Energy Transitions in Regulated Markets

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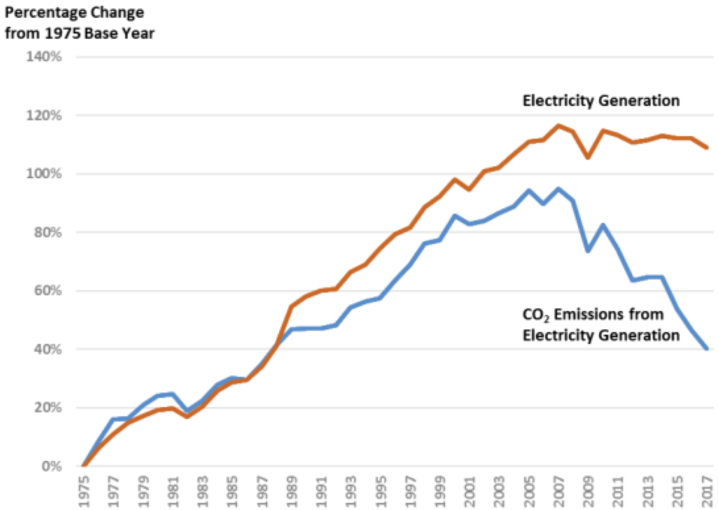
U.S. Electricity Generation Has Gotten Cleaner



Source: Congressional Research Service, 2019

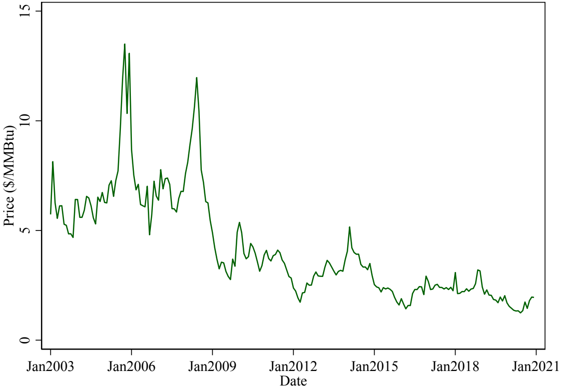
Why Has Generation Gotten Cleaner?

1) Improved Natural Gas Technologies

- Heat rates (fuel per MWh):
  - Natural gas turbine (NGT): 8,000-10,000 Btu/kWh
  - Combined-cycle natural gas (CCNG): 6,200-8,000 Btu/kWh

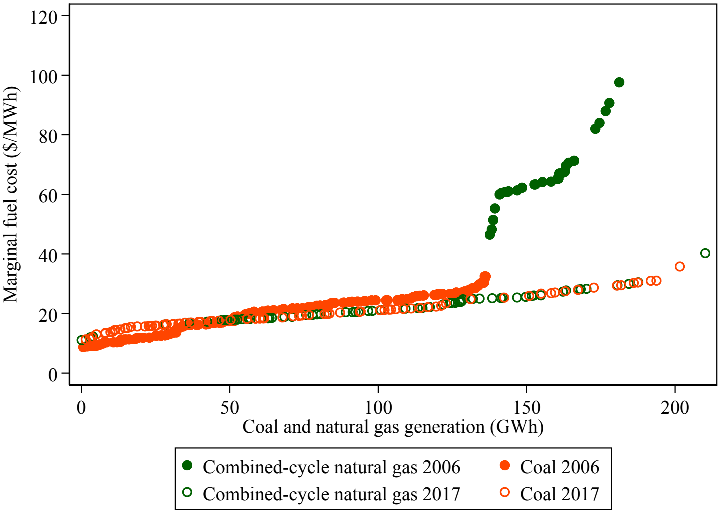
Source: Energy KnowledgeBase

2) Declining Natural Gas Fuel Prices



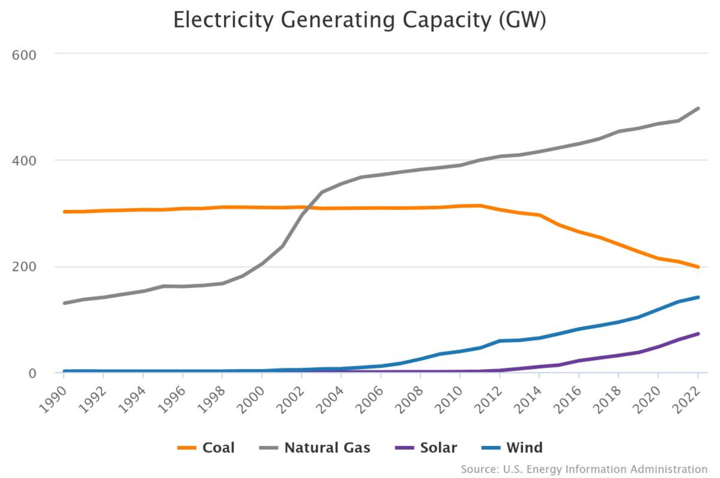
Source: Authors' calculations from analysis data

Natural Gas Fuel Costs Became Cheaper than Coal



Source: Authors' calculations from analysis data.

These Innovations Led to a Transition From Coal to Gas Capacity



- And the next energy transition to renewables has begun!

Electricity is Regulated in Much of the U.S.

- Electricity is historically viewed as a “natural monopoly.”
  - High fixed costs and low marginal costs imply that having one firm is efficient.
  - But, an unregulated monopoly would charge monopoly prices.
- Generally, *rate-of-return regulation* is used to limit the exercise of monopoly power:
  - Regulator grants the utility a monopoly to provide the service.
  - Sets a maximum price to cover costs and allow a fair rate of return on capital.
- In the electricity context, regulation has two main goals (Joskow, 1974):
  - *Reliability:* Regulator requires that the utility meet load (demand).
  - *Affordability:* It encourages low-cost generation and limits capital.
- Many states restructured electricity *generation* starting in the mid-1990s.
  - Created wholesale markets and forced utilities to sell off generation capacity.
  - 2001 CA electricity crisis stopped restructuring, leaving some states regulated.

The Current Regulatory Structure

- Regulator can observe costs, but not the costs of alternative choices.
  - Leads to broad asymmetric information issues.
  - Regulator creates an incentive structure against which the utility optimizes.
- Structure specifies:
  - Maximum rate of return on allowed capital (the “rate base”).
  - Approval process for how capital investments contribute to the rate base.
- Regulator’s task has become more complicated over the past 25 years:
  - The energy transitions have involved new technologies, changing fuel prices, and increased environmental concerns.
  - Accentuates the problem of the regulator not knowing costs of alternatives.
- This structure leads to known inefficiencies (e.g., Averch and Johnson, 1962):
  - Incentive to overinvest since utilities earn a rate of return on capital.

Retirement of Coal Capacity by Regulatory Status

- Coal exited more quickly in restructured states than in regulated ones.

Source: Authors' calculations from EIA data.

Regulatory Responses to Overinvestment

- To mitigate overinvestment, regulators require investments to be "prudent."
- Utilities may thus run old technologies to prove that they are "used and useful" (Gilbert and Newbery, 1994).

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Coal Is No Longer a Baseload Resource, So Why Run Plants All Year?

JOSEPH DANIEL, SENIOR ENERGY ANALYST | JANUARY 15, 2020, 12:12 PM EDT

This Paper

- How does the current regulatory structure affect energy transitions relative to a cost minimizer or a social planner?
- We develop and estimate a dynamic structural model of electric utility regulation.
  - Considers operations decisions and capacity investment and retirement.
  - Extends the literature on RoR regulation including allowing for long-run responses to energy transitions.
- With our estimated model, we simulate the impact of alternatives to RoR regulation:
  - Could competition facilitate the energy transition while maintaining reliability?
  - Can changing regulatory parameters improve outcomes?
  - How would carbon taxes interact with RoR regulation?

Overview of Model

- We model the regulator as having two instruments to create appropriate incentives:
  1. Offered maximum rate of return declines in utility's total variable costs, *TVC*.
  2. Extent to which coal enters the rate base depends on it being used and useful.
- Utility optimizes against the regulatory structure:
  - Long run: chooses coal retirement and combined-cycle natural gas investment.
  - Each hour: chooses generation mix and imports to meet load.
- Utility faces two conflicting incentives:
  1. Invests in and operates low-cost technologies to increase its rate of return.
  2. May use expensive coal generators to ensure that they are used and useful.

Empirical Approach

- Our model relies on both regulatory and cost parameters, including:
  - How much high *TVC* decreases the allowable rate of return.
  - How much usage increases coal's contribution to the rate base.
  - Operations and maintenance, ramping, and investment/retirement costs.
- Estimate regulatory and operations parameters with a nested fixed-point indirect inference approach that seeks to match important data correlations.
  - Find parameters that match key correlations in simulated model to data.
- Estimate investment/retirement costs with a GMM nested fixed-point approach.
  - Follow Gowrisankaran and Schmidt-Dengler (2024) algorithm that facilitates computation of models with many choices.

The Energy Transition Helps Identify the Model

- Consider a utility in 2006 with mostly coal capacity, but facing low-cost CCNG.
- Utility faces conflicting incentives:
  - If it invests in and uses CCNG, total variable costs fall and hence profits rise.
  - However, this reduces the usage rate of coal capacity.
  - Makes it harder to justify coal maintenance or upgrade expenditures as prudent.
- This tension will potentially lead the utility to keep and over-use legacy coal capacity.

- Contrast this with a utility with higher CCNG capacity before the energy transition.
  - Relative investment in and usage of CCNG identifies regulatory parameters.

Relationship to Literature

- We extend theoretical literature on RoR regulation design to study energy transitions:
  - Averch and Johnson (1962), Baumol and Klevorick (1970), Klevorick (1971,1973), Joskow (1974, 2007), Gilbert and Newbery (1994), Laffont and Tirole (1986), Armstrong and Sappington (2007).
- We add to empirical literature on RoR regulation with structural dynamic model:
  - Fowlie (2010), Davis and Wolfram (2012), Cicala (2015, 2020), Lim and Yurukoglu (2018), MacKay and Mercadal (2019), Abito (2020), Dunkle-Werner and Jarvis (2022).
- We build on literature on dynamics of electricity markets, which primarily focuses on restructured generators:
  - Myatt (2017), Eisenberg (2019), Linn and McCormack (2019), Abito et al. (2022), Elliott (2022), Aspuru (2023), Butters et al. (2023), Gowrisankaran, Langer, and Zhang (2023).

Outline of talk

Background on Regulated Electricity Industry

- State regulator is generally called Public Utility Commission.
- It acquires information from multiple sources:
  - *Integrated resource plans:* utilities describe long-run resource needs.
  - *Rate hearings:* utilities provide observed usage and cost information.
- Regulator uses information to adjust rate base and allowable rate of return:
  - Rate base determined by capital stock and prudent investments.
  - Consumer prices set to give allowable rate of return on rate base.
- We assume the regulator observes costs and usage but not costs of alternatives.
  - It therefore does not dictate choices to the utility.
  - Instead it sets a fixed regulatory framework to meet objectives.
  - Broad uncertainty like Averch & Johnson (1962) not Laffont & Tirole (1986).

Conceptual Model of Regulatory Incentives

1. Regulator uses prudence standards to limit incentive for over-investment.
   - For coal, utility demonstrates prudence by using it to meet load.
   - This limits capital but doesn't fully correct the AJ incentive.
2. Utility still doesn't have the incentive to generate with the lowest cost technologies.
   - Regulator therefore sets a maximum rate of return that is decreasing with *TVC*.
   - Incentivize utility (but imperfectly) to use lowest cost technology.
3. If a new technology suddenly becomes available:
   - AJ incentive implies that utility keeps too much of the legacy technology.
   - Prudence incentive leads to over-use of the legacy technology.
   - This may slow an energy transition.

Model of the Maximum Rate of Return

- In each year, y, regulator allows a maximum rate of return, $\bar{s}$, on its rate base of:

$$\bar{s}_y = \left(\frac{TVC_y}{CostBasis} \right)^{-\gamma}$$

- Incentivizes low costs since, for $\gamma > 0$, rate of return decreases in TVC, the total variable generation and import costs.
- Regulator uses observable fuel and import costs in an initial year, *CostBasis*, as a comparison, to capture any unavoidable costs (e.g. transmission costs).
- Use base year before the fracking revolution, when cost minimization is easier.

Model of the Rate Base

- The utility earns this rate of return on its rate base, B_y, which is the dollar value of "effective capital" K_y^e (measured in MW):

$$B_y = \alpha K_y^e.$$

- Effective capital sums over fuel/technology types $f \in \{COAL, CCNG, NGT\}$:

$$K_y^e \equiv \left[\alpha^{CCNG} K_y^{CCNG} + \alpha^{NGT} K_y^{NGT} + \alpha^{COAL} \left(\frac{exp(\mu_1 + \mu_2 U_y)}{1 + exp(\mu_1 + \mu_2 U_y)}\right) K_y^{COAL}\right],$$

- We model coal usage $U_y = \overline{Q}^{COAL} / K^{COAL}$ as influencing its effective capital.
  - Don't model this for CCNG generation, since relatively inexpensive in-sample
  - NGTs serve different purposes (e.g. peakers).
- We normalize $\alpha^{CCNG} = 1$.
- Regulator sets consumer rates such that $Revenues_y = TVC_y + \overline{s}_y \times B_y$.

Long-Run Retirement and Investment Decisions

- A utility facing this regulatory framework makes investment and retirement decisions every 3-year period, t, over 30 years, with 95% annual discount factor.
  - Utility keeps generators after this, but state doesn't evolve.
- Each period, utilities make capacity investment/retirement choices, x_t^f in turn:
  1. Choose coal capacity to retire, $x_t^{COAL} \leq 0$.
  2. Choose CCNG investment capacity, $x_t^{CCNG} \geq 0$.
- Investment costs build on Ryan (2012) and Fowlie, Reguant, and Ryan (2016):

$$\delta_0^f \mathbb{1}\{x_t^f \neq 0\} + x_t^f(\delta_1^f + x_t^f \delta_2^f + \sigma^f \varepsilon_t^f).$$

- Unobservable component is on linear marginal cost term:
  - Allows for a non-singleton density of x_t^f (Kalouptsidi, 2018; Caoui, 2023).
  - Each ε_t^f is distributed standard normal and observed before the x_t^f choice.

State and Timing for Investment/Retirement Decisions

- Investment and retirement decisions depend on:
  1. Natural gas fuel price p_t^{NG}, which follows an exogenous AR(1) process.
  2. Coal and CCNG capacity, which evolve endogenously.
  3. Time-invariant states:
     - Heat rates, coal fuel prices, demand, import supply curves, NGT capacity.
- Timing within each period is:
  1. Utility learns p_t^{NG} and makes its investment/retirement decisions
  2. Earns period profits, $\pi^*(K^{COAL}, K^{CCNG}, p^{NG})$ from operations decisions
  3. Realizes its retirements and investments

Hourly Operations Decisions

- $\pi^*(K^{COAL}, K^{CCNG}, p^{NG})$, determined by optimal operations decisions given state.
- Every hour, h, of year, y, the utility meets load with generation or imports.
  - Utility knows present and future hourly loads and import supply curves.
  - Import costs are the area under the inverse supply curve: it signs individual contracts with multiple sellers.
- Total variable costs TVC_y include import, fuel, startup/ramping, and O&M costs.
  - Import costs: supply curve depends on natural gas fuel price.
  - Fuel costs: price of fuel times fuel use per electricity generation.
  - Start-up/ramping costs: proportional to the increase in generation.
  - Operations and maintenance costs: all other costs per electricity generation.
- Hours are connected via ramping costs.
  - We don't model individual generators, so these costs are more conceptual.

Utility Operations Decision Problem

- Utility chooses generation quantities for each f across hours of the year, $\vec{q}_y$, to maximize profits conditional on fuel prices, p_y^{NG}, and fuel/technology capacities:

$$\pi^*(K^{COAL}, K^{CCNG}, p^{NG}) = \max_{\vec{q}_y} \overbrace{\left(\frac{TVC(p^{NG}, \vec{q}_y)}{CostBasis}\right)^{-\gamma}}^{\text{Rate of return}} \overbrace{B(\vec{q}_y, K^{COAL}, K^{CCNG})}^{\text{Rate base}}$$

$$\text{subject to: } \underbrace{\sum_{f=1}^{F} q_h^f + q_h^m = \ell_h \ \forall\ h}_{\text{Generation and imports meet load}} \quad \text{and } \underbrace{0 \leq q_h^f \leq K^f \ \forall\ f, h}_{\text{Capacity constraints}}$$

- We solve for the optimum with a finite horizon hourly Bellman equation.
  - State space: TVC and U to date and lagged q^{COAL} and q^{CCNG}.

Primary Data Sources

Our main sample includes utilities in the Eastern Interconnection from 2006–17.

- Generator-level information:
  - Utility ownership, generator regulatory status, efficiency, and capacity (EIA).
  - Hourly production by generator (EPA).
- Utility-level information:
  - Load-serving entities (Federal Energy Regulatory Commission, FERC).
  - Hourly load for each load-serving entity (FERC).
  - Nearest nodal price (various ISOs).
  - Annual revenue (EIA).
- State-level information:
  - Coal and gas contract fuel prices (EIA).

Summary Statistics from Data at Utility/Year Level

	Overall	2006	2017
Coal Capacity (GW)	3.51	3.77	2.86
	(4.57)	(5.03)	(3.15)
CCNG Capacity (GW)	1.95	1.07	2.97
	(3.84)	(2.94)	(5.08)
NGT Capacity (GW)	0.78	0.69	1.12
	(1.14)	(1.07)	(1.43)
Coal Fuel Price ($/MMBtu)	2.45	2.02	2.37
	(0.79)	(0.65)	(0.58)
Natural Gas Fuel Price ($/MMBtu)	5.35	7.97	3.12
	(2.27)	(1.02)	(0.42)
Utility Revenues (Billions of Dollars)	1.98	1.92	2.05
	(2.39)	(2.61)	(2.42)
Number of Unique Utilities	26	25	20

Summary Statistics from Data at Utility/Hour Level

	Overall	2006	2017
Load Served (GWh)	4.16	4.10	4.58
	(5.03)	(5.05)	(5.14)
Coal Production (GWh)	2.16	2.72	1.55
	(2.61)	(3.35)	(1.46)
CCNG Production (GWh)	1.01	0.53	1.52
	(1.76)	(1.23)	(2.34)
NGT Production (GWh)	0.10	0.07	0.21
	(0.24)	(0.20)	(0.36)
Import Quantity (GWh)	1.49	1.34	1.84
	(2.63)	(2.60)	(2.76)
Import Price ($/MWh)	33.05	40.99	23.25
	(19.33)	(21.12)	(8.24)
Number of Observations	2,476,657	214,955	175,194

Empirical Support for Our Regulatory Model

We investigate correlations in the data that underlie our model:

1. Relationship between observed rates of return and total variable costs.
2. Propensity for coal generators in regulated markets to run “out of dispatch order” relative to restructured markets.

Rate of Return on Variable Cost Measures

	Dependent Variable: Variable Profits per MW of Capacity					
Variable Costs per Capacity (Thou.$/MW)	−89.7 (94.5)	−360.1 (59.3)				
Variable Costs per High Load (Mil.$/MWh)			0.057 (0.127)	−0.462 (0.059)		
Variable Costs (Mil.$)					−0.017 (0.005)	−0.026 (0.007)
Utility FE	N	Y	N	Y	N	Y

Note: Each column presents regression results from a separate regression on our analysis data. Variable costs include fuel and import costs but not O&M and ramping costs. Variable profits are revenues net of these costs. High load is the 95th percentile of hourly load for the utility-year.

- Within utility, proxy for rate of return decreases with variable cost measures.

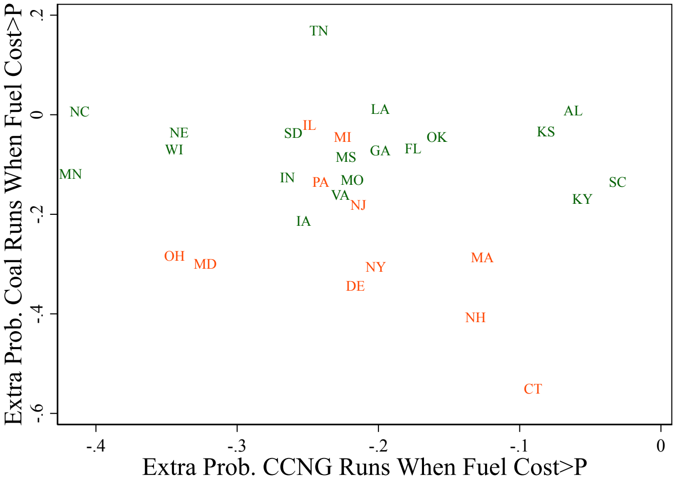
Out-of-Dispatch-Order Generation by Regulatory Status

	$\mathbb{1}\{$Fuel-Technology Operating$\}$	
	Coal	Combined Cycle Natural Gas
$\mathbb{1}\{$Fuel Cost $>$ Price$\}$	-0.031	-0.201
	(0.031)	(0.031)
$\mathbb{1}\{$Fuel Cost $>$ Price$\} \times$ Restructured	-0.122	0.005
	(0.050)	(0.029)
R^2	0.089	0.132
N	19,782,473	20,723,467

Note: Regressions are linear probability models that include state and year fixed effects. Data are for regulated and restructured utilities at the utility-hour level for the Eastern Interconnection. We cluster standard errors (in parentheses) at the state and year level.

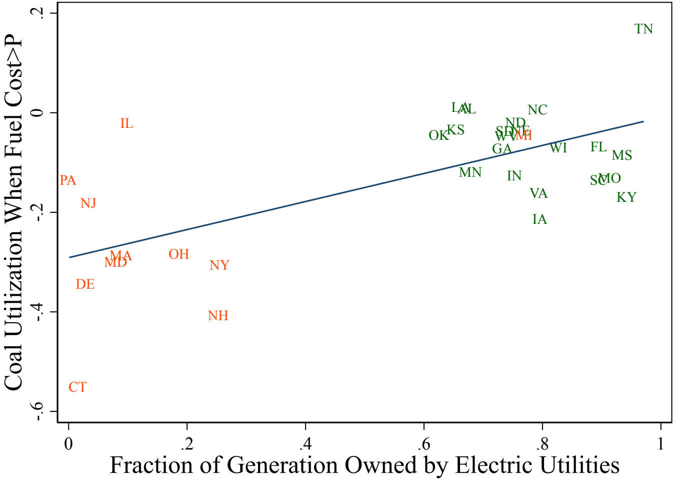
- Regulated coal (but not CCNG) runs “out of dispatch order” more frequently.

Out-of-Dispatch Order Generation Varies Across States



- Most restructured states behave differently than regulated with coal but not CCNG.

Out-of-Dispatch-Order Generation vs. Utility Ownership Share



- All regulated states have high utility ownership.
- Coal's responsiveness to low wholesale prices correlates strongly with utility ownership share.

Overview of Structural Estimation

1. Estimate import supply curves following Bushnell, Mansur, and Saravia (2008).
   - Allow intercept and slope to depend on natural gas fuel price.
2. Estimate most structural parameters from utilities' hourly generation decisions by fuel/technology type.
   - O&M and ramping cost parameters.
   - Response of maximum rate of return to total variable costs.
   - Parameters governing how much coal capacity contributes to effective capital.
3. Estimate investment/retirement costs from dynamic decisions.
   - Take as an input the annual profits in each state.
   - Estimate the operations model and simulate profits across a grid of time-varying states.

Structural Estimation: Operations Decisions

We estimate these parameters using indirect inference:

- GMM-style approach that finds parameters to match important data correlations.
- For given structural parameter vector, simulate utilities' optimal decisions.
  - Solve utility problem for each structural parameter using a full-solution Bellman equation over 8 representative weeks of data.
- Search for structural parameter vector that yields most similar regression coefficients for simulated data and real data.

Indirect Inference Regressions

Structural Estimation: Investment/Retirement Decisions

- Also estimate parameters with a full-solution GMM nested-fixed-point approach:
  - Payoffs in each state are period profits given optimal operations decisions.
- Choice variables are the coal retirement and gas investment capacities.
  - Approximate with finite grid of 10 investment levels.
  - Shock to MC of investment generates distribution of investment levels.
- Moments capture differences between model and data, for both coal and CCNG:
  - Investment/retirement: standard deviations, indicators for non-zero and quantiles, amounts, and amounts squared.
  - Interactions of above variables with capital.
- We apply Gowrisankaran and Schmidt-Dengler (2024) algorithm:
  - Idea: find ε^f cutoffs for chosen investment levels while eliminating others.
  - Quicker than simulation and continuous in parameters.

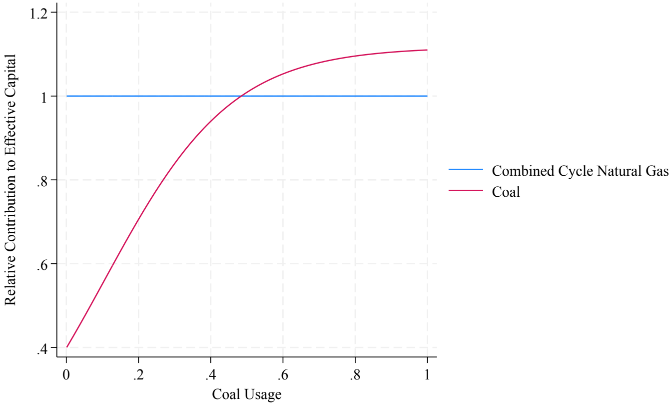
Identification

- Regulatory parameters:
  - Determinants of utility profits, α and γ: revenue variation with *TVC* and capital.
  - Coal usage incentives, μ_1 and μ_2: differences in hourly marginal coal generation across annual usage levels (and with respect to CCNG).
  - Technology contributions to the rate base, α^{COAL} and α^{NGT}: revenues change with capacity (given usage for coal).
- Operations cost parameters:
  - Ramping costs, ρ^{COAL} and ρ^{CCNG}: serial correlation in generation.
  - O&M costs, om^{COAL}, om^{CCNG}, and om^{NGT}: generation versus import choice.
- Investment and retirement cost parameters:
  - Extent to which utilities choose investment/retirement given profit differences.

Coefficient Estimates for Operations Model

Parameter	Notation	Estimate	Std. Error
Penalty for High TVC_t	γ	0.429	(0.08)
Rate Base per MW of Effective Capital (Millions $)	α	0.221	(0.06)
Coal Capacity Contribution to Effective Capital	α^{COAL}	1.117	(0.51)
Coal Usage Logit Base	μ_1	-0.589	(0.11)
Coal Usage Logit Slope	μ_2	5.641	(0.87)
NGT Contribution to Effective Capital	α^{NGT}	2.134	(1.00)
Ramping Cost for Coal (100$ / MW)	ρ^{COAL}	0.578	(0.11)
Ramping Cost for CCNG (100$ / MW)	ρ^{CCNG}	0.219	(0.31)
O&M Cost for Coal ($ / MWh)	om^{COAL}	16.350	(3.92)
O&M Cost for CCNG ($ / MWh)	om^{CCNG}	2.594	(0.10)
O&M Cost for NGT ($ / MWh)	om^{NGT}	19.767	(14.40)

Understanding Magnitudes: Coal Contribution to Effective Capital



- One MW of coal capacity increases the rate base by about 40% as much as CCNG if unused.
- When fully used, it contributes 115% as much.

Understanding Magnitudes: *TVC* penalty and Ramping Costs

- Rate of return is a function of γ and α:
  - A 500 MW change in effective capital (the mean CCNG generator capacity in the data) increases variable profits by 6.7% on average.
  - A 10% increase in *TVC* decreases variable profits by 4%, while a 10% decrease increases variable profits by 4.6%.
- Ramping costs:
  - A 100MW coal ramp costs $5,780.
  - A 100MW CCNG ramp costs $2,190.
  - Below Borrero et al. (2023) but similar to Reguant (2014).
- O&M costs:
  - Coal: $16.35/MWh, similar to Linn and McCormack (2019).
  - CCNG: $2.59/MWh, very close to EIA estimates of $2.67 and $1.96.

Operations Model Fit

	Data	Baseline
Annual Electricity Production (TWh):		
Coal	16.14	19.43
CCNG	6.93	3.94
Imports	13.04	11.46
Mean Usage Share (%):		
Coal	52.40	61.80
CCNG	35.89	21.66
Annual Costs (Millions of Dollars):		
Coal	677	809
CCNG	253	117
NGT	48	186
Total Variable Production Costs	1,644	1,338
Electricity Revenues (Dollars/MWh):	65.41	92.62

(We calculate data costs and profits using decisions in data and model parameters.)

Coefficient Estimates for Investment/Retirement Decisions

Parameter	Notation	Value	Std. Dev.
Fixed cost of coal retirement × 1e2	δ_0^{COAL}	-0.446	(9.79)
Linear coal cost per MW	δ_1^{COAL}	3.196	(0.44)
Quadratic coal cost per MW / 1e3	δ_2^{COAL}	0.117	(0.02)
Coal shock standard deviation per MW	σ^{COAL}	-0.430	(0.02)
Fixed cost of CCNG investment × 1e2	δ_0^{CCNG}	-0.509	(0.01)
Linear CCNG cost per MW	δ_1^{CCNG}	6.487	(0.08)
Quadratic CCNG cost per MW / 1e3	δ_2^{CCNG}	0.270	(0.05)
CCNG shock standard deviation per MW	σ^{CCNG}	-1.671	(0.06)

Note: All values in millions of 2006 dollars.

Retirement and Investment Cost Magnitudes

- Coal retirement:
  - 250 MW coal retirement yields $836 million in scrap value with mean cost shock.
  - Includes avoided regulatory costs (e.g. installing additional pollution abatement equipment, Gowrisankaran, Langer, and Zhang, 2023).
- CCNG investment:
  - 250 MW CCNG investment costs $1.6 billion with mean cost shock.
  - EIA estimates—which account for capital but not land, administrative, or regulatory costs—are 1/6 to 1/3 as large.

Counterfactual Approach

- First, examine counterfactual operations outcomes over utility-years in our data.
- Then evaluate the long-run impact of the energy transition:
  - Simulate investments/retirements and resulting operations over 30-year horizon.
  - Start with 2006 capacities but 2018-20 natural gas fuel price.
  - This captures utilities' reaction when hit with unexpected market shocks.
- We compare RoR regulation to different market and regulatory structures.
  - Cost minimizing competition.
  - Carbon taxes of $190/ton.
  - Changing regulatory parameters.

Operations (Short-Run) Counterfactuals

	Coal Usage (%)	CCNG Usage (%)	Total Var. Production Costs (Mil. $)	Carbon Costs (Mil. $)	Electricity Revenues ($/MWh)	Variable Profits (Mil. $)
Baseline	61.80	21.66	1,338	5,057	92.62	1,582
Social Planner	2.98	48.94	4,482	3,004	151.30	651
Cost Min., $\mu_2 = 0$	29.32	36.79	1,183	4,050	73.94	1,155
2$\times$ Usage Incentive, μ_2	47.44	29.62	1,266	4,575	92.29	1,650
Half *TVC* Penalty, γ	71.98	16.98	1,382	5,381	95.42	1,597
2$\times$ *TVC* Penalty, γ	51.59	27.01	1,291	4,735	93.40	1,633
Carbon Tax w/ RoR	63.81	31.14	6,661	5,106	238.87	792

Planner and Cost Minimization Reduce Coal Use

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Carbon Tax w/ RoR	63.81	31.14	6,661	5,106	238.87	792

But, Reliability May Suffer

	Coal Usage (%)	CCNG Usage (%)	Total Var. Production Costs (Mil. $)	Carbon Costs (Mil. $)	Electricity Revenues ($/MWh)	Variable Profits (Mil. $)
Baseline	61.80	21.66	1,338	5,057	92.62	$\boxed{1,582}$
Social Planner	2.98	48.94	4,482	3,004	151.30	$\boxed{651}$
Cost Min., $\mu_2 = 0$	29.32	36.79	1,183	4,050	73.94	$\boxed{1,155}$
2$\times$ Usage Incentive, μ_2	47.44	29.62	1,266	4,575	92.29	1,650
Half *TVC* Penalty, γ	71.98	16.98	1,382	5,381	95.42	1,597
2$\times$ *TVC* Penalty, γ	51.59	27.01	1,291	4,735	93.40	1,633
Carbon Tax w/ RoR	63.81	31.14	6,661	5,106	238.87	792

Doubling Usage Incentive *Decreases* Coal Use 23%

	Coal Usage (%)	CCNG Usage (%)	Total Var. Production Costs (Mil. $)	Carbon Costs (Mil. $)	Electricity Revenues ($/MWh)	Variable Profits (Mil. $)
Baseline	$\boxed{61.80}$	21.66	1,338	5,057	92.62	1,582
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Carbon Tax w/ RoR	63.81	31.14	6,661	5,106	238.87	792

Coal Use Inversely Related to Cost Penalty

	Coal Usage (%)	CCNG Usage (%)	Total Var. Production Costs (Mil. $)	Carbon Costs (Mil. $)	Electricity Revenues ($/MWh)	Variable Profits (Mil. $)
Baseline	$\boxed{61.80}$	21.66	1,338	5,057	92.62	1,582
Social Planner	2.98	48.94	4,482	3,004	151.30	651
Cost Min., $\mu_2 = 0$	29.32	36.79	1,183	4,050	73.94	1,155
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Carbon Tax w/ RoR	63.81	31.14	6,661	5,106	238.87	792

Carbon Taxes are Largely Just Passed Through

	Coal Usage (%)	CCNG Usage (%)	Total Var. Production Costs (Mil. $)	Carbon Costs (Mil. $)	Electricity Revenues ($/MWh)	Variable Profits (Mil. $)
Baseline	61.80	21.66	1,338	$\boxed{5{,}057}$	$\boxed{92.62}$	1,582
Social Planner	2.98	48.94	4,482	3,004	151.30	651
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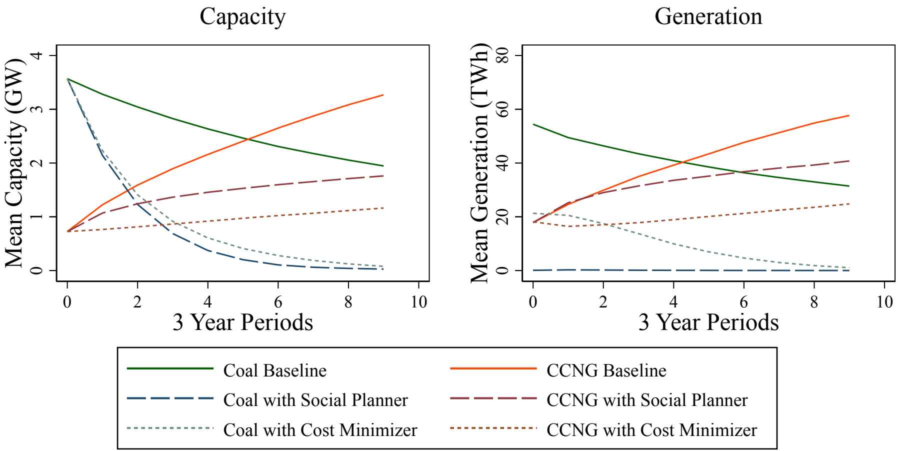
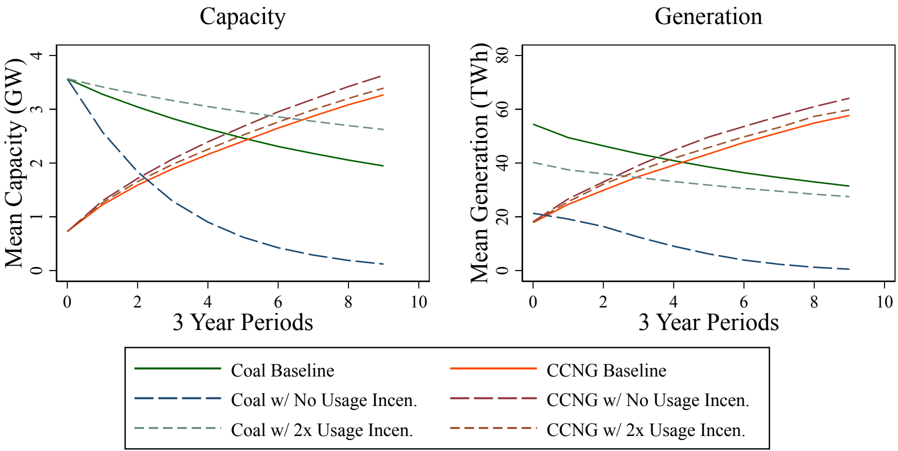
Carbon Tax w/ RoR	63.81	31.14	6,661	$\boxed{5{,}106}$	$\boxed{238.87}$	792

Capacity and Generation for Social Planner and Cost Minimizer



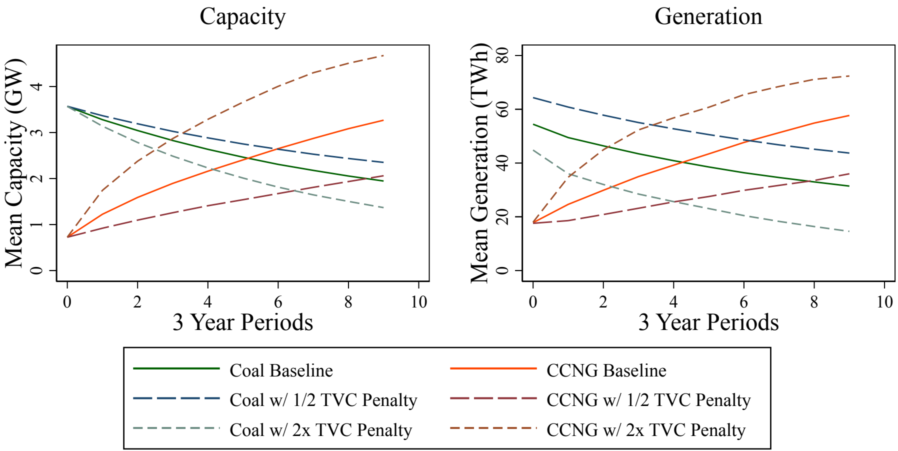
- Both social planner and cost minimizer retire virtually all coal capacity over horizon.
- Benefit of CO_2 tax compared to market incentives: less coal usage, not retirement.

Capacity and Generation for Different Coal Usage Incentives



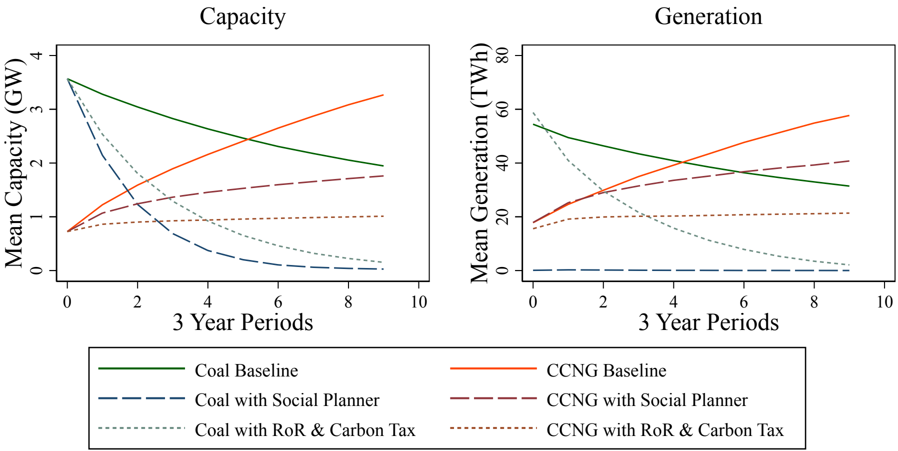
- Eliminating usage bonus causes coal exit by lowering coal's rate base contribution.
- Doubling coal usage bonus causes *less* usage because marginal incentive lower.

Capacity and Generation for Different TVC Penalties



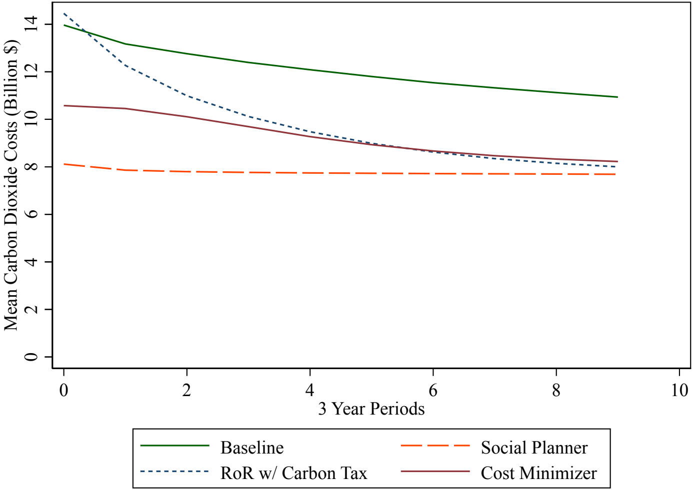
- Doubling the penalty causes a huge increase in CCNG capacity and generation.
- Only a small drop in coal capacity, but big drop in coal generation.

Capacity and Generation for Carbon Tax with RoR Regulation



- RoR carbon tax has small (and positive) short-run effect on coal generation.
- But, in the long run, capacity and generation drop to almost 0, like planner.

CO_2 Costs Across Counterfactuals



- Social planner reduces CO_2 costs more quickly than cost minimizer or RoR with carbon taxes.
- By end of 30-year horizon, all three reduce CO_2 costs about 25% below baseline.

Conclusion

- We develop and estimate a model of electricity regulation in energy transitions:
  - Regulator wants to keep rates low, but doesn't dictate production methods.
  - Utility chooses investment/retirement in long-run and generation in short-run.
- Current regulatory structure creates unintended incentives to use more coal:
  - Cost minimizer virtually eliminates coal capacity in the 30 years after natural gas prices fell, while social planner essentially stops *using* coal immediately.
  - Current RoR regulation retires only 45% of coal capacity over this horizon.
  - Marginal adjustments to RoR regulation don't approach cost minimization.
  - RoR with CO_2 tax has 90% short-run pass through, but similar long-run effect.
- Broader takeaways:
  - Cost min, planner, and RoR with CO_2 tax may require transfers for reliability.
  - Consistent with subsidies in 2022 Inflation Reduction Act.
  - Over-investment in CCNG may affect the transition to renewables.

Indirect Inference Regressions

- Regressions model key data features for model to replicate:
  1. **Penalty for High TVC_y:** Regress revenue minus costs over total capacity on TVC and utility fixed effects. Details
  2. **Value of Capacity by Type:** Regress variable profits on K_t^{COAL}, K_t^{COAL} times usage, K_t^{CCNG}, and K_t^{NGT}.
  3. **Coal usage Incentive:** Regress coal and CCNG generation share on quintiles of usage by utility-year, fuel prices, their interactions, and utility fixed effects, for hours where coal/CCNG are likely marginal. Details
  4. **Ramping Costs:** Regress hourly usage of coal and CCNG on lagged hourly usage and controls for continuation value. Details
  5. **Scaling:** Match mean generation by fuel/technology and annual variable profits by utility.
- We use clustered standard errors from regressions to determine GMM weights.

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Identification of *TVC* Penalty

- We would like to know how the rate of return varies with changes in total variable costs.
  - But the rate of return on the rate base, $\frac{Revenues_y - TVC_y}{B_y}$, is unobserved since the rate base, B, is unobserved.
- We therefore construct a variable that is correlated with this rate of return: revenues minus total variable costs divided by total capital.
- We regress this on *TVC*, including utility fixed effects to control for differences in costs across utilities, e.g. levels of transmission infrastructure costs.

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Identification of Coal Usage Incentives

- In hours with a choice of using coal, which utilities are more likely to use coal more?
  - Usage incentives will bite for utilities with low coal usage.
  - We want our regressions to capture this effect.
- Our approach:
  1. Selects hours where load is between 75% and 125% of CCNG capacity.
  2. Calculates the log of coal's hourly share of coal and CCNG generation.
     - There is a clear decision to be made since CCNG may not fully meet load.
  3. Regresses log coal share on quintiles of utility's annual coal usage, interacted with coal minus CCNG fuel costs (plus utility FEs).
- Difference in how usage affects choice identifies these incentives.
- We also match analogous regression for CCNG.
  - Difference between coal and CCNG usage patterns provides further identification.

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Coal Usage Incentives Regression Estimates

Dependent Variable: Hourly Fuel Share

	Coal	CCNG
Annual Utilization Quintiles (5th Omitted):		
Q1 Annual Fuel Utilization	0.801	−2.365
Q2 Annual Fuel Utilization	1.583	−1.073
Q3 Annual Fuel Utilization	1.607	−0.390
Q4 Annual Fuel Utilization	1.219	0.090
Interactions with Coal Cost Minus Gas Cost:		
Q1 Annual Fuel Utilization	0.044	−0.037
Q2 Annual Fuel Utilization	0.062	−0.026
Q3 Annual Fuel Utilization	0.066	0.003
Q4 Annual Fuel Utilization	0.029	0.034
Coal Cost Minus Gas Cost	−0.073	0.035

- Natural gas share monotonically increasing in annual utilization.
  - Reflects fact that hourly and annual utilization are correlated.
- However, coal share has an inverse-U shape.
  - Extra marginal utilization when annual utilization is relatively low.

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Indirect Inference Coefficient Matching

Dependent Variable	Regressor	Actual Data	Simulated Data
Usage Variable:			
Coal	Constant	0.524 (0.000)	0.524 (0.001)
CCNG	Constant	0.359 (0.001)	0.166 (0.001)
NGT	Constant	0.087 (0.001)	0.168 (0.001)
Variable Profit Proxy			
	Constant	861.102 (99.895)	1963.903 (122.898)
Rate of Return Proxy			
	Fuel and Import Costs	-26.000 (7.000)	-11.000 (2.000)
Variable Profit Proxy			
	Coal Capacity (MW)	-0.358 (0.060)	0.270 (0.017)
	Coal Capacity x Usage	0.603 (0.110)	0.054 (0.026)
	CCNG Capacity (MW)	0.254 (0.021)	0.269 (0.004)
	NGT Capacity (MW)	0.086 (0.076)	0.541 (0.016)
Log Coal Share			
	First Quintile Coal	0.461 (0.077)	-0.018 (0.070)
	Second Quintile Coal	1.072 (0.077)	1.129 (0.073)
	Third Quintile Coal	1.452 (0.076)	0.884 (0.065)
	Fourth Quintile Coal	1.263 (0.078)	1.852 (0.049)
Log CCNG Share			
	First Quintile CCNG	-2.369 (0.003)	0.000 (0.004)
	Second Quintile CCNG	-1.298 (0.004)	-2.867 (0.002)
	Third Quintile CCNG	-0.708 (0.004)	-2.796 (0.002)
	Fourth Quintile CCNG	-0.294 (0.028)	-1.614 (.)
Ramping:			
Coal Usage	Lagged Coal Usage	0.972 (0.000)	0.979 (0.002)
CCNG Usage	Lagged CCNG Usage	0.968 (0.001)	0.965 (0.000)

Identification of Ramping costs

- Ramping costs create dynamic links between hourly generation decisions.
- The ideal experiment would condition on the continuation value of each generation level and use variation in previous hour's generation to identify ramping costs:
  - Imagine 2 generators facing identical futures with high value from generation.
  - Generator A was at a low generation level and generator B was at a medium generation level last hour.
  - A's generation relative to B's identifies ramping costs: A will only increase generation if it's "worth it" from a profit standpoint.
- We regress current generation by fuel on lagged generation and controls for:
  - Fuel prices for both fuels, utility, year, and hour of day fixed effects.
  - 6 hourly leads of load, import supply curve intercept, and electricity price.
  - This is more information than the utility will have in any hour.

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Capacity and Generation for Social Planner, and Cost Minimizer with Fixed Imports