Impacts of the Clean Air Act on the Power Sector from 1938-1994: Anticipation and Adaptation

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Motivation

- Government regulation is pervasive in the modern economy
  - Landmark regulations, including the 1970 Clean Air Act (CAA), have fundamentally altered major sectors of the economy
  - Although transformative, these regulations are often the culmination of evolving social pressure and incremental policy change

Anticipation and Adaptation

- In the leadup to landmark regulations, economic agents may acquire information and take actions in anticipation of regulation

- Anticipatory behavior by producers makes it difficult to estimate the full economic impact of those regulations
  - Outcomes in the years leading up to enactment may not provide a valid pre-regulatory benchmark
  - Differences in producers' abilities to pre-emptively adapt can have important distributional consequences
  - These heterogeneous responses can have first-order effects on aggregate outcomes

This Paper

- Examines the impacts of the 1970 CAA on power plants
  - Newly digitized data on virtually every fossil-fuel power plant in the U.S. from 1938-1994
  - Extended time horizon allows us to establish a pre-regulatory benchmark that accounts for anticipation within a difference-in-differences estimation approach
  - Empirical evidence is interpreted in light of the predictions of a theoretical framework

This Paper

- Examines the impacts of the 1970 CAA on power plants
  - Identify heterogeneous impacts across cohorts of plants that were more vs. less able to anticipate regulation at time of opening
  - Assess aggregate impacts of the CAA, accounting for both the *direct* impacts on plant productivity and *indirect* impacts through cross-plant output reallocation

Main Findings

- Increased regulation in nonattainment counties led to large and persistent decreases in power plant productivity
  - Effects concentrated **only** among older plants that opened prior to 1963
  - Timing aligns with the passage of the 1963 CAA
    - plants that opened after 1963 appear to have pre-emptively adjusted behavior in anticipation of enforcement
  - Output declines in NA counties are offset by new nuclear and fossil fuel plants

Main Findings

- Failing to account for anticipation substantially alters policy estimates
  - Estimates based on post-1972 policy variation or shorter pre-regulatory time horizons are small and insignificant
- Heterogeneous impacts of the CAA significantly offset the aggregate productivity losses in the power sector
  - *Decreased* production by older/less efficient plants was offset by *increased* generation by post-1972 plants

Contributions

- This paper makes three main contributions to the literature
  - First, it demonstrates how anticipatory behavior can emerge as a response to policy uncertainty and alter costs of regulatory compliance
    - particularly when the costs of ex-post adjustment are large
    - in the context of the CAA, electric utilities have mitigated productivity costs with preemptive actions
    - mechanisms might be at play in other studies in the literature
      - Lueck and Michael (2003); Di Maria, Lange and van der Werf (2014); Malani and Reif (2015); Lemoine (2017)
    - framework may also have relevance for responses to environmental and climate policy in the developing world
      - many governments signaled shifting environmental priorities but uncertainty remains on policy implementation (Jayachandran, 2021)

Contributions

- This paper makes three main contributions to the literature
  - Second, it provides the first causal estimates of the impacts of the 1970 CAA allowing for anticipatory behavior
    - Large literature focused on later period
    - Manufacturing: Greenstone, List, and Syverson (2012)
      - TFP, very large data set, 1972-1993
    - Power industry: Gollop and Roberts (1983)
      - TFP, 56 utilities, 1973-1979

Contributions

- This paper makes three main contributions to the literature
  - Third, it shows how distributional impacts of regulation can have first-order effects on aggregate outcomes via reallocative responses
    - accounting for reallocation can substantially alter aggregate policy estimates

Historical Background

- Modern environmental movement arose in the post-WWII era
  - High profile incidents: 1948 Donora Smog and 1952 London Smog
  - 1955 Air Pollution Control Act was largely ineffective

- 1963 Clean Air Act
  - Gave federal government authority to "control" air pollution
  - Widely viewed as a signal of future legislation
  - 1967 Air Quality Act strengthened role of federal government, but enforcement remained an issue

- 1970 Clean Air Act
  - First federal effort to regulate air quality on a large scale
  - Established National Ambient Air Quality Standards (NAAQS)
  - Each county received an annual designation of **attainment** or **nonattainment** depending on whether air pollution concentrations exceeded the federal standard

The Donora Smog of 1948 began on October 27 and lasted until October 31, when rain cleared the combined

Theoretical Framework – Setup

- 3-period model
  - t=0: plant opens, chooses how to allocate capacity across dirty (θ) vs. clean (1-θ) production technologies – F_D and F_C
  - t=1,2: plant operates, chooses variable inputs V_D and V_C to maximize per-period profit from each technology – Π_D and Π_C
  - discount factor β

- Environmental regulation may pass in period t=1,2
  - reduces the per-period profit of dirty technology to $\delta\Pi_D$
  - plants can reallocate capacity across technologies by paying fixed cost **c**
  - let λ_1, λ_2 be the probabilities that legislation passes in period t=1,2 – expectation formed by electric utilities at t=0

Plant Decisions at t=1,2

- If there's no regulation, no changes – even if probs λ_1, λ_2 change
- If regulation passes at t=1 (when plants are young), then
  - adjust capacity to $\hat{\theta}$ if $\Pi(\hat{\theta}) - \Pi(\theta^*) \geq \frac{c}{1+\beta}$
- If regulation passes at t=2 (when plants are old), then
  - adjust capacity to $\hat{\theta}$ if $\Pi(\hat{\theta}) - \Pi(\theta^*) \geq c$
  - where $\Pi(\hat{\theta}) - \Pi(\theta^*) = \int_{\hat{\theta}}^{\theta^*} \Pi'_C(1-x) - \delta\Pi'_D(x)dx \approx \frac{1}{2}(\theta^* - \hat{\theta})(1-\delta)\Pi'_D(\theta^*)$

Plant Decision at t=0 (Anticipatory Effects)

- Plants choose $\boldsymbol{\theta}$ anticipating future regulation ($\boldsymbol{\lambda}_1$, $\boldsymbol{\lambda}_2$)

- Choice of $\boldsymbol{\theta}$ depends on ex-post response to regulation
  - Case 1 (always adjust, *AA*): Adjust capacity at t=1 or t=2

$$\Pi'_D(\theta^*_{AA}) = \Pi'_C(1 - \theta^*_{AA})$$

    - θ^*_{AA} is the optimal allocation – same as without regulation

Plant Decisions at t=1,2

- If there's no regulation, no changes – even if probs $\boldsymbol{\lambda}_1$, $\boldsymbol{\lambda}_2$ change

- If regulation passes at t=1 (when plants are young), then
  - adjust capacity to $\hat{\theta}$ if $\Pi(\hat{\theta}) - \Pi(\theta^*) \geq \frac{c}{1+\beta}$

- If regulation passes at t=2 (when plants are old), then
  - adjust capacity to $\hat{\theta}$ if $\Pi(\hat{\theta}) - \Pi(\theta^*) \geq c$

Plant Decision at t=0 (Anticipatory Effects)

- Choice of $\boldsymbol{\theta}$ depends on ex-post response to regulation
  - Case 2 (never adjust, *NA*): Do not adjust capacity in either t=1 or t=2

$$\left[1 - \lambda_1(1-\delta) - \lambda_2(1-\delta)\frac{\beta}{1+\beta}\right]\Pi'_D(\theta^*_{NA}) = \Pi'_C(1-\theta^*_{NA})$$

- $\theta^*_{NA} < \theta^*_{AA}$: because of losses from regulation – (1-$\boldsymbol{\delta}$) – and probs of regulation $\boldsymbol{\lambda}_1$, $\boldsymbol{\lambda}_2$
- allocation is more affected by $\boldsymbol{\lambda}_1$ than $\boldsymbol{\lambda}_2$ (regulation would affect only one period)

Plant Decisions at t=1,2

- If there's no regulation, no changes – even if probs $\boldsymbol{\lambda}_1$, $\boldsymbol{\lambda}_2$ change
- If regulation passes at t=1 (when plants are young), then
  - adjust capacity to $\hat{\theta}$ if $\Pi(\hat{\theta}) - \Pi(\theta^*) \geq \frac{c}{1+\beta}$
- If regulation passes at t=2 (when plants are old), then
  - adjust capacity to $\hat{\theta}$ if $\Pi(\hat{\theta}) - \Pi(\theta^*) \geq c$

Plant Decision at t=0 (Anticipatory Effects)

- Choice of $\boldsymbol{\theta}$ depends on ex-post response to regulation
  - Case 3 (sometimes adjust, *SA*): Adjust capacity at t = 1, do not adjust capacity at t = 2

$$\left[1 - \frac{\lambda_2}{1-\lambda_1}(1-\delta)\frac{\beta}{1+\beta}\right]\Pi_D'(\theta_{SA}^*) = \Pi_C'(1-\theta_{SA}^*)$$

- $\theta_{SA}^* < \theta_{AA}^*$: because of losses from regulation – (1-$\boldsymbol{\delta}$) – and probs of regulation $\boldsymbol{\lambda}_1$, $\boldsymbol{\lambda}_2$
- $\theta_{SA}^* > \theta_{NA}^*$: unless $\boldsymbol{\lambda}_2$ is more than twice as large as $\boldsymbol{\lambda}_1$

Theoretical Framework – Main Takeaways

- Anticipation of regulation leads plants to preemptively shift to cleaner production technologies
  - particularly with high ex-post adjustment costs (**c**, retrofits)

- There may be differences in preemptive adjustments across *different cohorts of plants* depending on
  - *informational channel*: change in priors of probability of regulation (λ_1, λ_2) and stringency (1-δ)
    - pre-1963 plants may have not expected the 1970 CAA to pass => no or limited adjustment
    - 1963-1971 plants may have expected the 1970 CAA to pass after 1963 CAA => adjustments
    - *prediction*: shift (discontinuity) in anticipatory responses in 1963

Theoretical Framework – Main Takeaways

- There may be differences in preemptive adjustments across ***different cohorts of plants*** depending on
  - *lifecycle channel*: timing of regulation in the plant lifespan (t=1 vs. t=2)
    - pre-1963 plants may have expected the 1970 CAA later in their lifespan => less likely to adjust
    - 1963-1971 plants may have expected the 1970 CAA early in their lifespan => more likely to adjust
    - *BUT* if ex-post adjustment costs binding only for older plants (case 3) => larger adjustment for pre-1963 plants
    - *prediction*: anticipatory responses should *increase* (or *decrease*) *monotonically* with plant vintage

Data Description

- Annual plant-level data for 655 fossil-fuel power plants for the period 1938-1994
  - *Newly-digitized* info on a range of plant outcomes (NSF grant)
  - Detailed data on operations allow us to estimate annual plant-level *pollution-unadjusted* productivity (PU-TFP) using quantity-based (inputs-output) approach
  - Our main sample: 387 coal-fired power plants opened before 1972
    - gas- and oil-fired plants: affected by oil shocks of the 1970s and federal government's response mandating transition to coal
    - definition: primary fuel used in the 5 first years: >1/3 total fuel

- Annual county attainment status from 1972-1994 determines regulation of power plants
  - Identification *both* based on initial 1972 designation and subsequent temporal variation

Figure C.1: Sample Data for Four Power Plants from the 1957 FPC Report

Line No.	Name of Utility	NEW BEDFORD GAS AND EDISON LIGHT COMPANY		CONSUMERS POWER COMPANY					
	Name of Plant	Cannon Street		B. C. Cobb		Bryce E. Morrow		Saginaw River	
	Region and Power Supply Area	I-2		II-11		II-11		II-11	
	Location of Plant	New Bedford, Mass.		Muskegan, Mich.		Kalamazoo, Mich.		Zilwaukee, Mich.	
1	Installed Generating Capacity-Nameplate-MW	137.5		510.5 1/		186.0		140.0	
2	Net Generation, Million Kilowatt-hours	555.7		2,785.7		679.3		166.9	
3	Plant Factor, Percent, Based on Nameplate Rating	46		--		42		14	
4	Peak Demand on Plant, Megawatts (60 Minutes)	126.4		523.9		209.5		154.0	
5	Net Continuous Plant Capability, Megawatts:								
6	(a) When not Limited by Condenser Water	147.0		504.0		192.0		151.0	
7	(b) When Limited by Condenser Water	147.0		NR		NR		NR	
8	COST OF PLANT: (Thousands of Dollars)								
9	Land and Land Rights	613		143		291		9	
10	Structures and Improvements	3,418		16,816		3,453		2,637	
11	Equipment	13,061		46,637		11,641		10,019	
12	Total Cost	17,092		63,596		15,385		12,665	
13	Cost per Kilowatt of Installed Capacity $	124		125		83		90	
14	PRODUCTION EXPENSES:	$1000	Mills Kwh	$1000	Mills Kwh	$1000	Mills Kwh	$1000	Mills Kwh
15	Operation Labor, Supervision and Engineering	424	.77	581	.21	388	.57	441	2.64
16	Operation Supplies and Expenses - Incl. Water	68	.12	136	.05	49	.07	43	.26
17	Maintenance (Labor, Material, and Expenses)	361	.65	465	.16	277	.41	377	2.26
18	Rents							2	.01
19	Steam from Other Sources or Steam Transferred	(23)	(.04)	(3)	-				
20	Joint Expenses	(10)	(.02)						
21	Total, Exclusive of Fuel	820	1.48	1.179	0.42	714	1.05	863	5.17
22	Fuel	3,424	6.16	8,801	3.16	2,918	4.30	1,089	6.52
23	Total Production Expenses	4,244	7.64	9,980	3.58	3,632	5.35	1,952	11.69
24	Production Expenses (except fuel) per Kilowatt $	5.96		-		3.83		6.16	
25	FUEL USED:	Quantity	Cost	Quantity	Cost	Quantity	Cost	Quantity	Cost
26	Coal consumed, 1000 tons of 2000 lbs. and Cost per ton $	126.5	11.73	1,142.5	7.65	318.3	9.09	126.2	9.03
27	Btu per Pound and Cost per Million Btu ¢	13,962	42.00	12,033	31.80	12,604	36.10	13,106	34.40
28	Cost per Ton, as delivered, f.o.b. Plant $		11.80		7.65		8.91		9.29
29	Oil consumed, 1000 bbls. of 42 gals. and Cost per bbl. $	150.2	2.97						
30	Btu per Gallon and Cost per Million Btu ¢	151,648	46.32						
31	Cost per Barrel, as delivered, f.o.b. Plant $		3.05						
32	Gas consumed, Million cu.ft., and Cost per 1000 cu.ft. ¢	3,901.2	37.73						
33	Btu per Cubic Foot and Cost per Million Btu ¢	1,000	37.73						
34									
35									
36									
37									
38	Average Btu per Kilowatt-hour Net Generation	15,111		9,853		11,747		17,215	
39	Average Number of Employees	119		135		96		130	
40	Type of Construction	Conventional		Conventional		Conventional		Conventional	
41	Initial Year of Plant Operation	1916		1948		1939		1924	

CHANGES OR ADDITIONS IN 1957

TURBO - GENERATOR CHARACTERISTICS

Units	MW	P.F.	P.S.I.	R.P.M.	Kv.	Year
1	156.2	85	2,000	3,600	18.0	1957
			(Added	- March,	1957)	

BOILER CHARACTERISTICS

No.	1000 lbs. Per Hour	P.S.I.	Heat F.	Reheat F.	Fuel	Year
1	1,050.0	2,300	1,050	1,000	Pulv. Coal	1957

Figure C.2: Map of Counties with Fossil-Fuel-Fired Power Plants

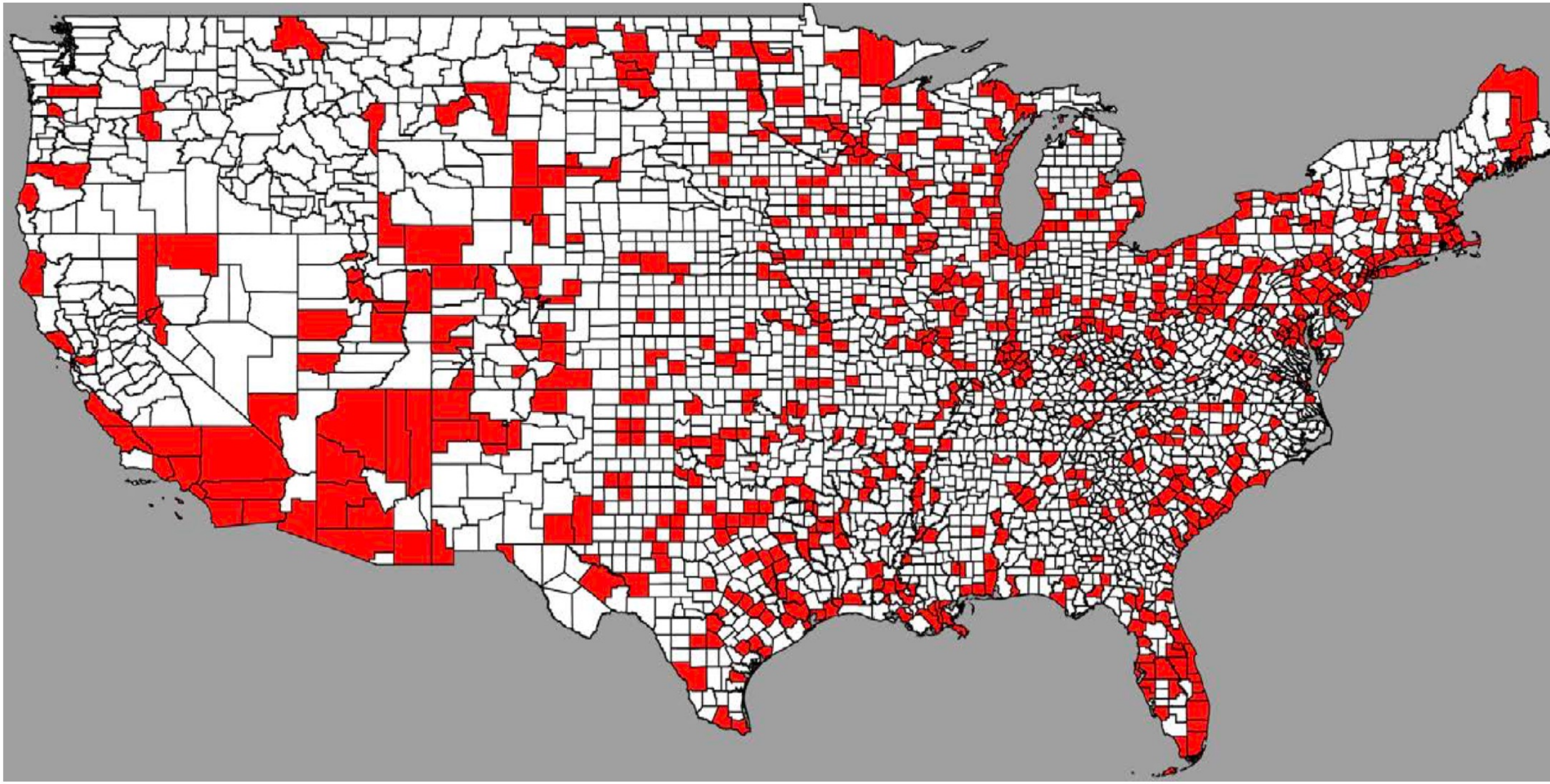


Table C.3: Summary Statistics: PU-TFP, Ouput, Inputs, and Attainment Status

Panel A: Power Plant Operations, Sample Period 1938-1994			
Variable	**No. of Obs.**	**Mean**	**Std. Dev.**
Log Pollution-Unadjusted Total Factor Productivity	13,102	0.32	0.76
Electricity Output (GWh)	13,102	2,145.06	2,568.36
Electricity Generating Capacity (MW)	13,102	472.36	506.64
Number of Employees	13,102	159.30	130.51
Fuel Burned (in Billion BTU)	13,102	22.25	25.43
Panel B: Indicator for NAAQS Noncompliance, Sample Period 1972-1994			
Variable	**No. of Obs.**	**Mean**	**Std. Dev.**
1[Out of Attainment with any NAAQS]	6,204	0.51	0.50
1[Out of Attainment with NAAQS: TSP or PM]	6,204	0.16	0.37
1[Out of Attainment with NAAQS: SO_2]	6,204	0.07	0.26
1[Out of Attainment with NAAQS: CO]	6,204	0.12	0.32
1[Out of Attainment with NAAQS: O_3 or NO_2]	6,204	0.41	0.49

Notes: This table presents summary statistics pertaining to our difference-in-differences regressions assessing the impact of nonattainment on power plant operations. We estimate annual plant-level PU-TFP based on a translog production function with capital (electricity generating capacity), labor (average number of employees), and fuel (the heat input in billions of BTU of fuel burned) using the estimation procedure developed by Ackerberg, Caves and Frazer (2015).

Empirical Strategy

- Difference-in-differences framework to estimate effects of *nonattainment* on plant outcomes *Y*

$$Y_{it} = \alpha_i + \lambda_{vt} + \theta_{st} + \beta Nonattain_{ct} + \epsilon_{it}$$

  - *i* indexes a plant in county *c* in year *t*
  - α_i: plant fixed effects
  - λ_{vt}: vintage-group-by-year fixed effects
  - θ_{st}: state-by-year fixed effects

Findings

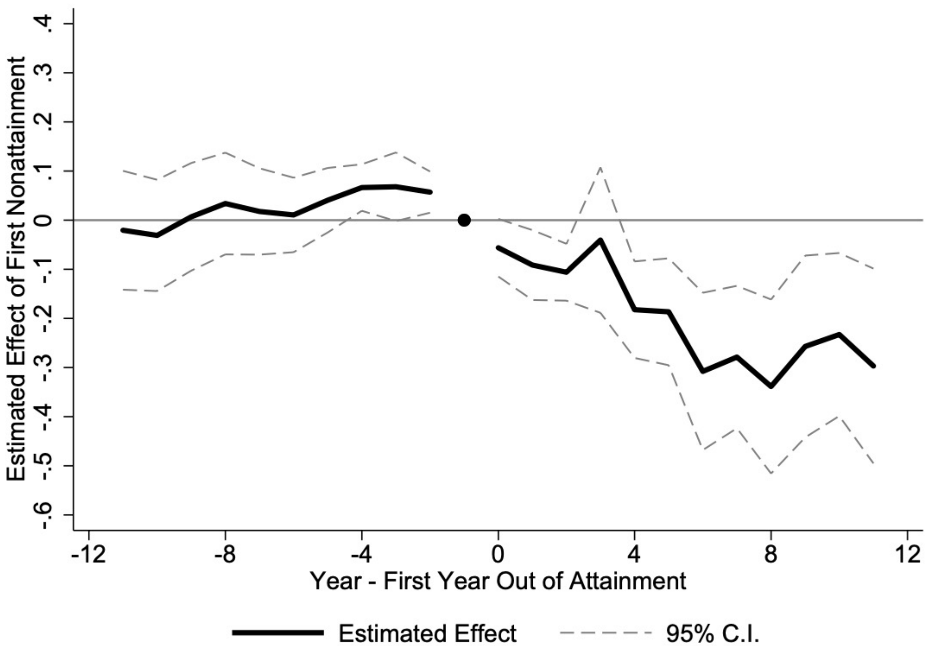
- We find negative effects of nonattainment on PU-TFP at coal-fired power plants but … only for plants built before 1963
    - effects driven by drop in output
    - effects are persistent for over a decade

  – Striking absence of an effect for 1963-1971
    - adaptation driven by anticipation

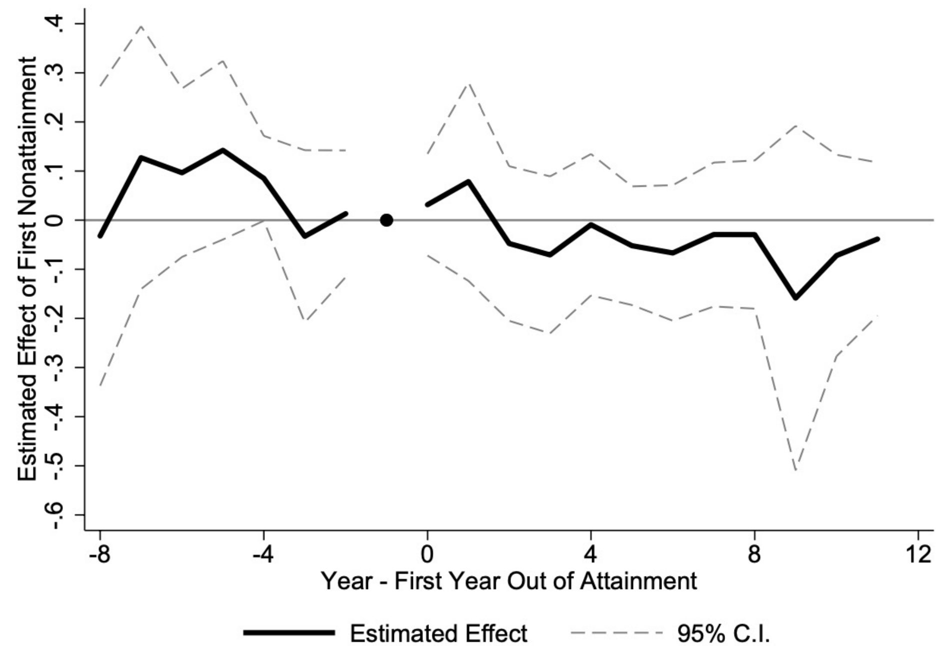
Table 1: Impacts of Nonattainment on Power Plant Operations from 1938-1994

Dep. Var. (in Logs):	(1) PU-TFP	(2) Output	(3) Fuel Use	(4) No. Employees	(5) Capacity
Panel A. Average Effects					
Nonattainment	-0.184***	-0.234***	-0.178**	-0.018	-0.100*
	(0.060)	(0.080)	(0.075)	(0.043)	(0.052)
R^2	0.681	0.828	0.791	0.851	0.908
Panel B. Effects by Plant Vintage					
NA × 1[Built Before 1963]	-0.230***	-0.283***	-0.223**	-0.025	-0.114*
	(0.067)	(0.090)	(0.084)	(0.048)	(0.059)
NA × 1[Built Between 1963-1971]	0.072	0.038	0.075	0.025	-0.024
	(0.056)	(0.079)	(0.086)	(0.057)	(0.056)
R^2	0.682	0.829	0.792	0.851	0.908
Plant FE	Y	Y	Y	Y	Y
State By Year FE	Y	Y	Y	Y	Y
Vintage Group By Year FE	Y	Y	Y	Y	Y
Mean Dep. Var.	6.965	0.322	9.409	4.768	5.601
Number of Obs.	13,102	13,102	13,102	13,102	13,102
Number of Plants	387	387	387	387	387

Figure 1: Event Study Analysis of the Impacts of First Year in Nonattainment on Power Plant Productivity



(a) Log PU-TFP, Built Before 1963



(b) Log PU-TFP, Built Between 1963-1971

Figure 2: Estimated Effect of Nonattainment on PU-TFP By Initial Year of Operation

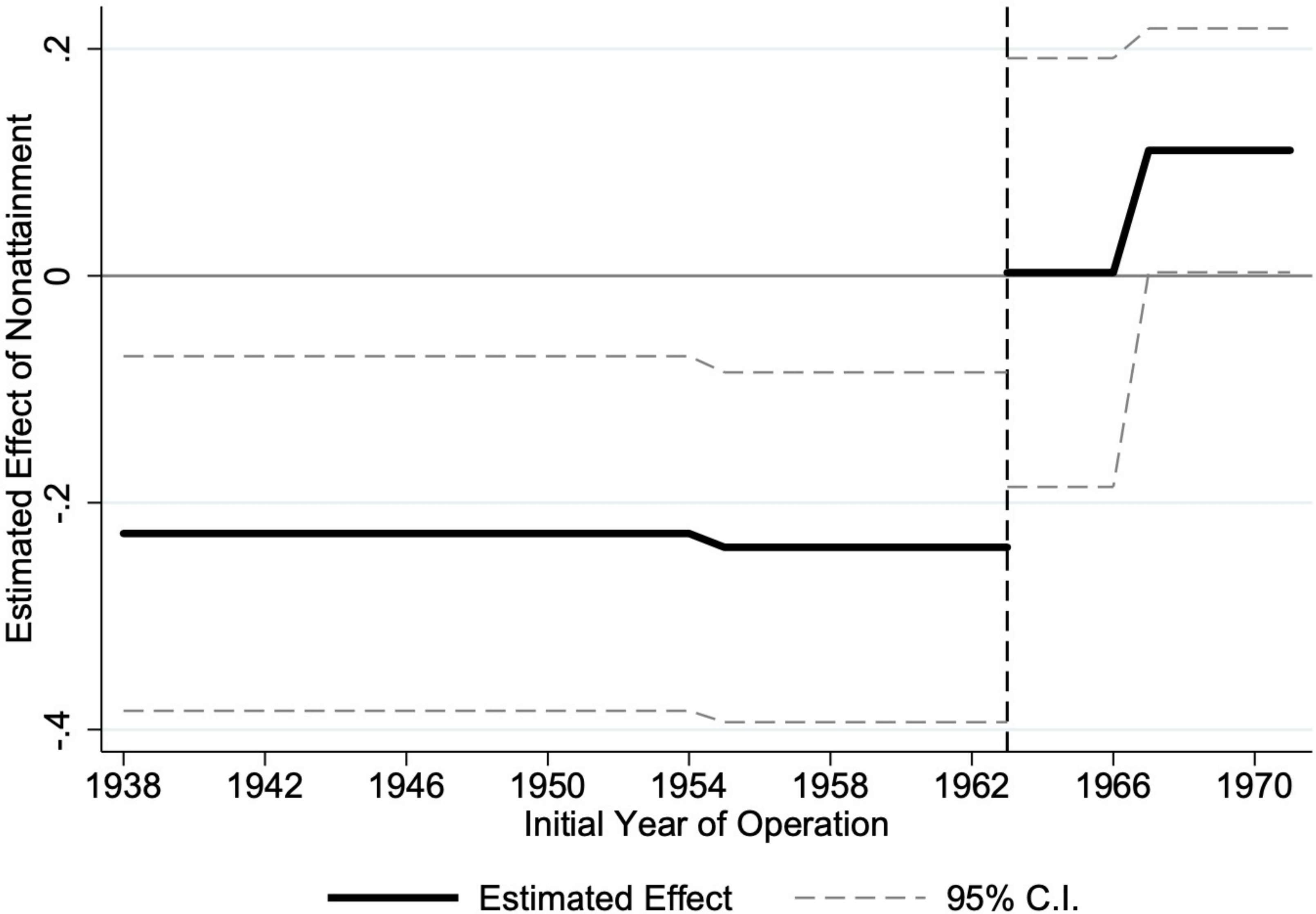
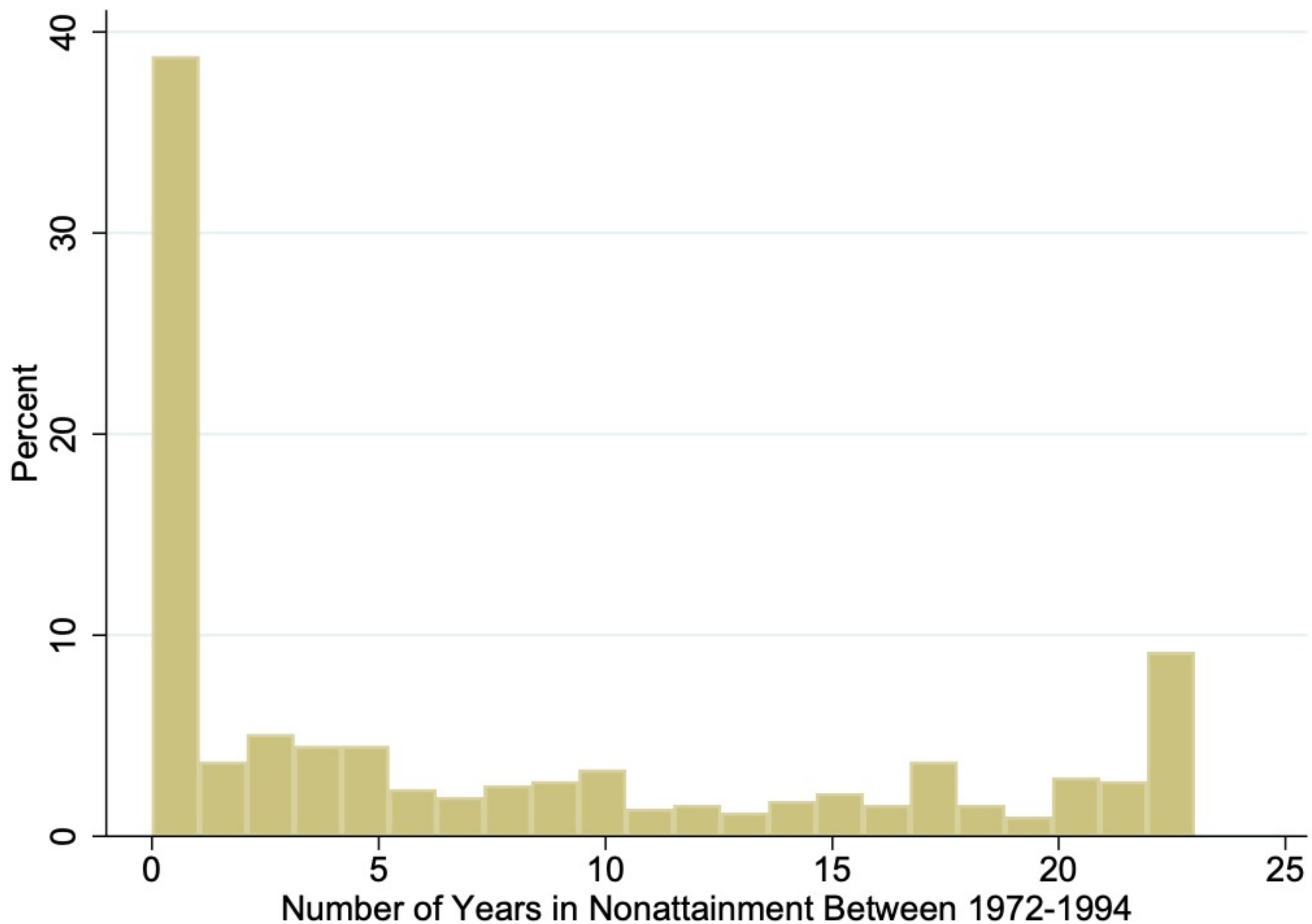


Table 2: Impacts of Nonattainment by Vintage and Years in Nonattainment

Dep. Var. (in Logs):	(1) PU-TFP	(2) Output	(3) Fuel Use	(4) No. Employees	(5) Capacity
Panel A. Effects for Plants Built Before 1963					
Years in NA ≤ 5	-0.125*	-0.180*	-0.093	0.003	-0.092
	(0.065)	(0.102)	(0.100)	(0.054)	(0.071)
Years in NA $\in [6, 10]$	-0.315***	-0.436***	-0.264*	-0.058	-0.187**
	(0.094)	(0.139)	(0.134)	(0.071)	(0.089)
Years in NA > 10	-0.464***	-0.646***	-0.509***	-0.017	-0.348***
	(0.116)	(0.167)	(0.156)	(0.093)	(0.114)
R^2	0.660	0.806	0.765	0.841	0.897
Mean of Dep. Var.	0.238	6.813	9.277	4.756	5.479
Number of Obs.	11,446	11,446	11,446	11,446	11,446
Number of Plants	321	321	321	321	321
Panel B. Effects for Plants Built Between 1963-1971					
Years in NA ≤ 5	-0.097	-0.197*	-0.208**	-0.114	-0.106
	(0.082)	(0.104)	(0.101)	(0.069)	(0.069)
Years in NA $\in [6, 10]$	-0.006	-0.101	-0.076	-0.079	-0.106
	(0.092)	(0.131)	(0.141)	(0.113)	(0.105)
Years in NA > 10	-0.020	-0.162	-0.146	-0.105	-0.150
	(0.103)	(0.147)	(0.153)	(0.140)	(0.123)
R^2	0.756	0.937	0.932	0.938	0.958
Mean of Dep. Var.	0.880	8.011	10.335	4.897	6.465
Number of Obs.	1,656	1,656	1,656	1,656	1,656
Number of Plants	66	66	66	66	66
Plant FE	Y	Y	Y	Y	Y
State By Year FE	Y	Y	Y	Y	Y
Vintage Group By Year FE	Y	Y	Y	Y	Y

Figure C.9: County-Level Distribution of the Number of Years Facing Nonattainment



Robustness Checks & Heterogeneity

- Productivity effects robust to
  - larger coal plants
  - one-plant utilities
  - states w/o standards by 1966

- Productivity effects driven by
  - first nonattainment 1972-1977
    - Goodman-Bacon (2021) decomposition: ~50% T vs. NT
  - ambient ozone NAAQS (similar to GLS 2012)

Evidence for Anticipation

- Pre-emptive adoption of pollution control technologies
- Patenting activity (innovation)
- Siting of new plants away from counties with pollution monitors

Installation of Pollution Control Technologies

Table 6: Impacts of Nonattainment and Vintage on the Adoption of FGP and FGD

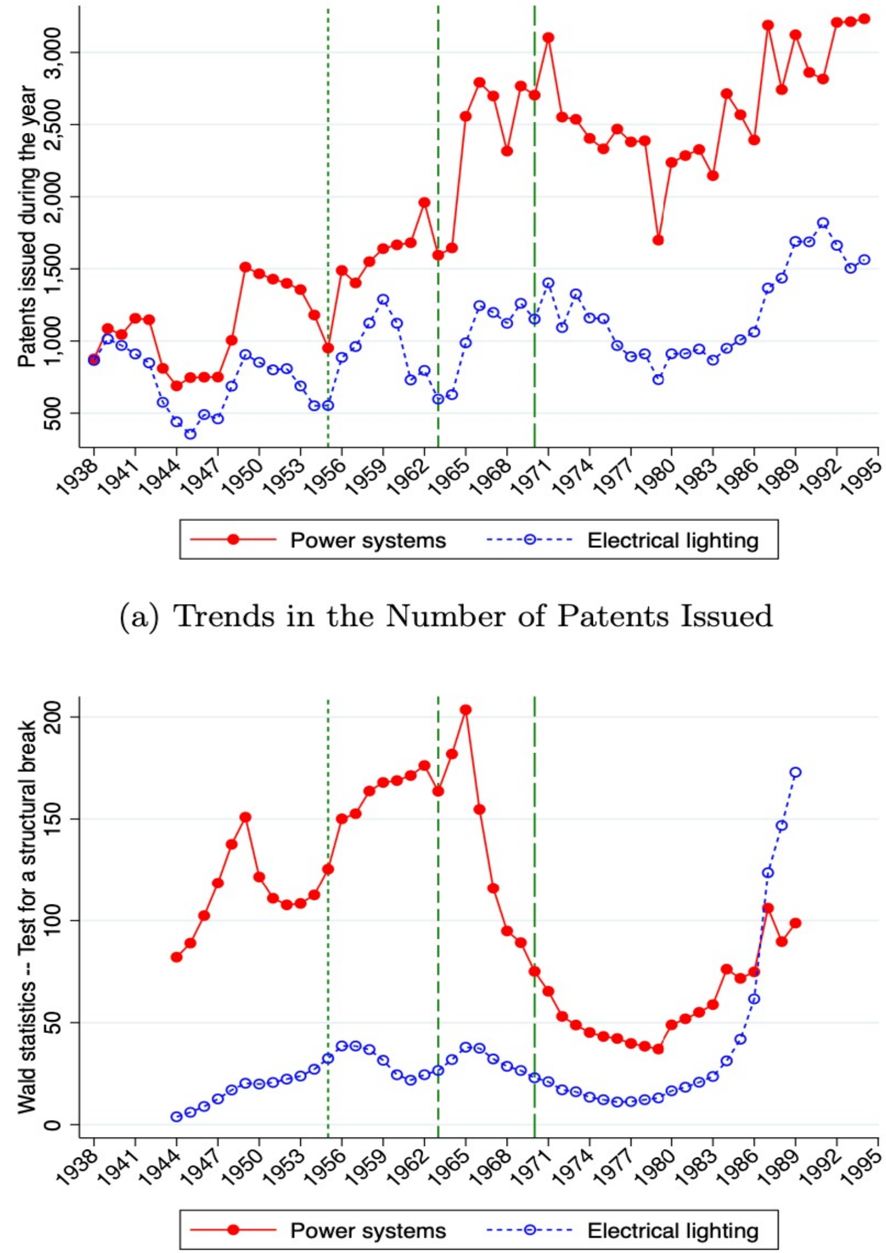
	(1)	(2)	(3)	(4)
Dependent Variable	1[FGP]	1[FGD]	1[FGP]	1[FGD]
1[Built Between 1963-1971]	0.060*	0.028		
	(0.033)	(0.026)		
1[Built After 1972]	0.062**	0.278***		
	(0.029)	(0.043)		
First NA × 1[Built Before 1963]			-0.077*	0.032
			(0.042)	(0.023)
First NA × 1[Built Between 1963-1971]			0.069	-0.064
			(0.077)	(0.049)
First NA × 1[Built After 1972]			0.018	-0.145**
			(0.103)	(0.056)
R^2	0.483	0.217	0.820	0.834
Mean of Dep. Var.	0.557	0.077	0.557	0.077
Number of Obs.	15,431	15,431	15,431	15,431
Number of Plants	562	562	562	562
Evernonattainment Indicator	Y	Y		
Year FE	Y	Y		
Plant FE			Y	Y
State By Year FE			Y	Y

Table 5: Impact of First Nonattainment on Log Coal Prices

Dep. Var.: Log Coal Price	(1)	(2)	(3)
First NA	0.058***		
	(0.018)		
First NA × 1[Built Before 1963]		0.059***	
		(0.020)	
First NA × 1[Built Between 1963-1971]		0.057*	
		(0.031)	
First NA × 1[Years in NA ≤ 5]			0.040**
			(0.016)
First NA × 1[Years in NA ∈ [6,10]]			0.103***
			(0.026)
First NA × 1[Years in NA >10]			0.140***
			(0.034)
R^2	0.870	0.870	0.871
Mean of Dep. Var.	3.629	3.629	3.629
Number of Obs.	11,751	11,751	11,751
Number of Plants	386	386	386
Plant FE	Y	Y	Y
State By Year FE	Y	Y	Y
Vintage Group By Year FE	Y	Y	Y

Patents

Figure A.3: Patents Related to Power Systems and Electrical Lighting



(a) Trends in the Number of Patents Issued

(b) Wald Statistics for Tests of Unknown Structural Break

Siting of New Power Plants

Table A.1: Where Electric Utilities Site Plants Before and After the Clean Air Act

Dependent Variable	(1) 1[County has a Pollution Monitor Before 1963]	(2) 1[County has a Pollution Monitor Before 1963]	(3) 1[County Ever in Nonattainment (ENA)]
1[Built Between 1955-1962]	-0.026 (0.036)	-0.044 (0.041)	0.045 (0.030)
1[Built Between 1963-1971]	-0.132*** (0.046)	-0.148** (0.066)	-0.057 (0.039)
1[Built Between 1972-1994]	-0.102*** (0.036)	-0.078** (0.035)	-0.064* (0.034)
State FE	Y	Y	Y
ENA Counties Only		Y	
R^2	0.156	0.166	0.194
Mean of Dep. Var.	0.326	0.395	0.811
Number of Obs.	1,083	878	1,083

Spillovers

- How did electric utilities compensate for the forgone output of older plants?

- We explore the effects of nonattainment spillovers on nearby producers
  - Existing plants
  - New plants

Effects on Existing Plants in Attainment Counties

Table 4: Spillover Impacts of Nonattainment in Nearby Counties on Log Output

Dependent Variable: Log Output	(1) State	(2) Utility	(3) State	(4) Utility
Capacity-Weighted Spillover NA	-0.215	-0.144		
	(0.141)	(0.184)		
Output-Weighted Spillover NA			-0.209	-0.102
			(0.137)	(0.187)
R^2	0.858	0.841	0.858	0.841
Mean of Dep. Var.	6.345	6.313	6.345	6.313
Number of Obs.	2,911	2,383	2,911	2,383
Number of Plants	120	87	120	87
Plant FE	Y	Y	Y	Y
Vintage Group By Year FE	Y	Y	Y	Y

Effects on New Sources of Generating Capacity

Table D.8: Impact of Proportion of Counties in Nonattainment on State-Level Capacity

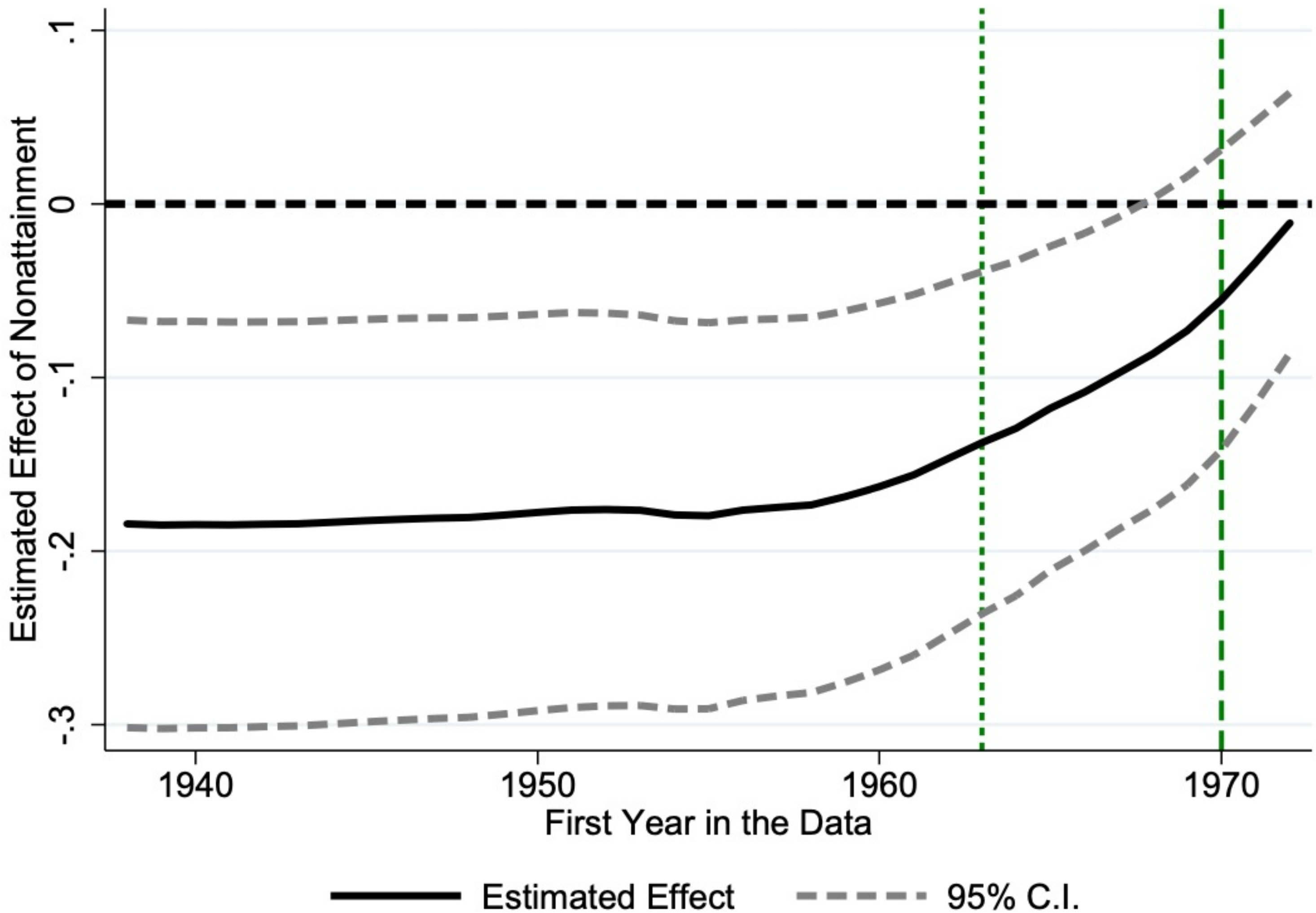
Dep. Variable: Capacity (in MW)	(1) Fossil Fuel: ST or IC	(2) Fossil Fuel: GT or CC	(3) Nuclear	(4) Hydro
Prop. in Nonattainment	3972.5*	1321.3***	1450.4**	-501.5
	(2182.9)	(491.2)	(713.2)	(948.7)
R^2	0.687	0.581	0.539	0.705
Mean of Dep. Var.	4,249.4	588.3	607.1	1,087.9
Number of Obs.	2,736	2,736	2,736	2,736
Number of States	48	48	48	48
State FE	Y	Y	Y	Y
Year FE	Y	Y	Y	Y

The Importance of Establishing a Pre-Regulatory Baseline

- The literature on the CAA has relied almost exclusively on post-1972 policy variation
- None of the literature has used data that pre-dates the passage of the 1963 CAA

The Importance of Establishing a Pre-Regulatory Baseline

Figure 3: Impacts of Nonattainment on PU-TFP by Initial Sample Year



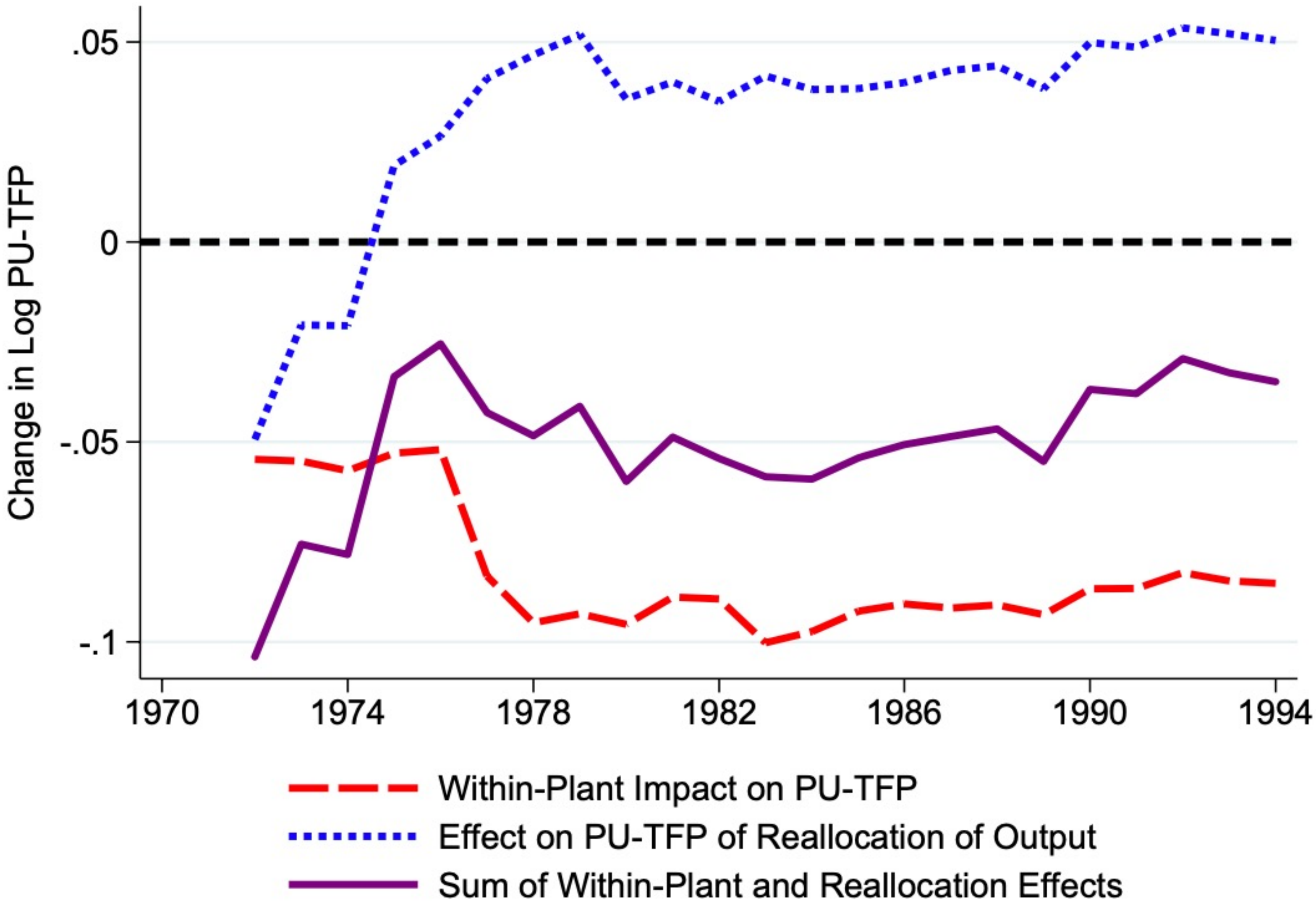
Aggregate Productivity Effects of the CAA

- Did the distributional impacts of the CAA help mitigate the economic costs?
  - Older/less efficient plants reduced output
  - Offset by *increased* generation by post-'72 plants

  - We can apply the DiD estimates to calculate the impact of the 1970 CAA on aggregate PU-TFP:

$$\Delta\overline{\text{PU-TFP}}_t = \sum_i [\underbrace{\frac{\text{Output}_{i,t}}{\sum_i \text{Output}_{i,t}} \cdot \Delta\text{PU-TFP}_{it}}_{\text{Within-Plant Efficiency}} + \underbrace{\frac{\Delta\text{Output}_{i,t}}{\sum_i \text{Output}_{i,t}} \cdot \text{PU-TFP}_{it}}_{\text{Across-Plant Reallocation}}]$$

Figure 4: Nationwide Effects of the 1970 CAA on Power Plant Productivity



Agg TFP Effects of 1970 CAA (NAAQS): ↓2.7% ($3.3 billion/yr)

Concluding Remarks

- This paper makes three main contributions
  - First, it demonstrates how anticipatory behavior can emerge as a response to policy uncertainty and alter costs of regulatory compliance
  - Second, it provides the first causal estimates of the impacts of the 1970 CAA that account for anticipatory behavior
  - Third, it shows how accounting for reallocative responses can substantially alter aggregate policy estimates

Concluding Remarks

- The historical experience in the U.S. may offer guidance to policymakers
  - Older plants unable to adapt operations in response to new environmental regulation even in the long run
  - Economic costs of regulation mitigated primarily through the reallocation of output across plants
  - To the extent that incumbent producers bear the economic costs of regulatory compliance and have disproportionate political influence
    - environmental policy may be enacted slowly and carve out exemptions for existing emitters

Concluding Remarks

- The historical U.S. experience may offer insights for environmental and climate policy in modern settings
  - credible signals of future regulatory oversight, even in the distant future, can induce substantial and immediate adjustments among producers
    - especially when decisions involve nearly irreversible investment

Thank You!

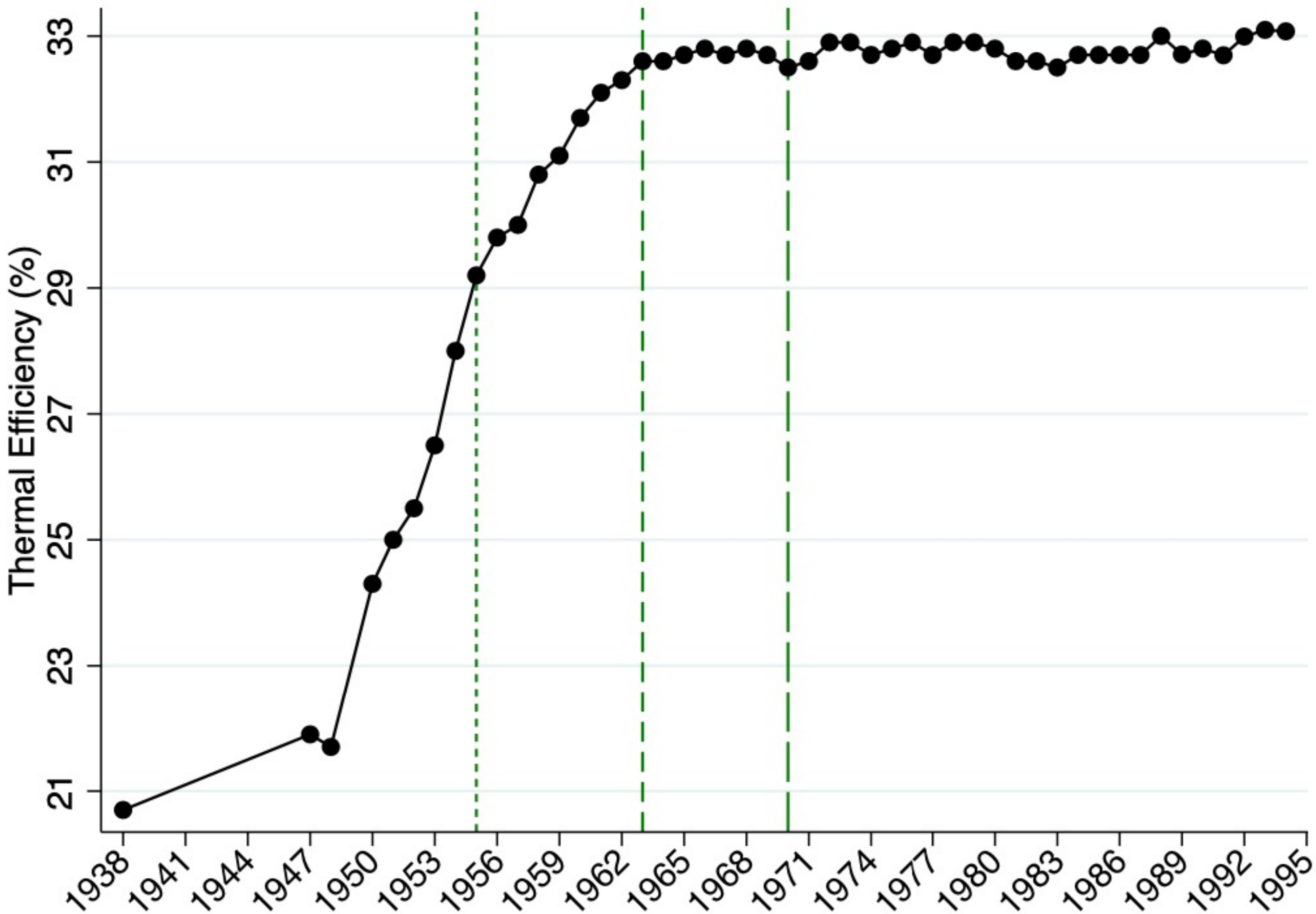
- Questions? Comments?
  - edsons@andrew.cmu.edu

Slide Appendix

Figure A.4: Real Construction Cost Index For Coal-Fired Power Plants

Notes: This figure reproduces Figure 2 from Joskow and Rose (1985). It plots an index of construction costs per kilowatt for coal-fired electricity generating units. Construction costs decline during the early 1960s, stabilize in the mid 1960s, and then increase starting around 1966 to a level that by 1980 is substantially higher than the level in 1960.

Figure A.7: Trends in Power Plant Thermal Efficiency



Notes: This figure displays the national average thermal efficiency of fossil-fueled steam-electric plants from 1938-1994. 100% thermal efficiency corresponds to 3,412 BTU of heat input energy producing 1 kWh of electricity. The data sources for this figure are (i) for the period 1938-1955:

Table A.3: Number of Years in Operation By County Attainment Status

Dep. Var.: Log of the Number of Years that the Plant is Operating	(1)	(2)	(3)	(4)
Ever Nonattainment	0.149*	0.898***		
	(0.082)	(0.334)		
ENA × 1[Built Before 1963]	0.515***	0.143		
	(0.057)	(0.308)		
Number of Years in Nonattainment			0.001	0.054*
			(0.003)	(0.028)
# of Years in NA × 1[Built Before 1963]			0.028***	0.018
			(0.003)	(0.027)
Capacity (GW)	0.081	1.057***	0.012	0.938**
	(0.073)	(0.396)	(0.072)	(0.388)
Constant	3.066***	3.281***	3.267***	3.496***
	(0.071)	(0.111)	(0.053)	(0.098)
Mean of Dep. Var.	3.480	3.480	3.480	3.480
Number of Obs.	387	387	387	387
Censored Model?		Y		Y

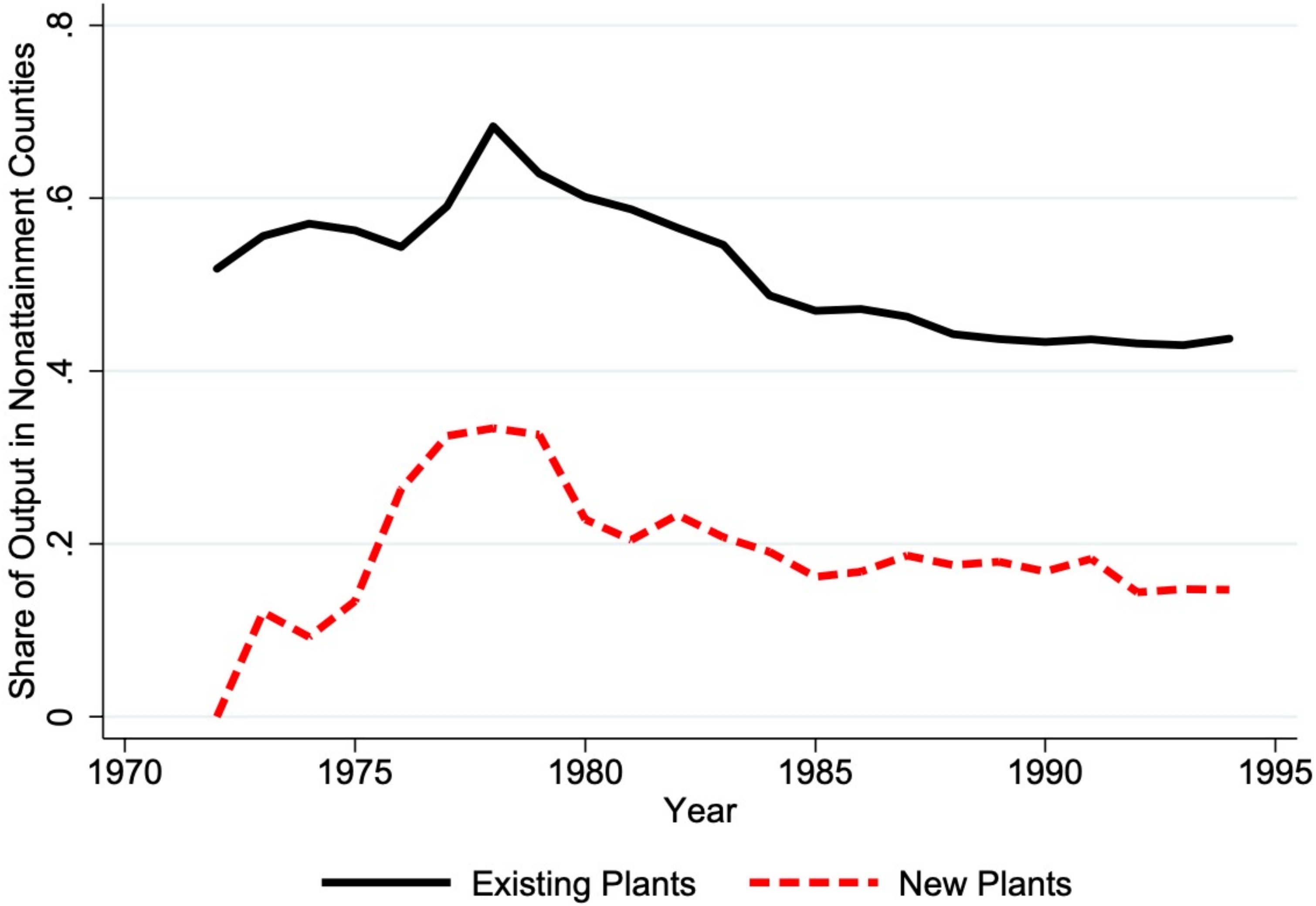
Table C.1: Number of Plants by Attainment Status and Vintage

Panel A. Number of Coal-Fired Power Plants			
	Built Before 1963	Built Between 1963-1971	Built After 1972
Always Attainment	104	24	105
Ever Nonattainment	227	44	65
Total	331	68	170
Panel B. Proportion By Vintage			
	Built Before 1963	Built Between 1963-1971	Built After 1972
Always Attainment	0.31	0.35	0.62
Ever Nonattainment	0.69	0.65	0.38

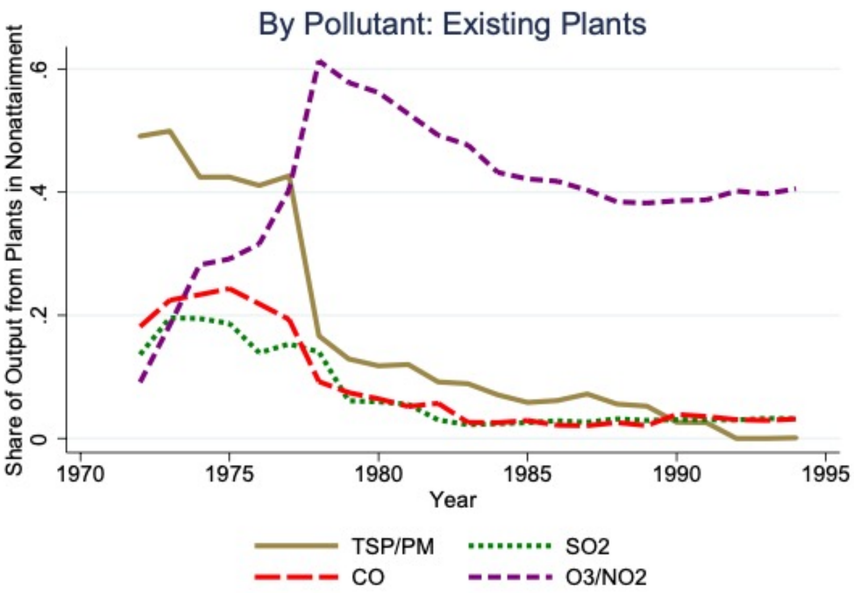
Table C.2: Attainment Status versus Lagged Attainment Status

Panel A. Number of Observations From 1972-1994		
	Attainment in Year t	Nonattainment in Year t
Attainment in Year *t-1*	4,417	2
Nonattainment in Year *t-1*	2	13
Panel B. Conditional Probability		
	Attainment in Year t	Nonattainment in Year t
Attainment in Year *t-1*	1.00	0.00
Nonattainment in Year *t-1*	0.13	0.87

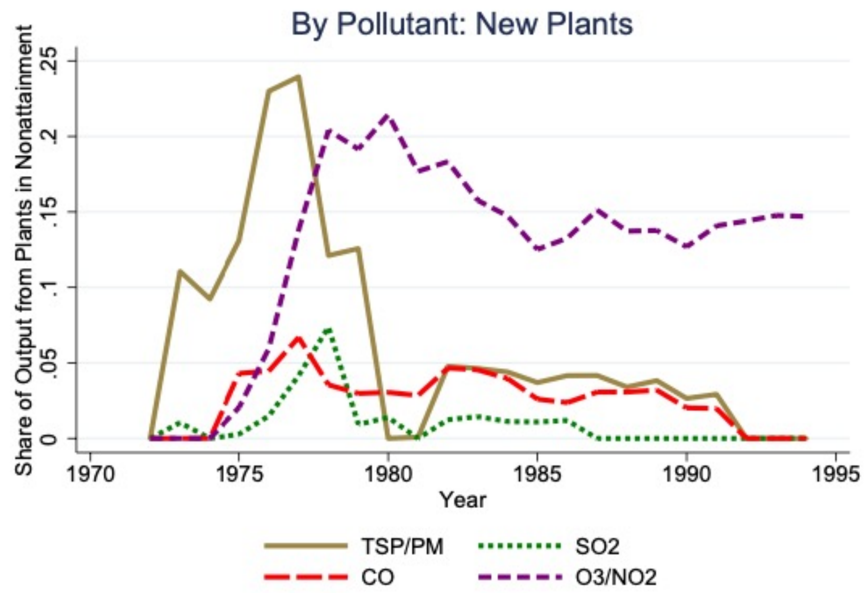
Figure C.3: Proportion of Electricity Generation Produced in Nonattainment Counties



(a) Share of Output from Nonattainment Counties: Any Pollutant Standard



(b) Share of Output from Nonattainment Counties by Pollutant – Existing Plants



(c) Share of Output from Nonattainment Counties by Pollutant – New Plants

Figure C.4: Annual Total Electricity Generating Capacity by Source Type

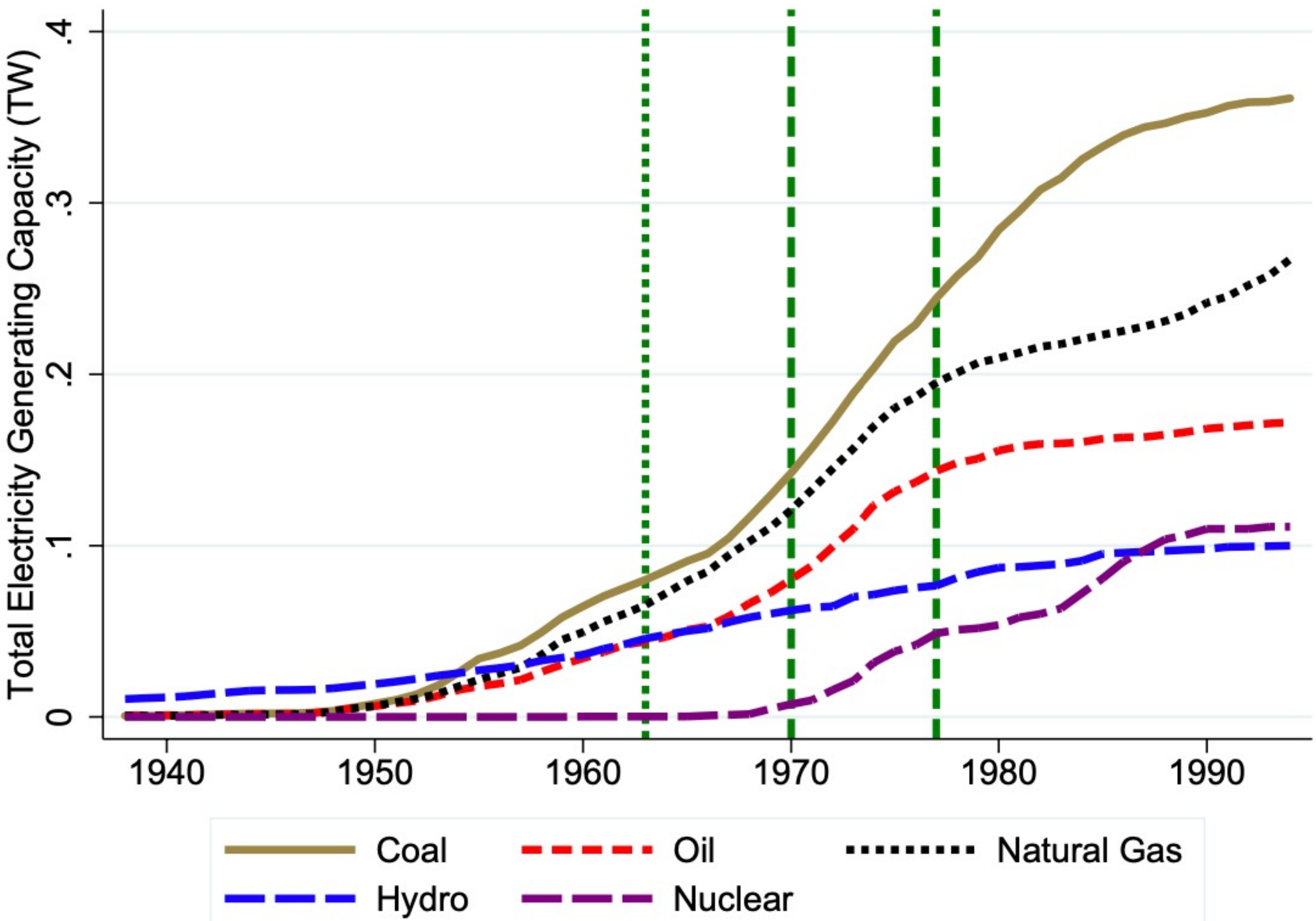
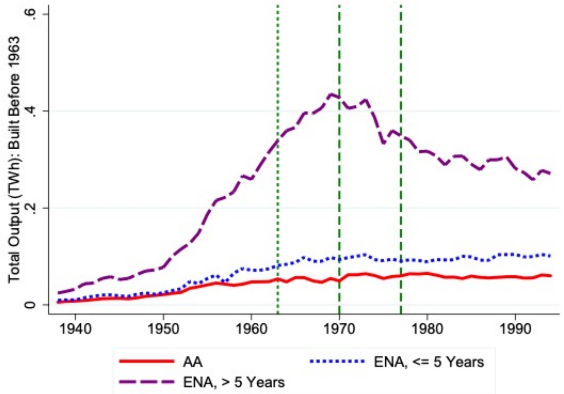


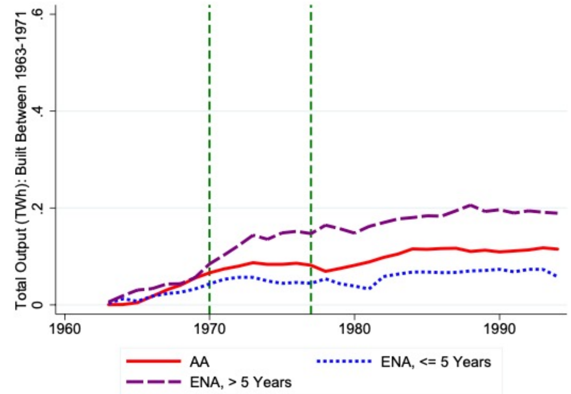
Table D.2: Impacts of Nonattainment on Power Plant Productivity from Alternative Specifications and Samples

Dep. Var.: Log PU-TFP	(1) Primary	(2) Larger	(3) One Plant Utilities	(4) No State Standard
Nonattainment	-0.184***	-0.179**	-0.368**	-0.184***
	(0.060)	(0.068)	(0.159)	(0.066)
R^2	0.681	0.684	0.873	0.684
Mean of Dep. Var.	0.322	0.429	0.205	0.303
Number of Obs.	13,102	10,325	2,163	11,210
Number of Plants	387	285	144	327
Plant FE	Y	Y	Y	Y
State By Year FE	Y	Y	Y	Y
Vintage Group by Year FE	Y	Y	Y	Y

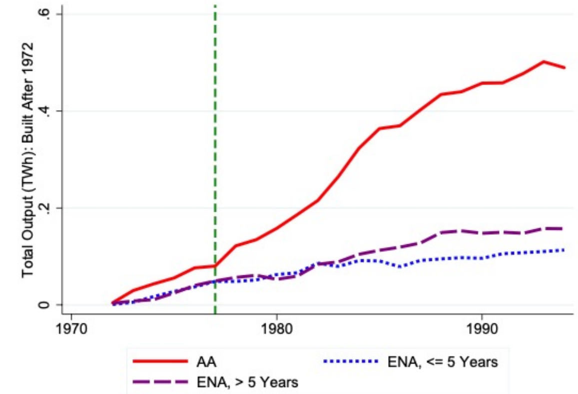
Figure C.6: Annual Total Electricity Generation and Capacity for Coal Power Plants by Vintage and Years in Nonattainment



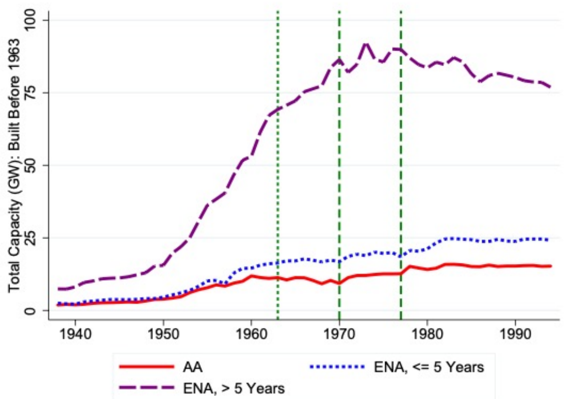
(a) Output – Built Before 1963



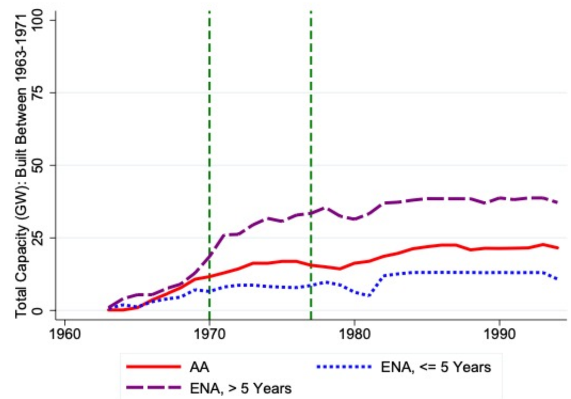
(b) Output – Built Between 1963-1971



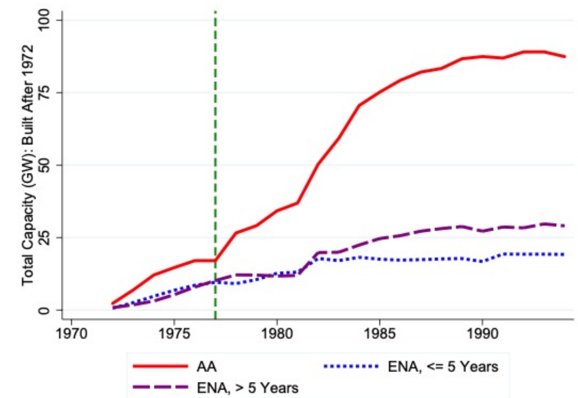
(c) Output – Built After 1972



(d) Capacity – Built Before 1963



(e) Capacity – Built Between 1963-1971



(f) Capacity – Built After 1972

Figure C.7: Annual Average Total Factor Productivity for Coal Power Plants by Vintage and Attainment Status

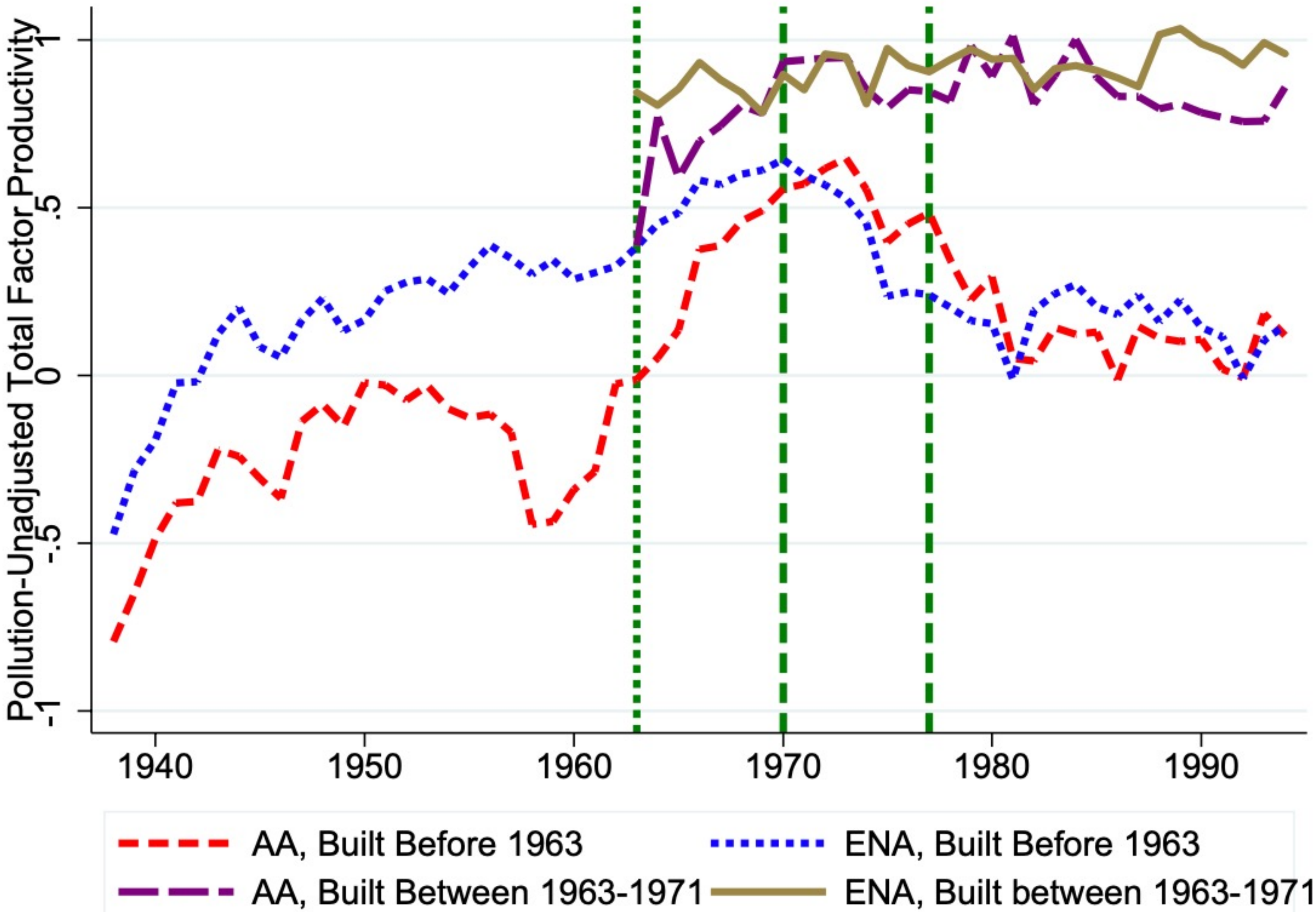
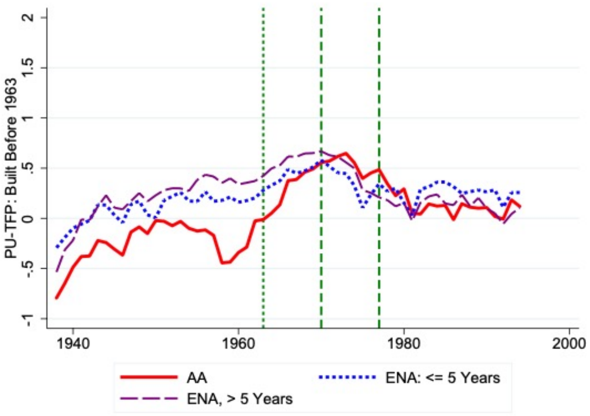
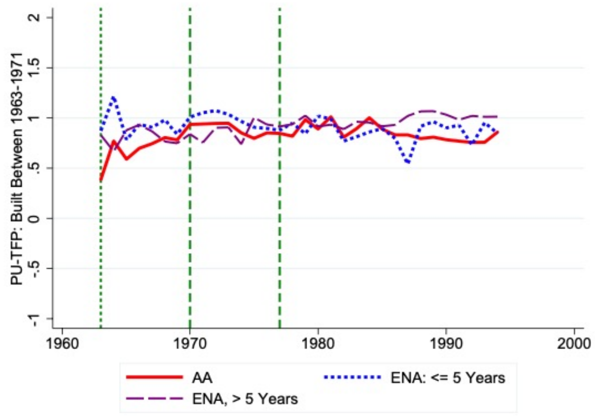


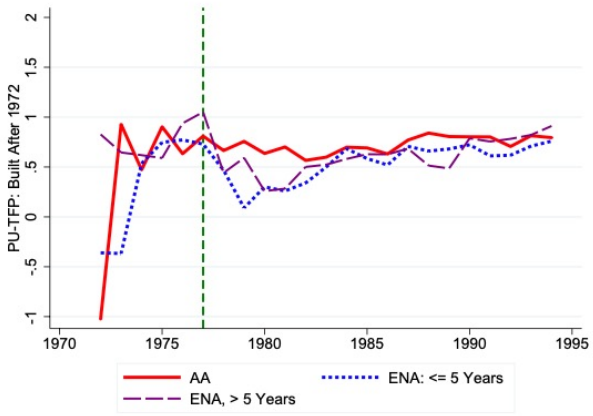
Figure C.8: Annual Average Total Factor Productivity for Coal Power Plants by Vintage and Years in Nonattainment



(a) PU-TFP – Built Before 1963



(b) PU-TFP – Built Between 1963-1971



(c) PU-TFP – Built After 1972

Table D.1: Impacts of Nonattainment on Power Plant Outcomes
By Additional Vintage Groups

	(1)	(2)	(3)	(4)	(5)
Dep. Var. (in Logs)	PU-TFP	Output	Fuel Use	No. Employees	Capacity
NA × 1[Built Before 1955]	-0.227***	-0.274***	-0.213**	-0.043	-0.105
	(0.078)	(0.102)	(0.095)	(0.051)	(0.063)
NA × 1[Built Between 1955-1962]	-0.239***	-0.303**	-0.247**	0.054	-0.135
	(0.077)	(0.122)	(0.117)	(0.083)	(0.100)
NA × 1[Built Between 1963-1966]	0.003	-0.057	-0.010	0.007	-0.064
	(0.094)	(0.135)	(0.142)	(0.093)	(0.089)
NA × 1[Built Between 1967-1971]	0.111**	0.097	0.135	0.040	0.012
	(0.054)	(0.073)	(0.082)	(0.070)	(0.064)
R^2	0.688	0.834	0.799	0.862	0.911
Mean of Dep. Var.	0.322	6.965	9.409	4.768	5.601
Number of Obs.	13,102	13,102	13,102	13,102	13,102
Number of Plants	387	387	387	387	387
Plant FE	Y	Y	Y	Y	Y
State By Year FE	Y	Y	Y	Y	Y
Vintage Group By Year FE	Y	Y	Y	Y	Y

Number of Plants by Vintage Group: There are 237 plants built before 1955, 84 plants built between 1955 and 1962, 30 plants built between 1963 and 1967, and 36 plants built between 1967 and 1971.

Table D.7: Impacts of Nonattainment on Outcomes by First Year in Nonattainment

Dep. Var. (in Logs)	(1) PU-TFP	(2) Output	(3) Fuel Use	(4) No. Employees	(5) Capacity
First NA in 1972-1977	-0.223***	-0.304***	-0.237***	-0.045	-0.146**
	(0.063)	(0.086)	(0.079)	(0.045)	(0.056)
First NA in 1978-1994	0.053	0.183	0.171	0.137	0.160
	(0.098)	(0.134)	(0.141)	(0.086)	(0.111)
R^2	0.683	0.830	0.793	0.851	0.909
Mean of Dep. Var.	0.322	6.965	9.409	4.768	5.601
Number of Obs.	13,102	13,102	13,102	13,102	13,102
Number of Plants	387	387	387	387	387
Plant FE	Y	Y	Y	Y	Y
State By Year FE	Y	Y	Y	Y	Y
Vintage Group by Year FE	Y	Y	Y	Y	Y

Table D.6: Results of the Goodman-Bacon Decomposition for First Nonattainment

Dep. Var. (in Logs)	(1) PU-TFP	(2) Output	(3) Fuel Use	(4) No. Employees	(5) Capacity
Overall DD Estimate	-0.126	-0.214	-0.132	-0.069	-0.102
DD Est.: T vs. Never Treated	-0.215	-0.376	-0.141	-0.100	-0.191
DD Est.: Earlier T vs. Later C	-0.079	-0.131	-0.160	-0.080	-0.056
DD Est.: Later T vs. Earlier C	0.037	0.093	-0.055	0.040	0.065
Weights: T vs. Never Treated	0.501	0.501	0.501	0.501	0.501
Weights: Earlier T vs. Later C	0.324	0.324	0.324	0.324	0.324
Weights: Later T vs. Earlier C	0.176	0.176	0.176	0.176	0.176
Number of Obs.	2,625	2,625	2,625	2,625	2,625
Number of Plants	125	125	125	125	125

Table D.4: Impacts of Nonattainment on Power Plant Outcomes by Primary Fuel Type

	(1)	(2)	(3)	(4)	(5)
Dep. Var. (in Logs)	PU-TFP	Output	Fuel Use	No. Employees	Capacity
NA × 1[Coal Plant]	-0.174***	-0.232***	-0.182**	-0.023	-0.106**
	(0.060)	(0.081)	(0.075)	(0.043)	(0.052)
NA × 1[Oil Plant]	-0.049	0.122	0.276	0.144	0.055
	(0.129)	(0.161)	(0.166)	(0.116)	(0.105)
NA × 1[Gas Plant]	-0.222**	-0.227**	-0.073	0.037	-0.060
	(0.085)	(0.113)	(0.103)	(0.050)	(0.067)
R^2	0.626	0.814	0.753	0.858	0.912
Mean of Dep. Var.	-0.754	6.761	9.184	4.502	5.494
Number of Obs.	20,415	20,415	20,415	20,415	20,415
Number of Plants	645	645	645	645	645
Plant FE	Y	Y	Y	Y	Y
State By Year FE	Y	Y	Y	Y	Y
Fuel Type By Year FE	Y	Y	Y	Y	Y
Vintage Group By Year FE	Y	Y	Y	Y	Y

Number of Plants by Primary Fuel Type: Focusing on plants built before 1972, there are 387 coal-fired plants, 67 oil-fired plants, and 201 gas-fired plants.

Table D.5: Impacts of Nonattainment on Plant Outcomes By Pollutant Standard

	(1)	(2)	(3)	(4)	(5)
Dep. Var. (in Logs)	PU-TFP	Output	Fuel Use	No. Employees	Capacity
NA: TSP or PM	-0.007	0.006	0.000	0.015	0.017
	(0.029)	(0.038)	(0.043)	(0.032)	(0.036)
NA: SO2	0.024	0.033	0.081	0.022	0.003
	(0.069)	(0.098)	(0.095)	(0.047)	(0.058)
NA: CO	-0.079	-0.199	-0.166	-0.143**	-0.174**
	(0.078)	(0.119)	(0.108)	(0.061)	(0.084)
NA: O_3 or NO_2	-0.193***	-0.205**	-0.142*	0.017	-0.042
	(0.064)	(0.081)	(0.076)	(0.042)	(0.052)
R^2	0.682	0.828	0.792	0.851	0.908
Mean of Dep. Var.	0.322	6.965	9.409	4.768	5.601
Number of Obs.	13,102	13,102	13,102	13,102	13,102
Number of Plants	387	387	387	387	387
Plant FE	Y	Y	Y	Y	Y
State By Year FE	Y	Y	Y	Y	Y
Vintage Group By Year FE	Y	Y	Y	Y	Y