega) \quad \leq \quad S$$

- Standard filters $\omega = l$ require low-sulfur Wyoming coal $\downarrow \bar{s}$. WY - Appalachia WY - South
- Expensive filters $\omega = h > l$ are compatible with a higher share of local coal $\uparrow \bar{s}$.

→ **Tradeoff** between filter fixed cost and local coal. Filter Cost

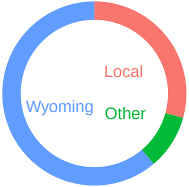

Figure 13: Coal blend - Standard filters

Coal Blend and Filter Efficiency

$$\bar{s} \cdot (1 - \omega) \quad \leq \quad S$$

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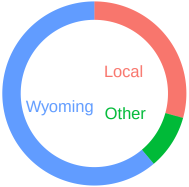

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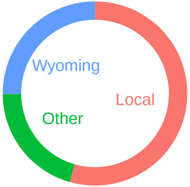

Figure 14: Coal blend - Expensive Filters

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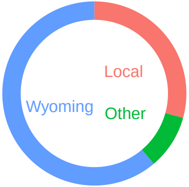

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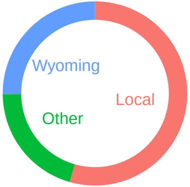

Figure 14: Coal blend - Expensive Filters

Model Agents

Principal-agent model: the regulator indirectly chooses the filter through the regulated price.

The electricity **regulator** (principal): offers a menu of electricity prices $p(\omega)$, depending on filter ω.

- The regulator utility function values welfare $W(p)$ and mine revenue $R(\omega)$.

$$U = W(p) + \alpha_1 \cdot R(\omega)$$

→ α_1 weights the mine revenue.

The coal plant **owner** (agent): chooses a filter $\omega \in \{h, l\}$, pays fixed cost F_ω.

$$\pi = q \cdot (p(\omega) - \overline{c}) - F_\omega$$

- More efficient filters are more expensive $F_h > F_l$.

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$$\underset{\textbf{Filter}}{\uparrow \omega} \rightarrow \begin{cases} \underset{\textbf{Fixed Cost}}{\uparrow F_\omega} \rightarrow \underset{\textbf{Price}}{\uparrow p(\omega)} \rightarrow \underset{\textbf{Welfare}}{\downarrow W(p)} \\ \underset{\textbf{Local Coal}}{\uparrow \rho} \rightarrow \underset{\textbf{Unit Cost}}{\downarrow \overline{c}} \rightarrow \underset{\textbf{Price}}{\downarrow p(\omega)} \rightarrow \underset{\textbf{Welfare}}{\uparrow W(p)} \end{cases}$$

→ Main tradeoff in **no-mining states**.

- Expensive filters always **increase** local-mine revenue.

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→ Additional force for expensive filters, **in mining states**. Scatter

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Coal Plant Dispatch

- Electricity supply.
  1. **Coal power plant** with unit capacity constraint (1MW) supplies at price p.
  2. Competitive fringe of **natural gas plants** sell at price $p^{gas} \sim \phi(p^{gas}|\mu)$
     - → μ is the **centering parameter** of the natural gas price distribution.
- Electricity demand.
  - Demand is inelastic $Q \geq 1$
  - Consumers only buy from coal plant when $p \leq p^{gas}$.
  - Coal plant expected output is

$$q = Pr(p \leq p^{gas}) = 1 - \Phi(p|\mu)$$

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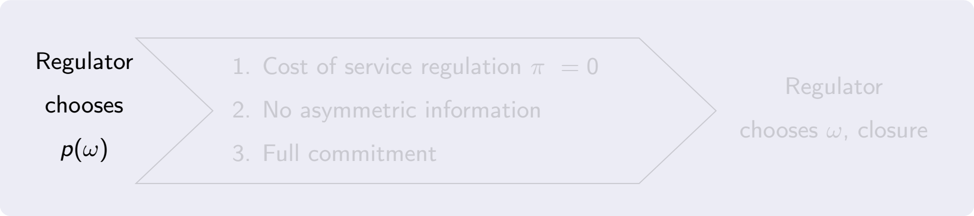
The Regulator Problem



Regulator chooses $p(\omega)$

1. Cost of service regulation $\pi = 0$
2. No asymmetric information
3. Full commitment

Regulator chooses ω, closure

1. For plant without filter: $\max\left\{\max_{\omega\in\{h,l,0\}}\{W(\omega)+\alpha_1\cdot R(\omega)\},\quad \Gamma_0\right\}$ Four choices.
    - Γ_0 is the payoff of closing the plant, net of owner compensation.
2. For plants with filter efficiency ω^*: $\max\{W(\omega^*)+\alpha_1\cdot R(\omega^*),\quad \Gamma\}$ Two choices
    - Γ is the payoff of closing, **after** installing a filter.
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Equilibrium Comparative Statics

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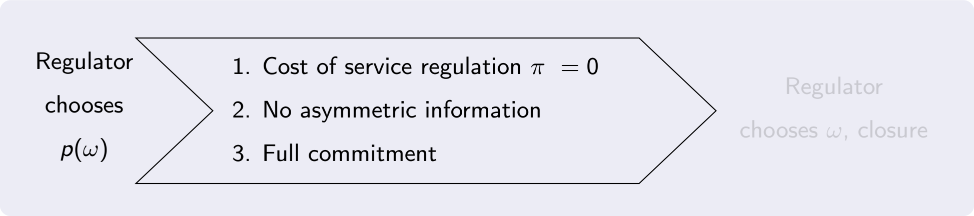

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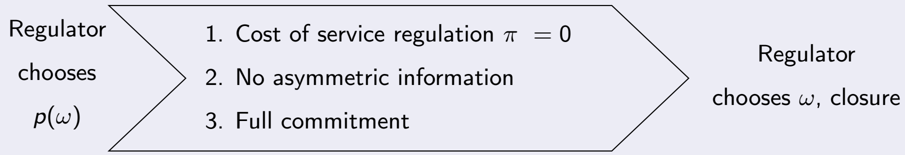

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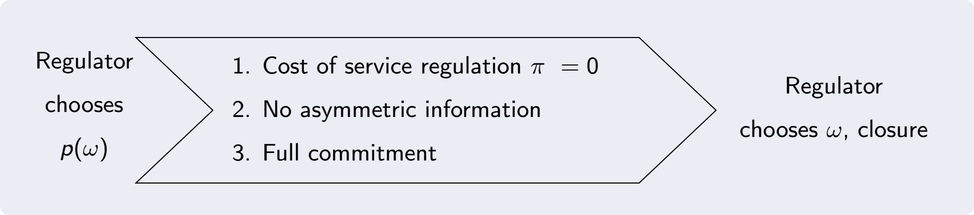

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Introducing Dynamics

- During 2008-2019, the price of natural gas $p^{gas} \sim \phi(p^{gas}|\mu)$ fell significantly.
  - Regulators made filter investment and closure decisions in a context of falling μ.
  - Allow for a dynamic μ_t, that changes every year t.
- The regulator problem becomes an **infinite-horizon dynamic discrete-choice model**:
  1. For plant with no filter yet, four-fold choice:

$$V\left(\omega_t = 0 \mid \mu_t\right) = \max\left\{\max_{\omega_{t+1} \in \{h,l,0\}} \left\{U\left(0 \mid \mu_t\right) + \beta E\left[V\left(\omega_{t+1} \mid \mu_{t+1}\right)\right]\right\}, \quad U\left(0 \mid \mu_t\right) + \beta \cdot \Gamma_0\right\}$$

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Estimation Overview

- Each generator i is characterized by a covariate vector χ_i, which includes age, size...
- Regulator utility becomes i-specific, includes EV-T1 shock ϵ_{it}^{EVT1} with scale parameter σ

$$U(\omega_{it}|\chi_i, \mu_{it}) = W(\omega_{it}|\chi_i, \mu_{it}) + \alpha_1 \cdot R(\mu_{it}|\chi_i, \mu_{it}) + \sigma \cdot \epsilon_{it}^{EVT1}$$

- The cost of standard and expensive filters becomes i-specific, parameterized on generator size.

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→ Six structural parameters to be estimated, remaining parameters β imputed.

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→ Six structural parameters to be estimated, remaining parameters β imputed.

Estimation Overview

- Each generator i is characterized by a covariate vector χ_i, which includes age, size...
- Regulator utility becomes i-specific, includes EV-T1 shock ϵ_{it}^{EVT1} with scale parameter σ

$$U(\omega_{it}|\chi_i, \mu_{it}) = W(\omega_{it}|\chi_i, \mu_{it}) + \alpha_1 \cdot R(\mu_{it}|\chi_i, \mu_{it}) + \sigma \cdot \epsilon_{it}^{EVT1}$$

- The cost of standard and expensive filters becomes i-specific, parameterized on generator size.

$$F_i^{\omega=h} = \beta_1 + \beta_2 \cdot Size_i + \epsilon_{it} \qquad F_i^{\omega=l} = \beta_3 + \beta_4 \cdot Size_i + \epsilon_{it}$$

  - ϕ unobserved cost parameter: plant adaptation, coal storage systems...
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Estimation Results

$$U = W + \alpha_1 \cdot R$$

Parameter	Note	Point-estimates	Standard Errors
α_1	Coal Revenue R_{it}	2.03^{**}	0.62
ϕ	Standard filter, Unobserved Cost	1581.64^{**}	304.66
γ_1	Closure - no filter	5698.67^{**}	645.85
γ_2	Closure - age	203.56^{**}	27.17
γ_3	Closure - size	9.72^{**}	2.58
σ	Scale Parameter	1392.04^{**}	172.22

→ The average regulator from a mining state values mining revenue twice as much as welfare.

Identification Intuition Algorithm Aggregate state Imputation Model Fit

US Coal Mining Sector

	US	West Virginia	Kentucky	Pennsylvania	Illinois	Wyoming
GDP	45.84	7.14	1.9	3.59	2.85	4.3
($Billion)	0.18%	7.46%	0.75%	0.39%	0.28%	9.02%
Labor income	21.98	3.35	0.95	2.24	1.12	1.14
($Billion)	0.22%	10%	0.93%	0.62%	0.27%	7.4
Employment	291,943	45,633	20,620	35,864	14,809	15,353
(#)	0.17%	6.05%	1.04%	0.57%	0.2%	5.46%

Table 1: The importance of coal mining in selected states, 2021

Back to introduction

Public Utilities Commission Election Method

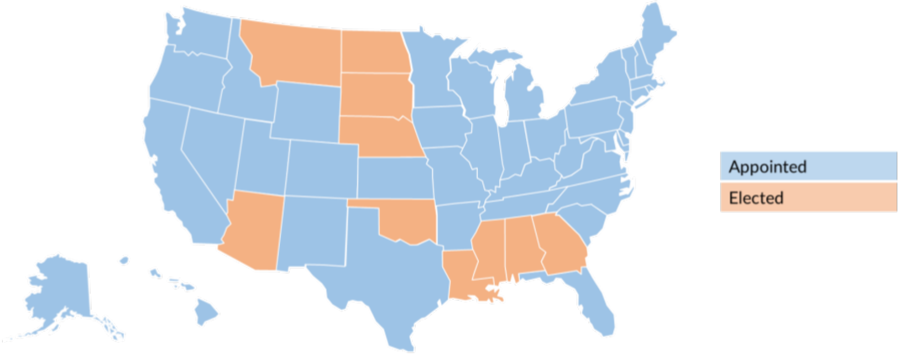

Figure 15: Electricity regulator election method

Back

Coal Electricity Production, Selected Countries

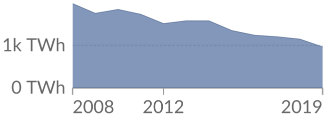

Figure 16: Coal electricity production, US

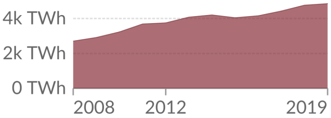

Figure 17: Coal electricity production, China

Back to introduction

CO2 Emissions Accounting

- Coal intensity is 900 gr CO2 / KWh.
- Natural Gas intensity is 450 gr CO2 / KWh.
- Absent local mine protection, the cal capacity is reduced in 10 GW
  - Assuming 50% capacity of coal power plants, these produced: 10 GW x 175 x 24 = 4.2 e4 GWh
- Emissions reduction: (900 - 4500) e6 gr CO2 / GWh x 4.2 e4 GWh = 18.9 e12 gr CO2.
- Emission reduction, relative terms
  - US CO2 emissions in 2023 were 5,000 million Ton Co2 → 0.4% of all US emissions
  - US mining state CO2 emissions in 2022 were 1,892 million Ton Co2 → 1.1%.
  - US electricity sector CO2 emissions in 2022 were 1,542 million Ton Co2 → 1.3%.
  - US mining state electricity sector CO2 emissions in 2022 were 675 million Ton Co2 → 2,96%.

Back to intro Back to counterfactuals

Filter Types in Detail

	Filter efficiency ω	Fixed Cost
Standard	$l = 95\%$	$F_l \approx 100M\$$
Expensive	$h = 99\%$	$F_h \approx 200M\$$

Back

MATS threshold and Coal Types

$$\bar{s} \cdot (1 - \omega) \quad \leq \quad S$$

- MATS threshold is $S = 0.2$ lbs/mm Btu
  - Equivalent to 1.5 SO2 lbs/MWh.
- S is **below** the lowest-sulfur coal $\bar{s}$...
- ...which forced the adoption of a filter ω.

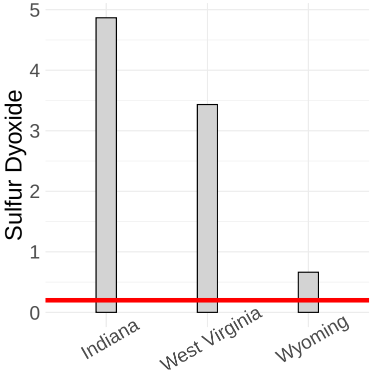

Figure 18: MATS threshold (lbs/MM Btu).

Back to MATS

Related Literature Back

1. **Coal plant upgrades and phase-out.** Gowrisankaran, Langer and Reguant (WP, 2023); Gowrisankaran, Langer and Zhang (WP, 2023); Fowlie (AER, 2010)
   - * Contribution: protection of local mines as a novel **obstacle** for the energy transition.
   - * Contribution: A theoretical and structural model on filter investment by **regulated** plants.
2. **Political economy of regulation.** Lim and Yurukoglu (JPE, 2018); Besley and Coate (JEEA, 2003)
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The (Patchy) Liberalization of the US Electricity Sector

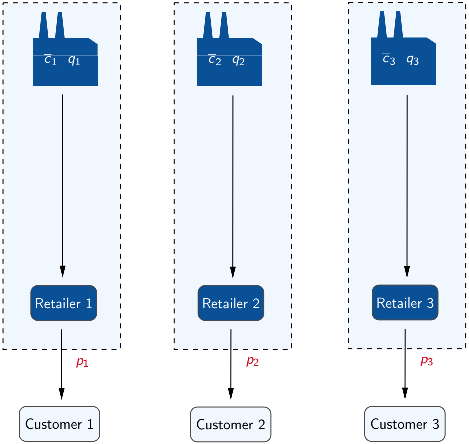
Back

- Vertical integration. $\pi_1 = q_1 \cdot (p_1 - \bar{c}_1) - F_\omega$
- Liberalization
  1. **Wholesale market** that sets p^{mkt}, q_2, q_3.
  2. Plant **divestures** → Plant 3 turns non-regulated.
- Regulated plant profits still depend on p_1.

$$\pi_2 = \underbrace{q_2 \cdot (p_2 - \bar{c}_2)}_{\text{Regulated Plant}} + \underbrace{(Q - q_2) \cdot (p_2 - p^{mkt})}_{\text{Import}} - F_\omega$$

- Non-regulated plant profits **do not** depend on p_3.

$$\pi_3 = q_3 \cdot (p^{mkt} - \bar{c}_3) - F_\omega \quad \perp \quad p_3$$



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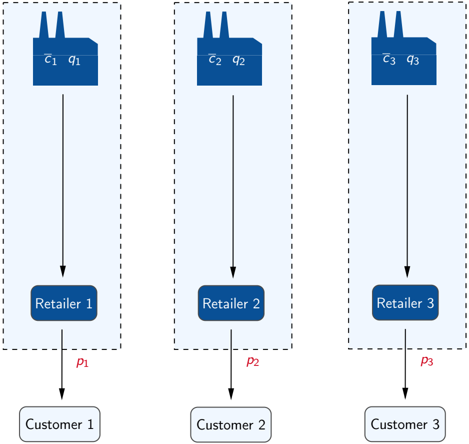

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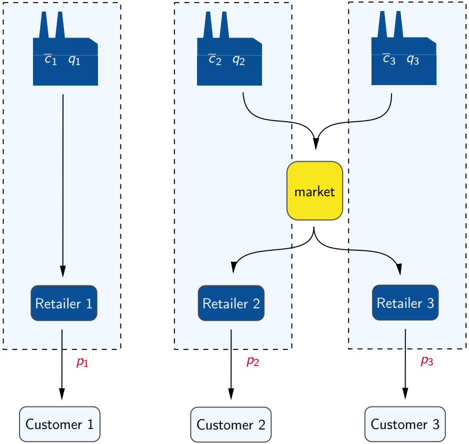

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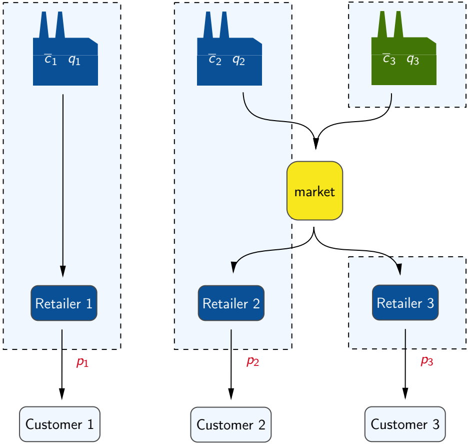

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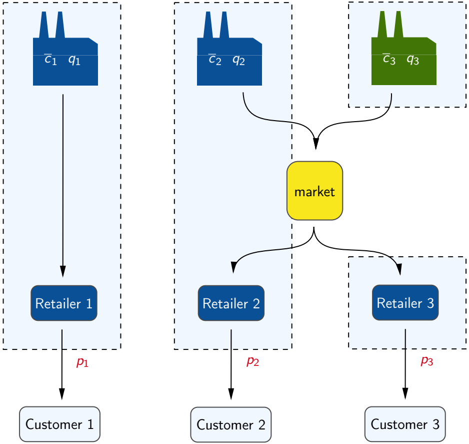

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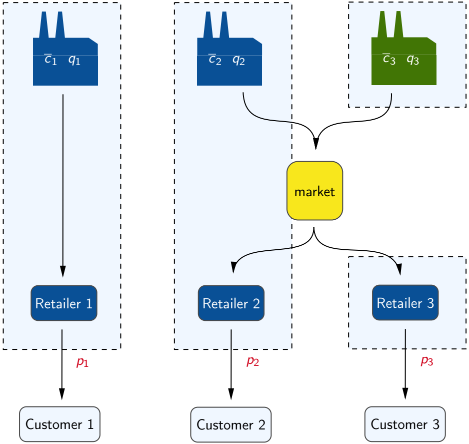

US Wholesale Electricity Markets

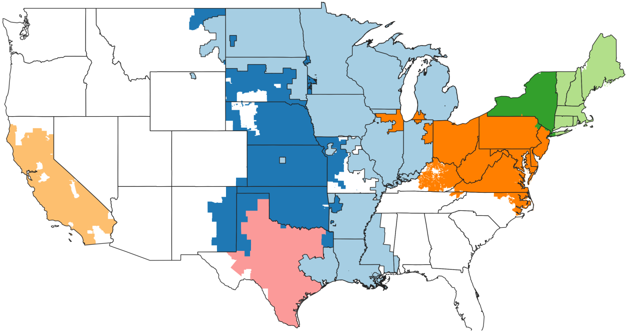

Figure 19: Wholesale electricity markets

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Wyoming Coal Destinations - Appalachia

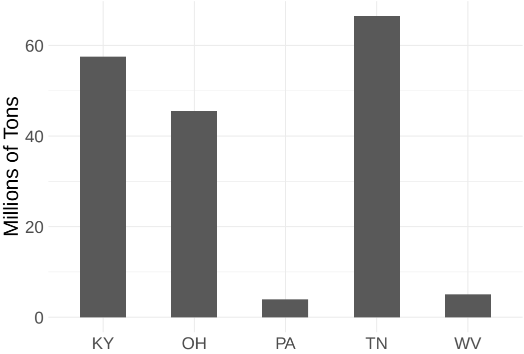

Figure 20: Wyoming Coal bought by Appalachian states 2008-2019

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Wyoming Coal Destinations - South

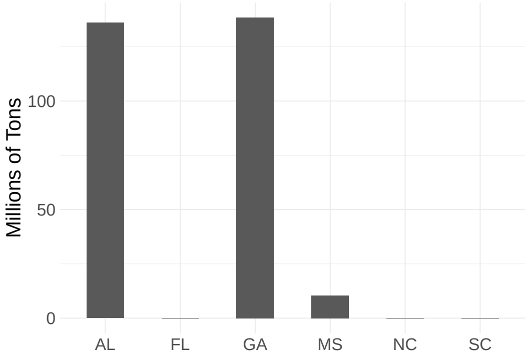

Figure 21: Wyoming Coal bought by Southern states 2008-2019

Back

Data

Back

1. Panel of the universe of coal generators i.
   - Filter efficiency at each year.
   - Annual electricity output.
   - Covariates: size, age, productivity etc.
2. Panel of the universe of coal mines.
   - Mine location.
   - Sulfur concentration.
3. Mine-plant transactions.
   - Transaction payment.
4. Natural gas cost.

Plants and Generators

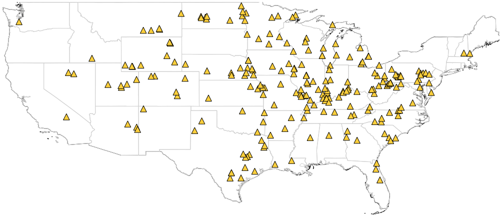

Figure 22: US coal plants, 2008

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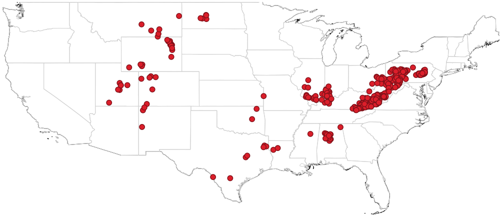

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Plants and Generators

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Plants and Generators

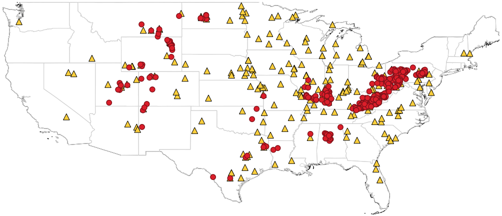

Figure 22: US coal plants and mines, 2008

Data

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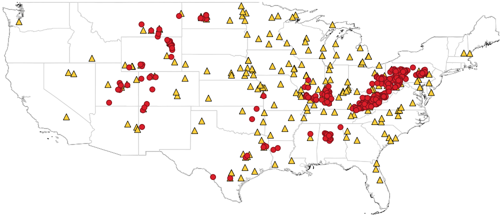


Figure 22: US coal plants and mines, 2008

Plants and Generators

Plants and Generators

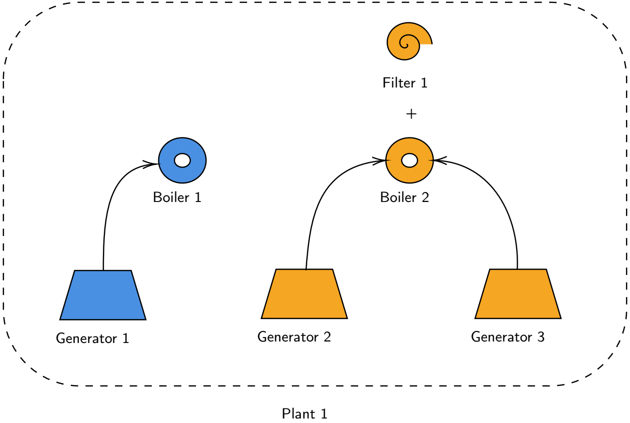


Figure 23: Differences between plants, boilers and generators

Back

Balance Table

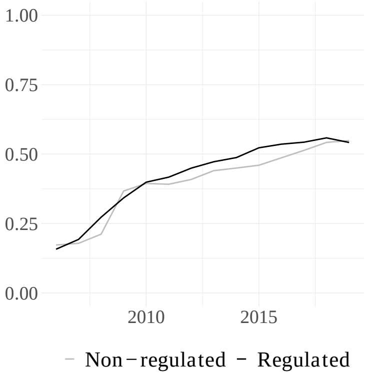
Table 2: Characteristics of coal generators open in 2008, by regulation and state type. Mean values.

	Regulated		Non-regulated	
	Mine-state	Non-mine state	Mine-state	Non-mine state
Age	40.38	40.98	37.84	35.05
Size	326.71	303.77	311.52	222.19
Heat rate	10099.13	10401.98	10015.13	9972.16
Closest mine distance	0.89	2.94	0.87	2.15
Closest mine sulfur	1.83	1.87	2.30	1.29
Distance to Wyoming	18.09	19.31	19.18	26.12
N	357	432	154	187

Back

Suggestive Evidence

Back

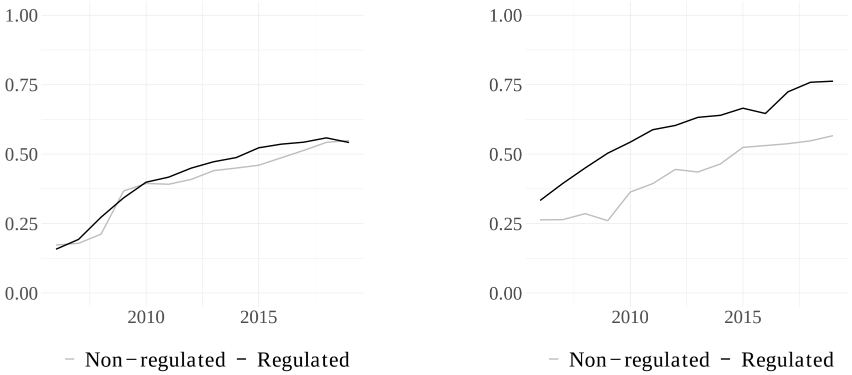


(24.1) No-mining states

(24.2) Mining states

Figure 24: Share of coal plants with expensive filters

Suggestive Evidence Back



(24.1) No-mining states

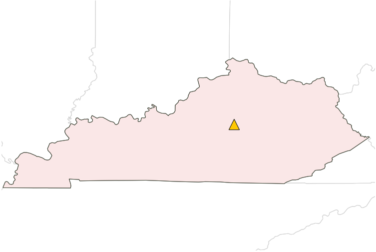
(24.2) Mining states

Figure 24: Share of coal plants with expensive filters

Treatment Construction

Back

1. Take one power plant location.
2. Take the mines within the plant's state.
3. Draw a circle around the mine.
   - Median distance of mine-plant transactions.
4. Select the in-state mines within the circle.



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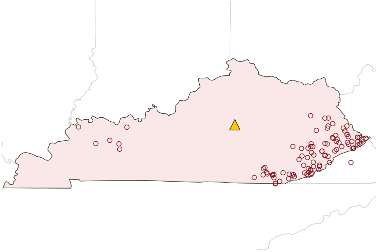

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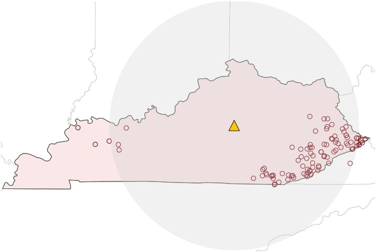

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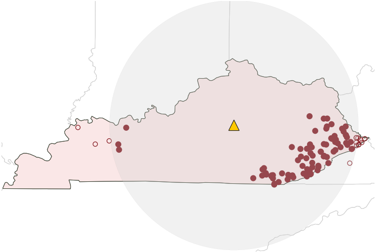

Results - Mine State Indicator

$$\log\left(\frac{p_j(\mathrm{x})}{p_J(\mathrm{x})}\right)=\sum_j\beta_{0j}+\sum_j\beta_{1j}\times X_i+\sum_j\beta_{2j}\times m_i+\sum_j\beta_{3j}\times \mathrm{Reg}_i+\sum_j\beta_{4j}\times \mathrm{Reg}_i\times m_i$$

	Dependent variable		
	j = retire	j = standard	j = expensive
Regulated	0.039	-0.176	1.058**
	(0.484)	(0.720)	(0.531)
Mine state	-0.010	-2.257**	0.175
	(0.543)	(0.947)	(0.586)
Regulated × Mine state	0.315	1.886*	0.735
	(0.601)	(1.015)	(0.651)
		McFadden R2	0.223
	*p<0.1	**p<0.05	***p<0.01

Back

Results - Share of in-state mines

$$\log\left(\frac{p_j(\mathrm{x})}{p_J(\mathrm{x})}\right) = \sum_j \beta_{0j} + \sum_j \beta_{1j} \times X_i + \sum_j \beta_{2j} \times m_i + \sum_j \beta_{3j} \times \mathrm{Reg}_i + \sum_j \beta_{4j} \times \mathrm{Reg}_i \times m_i$$

	Dependent variable		
	j = retire	j = standard	j = expensive
Regulated	-0.787	-0.250	-0.218
	(0.509)	(0.762)	(0.545)
Mine Share $\in [0, 1]$	-1.298**	-2.555**	-2.326***
	(0.660)	(1.082)	(0.744)
Regulated x Mine Share	1.884**	2.041*	3.480***
	(0.758)	(1.207)	(0.837)
		McFadden R2	0.225
	*p<0.1	**p<0.05	***p<0.01

Back

Results - Mine Employment

Back

$$\log\left(\frac{p_j(x)}{p_J(x)}\right)=\sum_j \beta_{0j}+\sum_j \beta_{1j}\times X_i+\sum_j \beta_{2j}\times m_i+\sum_j \beta_{3j}\times \mathrm{Reg}_i+\sum_j \beta_{4j}\times \mathrm{Reg}_i\times m_i$$

	Dependent variable		
	j = retire	j = standard	j = expensive
Regulated	0.221	1.207^{**}	1.159^{***}
	(0.341)	(0.571)	(0.363)
Miners (in Thousands, 2008)	0.542^{*}	0.443	0.183
	(0.277)	(0.407)	(0.293)
Regulated x Miners	0.733	-0.113	0.954^{**}
	(0.469)	(0.671)	(0.482)
		McFadden R2	0.226
	*p<0.1	**p<0.05	***p<0.01

→ +100 miners increase expensive filter adoption relative probability by 10%.

- This effect is only observed in regulated plants.

Coal Plant Closure - Empirical Specification Back

Test the correlation between filter investment on plant closure

- Cox Proportional-hazards model on filter investment and plant closure. Figure

$$h(t) = h_0(t)\exp\left(\beta_1 X_i + \beta_2 \cdot \omega_{it}\right)$$

  - $h(t)$ is the expected probability of **closing** at time t, having survived $t-1$.
  - X_i are generator covariates: age, size and heat rate.
  - ω_{it} is an indicator for generators with a filter.

- $\beta_2 < 0$ Plants are less likely to close after investing in a filter.

Coal Plant Closure - Empirical Specification Back

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Coal Plant Closure - Empirical Specification

Back

Test the correlation between filter investment on plant closure

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Coal Plant Closure - Empirical Specification Back

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- $\beta_2 < 0$ Plants are less likely to close after investing in a filter.

Coal Plant Closure - Results

Back

$$h(t) = h_0(t)\exp\left(\beta_1 X_i + \beta_2 \cdot \omega_{it}\right)$$

	Plant closure probability		
	(1)	(2)	(3)
Generator Age	0.037^{***}	0.024^{***}	0.021^{***}
	(0.007)	(0.008)	(0.008)
Filter indicator		-1.948^{***}	-2.009^{***}
		(0.191)	(0.196)
Coal capacity share			0.871^{**}
			(0.424)
Observations	7,109	7,109	7,109
Pseudo R^2	0.031	0.050	0.050

Regulated Prices and Filter Investment

Back to intro Back to model

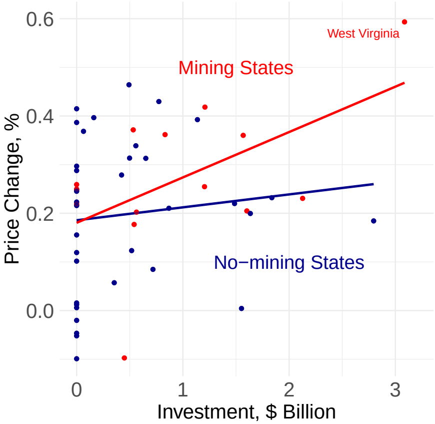

Figure 25: Electricity Price and filter Investment, by state

The Model - Equilibrium Conditions

1. Regulator chooses filter ω^* that maximizes its utility.
2. Filter efficiency determines the share of local coal and unit cost of coal:

   $$\omega^* \quad \rightarrow \quad \rho(\omega^*) \quad \rightarrow \quad \overline{c}(\omega^*)$$

3. Coal plant output q^* and regulated price p^* are jointly determined:
   - $q^*(p^*|\mu) = 1 - \Phi(p^*|\mu)$
   - Participation constraint: $\pi = q^*(p^*|\mu) \cdot (p^* - \overline{c}(\omega^*)) - F_{\omega^*} = 0$

Back

Comparative Statics - Filter Investment

- Regulators from non-mining states have no mining revenue to protect $R(\omega) = 0 \quad \forall \omega$
- Install a filter $\omega \in \{h, l\}$, if:
  1. Filter provides more welfare than exit: $W(\omega) \geq \Gamma_0$ and...
  2. Filter provides more welfare than no-filter: $W(\omega) \geq W(0)$

  → Choose expensive filter over standard if it increases welfare $W(h) \geq W(l)$
- Regulators from mining states want to protect mining revenue $R(\omega) \geq 0$:
  1. Are more likely to install filter. $W(\omega) + \alpha_1 \cdot R(\omega) \geq \Gamma_0$
  2. provides more welfare and local coal revenue than remaining no-filter: $W(\omega) + \alpha_1 \cdot R(\omega) \geq W(0)$

  → Are more likely to install an expensive filter. $W(h) + \alpha_1 \cdot (R(h) - R(l)) \geq W(l)$

Back

Comparative Statics - Filter Investment

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  → Are more likely to install an expensive filter. $W(h) + \alpha_1 \cdot (R(h) - R(l)) \geq W(l)$

Back

Comparative Statics - Plant Exit and Stranded Assets

- For a plant without filter, the regulator with some utility $U(\omega) = W(\omega) + \alpha_1 \cdot R(\omega)$ retires it if...
  - Closing is better than remaining: $\Gamma_0 \geq U(0)$.
  - Closing is better than investing: $\Gamma_0 \geq U(\omega) \quad \forall \omega$.
- For a plant with a filter, the regulator closes it if:
  - Closing is better than remaining: $\Gamma \geq U(\omega)$.
- Stranded assets: plants with filters that would have otherwise closed.

$$\Gamma_0 \geq U(0) \geq U(\omega) \geq \Gamma$$

→ Once a plant gets a filter, it **becomes less likely to close**, delaying the energy transition.

Back

Comparative Statics - Plant Exit and Stranded Assets

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$$\Gamma_0 \geq U(0) \geq U(\omega) \geq \Gamma$$

→ Once a plant gets a filter, it **becomes less likely to close**, delaying the energy transition.

Back

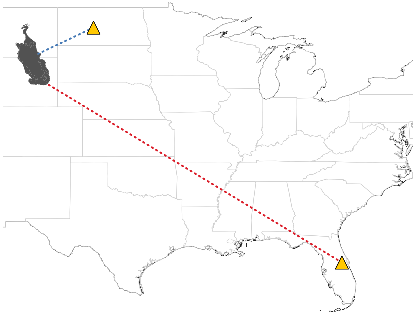
The Model - Identification

Back to Estimation

- The effect of filters on welfare depends on the distance *d* between the plant and Wyoming.

$$\downarrow \omega \quad \rightarrow \quad \uparrow \underbrace{(1-\rho)}_{\text{low-sulfur coal}} \quad \xrightarrow{d} \quad \uparrow \bar{c} \quad \rightarrow \quad \downarrow W$$

$$\xrightarrow{\uparrow d} \quad \uparrow \uparrow \bar{c} \quad \rightarrow \quad \downarrow \downarrow W$$



- The effect of filters on local mine revenue depends on plant location, mining state.

$$\uparrow \omega \quad \rightarrow \quad \uparrow \rho \quad \xrightarrow{\text{mines No}} \quad R = 0$$

$$\xrightarrow{\text{mines Yes}} \quad \uparrow R$$

The Model - Identification

Back to Estimation

- The effect of filters on welfare depends on the distance d between the plant and Wyoming.

$$\downarrow \omega \quad \rightarrow \quad \uparrow \underbrace{(1-\rho)}_{\text{low-sulfur coal}} \quad \xrightarrow{d} \quad \uparrow \overline{c} \quad \rightarrow \quad \downarrow W$$

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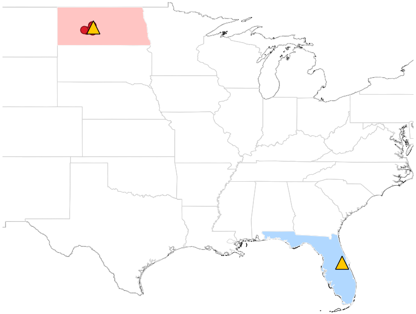

Estimation Algorithm

Back to Estimation

1. **Outer loop**: Candidate structural parameters

$$\theta = (\alpha, \gamma, \phi, \sigma)$$

    1.1 Obtain consumer welfare and local mine revenue for all generators i, at all aggregate state bins b and for all filter types ω.

    $$W_{ib\omega}, R_{ib\omega} \quad \forall \quad i \times b \times \omega$$

    1.2 **Inner loop**. Value function iteration to obtain conditional choice probabilities $\hat{P}_{ib\omega}$.

    1.3 Compute the Log Likelihood comparing conditional choice probabilities with actual choices P_{it}:

    $$LL = \sum_{t} \sum_{i} log \left(\hat{P}_{ib\omega} - P_{it} \right)$$

2. New candidate structural parameters θ' by Nelder Mead.

Aggregate State Space Discretization

Back to Estimation

Challenge: Model the **permanent** fall of natural gas prices, as in Gowrisankaran et.. al. (WP, 2023).

1. μ_{st}: The average cost of natural gas electricity is obtained at state s and year t level.
2. μ_{st} sample is discretized into $b = 1, 2, ..., B$ equal-size bins. Two-bin example $B = 2$:

$$\mu^{low} = 28.03\$/MWh \qquad \mu^{high} = 60.77\$/MWh$$

3. Obtain transition probability matrix

	μ_{t-1}^{low}	μ_{t-1}^{high}
μ_t^{low}	0.71	0.29
μ_t^{high}	0.17	0.83

→ $P(low|high) > P(high|low)$ It is more likely to transition from high to low than vice-versa.

Aggregate State Space Discretization

Back to Estimation

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$$\begin{array}{c|cc} & \mu^{low}_{t-1} & \mu^{high}_{t-1} \\ \hline \mu^{low}_{t} & 0.71 & 0.29 \\ \mu^{high}_{t} & 0.17 & 0.83 \end{array}$$

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Aggregate State Space Discretization, before and after MATS

	cheap gas, post MATS	expensive gas, post MATS	cheap gas, pre MATS	expensive gas, pre MATS
cheap gas, post MATS	0.62	0.05	0.33	0.00
expensive gas, post MATS	0.17	0.44	0.17	0.22
cheap gas, pre MATS	0.00	0.00	0.53	0.48
expensive gas, pre MATS	0.00	0.00	0.15	0.85

Imputation

Back to Estimation

- Model estimation requires the econometrician to observe $\{W, R\}_{ib\omega}$.
  - For all i generators, b aggregate state bins and $\omega \in \{h, l, 0\}$ filter types.
- Welfare contribution

$$W_{ib\omega} = K_i \cdot q_{ib\omega} \cdot \left(\mu^b - \overline{c}_{ib\omega}\right) - f_{i\omega}$$

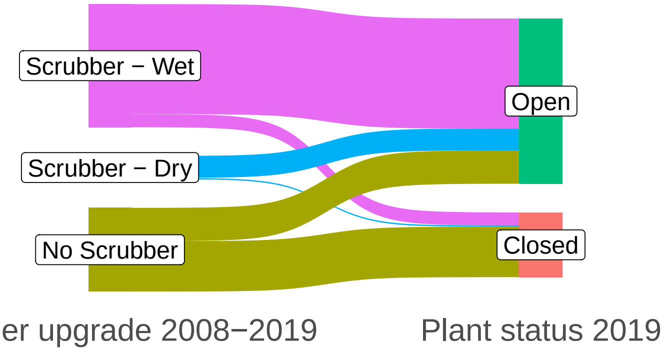
  - K_i and μ^b are observed.
  - $q_{ib\omega}$, $\overline{c}_{ib\omega}$ and $f_{i\omega}$ are imputed using event-studies.
- Local mine revenue

$$R_{ib\omega} = K_i \cdot HR_i \cdot q_{ib\omega} \cdot \rho_{ib\omega} \cdot c^m_{ib\omega}$$

  - K_i and HR_i are observed.
  - $q_{ib\omega}$, $\rho_{ib\omega}$ and $c^m_{i\omega}$ are imputed using event-studies.

Imputation q_{it} Imputation $\overline{c}_{it}$ Imputation $\overline{c}_{it}$ Imputation ρ_{it} Imputation F_{it}

Filter Investment and Plant Closure - Sankey Diagram



Back

Imputation - Dispatch

$$q_{it} = \alpha + \beta_1 \cdot \mu_{st} + \beta_2 \cdot Age_i + \beta_3 \cdot Size_i + \beta_4 \cdot HR_i + \beta_5 \cdot \omega_{it} + \beta_6 \cdot X_i + \beta_7 \cdot \omega_{it} \times X_i + \epsilon_{it}$$

	Dependent variable: Number of active hours per year q_{it}					
	(1)	(2)	(3)	(4)	(5)	(6)
Intercept	6,492.710***	10,091.550***	9,872.666***	7,809.374***	10,471.750***	10,154.180***
Natural gas cost (cent/MWh)	0.189***	0.231***	0.222***	0.154***	0.187***	0.186***
Plant Age	$-$22.569***	$-$6.288*	$-$6.763**	$-$49.987***	$-$35.786***	$-$36.522***
Plant Size (MW)	1.778***	1.644***	1.501***	0.534***	0.643***	0.625***
Heat Rate (Btu/KWh)	$-$0.054	$-$0.364***	$-$0.364***	$-$0.022	$-$0.221***	$-$0.218***
Filter Indicator	$-$82.658	$-$136.703	330.408	$-$115.805*	$-$34.753	366.443*
Wyoming dist.		$-$129.004***	$-$103.052***		$-$103.837***	$-$99.502***
Filter × Wyoming Dist.			$-$48.375***			$-$3.459
Filter type	Standard	Standard	Standard	Expensive	Expensive	Expensive
Observations	1,259	1,259	1,259	4,295	4,295	4,295
R^2	0.140	0.369	0.382	0.172	0.287	0.290

$^{*}p<0.1$; $^{**}p<0.05$; $^{***}p<0.01$. Regulated plants, 2008-2019 period.

Back

Imputation - Coal Bundle Cost

$$\bar{c}_{it} = \alpha + \beta_1 \cdot \omega_{it} + \beta_2 \cdot \omega_{it} \times X_i + \epsilon_{it}$$

	Dependent variable: Coal blend unit cost $\bar{c}_{it}$					
	(1)	(2)	(3)	(4)	(5)	(6)
Intercept	197.285^{***}	92.918^{***}	133.961^{***}	261.291^{***}	160.375^{***}	71.488^{**}
Filter Indicator	5.442	14.677^{***}	-28.859	-10.520	-9.048	89.664^{***}
Distance to Wyoming		8.482^{***}	0.252		8.717^{***}	19.506^{***}
Filter × Dist. to Wyoming			8.988^{***}			-11.844^{***}
Filter type	Standard	Standard	Standard	Expensive	Expensive	Expensive
Observations	702	684	684	1,344	1,301	1,301
R^2	0.001	0.626	0.638	0.001	0.473	0.484
Adjusted R^2	-0.001	0.623	0.632	0.001	0.471	0.480

$^{*}p<0.1$; $^{**}p<0.05$; $^{***}p<0.01$. All coal plants, 2008-2019 period.

Back

Imputation - Share of Local Coal

$$\rho_{it} = \alpha + \beta_1 \cdot \omega_{it} + \beta_2 \cdot \omega_{it} \times X_i + \epsilon_{it}$$

	Dependent variable: Share of Local Coal ρ_{it}					
	(1)	(2)	(3)	(4)	(5)	(6)
Intercept	0.163^{***}	0.550^{***}	0.671^{***}	0.279^{***}	0.428^{***}	0.964^{***}
Filter Indicator	0.137^{***}	0.076^{*}	0.088	0.234^{***}	0.195^{***}	-0.471^{***}
Distance to Closest Mine		-0.103^{***}	-0.163^{**}		-0.121^{***}	-0.277^{***}
Closest Mine Sulfur		-0.122^{***}	-0.176^{***}		0.0001	-0.262^{***}
Distance × Sulfur			0.033			0.075
Filter × Distance			-0.034			0.283^{***}
Filter × Closest Sulfur			-0.050			0.353^{***}
Filter × Distance × Sulfur			0.039			-0.188^{***}
Filter type	Standard	Standard	Standard	Expensive	Expensive	Expensive
Observations	443	443	443	1,144	1,144	1,144
Adjusted R^2	0.017	0.174	0.200	0.022	0.156	0.232

$^{*}p<0.1$; $^{**}p<0.05$; $^{***}p<0.01$. All coal plants, 2008-2019 period.

Back

Imputation - Filter Fixed Cost

$$F_i = \alpha + \beta_1 \cdot h_i + \beta_2 \cdot Size_i + \beta_3 \cdot h_i \times Size_i + \epsilon_{it}$$

	Dependent variable: Filter fixed cost F_i		
	(1)	(2)	(3)
Intercept	118.398^{***}	96.072^{***}	54.408^{**}
Expensive filter	81.613^{***}	56.137^{***}	116.842^{***}
Plant size (MW)		0.030^{**}	0.085^{***}
Expensive × Plant Size			-0.067^{**}
Observations	219	219	219
Adjusted R^2	0.073	0.096	0.112

$^{*}p<0.1$; $^{**}p<0.05$; $^{***}p<0.01$. All filter installations 2008-2019.

Back

Model Fit Back

1. Take the sample of open regulated plants in 2008.
2. Simulate their investment and exit behavior according to the estimated parameters until 2019.
3. Compare 2019 simulated outcome with the actual 2019 outcome.

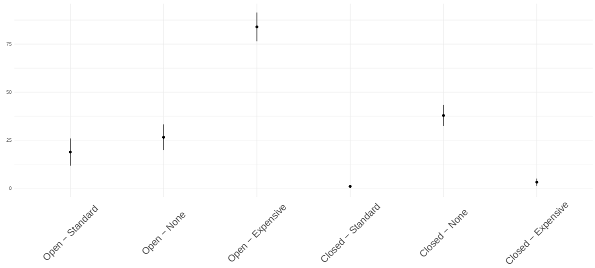


Figure 26: Actual and predicted capacity by the end of the period (GW).

Fit - N Investment - GW Investment - N Dynamics

Model Fit

Back

1. Take the sample of open regulated plants in 2008.
2. Simulate their investment and exit behavior according to the estimated parameters until 2019.
3. Compare 2019 simulated outcome with the actual 2019 outcome.

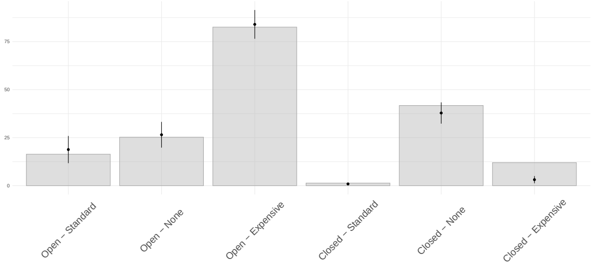


Figure 26: Actual and predicted capacity by the end of the period (GW).

Fit - N Investment - GW Investment - N Dynamics

Model Fit - Number of Generators

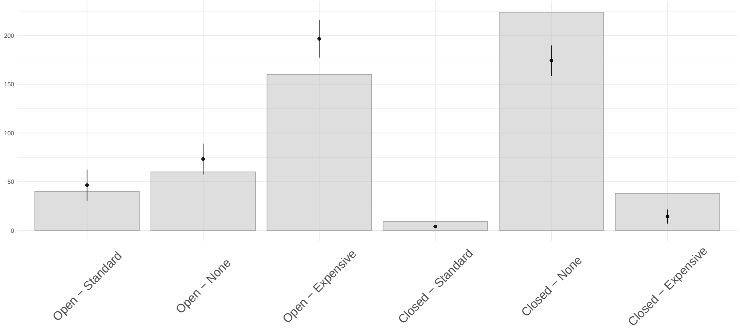


Figure 27: Actual and predicted capacity by the end of the period (number of generators).

Back

Model Fit - Investment

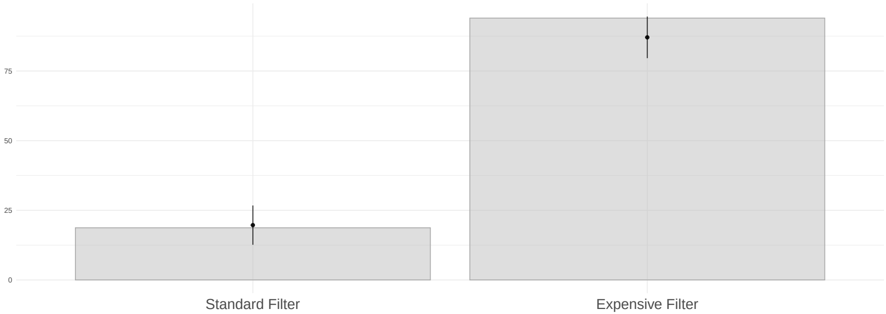


Figure 28: Actual and predicted capacity by the end of the period (GW).

Back

Model Fit - Investment

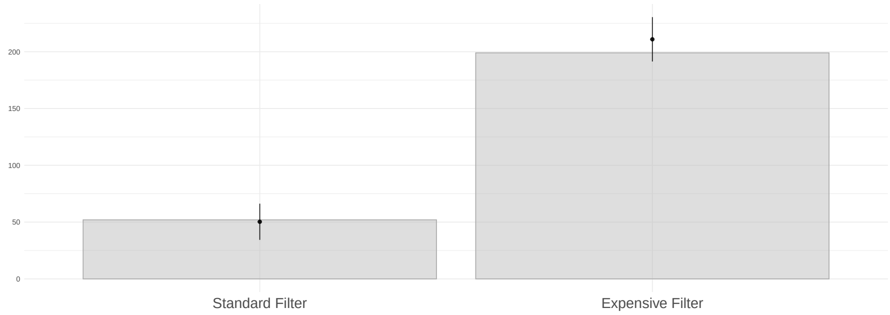
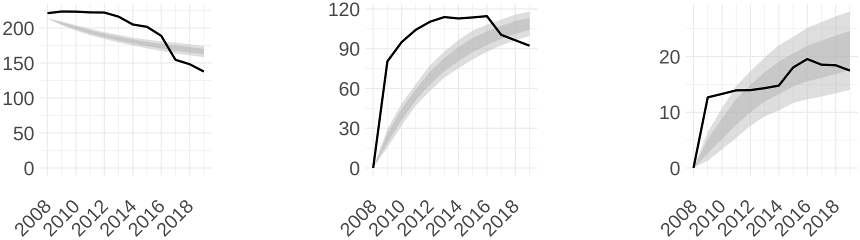


Figure 29: Actual and predicted capacity by the end of the period (number of generators).

Back

Model Fit - Dynamics



(30.1) Total Capacity (GW) (30.2) Expensive Filters (GW) (30.3) Standard Filters (GW)

Figure 30: Actual and predicted regulated coal plant capacity in the US, 2010-2019

Back