Burnout to Buildout: Coal Exit and the Geography of Transition Costs

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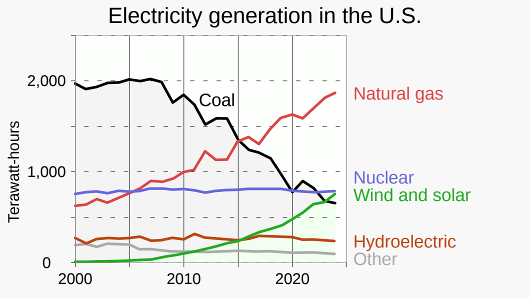
Background: U.S. power generation

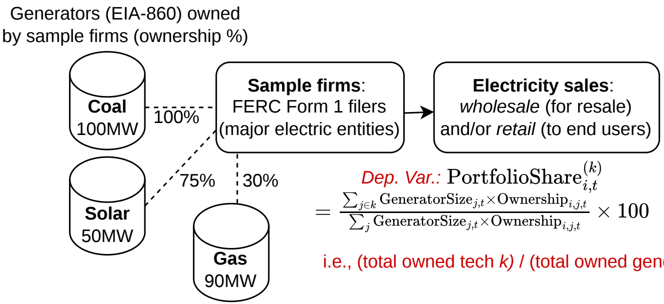
- **From 2000 to 2023:**
  - Coal: 51.4% → 16.2%
  - Renewables: 8.9% → 21.4%
- **Why coal is not favored?**
  - Coal generation → *toxic* pollutants
    - e.g., SO_2, NO_x, mercury
  - Other technologies get cheaper
    - Linn & McCormack (2019 *RandJE*): gas prices → coal profit declines
- ***Question*: Is cutting coal sufficient for a green transition?**
  - Macro trends: renewables ↑
  - What about incumbent fossil-reliant electric utility firms?



Source: Calma, Justine (March 12, 2025). "Solar and wind beat coal in the US for the first time". *The Verge*

My analysis angle: Electric utility companies & portfolios

- **Why**: Treat generation as firm portfolios to observe firm-level transition (brown vs. green)
- **Who**: U.S. electric utilities (operating legal entities from EIA and FERC)
- **Product features**: Electricity = *mostly* local service (wholesale/retail delivery); Same final output, regardless of production process
- **Focus**: Portfolio composition changes (e.g., in Firm A's portfolio, 61% is coal)

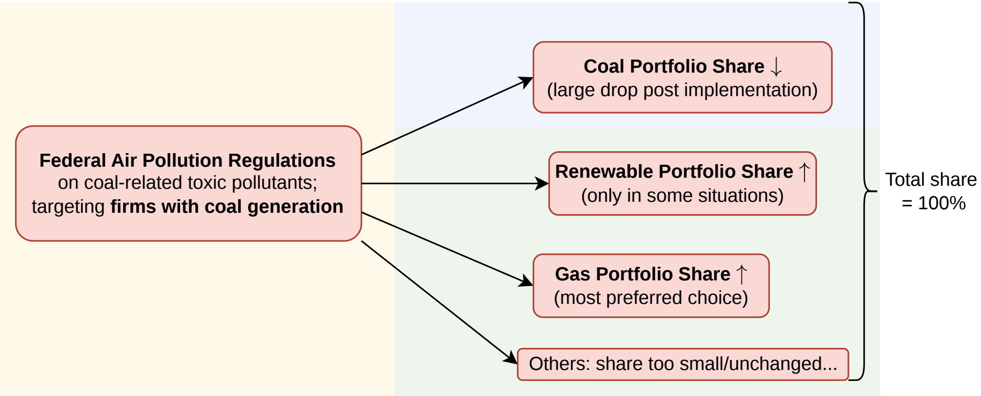


Dep. Var.: $\text{PortfolioShare}^{(k)}_{i,t}$

$$= \frac{\sum_{j\in k} \text{GeneratorSize}_{j,t} \times \text{Ownership}_{i,j,t}}{\sum_{j} \text{GeneratorSize}_{j,t} \times \text{Ownership}_{i,j,t}} \times 100$$

i.e., (total owned tech *k*) / (total owned generation)

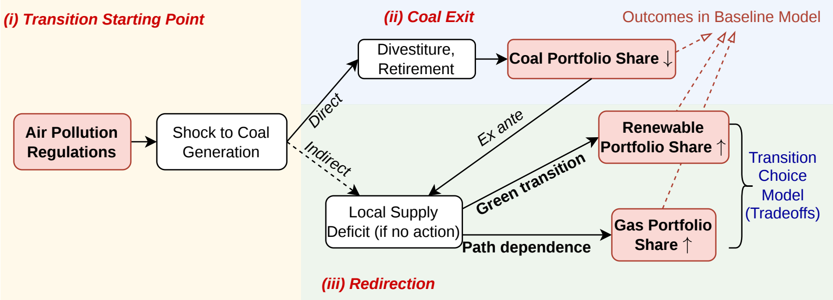
Baseline finding preview (firm-level portfolio adjustments)



- ***Q***: For firms, what are the (i) mechanisms and (ii) heterogeneity in tradeoffs behind this?

This paper's main message

- *Key argument*: **Unsmooth green transition after coal exit, with policy roles that**:
  - → Cut emission → effectively phase out coal
  - → Promote renewables → but bring transition in low-resource locations



- **Conditions for the argument**:
  - Local transition focus: coal exit creates a local supply deficit; limited long-distance delivery
  - Only renewables rely on local geographic resources

Regulatory environment

- **Coal exit pressure** (EPA air emission rules; main shocks to coal-reliant firms)
  - *CSAPR* (SO_2, NO_x): state emission budgets with tradable allowances
    - Scope: Eastern U.S. (32 proposed, 27 finalized)
    - Timing: 2010 proposed, 2011 finalized, 2015 implemented
    - Surplus: allowances held – emissions (bank/sell)
  - *MATS* (mercury, toxics): unit-level limits, no trading; costly controls/retirements
    - Scope: Nationwide
    - Timing: 2011 proposed, 2012 finalized, 2015–16 compliance (select to 2017)
  - Not the focus: NBP (2003, *only* ozone-season trading), CAIR (2005; challenged & replaced)
- **Green transition pressure** (Renewable Portfolio Standards (*RPS*))
  - Annual renewable share targets; compliance via credits (build or buy); penalties if short
    - Coverage (2023): state-level; 28 states + DC binding; 7 states voluntary goals
    - Surplus: credits acquired – (required % $\times$ retail load)

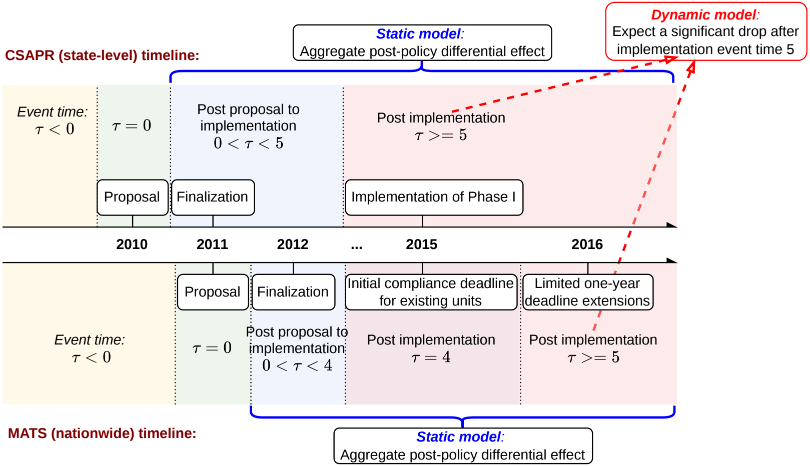
CSAPR and MATS timelines and treated status

Event time:

<0: Pre-policy period;
no firms exposed to policies (benchmark -1)

$>=1$: Post-proposal periods;
all firms exposed to (potential) compliance

$>=5$: Post-implementation periods;
all firms exposed to fixed compliance



Preview of analyses & findings

- **Part 1: Shock to the generation system**
  - Coal-reliant firms → coal ownership (↓) → retire vs. divest → emissions compliance
- **Part 2: Redirection after coal exit** (continued local service)
  - Coal exit → expected local supply gap → "Brown" vs. "Green" transition → identify policy-induced green capital investment
  - Heterogeneity: incentives/subsidies → more *specific* technology targeting
- **Part 3: Geography of transition costs** & policy counterfactuals
  - Financial: low-resource siting → electric revenue per kW (↓)
  - Social: "E" vs. "S" dilemma → remote workplaces
  - Counterfactual: align policy with resource quality → *fewer* solar projects, *higher* solar share

Contribution to Literature

- **Air pollution regulations and fossil reallocation**
  - Emission regulation & compliance (e.g., Shapiro & Walker 2018 *AER*: environmental regulations → manufacturing emissions; Gowrisankaran et al. 2025 *JPE*: model MATS uncertainty for coal generators)
  - This paper: decomposes divestiture vs. closure channels and coal-to-gas substitution in firm-level portfolio (post CSAPR & MATS)
- **Renewable transition: Geography and operational inefficiency**
  - Intermittency costs & location-specific grid values (e.g., Gowrisankaran et al. 2016 *JPE*; Callaway et al. 2018 *JAERE*: grid-regional differences in carbon displacement)
  - This paper: maps misalignment to firm-level loss (lower electric operating revenue per kW)
- **Environmental vs. Social dilemma in the transition**
  - Local externalities & coal-closure frictions (e.g., Isen et al. 2017 *JPE*: pollution exposure and later-life outcomes; Darmouni & Zhang 2024 *WP*: social factors mitigate coal exit)
  - This paper: quantifies an “E” vs. “S” dilemma via remote renewable siting

Main data & sample

- Main data sources:
  - **U.S. Energy Information Administration (EIA)** → U.S. electricity-sector entities (plants and owners/operators)
    - Generator/plant/operation data: capacity (MW), fuel, ownership shares, status, location, etc.
  - **Federal Energy Regulatory Commission (FERC Form 1)** → Major electric entities
    - Detailed firm-level financial statements
  - **EIA–FERC matched sample:**
    - Period: 2007–2023 (restricted by state demand data, FERC Form 714)
    - Main matched sample (all operation + financials non-missing): 189 major "Form 1" filers
    - Fuzzy RD sample (less restriction on financial missing): 295 EIA–FERC utilities
    - Project-level sample: 5,954 EIA projects, 1,075 matched EIA–FERC projects (solar + fossil)
- Summary
  - 147 (78%) out of 189 EIA–FERC major filers are coal-reliant before air pollution regulations
  - Average portfolio share across main sample: Coal: 43%; Gas: 35%; Renewables: 9%
  - Pre-policy: 56% operated in only one state; 94% in ≤ 3 states
  - Average number of plants: 9.8; generators: 28.2

1.1.1 Baseline: Policy pressures and portfolio changes

- $\text{PortfolioShare}_{i,t}^{(k)} = \alpha_0 + \beta \left(\text{Exposed}_i \times \text{PostPolicy}_{i,t}^{\text{Air}} \right) + X'_{i,t-1}\gamma + Z'_{s(i),t-1}\delta + \theta_i + \lambda_\tau + \varepsilon_{i,t}$
- **Treated status** (with time-invariant *pre-policy* defined treated group):
  1. Firm coal reliance ([0, 1], heterogeneous) exposed to CSAPR or MATS (*post*)
  2. Under-RPS firms ($\mathbb{1}$) exposed to CSAPR or MATS (*post*) (coal subsample)
- **Specifications**
  - k: generation type, including coal, gas, renewables, and other clean fuels
  - Control variables: lagged firm-level financial & operational variables ($X_{i,t-1}$), lagged state-level demand & electricity price ($Z_{s(i),t-1}$), and $PortfolioShare_{i,t-1}^{(k)}$ (for $k \neq$ coal)
  - Robust estimator (de Chaisemartin and D'Haultfoeuille 2024: switcher-vs-stayer 2×2 comparison & treatment change as weight) for treated status in:
    - Pre-policy time-invariant continuous coal reliance
    - Time-variant continuous RPS intensity
    - Reported in dynamic model

1.1.2 Post-policy: Fossil path dependence & Renewable redirection

- **Coal exit**: Coal (↓); Gas (↑); Others (no clear change)
- **RPS heterogeneity**: Coal exit → Renewables (↑) more in *RPS* states than *non-RPS* states

Panel A. Exiting Coal and Path Dependence

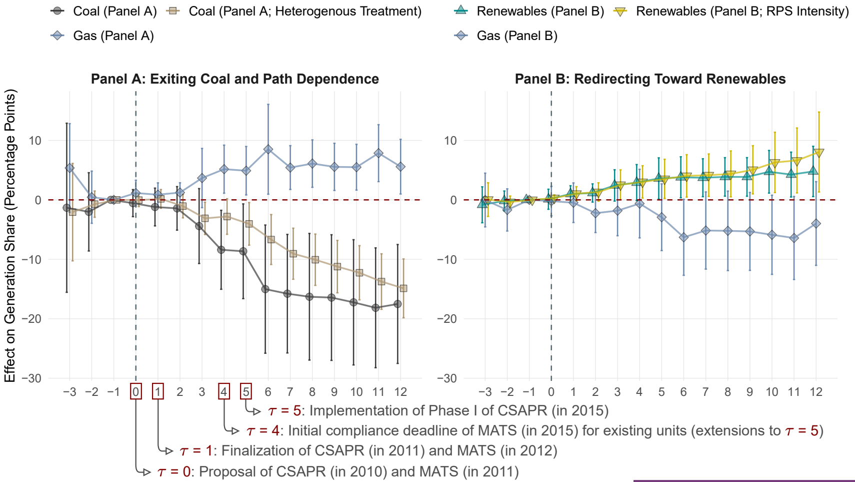
Dep. Var.: $\text{PortfolioShare}_{i,t}^{(k)}$				
k =	*Coal*	*Gas*	*Renewables*	*Other Clean*
	(1)	(2)	(3)	(4)
$\text{CoalReliance}_i \times \text{PostPolicy}_{i,t}^{\text{Air}}$	-9.503***	3.029***	1.121	0.434
	(3.622)	(1.073)	(1.059)	(0.470)
Sample (pre-policy defined)	All firms	All firms	All firms	All firms

Panel B. Redirecting Toward Renewables

Dep. Var.: $\text{PortfolioShare}_{i,t}^{(k)}$				
k =	*Renewables*	*Gas*	*Renewables*	*Gas*
	(1)	(2)	(3)	(4)
$\text{InRPS}_i \times \text{PostPolicy}_{i,t}^{\text{Air}}$	3.241**	-2.969	2.418**	-3.887*
	(1.446)	(2.052)	(1.138)	(2.249)
Sample (pre-policy defined)	All firms	All firms	Coal-based	Coal-based

Note: (1) Obs: 2,312 (all firms), 1,897 (coal-based); (2) TWFE/Firm & State Controls/Constant: Yes

1.1.3 Dynamic treatment effects (with robust estimator for intensity)



1.2.1 Exit channel: Divestiture vs. Retirement

An overview (single difference mlogit)

- Multinomial logit model; sample: coal-based (pre-policy defined)
- Three outcomes (**0.Keep**, **1.Sell**, and **2.Retire**): CSAPR and MATS raise the likelihood of firms doing both divestiture and retirement, compare to no action

Dep. Var.: $\text{ExitType}_{i,t}^{(m)}$				
$m =$	*1.Divestiture Only*	*2.Closure*		
	(1)	(2)		
$\text{PostPolicy}_{i,t}^{\text{Air}}$	1.425***	1.390***	Benchmark (m)	*0.No Exit*
	(0.392)	(0.389)	Observations	1,897
Marginal Effect	4.48%***	3.87%***	Pseudo-R^2	0.134
	(0.013)	(0.012)		
Controls (Firm & State)	Yes	Yes		
Sample (pre-policy defined)	Coal-based	Coal-based		

1.2.2 Exit channel: Where gas share increases more

- **Baseline shows**: on average, gas is the most preferred transition choice (share ↑)
- **Heterogeneity**: regions where gas has larger advantages than coal → will coal exit channels (sell vs. retire) be affected?
  - U.S. natural gas pipeline makes some areas more accessible (e.g., Scott 2023 *REStat*)
  - Gas is less pollutive for CSAPR/MATS-relevant emissions; also less carbon emission
- **Theoretical framework of coal exit** (Darmouni & Zhang 2024 *JFE RR*) implies:
  - "Sell" and "Keep" are always feasible; "Retire" only when regulatory pressure exists
  - **Model extension**: regions with larger coal fuel-cost disadvantage → owners of coal assets need to push down the price (discount) to "Sell" (coal is less favored) → higher "Retire" margins (relative to "Sell")

▸ Model expression ▸ Equilibrium illustration

1.2.3 Exit channel: Coal-to-gas substitution effect

- **Dep. Var.**: *Closure* & *Divestiture* are dummy × 100
  - *Closure*: full generator shutdown (with EIA retirement flag)
  - *Divestiture*: reduction in ownership share (without retirement flag)
- **Gas advantage** (standardized): each firm's coal marginal fuel cost – state-average gas marginal fuel cost (gas plants) (time-invariant; measured at event time 1)
- **Retirement margin**: regional coal-to-gas fuel costs → only significantly affect "Retire"
- **Substitution effect**: 1-SD fuel cost difference → 4.8% Coal (↑) & 5.1% Gas (↓)

Dep. Var.:	Exit for Coal Units		$\text{PortfolioShare}^{(k)}_{i,t}$	
	$Closure_{i,t}$	$Divestiture_{i,t}$	$k = Gas$	$k = Coal$
	(1)	(2)	(3)	(4)
$\text{PostPolicy}^{\text{Air}}_{i,t} \times$	5.404***	0.694	5.138***	-4.815***
$\text{FuelCostGap}^{\text{Coal-Gas}}_{i}$	(2.014)	(0.998)	(1.507)	(1.350)
Note: (1) Obs: 1,820 (coal-based); (2) TWFE/Firm & State Controls/Constant: Yes				

1.2.4 Exit outcome: Emission reduction compliance

- **Panel A**: Emission reduction after CSAPR and MATS: SO_2 (> 100% of pre-policy mean); NO_x (≈ 77% of pre-policy mean); CO_2 (≈ 45% of pre-policy mean)
- **Panel B**: Coal-to-gas substitution effect explains more reduction in SO_2 and NO_x in relative magnitudes (reference: Panel A), compared to CO_2

Panel A. Compliance Outcomes for Coal-Reliant Firms

Dep. Var.:	SO_2 (k lbs)	NO_x (k lbs)	CO_2 (k tons)
	(1)	(2)	(3)
$\text{CoalBased}_i\,(\mathbb{1}) \times \text{PostPolicy}^{\text{Air}}_{i,t}$	-8.665***	-2.013***	-0.628***
	(1.836)	(0.380)	(0.219)
Sample (pre-policy defined)	All firms	All firms	All firms

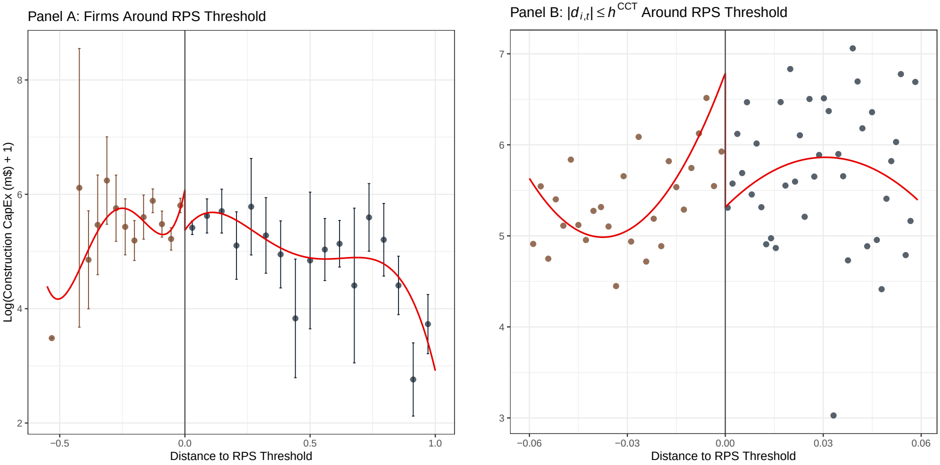
Panel B. Substitution Effect: Fuel Relative Prices and Compliance Outcomes

Dep. Var.:	SO_2 (k lbs)	NO_x (k lbs)	CO_2 (k tons)
	(1)	(2)	(3)
$\text{PostPolicy}^{\text{Air}}_{i,t} \times \text{FuelCostGap}^{\text{Coal-Gas}}_i$	-7.792***	-1.219***	-0.211**
	(2.616)	(0.454)	(0.095)
Sample (pre-policy defined)	Coal-based	Coal-based	Coal-based

2.1.1 Transition channel: RPS-induced renewable investment

- **Another dimension: Transition after coal exit shock**
  - Prior section: under-RPS $\rightarrow$ renewable portfolio share ($\uparrow$)
  - *Hypothetical* compliance channels:
    - Build new renewables (via construction)
    - Acquire existing renewables (limited existing projects locally)
    - Cut other generation (limited by local demand)
    - Buy renewable power in the wholesale market (cannot explain physical share increase)
    - Buy credits (RECs) from other utilities (compliance only; cannot explain physical share increase)
- **Thus, goal is to idenfity: "Capital investment → Renewable buildouts"**
  - Fuzzy RD running variable: $d_{i,t}$ = renewable capacity share − RPS annual target
  - Reason for fuzzy: below-target firms face stronger incentives (likelihood only) to make renewable investment, but credit deficit (true compliance status) is unobserved
  - 2SLS: below-target ($\mathbb{1}$) $\rightarrow$ construction capital expenditure $\rightarrow$ future renewable share

Discontinuity in construction CapEx



2.1.2 Transition channel: RPS-induced construction and transition

Dep. Var.: $\text{PortfolioShare}^{(k)}_{i,forward}$					
$k =$	*Renewables*			*Gas*	*Other Clean*
$forward =$	$t+1$	$[t+1, t+3]$	$[t+1, t+3]$	$[t+1, t+3]$	$[t+1, t+3]$
	(1)	(2)	(3)	(4)	(5)
Second Stage					
$\widehat{\text{ConstructCapEx}}_{i,t}$	5.270***	5.766***	5.407**	-7.368	1.202
	(2.001)	(2.186)	(2.208)	(4.495)	(0.927)
First Stage (Instrumenting $ConstructCapEx_{i,t}$)					
$\text{BelowRPS}_{i,t}$	1.015***	1.015***	0.995***	1.015***	1.015***
	(0.288)	(0.288)	(0.288)	(0.288)	(0.288)
Specification Category	Main	Main	Main	Placebo	Placebo
Sample (pre-policy defined)	All firms	All firms	Coal-based	All firms	All firms
Weak Instrument Test					
Kleibergen-Paap Wald F-stat	12.42	12.42	11.91	12.42	12.42
Test of Endogeneity					
Anderson-Rubin Wald Chi-sq	16.19	16.44	12.27	3.08	1.67
p-value	0.00	0.00	0.00	0.08	0.20

Note: (1) Obs: 1,277 (all firms), 1,064 (coal-based); (2) Firm Fuel-Type FE/Year FE/Constant: Yes; (3) Polynomial Control: $K = 2$

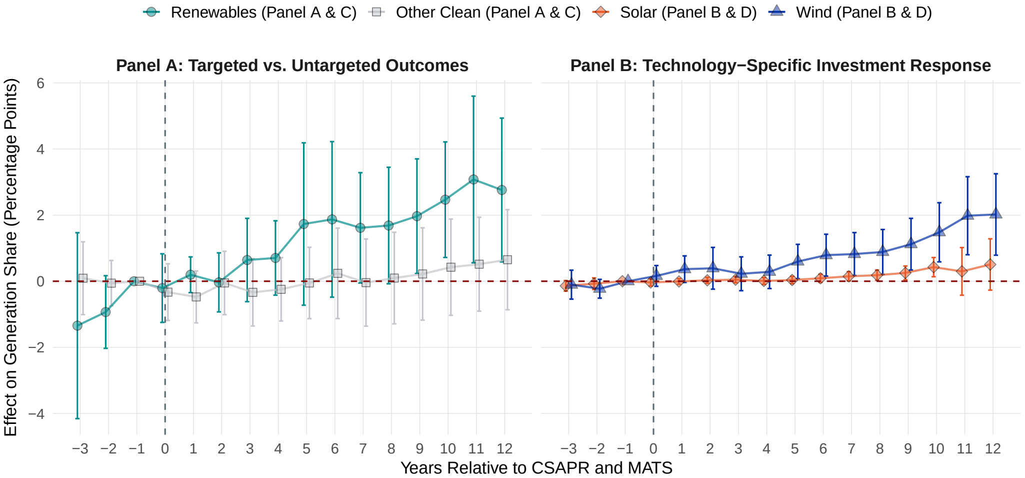
2.2.1 Renewable financial incentives and the direction of transition

- **Question**: Two types of renewable policy
  - Mandates (e.g., RPS) are *mostly* technology-neutral
  - Financial incentives: more targeted and flexible
- DSIRE → state-level programs → tag: solar, wind, or hydro → tag: "financial incentives" → (subsidies) direct financial support (grants, rebates, and performance-based incentives)
- Baseline: $\text{Incentive}_i^{(r)}$: = 1 if firm in a state with "financial incentives" for tech r

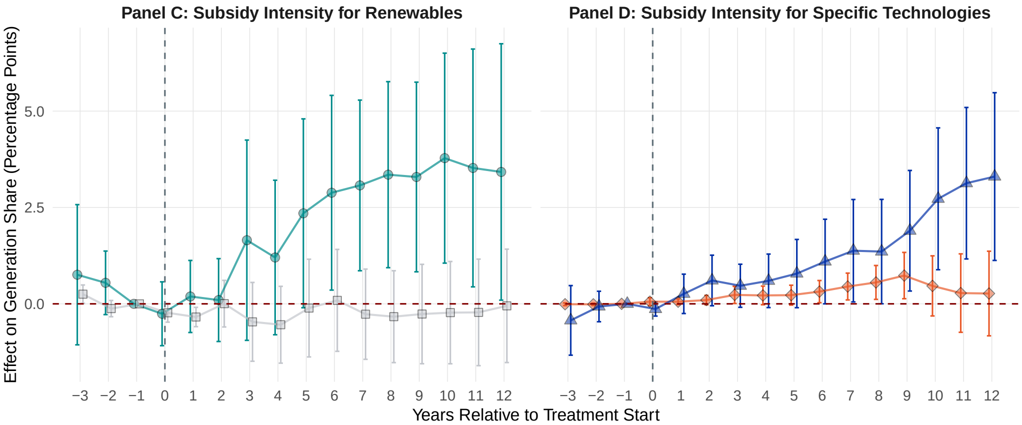
Dep. Var.: $\text{PortfolioShare}_{i,t}^{(k)}$					
k =	*Renewables*	*Solar*	*Wind*	*Gas*	*Other Clean*
Incentive technology (r=)	*Renewables*	*Solar*	*Wind*	*Renewables*	*Renewables*
	(1)	(2)	(3)	(4)	(5)
$\text{Incentive}_i^{(r)} \times \text{PostPolicy}_{i,t}^{\text{Air}}$	2.488***	0.239**	1.848***	-5.371	0.257
	(0.827)	(0.106)	(0.424)	(3.379)	(0.397)
Specification Category	Main	Main	Main	Placebo	Placebo
Sample (pre-policy defined)	Coal-based	Coal-based	Coal-based	Coal-based	Coal-based

Note: (1) Obs: 1,897 (coal-based); (2) TWFE/Firm & State Controls/Constant: Yes

2.2.2 Dynamic effects: Financial incentive status



2.2.3 Dynamic effects: Subsidy intensity (# of programs in a state)



3.1.1 Transition tradeoffs and geographic factors

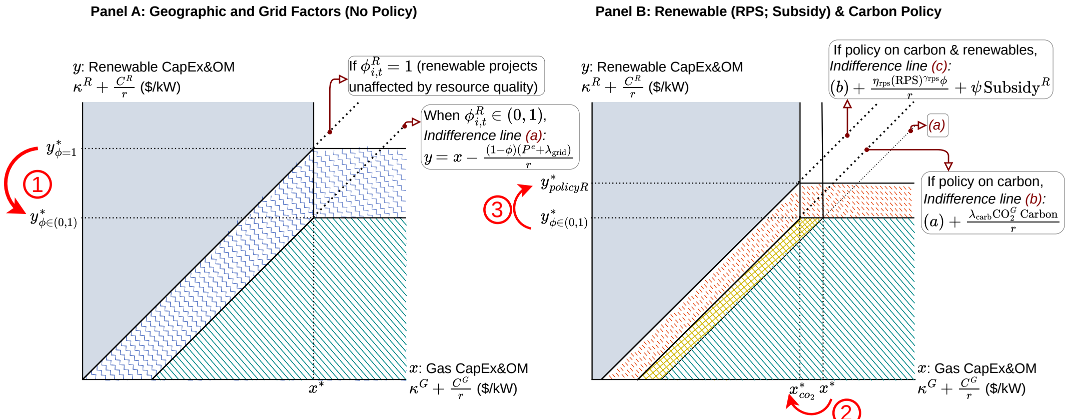
- **Why a parsimonious tradeoff model?**
  - Clarify overlapping margins around technology choices (brown vs. green transition)
  - Bring in geography: minor for fossil di/investment, but central for renewable transition
  - Empirical implication & policy counterfactuals (later)

- **Firm's decision between two technologies $k \in \{R, G\}$:**
  - Geographic factor: $\phi^R_{i,t} \in (0,1) \rightarrow$ how much sunshine to power; $\phi^G_{i,t} = 1$: gas unaffected
  - Local electricity price: $P^e_{s,t}$; fixed O&M costs (incl. fuels): $C^k_{s,t}$; upfront CapEx: κ^k
  - RPS target: $\text{RPS}_{s,t}$; Subsidy exposure: $\text{Subsidy}^k_{s,t}$; Carbon pricing: $\text{Carbon}_{s,t}$

3.1.2 Project NPV and indifference choice lines

- **Upfront capital investment** per kW for technology k:
  - $I^k_{i,t} = \underbrace{\kappa^k}_{\text{CapEx}} - \underbrace{\psi \text{ Subsidy}^k_{s,t}}_{\text{Scaled Subsidy}}$, where Subsidy only exists for renewable investment ($k = R$)
- **Expected annual operating cash flow** per kW, assuming fixed environment:
  - $\pi^k_i =$
    $\underbrace{\left(P^e_{s,t} + \eta_{\text{rps}} (\text{RPS}_{s,t})^{\gamma_{\text{rps}}} \mathbb{1}\{k = R\}\right) \phi^k_{i,t}}_{\text{Revenue \& Compliance Benefit}} - \underbrace{C^k_{s,t}}_{\text{O\&M}} - \underbrace{\lambda_{\text{grid}} (1 - \phi^k_{i,t})}_{\text{Grid Cost}} - \underbrace{\lambda_{\text{carb}} \text{CO}_2^k \text{ Carbon}_{s,t}}_{\text{Carbon Cost}}$
- **Project NPV** (perpetual cash flows with discount rate $r > 0$):
  - $\text{NPV}^k_{i,t'} = -I^k_{i,t} + \frac{\pi^k_i}{r}$, with indifference line: $\text{NPV}^R_{i,t} = \text{NPV}^G_{i,t}$

Effect of geography and policy factors on transition choices



R_0 (renewables, if $\phi^R_{i,t} \in (0,1)$ & no policy) (Panel A & B)

G (gas projects) (Panel A & B)

ΔR_2 (renewables, if policy on CO_2) (Panel B)

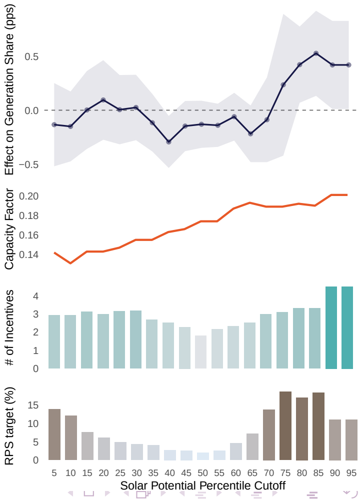
ΔR_1 (renewables, if resource is irrelevant $\phi^R_{i,t} = 1$) (Panel A)

No investment (Panel A & B)

ΔR_3 (renewables, if RPS & Subsidy) (Panel B)

3.1.3 Empirical implication: Policy-induced geographic misalignment

- **Empirical implications**:
  - Post-coal-exit **margins** for choosing $\boldsymbol{R}$ over $\boldsymbol{G}$:
    - (First-order margins) Geographic factor & Renewable policies: $\uparrow \boldsymbol{R}$ via: (i) $\downarrow$ no decision area, (ii) $\downarrow \boldsymbol{G}$ area
    - Carbon pricing: $\uparrow \boldsymbol{R}$ *only* via: (i) $\downarrow \boldsymbol{G}$ area
  - What if policy makes $\boldsymbol{R}$ favorable in low-resource areas?
- **Overview**: Renewable transition & descriptive evidence in different solar irradiance cutoffs (RHS figure)
  - 1st row of figure: Estimated coefficients (95% CIs) from $\text{PortfolioShare}^{(k)}_{i,t} \sim \text{Solar}(\mathbb{1}\{\in \text{cutoffs}\})_i \times \text{PostPolicy}^{\text{Air}}_{i,t}$
  - 2-4 rows are:
    - Realized capacity factor (% solar $\rightarrow$ power): $\uparrow$ with solar
    - Number of state incentive programs (non-monotonic)
    - RPS targets (non-monotonic)



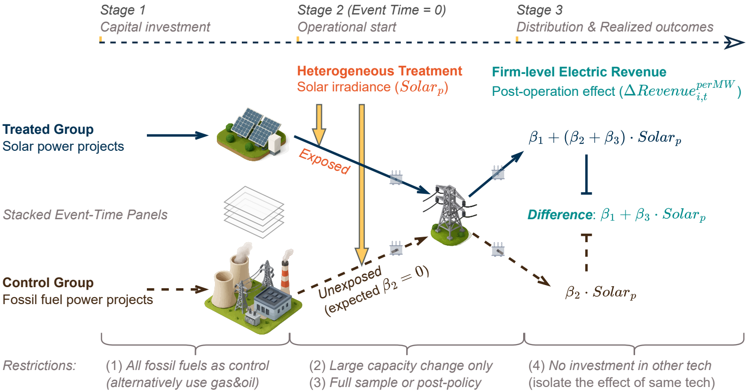
3.2.1 Geography of transition costs

- **Geography of transition costs may arise financially and socially**, when:
  - *Max Profit*{geographic factor, renewable policies} → e.g., solar PV in cloudy states
  - Locally, if same policy exposure: *Max Profit*{geographic factor} → solar PV on a mountain
- **Objective: Quantify both costs** (solar PV as representative tech for renewables)
- **Situation 1 (financial cost)**: performance across resource quality from solar investment
  - Compare: solar PV vs. fossil plants across irradiance (sunny vs. cloudy)
  - Heterogeneity: solar irradiance
  - Outcome: firm-level electric operating revenue per installed kW
- **Situation 2 (social cost)**: siting remoteness of new buildouts
  - Compare: fossil-based firms' new solar vs. new gas sites (within state-year)
  - Setting: (new site – legacy fossil baseline) × (solar vs. gas)
  - Assumptions: "just transition" and grid access
  - Outcome: population density around sites

3.2.2 Illustration: Quantifying financial costs

- **Project-level stacked**: $\text{Revenue}_{i,t}^{\text{perMW}} \sim$

$$\beta_1 \left(\text{InvestType}_p \times \text{PostActive}_{p,t}\right) + \beta_2 \left(\text{Solar}_p \times \text{PostActive}_{p,t}\right) + \beta_3 \left(\text{InvestType}_p \times \text{Solar}_p \times \text{PostActive}_{p,t}\right)$$



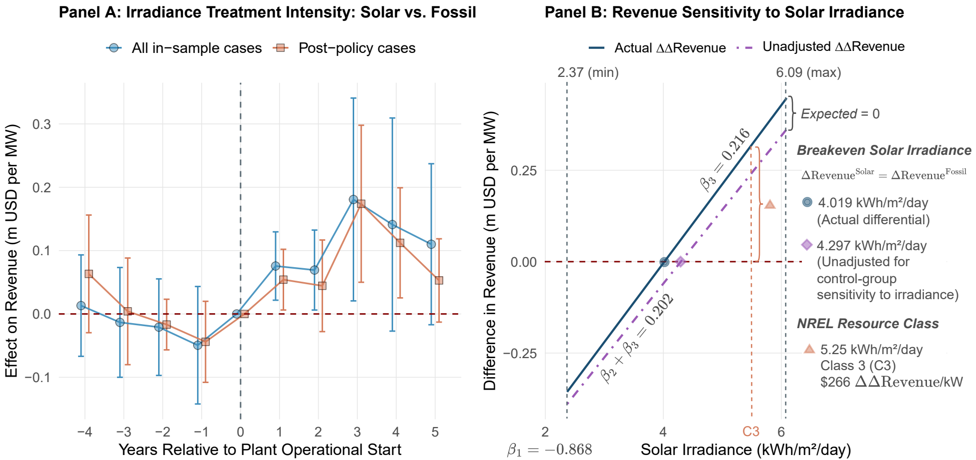
3.2.3 Geographic advantage and electric revenue

- Observed projects (***R*** or ***G***) are treated as given (reduced-form does not explain tradeoffs); Estimation only focuses on outcome variation from heterogeneous solar irradiance
- At sample mean irradiance of 4.54 kWh/m^2/day: Post-operation revenue differential of \$113 per kW capacity ($-0.868 + 0.216 \times 4.54$) between solar and fossil fuel projects
- β_3: additional unit of solar → \$216 per kW capacity from solar projects relative to fossil

Panel A. Electric Operating Revenue: Solar vs. Fossil Fuels

Dep. Var.: $\text{Revenue}^{\text{perMW}}_{i,t}$	(1)	(2)	(3)	(4)
$\text{InvestType}_p \times \text{PostActive}_{p,t}$	-0.868***	-0.820***	-0.859***	-0.774***
	(0.188)	(0.150)	(0.206)	(0.164)
$\text{Solar}_p \times \text{PostActive}_{p,t}$	-0.014	-0.023	-0.015	-0.024
	(0.031)	(0.035)	(0.032)	(0.038)
$\text{InvestType}_p \times \text{Solar}_p \times \text{PostActive}_{p,t}$	0.216***	0.204***	0.214***	0.194***
	(0.040)	(0.034)	(0.044)	(0.037)
Sample	All cases	Post-policy	All cases	Post-policy
Control Group ($\text{InvestType}_p = 0$)	Fossil Fuels	Fossil Fuels	Gas&Oil	Gas&Oil

3.2.4 Robust treatment intensity estimator & Sensitivity to solar



3.3.1 Social costs of renewable transition

- If same policy exposure: *Max Profit*{geographic factor}
    - *Example*: given a feasible set of land and grid access, solar PV shifts toward higher irradiance; gas stays closer to existing preferences
- Quantifying workplace accessibility to local community:
    - $\text{CommunityAccess}_{i,p,t}^{(b)} = \begin{cases} \frac{1}{|\mathcal{F}_i|} \sum_{j \in \mathcal{F}_i} \text{Population}_{j,t}^{(b)}/100, & \tau < 0, \\ \text{Population}_{p,t}^{(b)}/100, & \tau \geq 0 \end{cases}$
    - $\tau = t - g_p$ event time (relative to operational start g_p); $\mathcal{F}_i$ fossil plants of i prior to p's start
    - Population density: people per km^2 within buffer b km (ORNL LandScan)
- Capturing double differences matters because:
    - "Just transition": Comparing with each firm's incumbent fossil siting, new sites matter for local workforce transition
    - "E" vs. "S" dilemma: Renewable investments (pursuing "E" factor) will inevitably lead to more social costs (losing "S" factor) than fossil investments

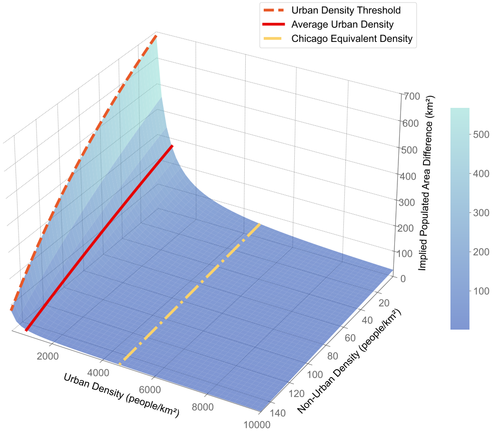
3.3.2 Social cost results and interpretation

- **Stacked model**: $\text{CommunityAccess}^{(b)}_{i,p,t} \sim \beta(\text{InvestType}_p \times \text{PostActive}_{p,t})$; EIA sample
- **Decomposing** ***populated*** (share w_c) and ***non-urban*** (share w_s) areas within 10–25 km buffer (s.t. $w_c + w_s = 1$) → Observed average population difference: $\bar{\mathcal{P}} = w_c\mathcal{P}_c + w_s\mathcal{P}_s$
  - Assume $\mathcal{P}_s = 10$ people/km^2, calculate w_c: Column (4) difference translates into 40% US small cities, 15% average US urban, or 3% central Chicago, within buffer see calculation

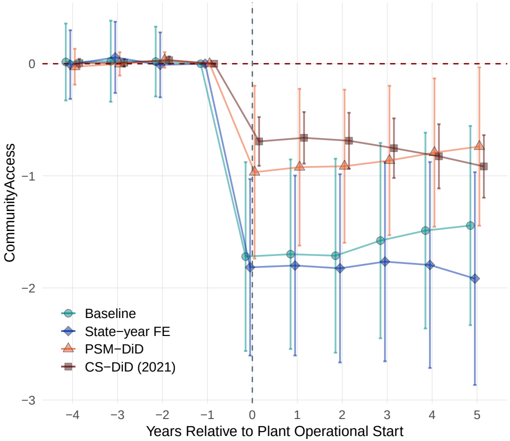
Dep. Var.: $\text{CommunityAccess}^{(b)}_{i,p,t}$ $b =$	0–10 km			10–25 km		
	(1)	(2)	(3)	(4)	(5)	(6)
$\text{InvestType}_p \times \text{PostActive}_{p,t}$	-2.686***	-2.786***	-1.658**	-1.612***	-1.830***	-0.859**
	(0.764)	(0.772)	(0.750)	(0.448)	(0.452)	(0.349)
TWFE FE	Yes	Yes	Yes	Yes	Yes	Yes
State-year FE	No	Yes	No	No	Yes	No
PSM-DiD	No	No	Yes	No	No	Yes
Observations	10,570	10,570	4,118	10,570	10,570	4,118

3.3.3 Decomposition illustration and dynamic treatment effects

Panel C: Implied Populated Area Difference (10–25 km Buffer)



Panel D: Dynamic Treatment Effects (10–25 km Buffer)

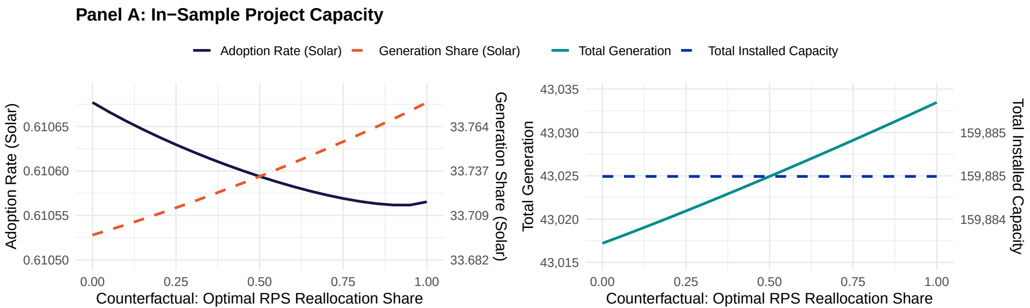


3.4.1 Transition tradeoff and policy counterfactual

- **Reasons for a choice model**
  - Reduced-form evidence is conditional on *realized* projects (what is already selected)
  - Counterfactual choice: when a firm must add capacity (to replace coal / meet demand) in a site, which technology is chosen (solar vs. gas) and what are the implied outcomes?
- **Choice rule (economic logic)**
  - Indifference choice condition: $\text{NPV}^R_{i,t} = \text{NPV}^G_{i,t} \implies \phi^\star_{i,t}$ (required solar resource)
  - If local solar resource $\phi^R_{i,t} \geq \phi^\star_{i,t}$: choose Solar ($\boldsymbol{R}$); else Gas ($\boldsymbol{G}$)
  - $\phi^R_{i,t}$: NREL estimated solar PV capacity factor (higher = sunnier)
- **From decision rule to choice probability (logit)**
  - Index: $z_{i,t} = \alpha_\phi\, \widehat{\phi}^R_{i,t} - \phi^\star_{i,t} + \beta\, Controls$
  - Map to probability: $p_{i,t} = \Lambda(z_{i,t})$ (logistic CDF), $p_{i,t} \in [0,1]$
- **Estimation (simulated method of moments)**
  - Draw shocks $\rightarrow$ compute $p_{i,t}$ $\rightarrow$ simulated solar choice probability (uniform(0,1) $\leq p_{i,t}$)
  - Choose parameters θ to minimize distance between *simulated moments* and *empirical moments* (17 moments for 14 parameters)

3.4.2 Counterfactuals

- Choose $RPS^{\star}$ to maximize $\sum_{s,t} \widehat{\phi}^{R}_{s,t}\, x_{s,t}$
  - Subject to $\sum_{s,t} x_{s,t} = \sum_{s,t} RPS_{s,t}$ and $0 \leq x_{s,t} \leq 100$
  - Greedy solution: sort state-years by irradiance ($\widehat{\phi}^{R}_{s,t}$) $\rightarrow$ fill to 100 till the sum RPS is used
  - Linear path $RPS(\lambda) = (1-\lambda)\, RPS + \lambda\, RPS^{\star}$ for $\lambda \in [0, 1]$



Extended discussion (results $\longrightarrow$ constraints)

- **Result: concentrate renewables in high-resource states**
  - Concern: limited long-distance deliverability $\Rightarrow$ curtailment risk
  - Practical: transmission expansion to move power to load centers
- **Result: large grid-integration costs for renewables**
  - Concern: intermittency $\Rightarrow$ output volatility
  - Practical: needs flexibility investments (storage / dispatchable backup)
- **Result: renewables shift to more remote areas ("E vs. S")**
  - Concern: remoteness $\Rightarrow$ harder maintenance, longer travel, job relocation
  - Practical: needs workforce planning ("just transition"), and tools that reduce on-site work (e.g., drone inspection)

Key takeaways

- **Roles of policies**:
  - Cut emission $\longrightarrow$ effectively phase out coal
  - Promote renewables $\longrightarrow$ but bring transition in low-resource locations
- **Hard green transition after brown exit** (geography):
  - Financial costs: when policy-driven buildouts in low-resource locations
  - Social costs: every buildout tends to be more remote

Exit channel: Dissect sell-retire tradeoffs and coal-to-gas substitution

- **Darmouni & Zhang (2024)**: (i) Keep ($\pi^c - \epsilon$), (ii) Sell ($P^c - \theta\epsilon$), and (iii) Retire (0)
  - π^c: operating profit; ϵ: environmental externality costs; θ: mandate stringency for selling
  - For buyers: (i) eq. pricing line: $P^c = \pi^c$, (ii) with financial frictions: $P^c = (\xi/r)\pi^c$ with $\xi/r < 1$
    - Only a fraction $\xi \leq 1$ of future operating profits π^c is pledgeable to financiers, who require an expected gross return $r \geq 1$: Purchase is feasible only if $\xi\pi^c \geq rP^c$
- **Model extension: coal-vs-gas relative fuel costs**
  - Empirical test variable: $FuelCostGap_i^{Coal\text{-}Gas}$: coal-reliant firm's standardized (firm's coal costs) – (average gas fuel costs in a state), measured in year of policy finalization ($\tau = 1$)
  - Model function: $V^g(\Delta)$, where Δ captures coal's marginal fuel-cost disadvantage relative to gas. Owner's divestiture payoff (discounted due to better alternative): $P^c - \theta\epsilon - V^g(\Delta)$

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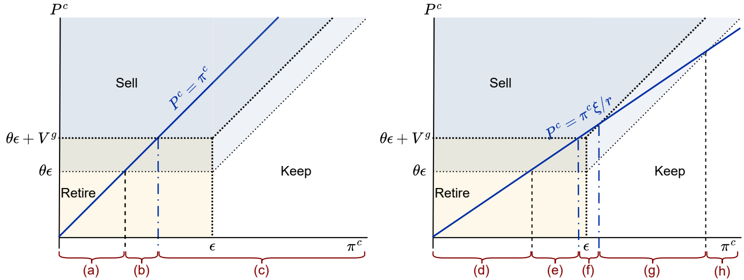
Exit channel: Illustration and empirical implication

- "Sell" and "Keep" are always feasible; "Retire" only when regulatory pressure $\theta \neq 0$
- A larger coal fuel-cost disadvantage ($V^g(\Delta)$) $\longrightarrow$ increase "Retire" & "Keep" margin

Panel A: No Financial Frictions | **Panel B: High Financial Frictions** ($\xi/r < 1$)



Owners' allocation in equilibrium (Panel A)

Buyer constraints:	*Baseline*	*With $V^g(\Delta)$*
Coal units turned off	(a)	(a) + (b)
Coal units sold	(b) + (c)	(c)
Coal units kept on	*None*	*None*

Owners' allocation in equilibrium (Panel B)

Buyer constraints:	*Baseline*	*With $V^g(\Delta)$*
Coal units turned off	(d)	(d) + (e)
Coal units sold	(e) + (f) + (g)	(f)
Coal units kept on	(h)	(g) + (h)

Calculation example for social costs: implied small-city share

- Inputs (10–25 km ring): $\bar{\mathcal{P}}_{\text{gap}} = 161$, $\mathcal{P}_s = 10$, $\mathcal{P}_c = 386$ (people/km^2)
- Implied populated-share difference:

$$w_c = \frac{\bar{\mathcal{P}}_{\text{gap}} - \mathcal{P}_s}{\mathcal{P}_c - \mathcal{P}_s} = \frac{161 - 10}{386 - 10} = \frac{151}{376} \approx 0.40$$

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