Online Appendix (Not For Publication)

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

Karen Clay, Akshaya Jha,

Joshua Lewis, and Edson Severnini[*]

This online appendix provides additional information supporting the description and discussion of the setting, data, methods, and results. *Appendix A* presents background information alluded to in the paper. *Appendix B* more fully develops the conceptual framework included in the paper. *Appendix C* explains further details on the data sources and construction of the final dataset, and provides additional descriptive figures and tables. *Appendix D* reports additional results, including a variety of robustness checks regarding alternative specifications, samples, and variable definitions.

[*]Clay, Jha, and Severnini: H. John Heinz III College, Carnegie Mellon University, 4800 Forbes Avenue, Pittsburgh, PA 15213. Emails: kclay@andrew.cmu.edu, akshayaj@andrew.cmu.edu, and edsons@andrew.cmu.edu. Lewis: Université de Montréal, 3150, rue Jean-Brillant, Montréal, QC, H3T 1N8. Email: joshua.lewis@umontreal.ca.

A Additional Background Information

This appendix section provides further information supporting the description of the historical setting in Section 2. Appendix A.1 presents figures and tables alluded to in the text, and Appendix A.2 provides an example of how electric utilities adjusted to the Clean Air Act. This appendix section includes the figures and tables outlined below.

- Figure A.1. Trends in Plant Capacity and Stack Height
- Figure A.2. Histogram of First Year with FGD or FGP
- Figure A.3. Patents Related to Power Systems and Electrical Lighting
- Figure A.4 Real Construction Cost Index For Coal-Fired Power Plants
- Figure A.5. Trends in Scrubber Adoption
- Figure A.6. Trends in TSP by County Attainment Status
- Figure A.7 Trends in Power Plant Thermal Efficiency

- Table A.1. Electric Utility's Locational Choices Before and After the Clean Air Act
- Table A.2. Pollution Abatement Strategies: The Case of the Tennessee Valley Authority
- Table A.3. Number of Years in Operation By County Attainment Status

A.1 Additional Background Figures and Tables

The figures and tables in this appendix subsection provide information on a variety of actions taken by the electric utilities aimed at reducing pollution concentration around power plant sites. Appendix Figure A.1 shows the power plants were becoming larger after 1950, and installing taller and taller smokestacks to send emissions further away. Appendix Figure A.2 depicts a histogram of adoption of flue gas particulate (FGP) collectors and flue gas desulfurization (FGD) technology. Several plants adopted FGP collectors even before 1950, but FGD technology only became commercially available in the early 1970s. Appendix Figure A.3 provides evidence suggesting that power plant innovation increases systematically with the passage of the Clean Air Act of 1963, which funded a number of initiatives to help plants reduce emissions. Appendix Figure A.4 depicts an index for real construction costs of fossil fuel power plants. Appendix Figure A.5 shows that power plants ramp up efforts to install scrubbers (FGD) rapidly in the 1970s, once they became commercially operational. Appendix Figure A.6 displays trends in particle pollution (total suspended particulates – TSP). Lastly, Appendix Figure A.7 displays the national average thermal efficiency of fossil-fueled steam-electric plants over our sample period 1938-1994.

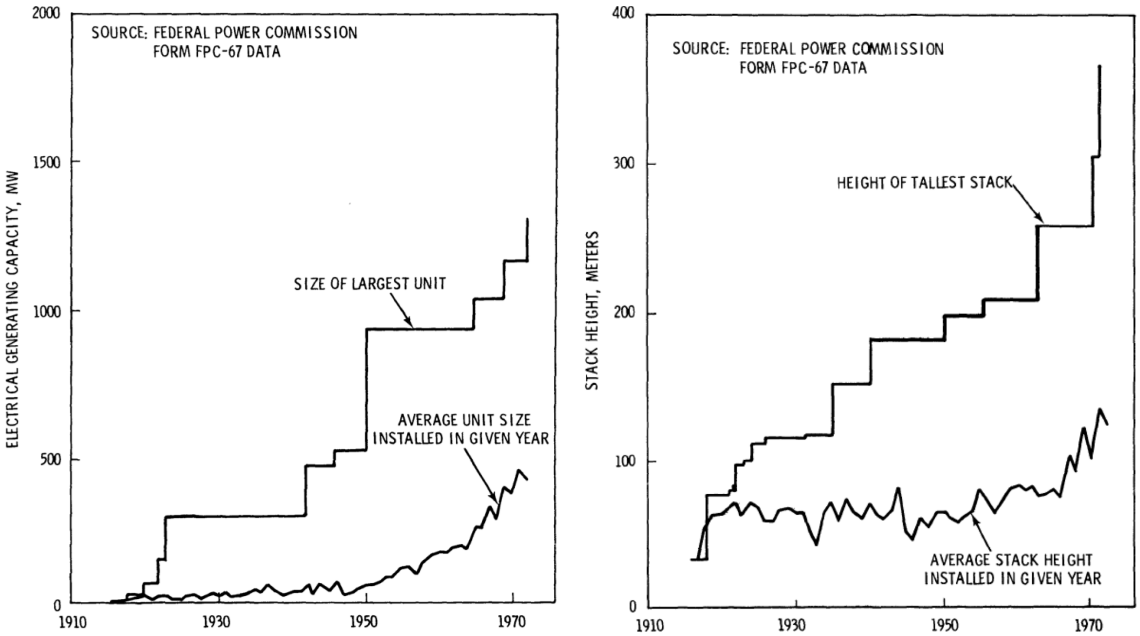
Appendix Table A.1 reveals that electric utilities were also using all information available to infer where impending environmental regulation would be binding, and avoiding installing fossil-fuel power plants in those locations. In the table, the information is the location of the earliest network of pollution monitoring stations. Appendix Table A.3 provides descriptive evidence suggesting that electric utilities were running older plants longer to potentially avoid building new plants that would be subject to stricter regulations regardless of the county attainment status.

A.2 Tennessee Valley Authority: An Example

To illustrate the variety of strategies used by electric utilities to reduce emissions, we present the case of the ten coal-fired power plants from the Tennessee Valley Authority (TVA). Those plants were built before 1972, but only complied with the CAA regulations after TVA and EPA reached a settlement in 1979-80 (GAO, 1980). Appendix Table A.2 shows that many plants ended up switching to a cleaner fuel: either medium or

low sulfur coal. Several plants combined that strategy with coal washing, electrostatic precipitators, baghouses, and scrubbers. The U.S. Government Accountability Office (GAO)'s estimated that the total cost of the consent decree over the life span of the projects was substantial: over $14 billion (2019 USD). Capital costs comprised 14% of that amount, operating and maintenance costs 30%, and the incremental fuel costs 56%.

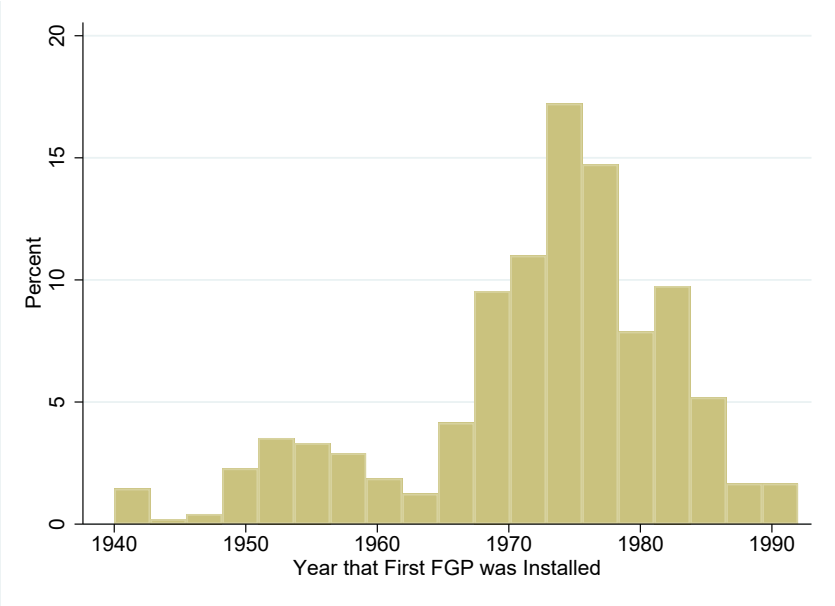
Figure A.1: Trends in Plant Capacity and Stack Height



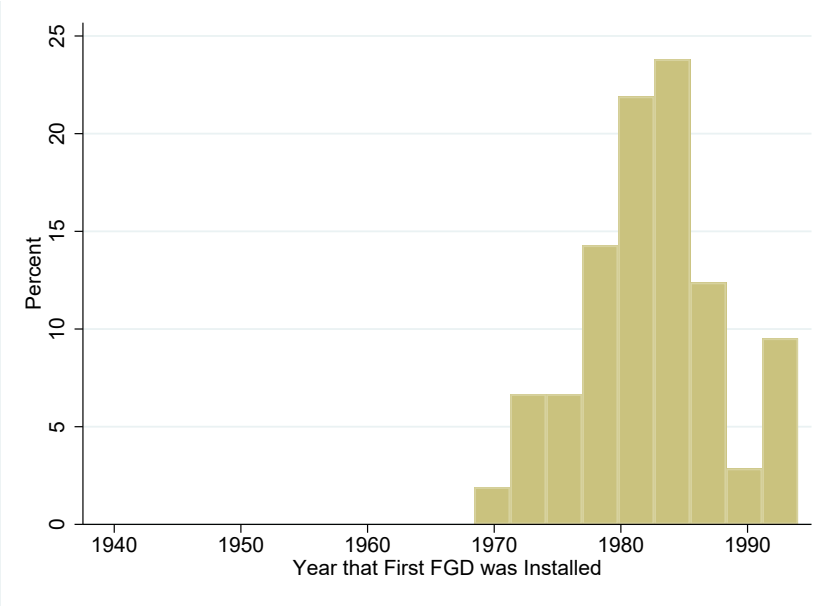
(a) Trends in Plant Size (b) Trends in Smokestack Height

Notes: This figures displays trends in plant size and smokestack height. Panel (a) documents the average and maximum capacities (in MW) of electricity generating units in each year. Panel (b) documents the average and maximum smokestack height (in meters) of electricity generating units in each year. The data used to construct these figures come from Federal Power Commission Form FPC-67. *Source*: Figures 3 and 4, EPA (1976*c*).

Figure A.2: Histogram of First Year with FGP or FGD



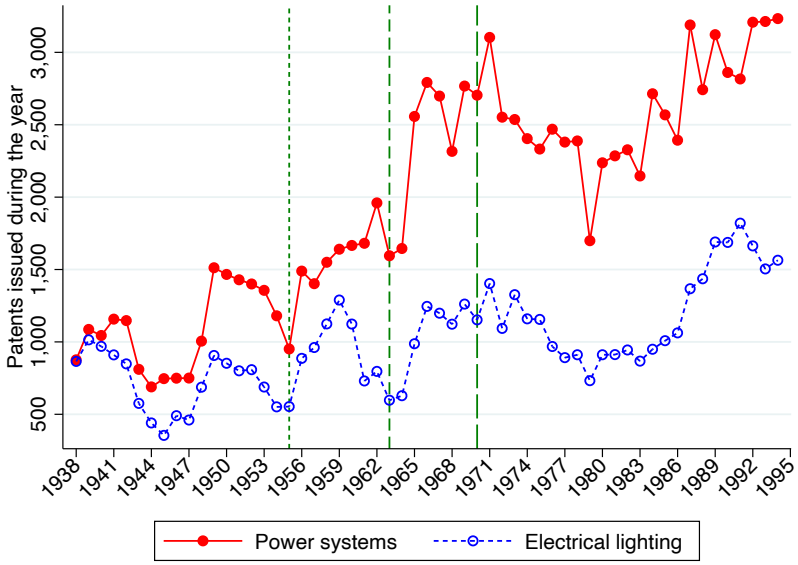
(a) FGP Adoption



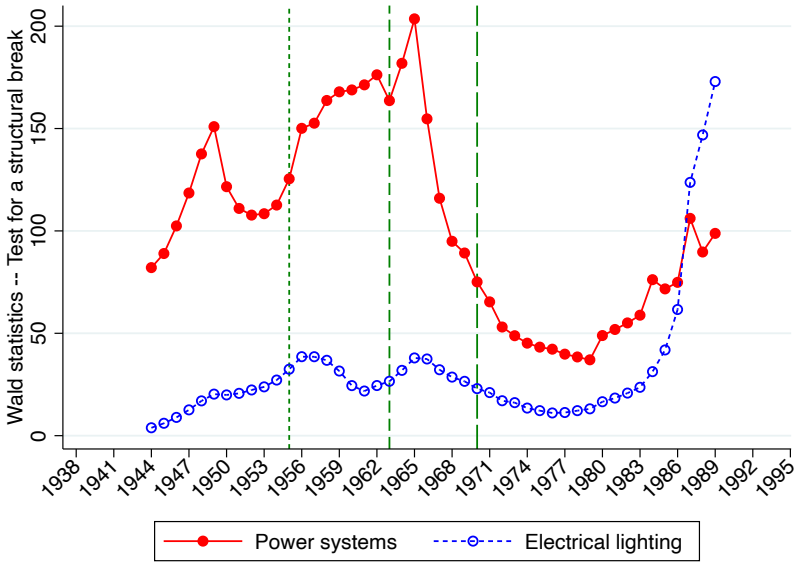
(b) FGD Adoption

Notes: This figure displays the timeline of adoption of emission control technologies. Panel (a) plots the plant-level distribution of the year that the first flue gas particulate (FGP) collector was installed on the plant. Panel (b) plots the plant-level distribution of the year that the first flue gas desulfurization (FGD) system was installed on the plant. Data on the installation year of each FGP and FGD come from Form 767 administered by the Energy Information Administration.

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



(a) Trends in the Number of Issued Patents



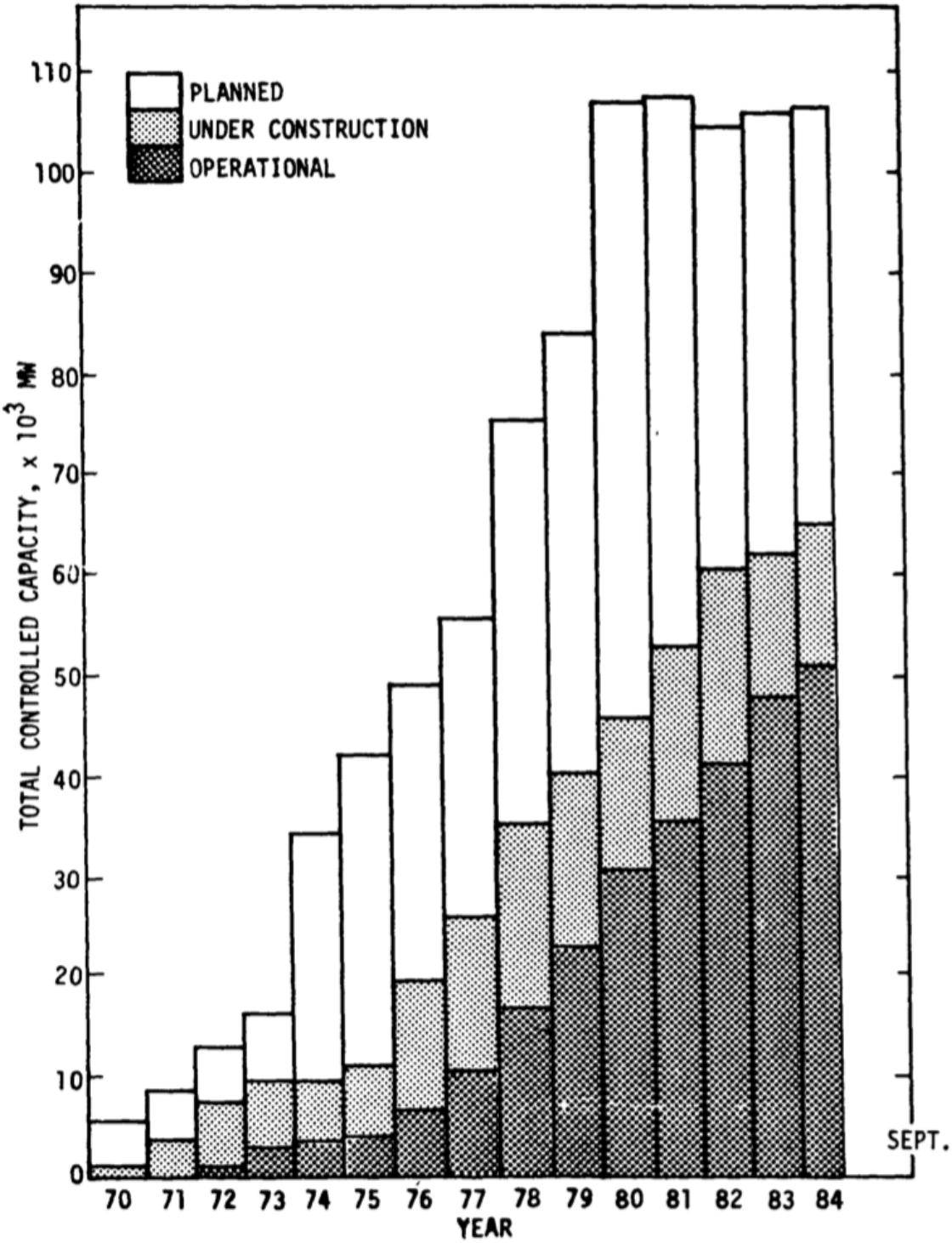
(b) Wald Statistics for Tests of Unknown Structural Break

Notes: This figure displays trends in patents for categories related to electricity. Panel (a) plots the number of patents issued per year for two broad categories: (i) "power systems," which includes power plants, electrical generator, and single generator systems, and (ii) "electrical lighting," which includes electric lamp and discharge devices, illumination, and coherent light generators. For a complete description of these broad categories, visit https://historicip.com/nber/. Panel (b) plots the Wald statistics of tests for a structural break in time-series data with an unknown break date, with an equal left and right trimming percentage of ten percent. The break is estimated to happen in 1965 for power systems, and only in 1989 for electrical light. For the years of interest referenced as green vertical lines – the short-dashed line for the Air Pollution Control Act of 1955, the dashed line for the Clean Air Act of 1963, and the long-dashed line for the Clean Air Act of 1970 – the electrical lighting subcategory appears to be a good "control group" for power systems. *Data Source:* The U.S. Patent and Trademark Office (USPTO) Historical Patent Data Files, available at https://www.uspto.gov/learning-and-resources/electronic-data-products/historical-patent-data-files.

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

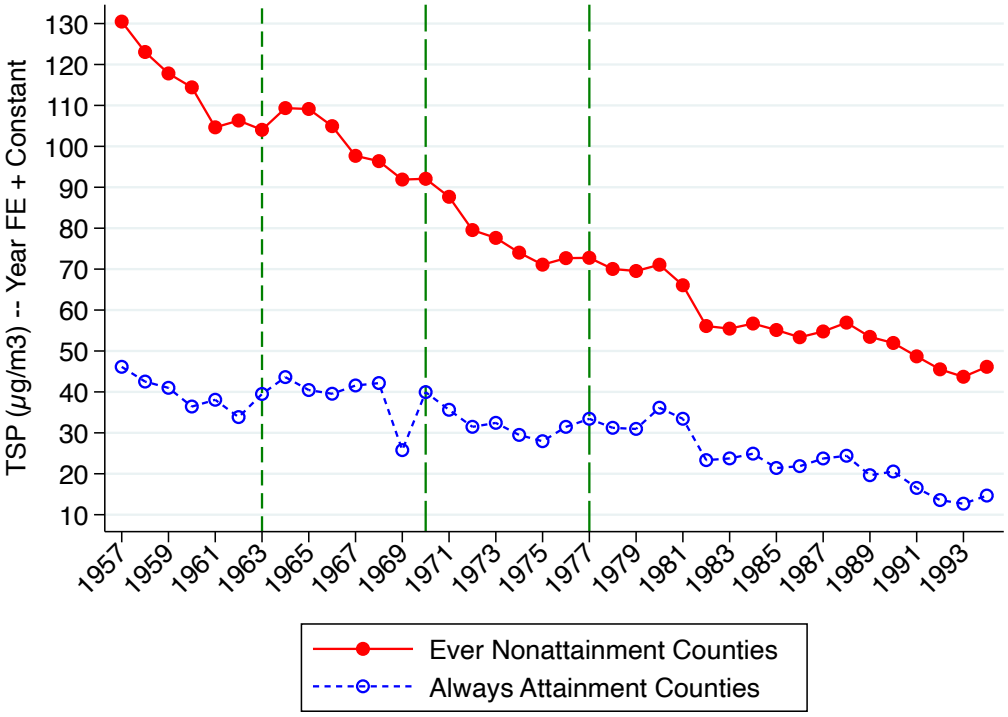
Notes: This figure reproduces Figure 2 from Joskow and Rose (1985). It plots the index of real costs per kilowatt of installed capacity associated with the construction of coal-burning electricity generating units. Notice that it declines during the early 1960s, stabilizes in the mid 1960s, and then increases starting around 1966 to a level that by 1980 is substantially higher than the level in 1960.

Figure A.5: Trends in Scrubber Adoption



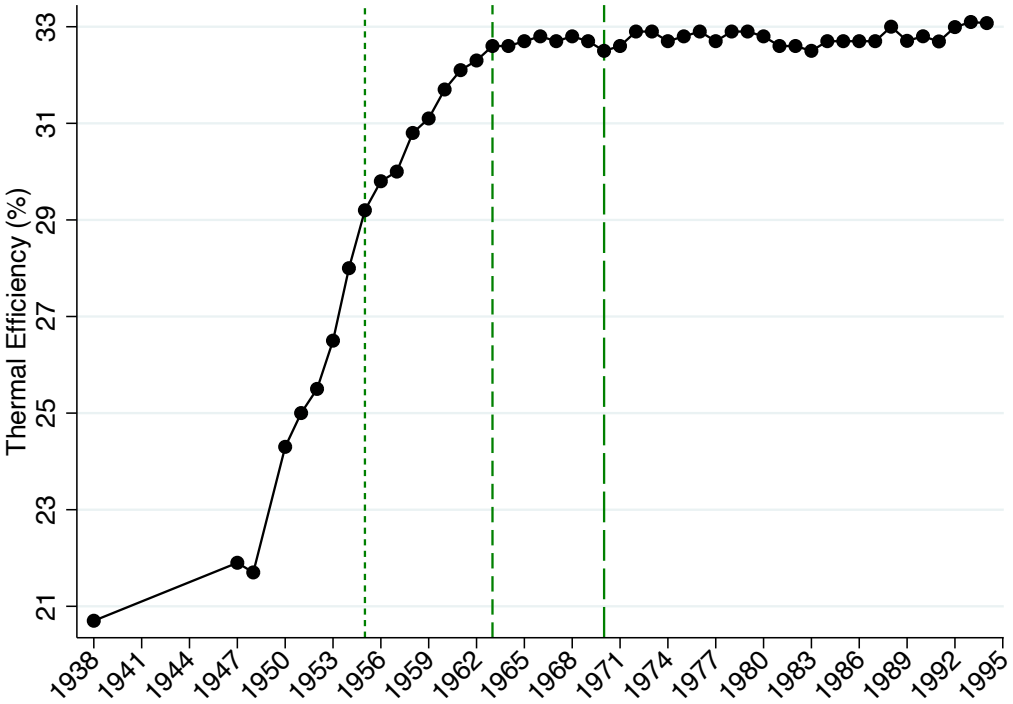
Notes: This figure presents a historical breakdown of utility status reports for operational, under construction, and planned flue gas desulfurization (FGD) capacity – December 1970 through September 1984. *Source*: Figure 2, EPA (1984).

Figure A.6: Trends in TSP by County Attainment Status



Notes: This figure displays trends in total suspended particulates (TSP) by county attainment status. Specifically, it plots the estimated coefficients of a regression of TSP on year fixed effects interacted with attainment status, controlling for pollution monitor fixed effects. Attainment (nonattainment) status is defined as the county being in (out of) compliance with the National Ambient Air Quality Standards (NAAQS) for any pollutant in the year. The green vertical dashed lines refer to the passage of the Clean Air Act of 1963, and the long-dashed lines to the Clean Air Act of 1970 and its amendments in 1977. Data on TSP concentration, which start in 1957, were provided by EPA under a Freedom of Information Act (FOIA) request.

Figure A.7: Trends in Power Plant Thermal Efficiency



Notes: This figure displays the national average thermal efficiency (heat rate) of fossil-fueled steam-electric plants over our sample period 1938-1994. Thermal efficiency is based on 3,412 Btw as the energy equivalent of 1 kWh of electricity. The data sources are (i) for the period 1938-1955: FPC 1965 Report (FPC, 1966), Table 9, p.xxxi; (ii) for the period 1956-1988: EIA 1990 Report (EIA, 1992), Table 11, p.37; and (iii) for the period 1989-1994: MER February 2021 (EIA, 2021), Table A6, p.215. For the years of interest referenced as green vertical lines, the short-dashed line represents the Air Pollution Control Act of 1955, the dashed line the Clean Air Act of 1963, and the long-dashed line the Clean Air Act of 1970.

Table A.1: Electric Utility's Locational Choices Before and After the Clean Air Act

Dependent Variable	(1) 1[County with Pollution Monitors Before 1963]	(2) 1[County with Pollution Monitors Before 1963]	(3) 1[County Ever in Nonattainment (ENA)]
1[Built Between 1955-1962]	-0.026	-0.044	0.045
	(0.036)	(0.041)	(0.030)
1[Built Between 1963-1971]	-0.132***	-0.148**	-0.057
	(0.046)	(0.066)	(0.039)
1[Built Between 1972-1994]	-0.102***	-0.078**	-0.064*
	(0.036)	(0.035)	(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

Notes: This table reports estimates from linear probability models aiming at examining the choice of electric utilities regarding where to install a new fossil-fuel-fired power plant. The goal is to estimate the probability of a plant from a certain vintage – 1955-1962, 1963-1971, or 1972-1994 – to be installed in a county with a high chance to be regulated later on. The (omitted) reference vintage group is 1938-1954. The unit of observation for these regressions is a plant that was installed in any county during our sample period – see all the counties with at least one power plant in Appendix Figure C.2. In columns 1 and 2, the dependent variable is an indicator for whether the county where a plant was installed had at least one pollution monitor measuring air pollution within its boundaries before the passage of the Clean Air Act of 1963. Column 2 restricts the sample to counties that would be ever out of compliance (in "nonattainment") with the NAAQS for any pollutant during our sample period 1938-1994. In column 3, the dependent variable is an indicator for whether the county where a plant was installed was ever in nonattainment with the NAAQS over our sample period. For reference, 353 plants that opened over our sample period were installed in counties that had at least one pollution monitor operating in at least one year during the baseline years 1957-1962. This is the earliest period that we have obtained information on the location of the network of pollution monitoring stations, through a FOIA request at the U.S. EPA. Standard errors in parentheses are clustered at the state level. *** denotes statistical significance at the 1% level, ** at the 5% level, and * at the 10% level.

Table A.2: Pollution Abatement Strategies: The Case of the Tennessee Valley Authority

Coal Power Plant	County	State	Attainment in 1978	Compliance Method	Millions (2019 USD)
Allen	Shelby	TN	No	Medium Sulfur Coal	271.46
Colbert	Colbert	AL	No	Medium Sulfur Coal	531.26
Cumberland	Stewart	TN	Yes	Coal Washing Electrostatic Precipitators	1,842.92
Gallatin	Sumner	TN	No	Medium Sulfur Coal Electrostatic Precipitators	421.89
Johnsonville	Humphreys	TN	No	Medium Sulfur Coal	1,107.55
Kingston	Roane	TN	No	Low Sulfur Coal	1,007.10
Paradise Unit 3	Muhlenberg	KY	No	Coal Washing and Partial Scrubbing Electrostatic Precipitators	3,715.81
Shawnee	McCracken	KY	No	Low Sulfur Coal, Baghouses	2,771.06
Watts Bar	Rhea	TN	Yes	Medium Sulfur Coal	Not Available
Widows Creek	Jackson	AL	No		
Units 1-6				Low Sulfur Coal	564.05
Units 7-8				Scrubbing and Medium Sulfur Coal	1,990.54
Total					14,223.67

Notes: This table provides the pollution abatement strategy of each of the ten coal-fired power plants from the Tennessee Valley Authority (TVA), as agreed in the clean air settlement between TVA and EPA in 1979-80. All plants were built before 1972, the year the enforcement of the Clean Air Act began. The costs in the last column were estimated by the U.S. Government Accountability Office (GAO), and refer to the total cost of the consent decree over the life span of the projects. All the information was compiled from GAO (1980).

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

Dep. Var.: Log of Number of Years the Plant is Operating	(1)	(2)	(3)	(4)
main				
Ever Nonattainment	0.133**	0.562***		
	(0.063)	(0.193)		
ENA × 1[Built Before 1963]	0.511***	0.472***		
	(0.043)	(0.177)		
Number of Years in Nonattainment			0.003	0.072***
			(0.003)	(0.019)
# of Years in NA × 1[Built Before 1963]			0.026***	0.007
			(0.002)	(0.018)
Capacity (GW)	0.080	1.438***	-0.032	1.059***
	(0.066)	(0.398)	(0.068)	(0.397)
1[Coal Plant]	0.050	-0.017	0.159*	-0.008
	(0.109)	(0.326)	(0.092)	(0.301)
1[Gas Plant]	0.019	-0.189	0.109	-0.326
	(0.117)	(0.341)	(0.103)	(0.318)
1[Oil Plant]	-0.070	-0.258	0.016	-0.267
	(0.112)	(0.324)	(0.097)	(0.300)
Mean of Dep. Var.	3.432	3.432	3.432	3.432
Number of Obs.	686	686	686	686
Censored Model?		Y		Y

Notes: This table reports estimates of the relationship between the number of years each plant is in operation and measures of attainment status with the National Ambient Air Quality Standards (NAAQS) for any criteria pollutant. The unit of observation for all of the regressions in this table is power plant, considering all plants built before 1972. The dependent variable considered for all regressions is the log of the last year the plant is recorded as producing positive output in our dataset minus one plus the first year the plant is recorded as producing positive output. The independent variable of interest in Columns 1 and 2 is an indicator variable that is equal to one if the plant ever faced nonattainment between 1972-1994. The independent variable of interest in Columns 3 and 4 is the count of the number of years that the plant faced nonattainment between 1972-1994. We also interact the relevant independent variable with an indicator for plants built before 1963. All specifications control for the plant's capacity in its first year of operation as well as primary fuel type (the reference category is plants that burn multiple types of fuel). In Columns 1 and 3, we estimate the model using ordinary least squares. In Columns 2 and 4, we estimate the model using a censored regression model that accounts for the fact that some plants are still in operation at the end of our sample period. Heteroskedasticity-consistent standard errors are reported in parentheses. *** denotes statistical significance at the 1% level, ** at the 5% level, and * at the 10% level.

B Details on the Conceptual Framework

This appendix section describes our conceptual framework for how plants respond to the Clean Air Act (CAA), as summarized in Section 3. Appendix B.1 specifies the two-period expected cost minimization problem solved by plant managers. Appendix B.2 discusses how the CAA impacts this expected cost minimization problem for plants built before 1963, built between 1963-1971, and built after 1972.

B.1 Two-Period Cost Minimization Problem

Our conceptual framework, based on Fabrizio, Rose and Wolfram (2007), focuses on a plant manager tasked with choosing the levels of three inputs in each of two periods $t \in \{1, 2\}$: the level of capacity of her power plant K_t, the number of employees at the plant site L_t, and the quantity of fuel in units of heat E_t.[1] She faces input prices P_t^K, P_t^L, and P_t^E associated with capacity, labor, and fuel, respectively. The plant manager can also choose to install pollution abatement technology at fixed cost c^I. The indicator variable I_t equals 1 if and only if the plant manager has installed this technology on or before period t.

The timing of the model in each period t works as follows. The plant manager first chooses the capacity of her plant K_t. At this point, the plant can also choose to install pollution abatement technology I_t. Next, a productivity shock ω_t is realized. After this shock is realized, the plant manager chooses labor L_t. Finally, a separate shock ϵ_t is realized, after which fuel E_t is chosen. This ϵ_t term captures a variety of different short-run production shocks such as unexpectedly high electricity demand or transmission constraints.

Building on Fabrizio, Rose and Wolfram (2007), we assume that fuel is a perfect complement to the other two inputs. Specifically, electricity is produced in each period based on the following Leontiff production function:

[1] There is a large previous literature that models the production of electricity as a function of capital, labor and fuel (Barzel (1963); Nerlove (1963); Atkinson and Halvorsen (1976); Christensen and Greene (1976); Gollop and Roberts (1983); Nelson and Wohar (1983); Gollop and Roberts (1985); Carlson et al. (2000)).

$$Q_t^A = min\{0.95^{I_t} \underbrace{F(K_t, L_t)exp(\omega_t + \epsilon_t)}_{\text{Maximum Potential Output}}, g(E_t)\} \tag{B.1}$$

where Q_t^A is the actual quantity of electricity produced by the plant. We include the 0.95^{I_t} term based on the assumption that roughly 5% of the plant's electricity is used to run the pollution abatement technology if $I_t = 1$. We estimate total factor productivity (TFP) ω_t using the method described in Ackerberg, Caves and Frazer (2015). When estimating ω_t, we assume that $F(K, L)$ is a translog production function (Atkinson and Halvorsen, 1976; Christensen and Greene, 1976; Boisvert, 1982; Gollop and Roberts, 1983; Carlson et al., 2000).[2] Finally, one should think of $g(E)$ as being "S-shaped" like, for example, a logistic function. This is because power plants have an optimal output level; it takes energy to ramp up to this optimal level and not as much output can gleaned from additional fuel use for output levels higher than this optimal level.

Conceptually, the timing assumptions for each period reflect the notion that building plant capacity takes a longer time than adjusting the number of employees at the plant site. It is thus difficult to adjust capacity in the short-run or medium-run in response to productivity shocks such as advances in generating technology. Moreover, labor is more difficult to adjust than fuel in the short-run due to hiring and firing frictions. Plant managers can thus adjust their fuel input but not their labor or capital in response to short-run shocks such as unexpectedly high electricity demand on a hot day.

The plant manager minimizes her expected total costs across the two periods subject to output levels being governed by the production function presented in Appendix Equation (B.1). Her *realized* total cost across the two periods is:

$$c^L(L_2 - L_1)^2 + \sum_{t=1}^{2} \beta^{t-1}(P_t^K(K_t - K_{t-1}) + P_t^L L_t + P_t^E E_t) \tag{B.2}$$

noting that $K_0 = 0$ because the plant is first built in $t = 1$, and K_t must be greater than K_{t-1} for t=1,2.[3] The squared difference between labor in periods 1 and 2 – i.e.: $(L_2 - L_1)^2$

[2]Boisvert (1982) argues that the translog specification can be viewed in three ways: "as an exact production function, as a second-order Taylor series approximation to a general, but unknown production function, or as a second-order approximation to a CES production function." (p. 6).

[3]Input price P_t^K thus captures the per-unit cost of building electricity generating capacity rather than the relatively small costs associated with maintaining this capacity.

– captures the adjustment costs associated with choosing different levels of labor in period 2 versus period 1. Examples of these adjustment costs include union contracts that must be renegotiated or litigated in order to fire employees, and redesigning the plant to function with fewer workers.

Given the stylized nature of the model, we deliberately do not specify the evolution over time of either the productivity shocks ω_t or the "short-run shocks" ϵ_t. That being said, the plant manager chooses K_1 without having observed any shocks, L_1 having observed only ω_1, E_1 and K_2 having observed (ω_1, ϵ_1), chooses L_2 having observed $(\omega_1, \epsilon_1, \omega_2)$ and E_2 having observed $(\omega_1, \epsilon_1, \omega_2, \epsilon_2)$. When choosing each input in each time period, the plant manager takes the expectation over the unobserved shocks conditioning on the information in the shocks already observed to that point.

B.2 How does the CAA Impact Plants of Different Vintages?

The previous subsection discussed the plant manager's expected cost minimization problem in the absence of any air quality regulations. The Clean Air Act imposed two separate types of regulation on fossil-fuel fired power plants. First, the National Ambient Air Quality Standards (NAAQS) mandated that annual county-level concentrations of different pollutants remain below the specified thresholds. Counties out of attainment with the NAAQS often tasked the power plants located within their boundaries to reduce their emissions. Second, "new" plants built after 1972 were subject to additional environmental regulations termed New Source Performance Standards (NSPS). Existing plants built before 1972 were exempt from these additional regulations as long as they did not make any "major modifications".

The plant's pollution "production function" is

$$M_t = \begin{cases} M(E_t, x_t) \text{ if } I_t = 0 \\ 0 \text{ if } I_t = 1 \end{cases}$$

where, for simplicity, we set emissions M_t equal to zero if the plant has installed pollution abatement technology, that is, $I_t = 1$. If $I_t = 0$, emissions are a function of heat energy E_t and characteristics of the fuel burned x_t. For example, for the same heat energy, burning lower sulfur coal results in less emissions.

Once the power plant is built, the plant manager can reduce emissions in three different ways. First, they can simply burn less fuel, i.e., reduce their level of output. Second, they can change the type of fuel they burn; for example, a coal-fired power plant can burn lower sulfur coal. Third, the plant can install a pollution abatement technology. It is important to observe, though, that the NSPS potentially distort how plants respond to air quality regulations. Specifically, existing plants might choose not to install pollution abatement technology because this would be a considered a major modification, and thus subject the plant to a new source review. Moreover, the NSPS obligated coal-fired plants built after 1978 to install flue-gas-desulfurization technology ("scrubbers"), which removes some portion of the sulfur dioxide, nitrogren dioxide, and fine particulates from the emissions associated with burning coal.

We consider three types of plants: plants built before 1963, plants built between 1963 and 1971, and plants built after 1972. We model the CAA as being implemented between periods 1 and 2 for the plants built before 1963, but before period 1 for the plants built after 1963. Plants built after 1963 can thus choose initial levels of capital, boiler technology, plant site, etc. with advance knowledge that the CAA will be implemented.

Plants built before 1963 can comply with nonattainment by reducing output, changing the mix of inputs, or installing pollution abatement technology. If the plant manager chooses to reduce output, it will be difficult to adjust inputs to reflect this decrease in output because capital and labor were chosen in period 1 without knowledge of the CAA. Adjusting capital downward in period 2 in response to the CAA is impossible while adjusting labor downward comes with adjustment costs. In addition, power plants typically have an optimal level of output; producing less than the optimum lowers the thermal efficiency of the plant. As a result, the plant produces less output per unit of input heat.

Reducing emissions by changing the mix of inputs also comes with costs. First, plants may hire labor specifically to ascertain how best to comply with environmental regulations. This ranges from lawyers who interpret these regulations to engineers who install and run pollution abatement technology as well as make other regulation-induced modifications to the plant. In addition, coal and oil fired power plants may switch to fuel that emits less pollution when burned. This typically comes at thermal efficiency losses, especially for boilers tuned to burn different fuel. For example, low-sulfur coal

from the Powder River Basin has less heat energy per ton than higher-sulfur coal from Appalachia.

Plants built between 1963-1971 can also comply with nonattainment by reducing output, changing the mix of inputs, or installing pollution abatement technology. However, these plants know that the CAA will be implemented prior to period 1, and will thus choose capital and labor optimally in period 1 to reflect this information. Moreover, electric utilities with advance knowledge of the CAA will likely to choose to site plants in counties less likely to face nonattainment.

Finally, both sets of plants built before 1972 may choose to install pollution abatement technology. However, installing this technology may be considered a "major modification" and thus subject the plant to the stricter environmental regulation associated with New Source Performance Standards (NSPS). If the plant chooses this compliance option, the plant incurs the costs associated with installing the technology as well as the costs of operating this technology using electricity from the plant.

Plants built after 1972 ("new plants") are already subject to the NSPS; installing a pollution abatement technology does not cause the plant to face stricter regulation. Indeed, the NSPS obligated coal-fired plants built after 1978 to install scrubbers; our empirical specifications explore differences between plants built after 1978 versus between 1972-1977. Of course, as with plants built between 1963-1971, new plants were built and staffed with knowledge of the CAA. Capital K_1 and labor L_1 are thus chosen optimally to reflect the requirements of the CAA. Summarizing, our conceptual framework provides several sets of main hypotheses. First, for plants built before 1963, we expect that nonattainment with NAAQS will result in less output, little changes in capital, no change (or even an increase) in labor, and an increase in heat energy per MWh. We expect smaller changes in output and heat energy per MWh for plants built between 1963-1971 because these plants were built and sited with knowledge that environmental regulations were forthcoming.

Existing plants located in nonattainment counties are more likely to install pollution abatement technology than existing plants located in attainment counties. However, existing plants are less likely to install this technology than new plants because installing pollution abatement technology might subject existing plants to the stricter environmental regulations associated with New Source Performance Standards (NSPS). In contrast,

every new plant is subject to NSPS; we thus should not expect substantial differences across new plants located in attainment versus nonattainment counties. Moreover, new plants are more likely to comply with the NSPS by installing pollution abatement technology rather than reducing output or changing their input mix for two reasons: (1) the NSPS rules require relatively large reductions in emissions and (2) plants built after 1978 are obligated to install this technology.

C Data Construction and Data Description

This appendix section provides further details about the data sources, data construction, and data description, supporting the broad overview given in Section 4. Appendix C.1 addresses the digitization of historical information on fossil-fuel-fired power plants. Appendix C.2 describes the variables used in the estimation of our measure of pollution-unadjusted total factor productivity (PU-TFP), and provides the estimates of the parameters of a few power plant production functions. Appendix C.3 presents additional descriptive information via figures and tables. The outline of all figures and tables in this appendix section is below.

- Figure C.1. Sample Data for Four Power Plants from the 1957 FPC Report
- Figure C.2. Map of Counties with Fossil-Fuel-Fired Power Plants in Our Sample
- Figure C.3. Share of Electricity Generation in Nonattainment Counties
- Figure C.4. Annual Total Electricity Generating Capacity by Fuel Type
- Figure C.5. Annual Total Electricity Generation and Capacity from Fossil-Fuel Power Plants by Vintage and Years in Nonattainment
- Figure C.6. Annual Average Total Factor Productivity from Fossil-Fuel Power Plants by Attainment Status
- Figure C.7. Annual Average Total Factor Productivity from Fossil-Fuel Power Plants by Vintage and Years in Nonattainment
- Figure C.8. Distribution of the Number of Years of a County in Nonattainment

- Table C.1. Number of Plants by Attainment Status and Vintage
- Table C.2. Attainment Status versus Lagged Attainment Status
- Table C.3. Summary Statistics: PU-TFP, Production Function, and NAAQS
- Table C.4. Production Function Estimates from Different Methods and Functional Forms

C.1 Data Construction

We have digitized power plant level data from the Federal Power Commission (FPC) reports for the years 1938-1981. (In 1977, Congress reorganized FPC as the Federal Energy Regulatory Commission – FERC). Most of the digitization was funded by the NSF grant SES 1627432. We hired undergraduates and master's students to enter manually the information from the historical reports. Then, a different set of students checked the accuracy of the information entered by the first group, and made corrections if needed.

Beginning in 1938, detailed annual data are available for large steam power plants. Steam power plants include coal-fired, gas-fired, and oil-fired electricity plants. The number of power plants changed from 151 in 1938 to 200 in 1947, which were all published in a single volume, to 277 in 1950, 528 in 1960, 553 in 1970, and 647 in 1980.[4] As an example, we present a page from the 1957 report in Appendix Figure C.1.

These are the titles of the FPC reports:

– 1938-1947: *Steam-Electric Plant Construction Cost and Annual Production Expenses, 1938-1947* (Single Volume);

– 1948-1978: *Steam-Electric Plant Construction Cost and Annual Production Expenses* (Annual Supplements);

– 1979-1981: *Thermal-Electric Plant Construction Cost and Annual Production Expenses* (Annual Supplements).

Starting in 1982, the annual reports include only a small sample of steam-electric power plants. For that reason, we collect data from several other sources to continue our panel until 1994.

– capacity and plant locations: eGrid – *epa.gov/egrid/download-data*;[5]

– generation and consumption by fuel type: EIA-Form 759 which later became EIA-Form 906 – *eia.gov/electricity/data/eia923/eia906u.html*;

[4]The plants reported in 1938 accounted for 59% of the capacity and 75% of the generation of utility-owned, fossil-fueled steam-electric plants in the United States. For the 1947 plants, those numbers are 65 and 73%, respectively. For the 1950 plants, those numbers are 70 and 80%, respectively. For the 1960 plants, those numbers are 90 and 94%, respectively. For the 1970 plants, those numbers are 93 and 96%, respectively. For the 1980 plants, those numbers are 92 and 91%, respectively.

[5]We used EIA Form 860 data to supplement capacity where it was not listed in eGrid because the plant shut down before 1996.

– FGD + FGP: EIA Form-767 – *eia.gov/electricity/data/eia767/*;

– fuel purchases and fuel costs: EIA-Form 423 – *eia.gov/electricity/data/eia423/*;

– number of employees and nonfuel expenses: FERC Form 1 – *ferc.gov/industries-data/electric/general-information/electric-industry-forms/form-1-electric-utility-annual*.[6]

C.2 Estimation of Total Factor Productivity

We estimate total factor productivity (TFP) using the procedure proposed by Ackerberg, Caves and Frazer (2015). The output is the annual plant-level electricity generation measured in megawatt-hours. The first input, *labor*, is a count of full-time equivalent employees at the plant. The second input, *fuel*, is the quantity of fuel consumed by type of fuel (tons of coal, barrels of oil, and Mcf of natural gas). We convert fuel into BTUs using the reported annual plant-specific BTU content of each fuel to obtain total BTU input at the plant for each year. The third input, *nonfuel_costs*, which is of interest on its own but will be used only for robustness checks regarding the estimation of TFP, includes all nonfuel operations and maintenance expenses, such as those for coolants, repairs, maintenance supervision, and engineering. As pointed out by Fabrizio, Rose and Wolfram (2007), this variable is less than ideal as a measure of nonfuel materials, both because it reflects expenditures rather than quantities, and because it includes the wage bill for the employees counted in *labor*. As *nonfuel_costs* includes payroll costs, both this and *labor* reflect changes in staffing. The final input, *capital*, is the capital stock of the plant, which is the plant nameplate capacity, measured in megawatts.

As explained in Appendix B, we build on Fabrizio, Rose and Wolfram (2007) and assume a Leontief-like production function. Fuel is assumed to be a perfect complement for the other two inputs, capital and labor. We also follow the literature and assume that the function of capital and labor is translog (Atkinson and Halvorsen, 1976; Christensen and Greene, 1976; Boisvert, 1982; Gollop and Roberts, 1983; Carlson et al., 2000). Appendix Table C.4 reports the estimates of the parameters of the production function.

[6]Most of this data were generously provided by Ron Shadbegian and other researchers at the USEPA. We use data from Fabrizio, Rose and Wolfram (2007) to supplement number of employees and nonfuel expenses.

C.3 Additional Descriptive Figures and Tables

Appendix Figure C.2 shows the map of the United States with all the counties where the fossil fuel power plants are located. Appendix Figure C.3 plots the share of annual electricity generation from fossil-fuel-fired plants located in counties in nonattainment for each pollutant and overall, separately for existing plants and new plants. Appendix Figure C.4 displays the annual electricity generating capacity by each fuel type, including nuclear and hydro. Appendix Figure C.5 shows the trends in annual electricity generation and electricity-generating capacity by vintage and *detailed* attainment status. Appendix Figures C.6 and C.7 display the trends in annual pollution-unadjusted total factor productivity by vintage and attainment status, overall and detailed, respectively. Appendix Figure C.8 presents the county-level distribution of the number of years a county has been out of attainment between 1972-1994.

Appendix Table C.1 reports the number of plants in the sample by vintage and attainment status, and Appendix Table C.2 shows the transition from nonattainment to attainment status, and vice versa. Appendix Table C.3 presents summary statistics for the main variables used in the analysis.

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	

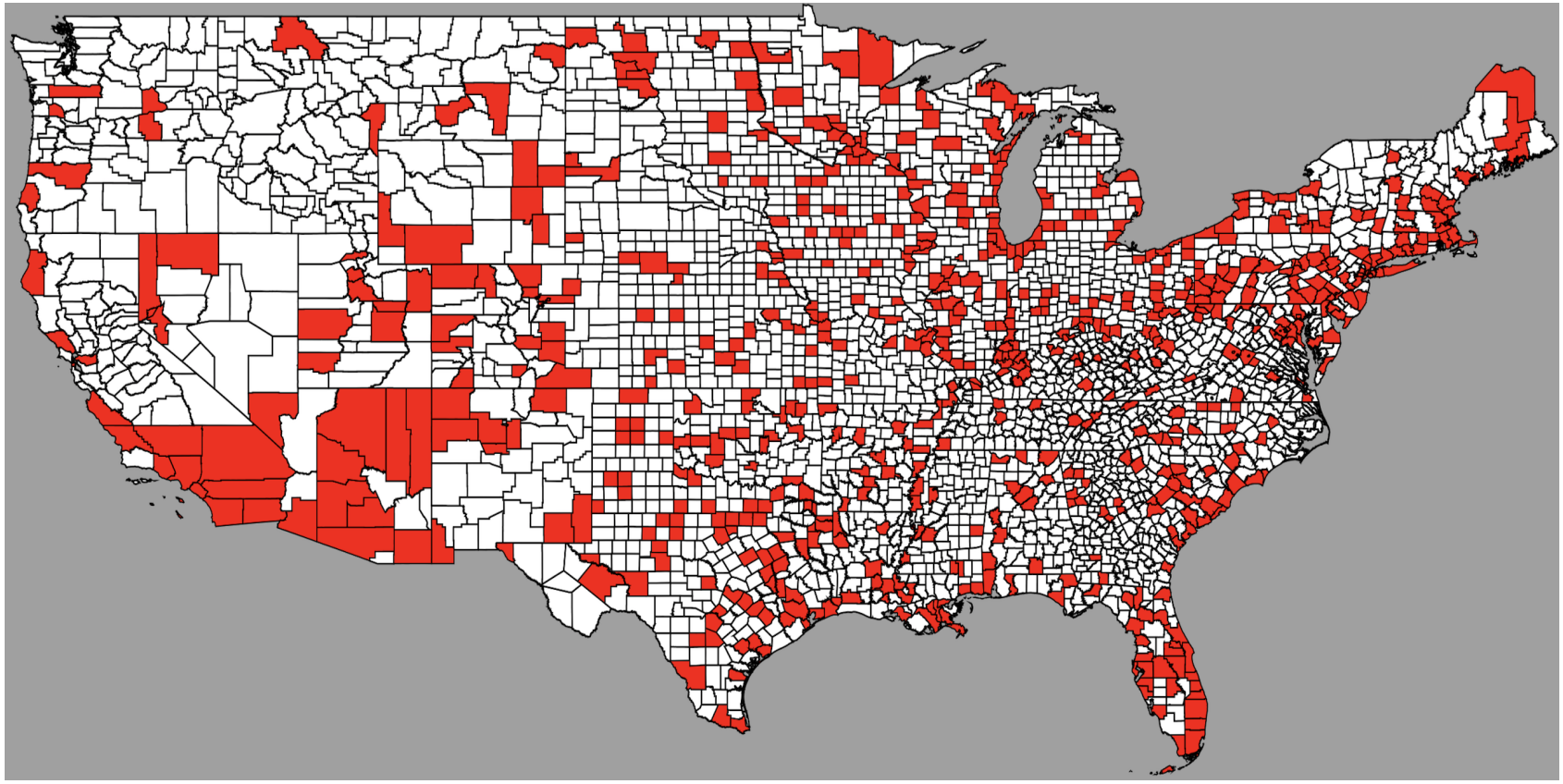
CHANGES OR ADDITIONS IN 1957

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

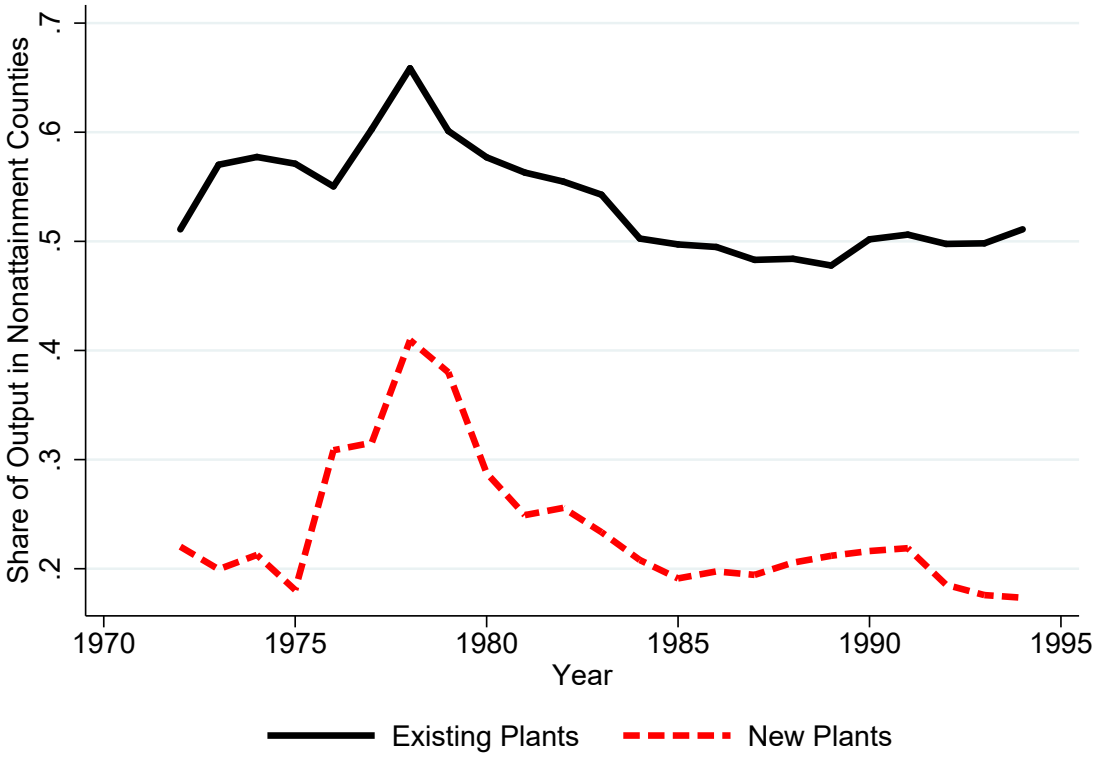
Source: Federal Power Commission Report "*Steam-Electric Plant Construction Cost and Annual Production Expenses – Tenth Annual Supplement*", 1957.

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

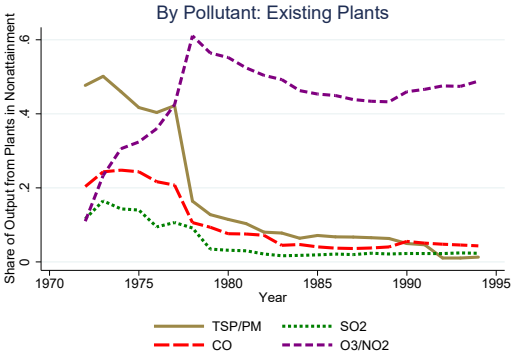


Notes: This figure displays which counties had fossil-fuel power plants at any point during our period of analysis 1938-1994. The counties shaded in red were home to at least one fossil-fuel plant in our sample. There were no power plants in any year of our sample in the counties shaded in white.

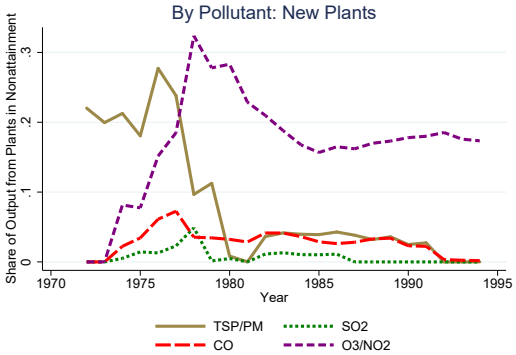
Figure C.3: Share of Electricity Generation in Nonattainment Counties



(a) Share of Electricity Generation in Nonattainment Counties



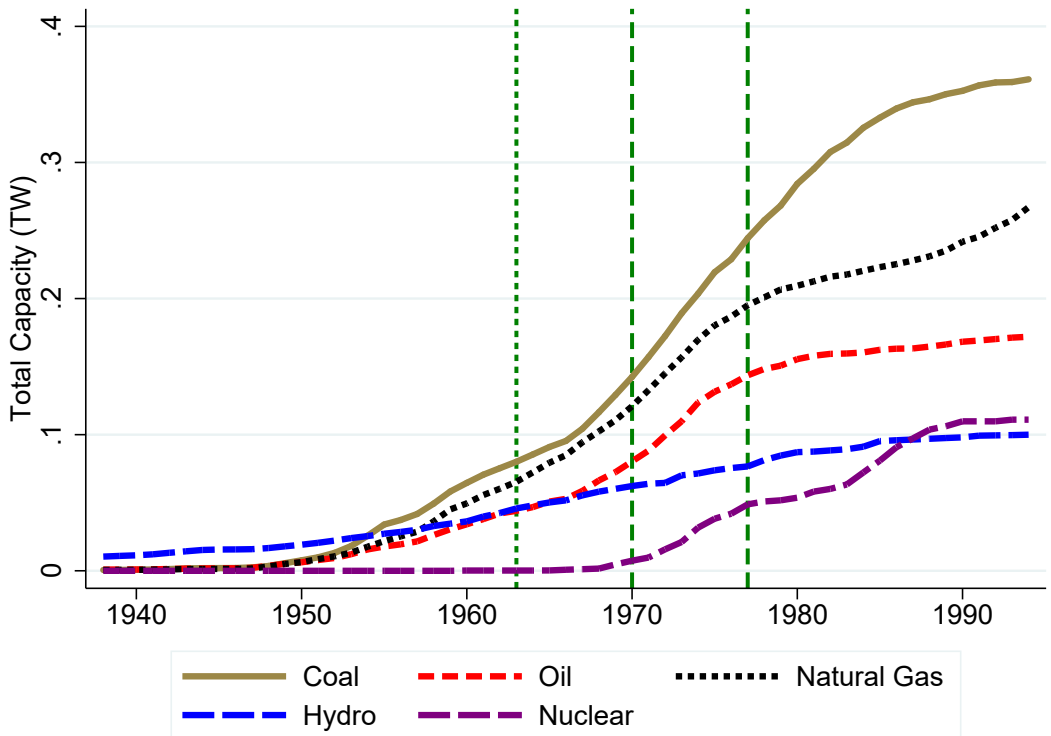
(b) Share of Generation in Nonattainment by Pollutant – Existing Plants



(c) Share of Generation in Nonattainment by Pollutant – New Plants

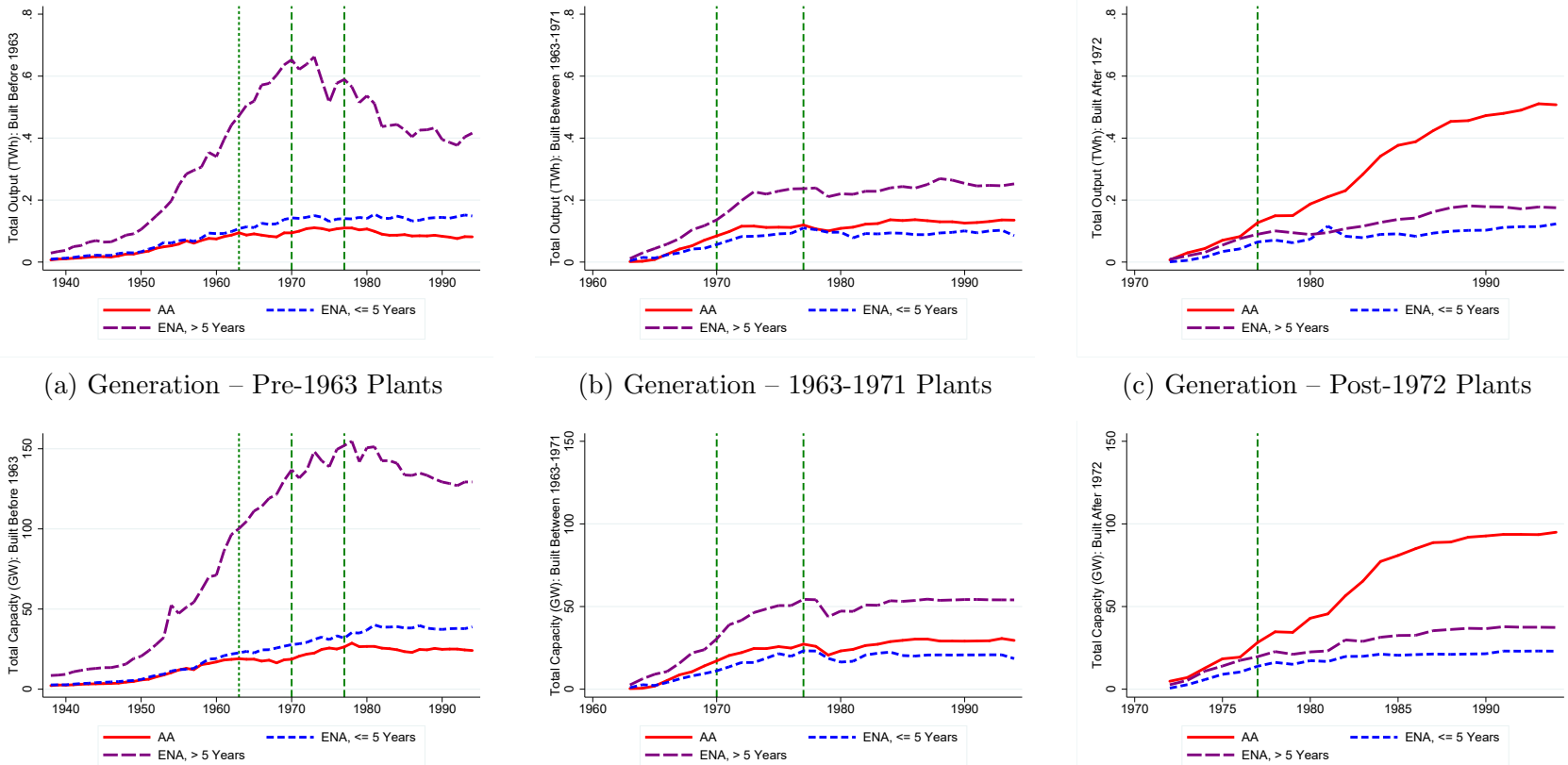
Notes: The top panel of this figure documents the aggregate proportion of electricity production from plants in counties out of attainment with NAAQS for any pollutant for the sample period 1972-1994. The bottom panels document the aggregate proportion of electricity production from "existing" (pre-1972) plants and "new" (post-1972) plants in counties out of attainment with NAAQS by pollutant for the same sample period, respectively. "TSP/PM" refers to standards pertaining to either total suspended particles (TSP) or particulate matter (PM), "SO2" refers to the standard associated with sulfur dioxide, "CO" refers to the standard associated with carbon monoxide, and "O3/NO2" refers the standards pertaining to either ambient ozone (O_3) or nitrogen dioxide (NO_2).

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



Notes: This figure documents annual national total electricity production capacity by fuel type. The data underlying this figure come from the EIA Form 767. The thin dashed vertical green line represents the Clean Air Act of 1963 while the thicker green vertical lines represent the 1970 Clean Air Act and its amendments in 1977.

Figure C.5: Annual Total Electricity Generation and Capacity from Fossil-Fuel Power Plants by Vintage and Years in Nonattainment

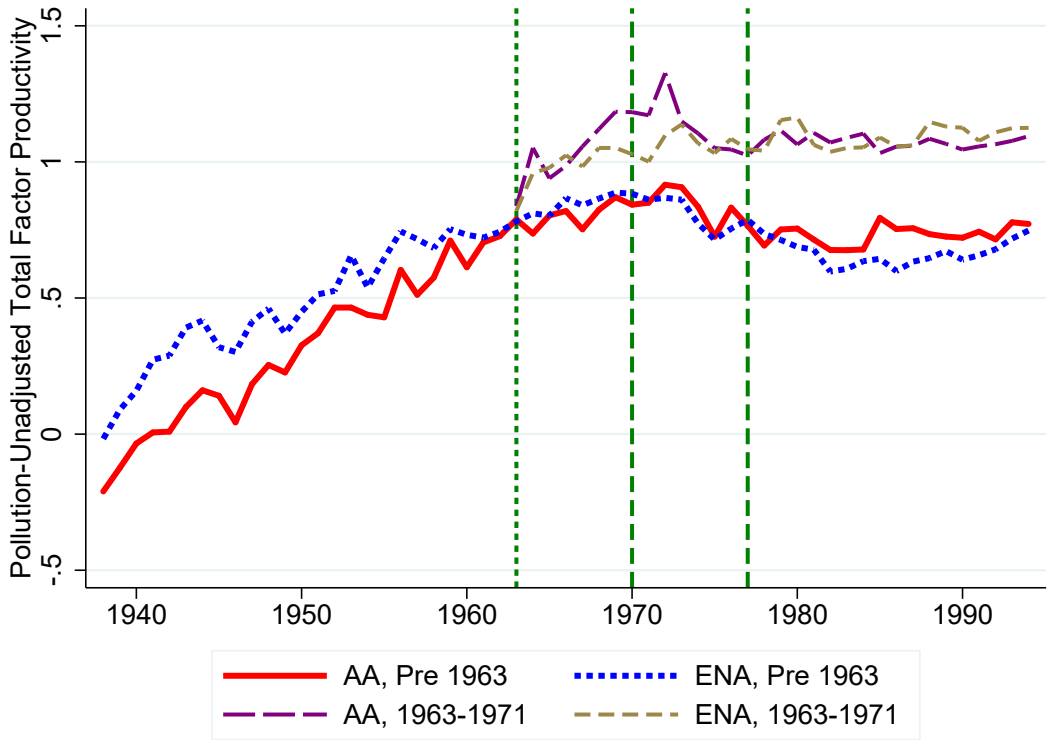


(a) Generation – Pre-1963 Plants (b) Generation – 1963-1971 Plants (c) Generation – Post-1972 Plants

(d) Capacity – Pre-1963 Plants (e) Capacity – 1963-1971 Plants (f) Capacity – Post-1972 Plants

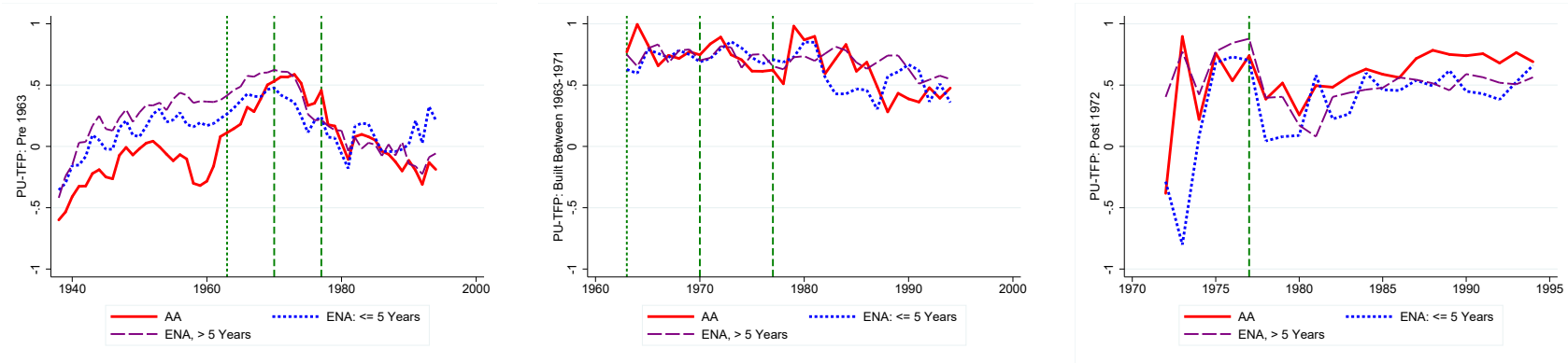
Notes: This figure documents annual total electricity generation and electricity-generating capacity by fossil-fuel-fired plants in the United States. We consider three vintage categories: plants built before 1963, 1963-1971, and post-1972. We consider three regulatory status categories: "always-attainment" (AA) – counties that never went out of attainment during our sample period 1938-1994; "ever-nonattainment" for less than five years (ENA, <=5 Years) – counties that went out of attainment with the National Ambient Air Quality Standards (NAAQS) for less than five years over that period of analysis; and ENA for more than five years. The thin dashed vertical green line represents the Clean Air Act of 1963 while the thicker green vertical lines represent the 1970 Clean Air Act and its amendments in 1977.

Figure C.6: Annual Average Total Factor Productivity from Fossil-Fuel Power Plants by Vintage and Attainment Status



Notes: This figure plots annual generation-weighted average pollution-unadjusted total factor productivity separately across plants built before 1963 versus built between 1963-1971 located in always attainment ("AA") counties versus ever-nonattainment ("ENA") counties. "AA" counties never faced nonattainment during our 1938-1994 sample period while "ENA" counties faced nonattainment at least once between 1972-1994. Finally, the thin dashed vertical green line represents the Clean Air Act of 1963 while the thicker green vertical lines represent the 1970 Clean Air Act and its amendments in 1977.

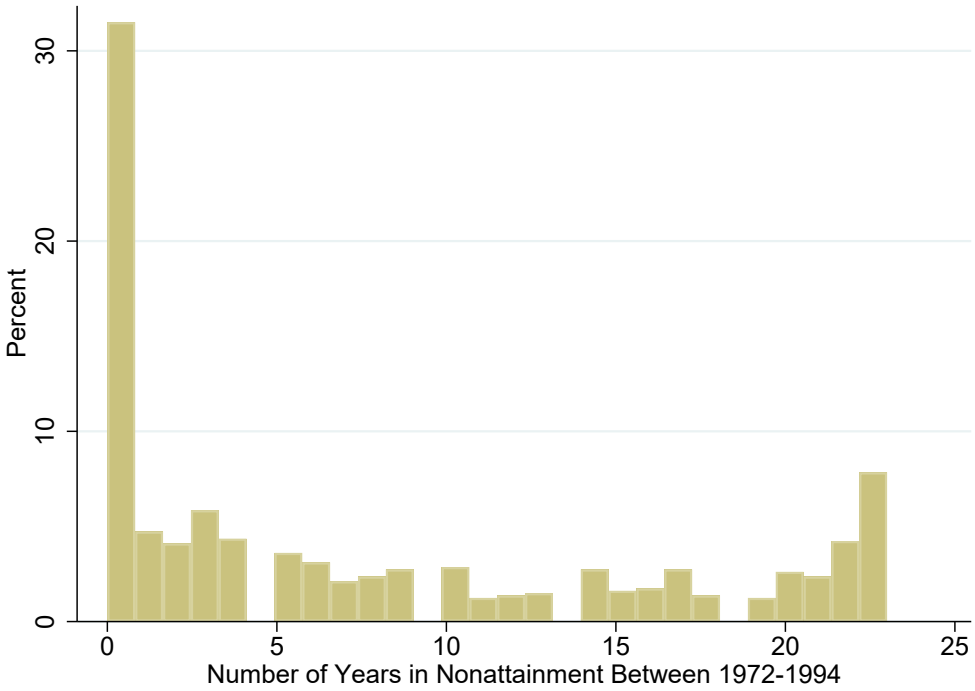
Figure C.7: Annual Average Total Factor Productivity from Fossil-Fuel Power Plants by Vintage and Years in Nonattainment



(a) PU-TFP – Pre-1963 Plants (b) PU-TFP – 1963-1971 Plants (c) PU-TFP – Post-1972 Plants

Notes: This figure documents annual pollution-unadjusted total factor productivity (PU-TFP) by fossil-fuel-fired plants in the United States. We consider three vintage categories: plants built before 1963, 1963-1971, and post-1972. We consider three regulatory status categories: "always-attainment" (AA) – counties that never went out of attainment during our sample period 1938-1994; "ever-nonattainment" for less than five years (ENA, <=5 Years) – counties that went out of attainment with the National Ambient Air Quality Standards (NAAQS) for less than five years over that period of analysis; and ENA for more than five years. The thin dashed vertical green line represents the Clean Air Act of 1963 while the thicker green vertical lines represent the 1970 Clean Air Act and its amendments in 1977.

Figure C.8: Distribution of the Number of Years of a County in Nonattainment



Notes: This histogram plots the distribution of the number of years that the county was in nonattainment between 1972-1994. The unit of observation for this histogram is a county.

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

Panel A. Number of Fossil-Fuel-Fired Power Plants			
	Built Before 1963	Built Between 1963-1972	Built After 1972
Always Attainment	194	44	118
Ever Nonattainment	375	82	92
Total	569	126	210
Panel B. Conditional Probability			
	Built Before 1963	Built Between 1963-1972	Built After 1972
Always Attainment	0.34	0.35	0.56
Ever Nonattainment	0.66	0.65	0.44

Notes: This table lists the number of fossil-fuel-fired power plants in our sample in each cell defined by the intersection of two different categorizations. The first row focuses on plants that never faced nonattainment between 1972-1994 while the second row focuses on plants that faced nonattainment at least once between 1972-1994. The first column considers plants built before 1963, the second column plants built between 1963-1971, and the third column plants built after 1972.

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*	6,594	615
Nonattainment in Year *t-1*	348	5,455
Panel B. Conditional Probability		
	Attainment in Year t	Nonattainment in Year t
Attainment in Year *t-1*	0.91	0.09
Nonattainment in Year *t-1*	0.06	0.94

Notes: This table lists the number of observations in each of the four categories defined by attainment status in years t and $t-1$. For example, a county that is in attainment in both 1980 and 1981 would be counted as part of the sum in the top-left cell of the table. The unit of observation underlying this table is county-year, spanning the sample period 1972-1994. We consider observations corresponding to counties that house a power plant in the year-of-sample.

Table C.3: Summary Statistics: PU-TFP, Production Function, and NAAQS

Panel A: Power Plant Operations, Sample Period 1938-1994			
Variable	**No. of Obs.**	**Mean**	**Std. Dev.**
Log Pollution-Unadjusted Total Factor Productivity	22,134	-0.62	0.76
Electricity Output (GWh)	22,134	1.88	2.43
Capacity (MW)	22,134	442.96	511.95
Number of Employees	22,134	128.76	129.23
Fuel Burned (in Billion BTU)	22,134	19.69	30.35
Panel B: Indicator for NAAQS Noncompliance, Sample Period: 1972-1994			
Variable	**No. of Obs.**	**Mean**	**Std. Dev.**
1[Out of Attainment with any NAAQS]	10,590	0.51	0.50
1[Out of Attainment with NAAQS: TSP or PM]	10,590	0.17	0.38
1[Out of Attainment with NAAQS: SO_2]	10,590	0.05	0.22
1[Out of Attainment with NAAQS: CO]	10,590	0.12	0.33
1[Out of Attainment with NAAQS: O_3 or NO_2]	10,590	0.41	0.49

Notes: This table presents summary statistics for our difference-in-differences regressions relating NAAQS attainment status and different plant-level outcome variables. We estimate plant-year level PU-TFP based on a translog production function with capital (the plant's 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).

Table C.4: Production Function Estimates from Different Methods and Functional Forms

Dep. Var.: Log Output	(1)	(2)	(3)	(4)
Panel A. Estimated Parameters				
	(1)	(2)	(3)	(4)
Log Labor	1.686***	1.839***	0.302	0.289***
	(0.003)	(0.015)	(.)	(0.019)
Log Capacity	0.197***	-0.167***	0.896***	0.889***
	(0.003)	(0.014)	(0.000)	(0.035)
l × l	-0.169***	-0.130***		
	(0.001)	(0.019)		
l × k	0.067***	-0.134***		
	(0.000)	(0.016)		
k × k	0.017***	0.003		
	(0.004)	(0.014)		
Functional Form	Translog	Translog	Cobb-Douglas	Cobb-Douglas
Number of Obs.	24,922	24,528	24,922	24,528
Number of Plants	905	900	905	900
Panel B. Post-Estimation Own Elasticities				
log(Employees)	0.53	0.19	0.30	0.29
log(Capacity)	0.69	0.81	0.90	0.89
log(Nonfuel Expenses)		0.22		-0.01

Notes: This table reports production function estimates that are used to generate the pollution-unadjusted total factor productivity (PU-TFP) variable used in the analysis. Panel A presents the estimated parameters of the production function with capital (the plant's capacity), labor (average number of employees), and fuel (the heat input in mmBTUs from the fuel burned) using the estimation procedure developed by Ackerberg, Caves and Frazer (2015). We use two functional forms – translog and Cobb-Douglas, and two specifications – with and without nonfuel expenses, which refers to nonfuel materials expenses. Our preferred specification, which is the basis for the PU-TFP variable used in the main analysis, is presented in column 1. Panel B reports implied elasticities regarding each input. The unit of observation for all these analyses is a plant-epoch-year. Similar to Fabrizio, Rose and Wolfram (2007), we define an "epoch" for each plant based on periods of time during which there were no substantial changes in the plant's electricity generating capacity. *** denotes statistical significance at the 1% level, ** at the 5% level, and * at the 10% level. Standard errors in parentheses are two-way clustered by county and year.

D Additional Results

This appendix section reports additional estimates in support of the main findings in the paper. They shed light on mechanisms behind the main findings, consider heterogeneity in the estimated effects, or test the robustness of the main results.

Appendix Figure D.1 examines how the estimated impacts of nonattainment on power plant outcomes by vintage vary by the first year of data in the analysis, indicating the importance of including a long time horizon.

Appendix Table D.1 reports the estimated impacts of nonattainment on power plant outcomes by additional vintage groups. For reference, the main analysis includes only the vintage groups before 1963 and 1963-1971. Appendix Table D.2 presents robustness checks for the main findings using alternative econometric specifications and sample restrictions. Appendix Table D.3 reports the results of the Goodman-Bacon Decomposition for the first nonattainment designation, indicating the importance of the pre-regulatory period in the estimation of the 1970 CAA impacts and the major role of the subgroups treated versus never treated.

Appendix Table D.4 checks the robustness of the nonattainment impacts on pollution-unadjusted total factor productivity (PU-TFP) to alternative production functions and specifications in the estimation of PU-TFP. Appendix Table D.5 examines the heterogeneity of the main results based on the plant primary fuel type. Appendix Table D.6 investigates heterogeneity by nonattainment for specific pollutants rather than nonattainment for any pollutant.

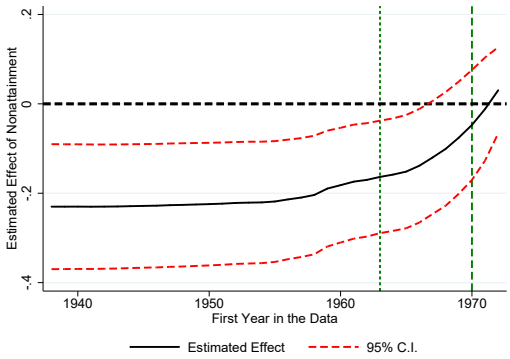
Appendix Table D.7 reports heterogeneous impacts of nonattainment by the first year a county is in nonattainment, shedding light on which transitions to nonattainment matter the most for the main findings. Appendix Table D.8 examines how statewide electricity generating capacity by fuel type responds to the proportion of counties in nonattainment in that state, providing evidence against geographical spillovers. Appendix Table D.9 presents the estimated impacts of nonattainment and plant vintage on the adoption of FGP, complementing analysis in the paper regarding the adoption of FGD.

The outline of figures and tables in this appendix section is below.

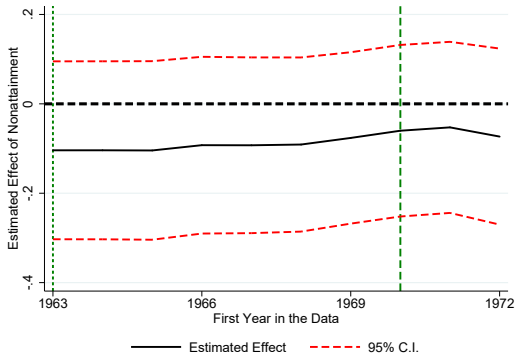
- Figure D.1. Impacts of Nonattainment on Power Plant Outcomes by Vintage and Initial Sample Year

- Table D.1. Impacts of Nonattainment on Power Plant Outcomes by Additional Vintage Groups
- Table D.2. Impacts of Nonattainment on Power Plant Outcomes from Alternative Specifications and Samples
- Table D.3. Results of the Goodman-Bacon Decomposition for First Nonattainment
- Table D.4. Impact of Nonattainment on PU-TFP Estimated from Alternative Production Functions and Specifications
- Table D.5. Impacts of Nonattainment on Power Plant Outcomes by Primary Fuel Type
- Table D.6. Impacts of Nonattainment for a Specific Pollutant on Power Plant Outcomes
- Table D.7. Impacts of Nonattainment on Power Plant Outcomes by First Year in Nonattainment
- Table D.8. Extensive Margin Response: State-Level Regressions of Capacity on Proportion of Counties in Nonattainment
- Table D.9. Impacts of Nonattainment and Plant Vintage on the Adoption of FGP

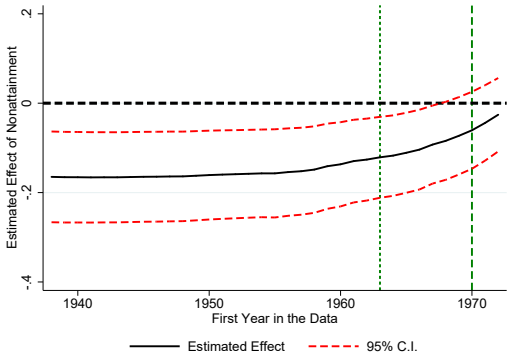
Figure D.1: Impacts of Nonattainment on Power Plant Outcomes by Vintage and Initial Sample Year



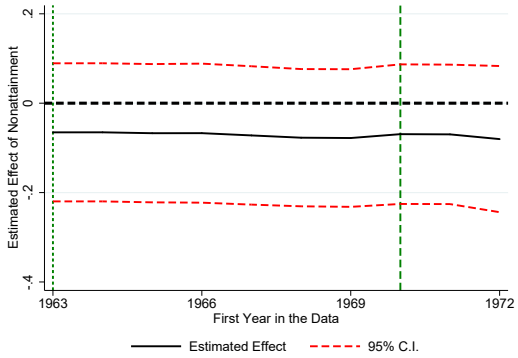
(a) Effects on Log Output – Pre-1963 Plants



(b) Effects on Log Output – 1963-1971 Plants



(c) Effects on Log PU-TFP – Pre-1963 Plants



(d) Effects on Log PU-TFP – 1963-1971 Plants

Notes: This figure displays the estimated impacts of nonattainment on log output and the log of pollution-unadjusted total factor productivity (PU-TFP) by initial sample year, separately for plants built before 1963 and for plants built between 1963-1971. These estimates are based on annual plant-level data from 1938-1994, considering all plants that were built before 1972. The short-dashed green vertical line represents the passage of the Clean Air Act of 1963 and the dashed green vertical lines represent the Clean Air Act of 1970 and its amendments in 1977. All specifications include plant fixed effects, state-by-year fixed effects, fuel-type-by-year fixed effects, and vintage-group-by-year fixed effects; plants built before 1963 are in vintage group 1 while plants built between 1963-1971 are in vintage group 2. The 95% confidence intervals reported in these figures are based on standard errors that are two-way clustered by county and year.

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

	(1)	(2)	(3)	(4)	(5)
Dep. Var. (in Logs)	Output	PU-TFP	Fuel Use	No. Employees	Capacity
NA × 1[Before 1955]	-0.331***	-0.159***	-0.260***	-0.143***	-0.189***
	(0.083)	(0.057)	(0.077)	(0.041)	(0.052)
NA × 1[1955-1962]	0.016	-0.171***	0.158*	0.233***	0.051
	(0.077)	(0.061)	(0.082)	(0.053)	(0.057)
NA × 1[1963-1966]	-0.122	0.004	-0.042	-0.085	-0.086
	(0.129)	(0.087)	(0.133)	(0.082)	(0.075)
NA × 1[1967-1971]	0.027	-0.045	0.102	0.057	0.081
	(0.118)	(0.104)	(0.100)	(0.052)	(0.054)
R^2	0.820	0.616	0.753	0.868	0.914
Mean of Dep. Var.	6.736	-0.621	9.168	4.498	5.474
Number of Obs.	22,134	22,134	22,134	22,134	22,134
Number of Plants	686	686	686	686	686
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 in Each Group: There are 402 plants built before 1955, 168 plants built between 1955 and 1962, 66 plants built between 1963 and 1967, and 60 plants built between 1967 and 1971.

Notes: This table reports the impacts of nonattainment status on power plant outcomes by additional vintage groups. For reference, in the main analysis, we consider only two vintage groups: plants built before 1963, and plants built between 1963-1971. For all specifications, "nonattainment" (NA) is defined as the county being out of attainment with the NAAQS for any pollutant in the year. PU-TFP stands for pollution-unadjusted total factor productivity. Fuel use is measured in units of heat. The unit of observation for these regressions is a plant-year. Standard errors in parentheses are two-way clustered by county and year. *** denotes statistical significance at the 1% level, ** at the 5% level, and * at the 10% level.

Table D.2: Impact of Nonattainment on Power Plant Outcomes from Alternative Specifications and Samples

	(1) Primary	(2) Utility FE	(3) Larger	(4) Coal	(5) Non-Gas	(6) No State Standard
Panel A. Log Output						
Nonattainment	-0.203***	-0.202***	-0.185***	-0.216***	-0.181***	-0.253***
	(0.062)	(0.063)	(0.066)	(0.077)	(0.062)	(0.076)
R^2	0.819	0.824	0.777	0.842	0.833	0.826
Mean of Dep. Var.	6.736	6.737	7.108	7.077	6.743	6.731
Panel B. Log PU-TFP						
Nonattainment	-0.140***	-0.146***	-0.095**	-0.142**	-0.145***	-0.151***
	(0.043)	(0.043)	(0.044)	(0.053)	(0.045)	(0.051)
R^2	0.616	0.637	0.636	0.621	0.607	0.628
Mean of Dep. Var.	-0.621	-0.620	-0.593	-0.577	-0.583	-0.653
Number of Obs.	22,134	22,120	17,653	12,453	19,444	16,571
Number of Plants	686	686	507	356	609	496
Plant FE	Y	Y	Y	Y	Y	Y
Utility FE		Y				
State By Year FE	Y	Y	Y	Y	Y	Y
Fuel Type By Year FE	Y	Y	Y	Y	Y	Y
Vintage Group by Year FE	Y	Y	Y	Y	Y	Y

Notes: This table presents our regression results measuring how each plant's log of pollution-unadjusted total factor productivity (PU-TFP) in a given year-of-sample changes when the county this plant is located in moves in and out of compliance with the NAAQS for any pollutant. All five columns are based on specifications estimated on plants built before 1972 and include plant fixed effects, state-by-year fixed effects and fuel-type-by-year fixed effects. The specifications considered in Column 2 additionally include utility-by-state by year fixed effects. For Column 3, we keep only plants with capacity in the year they were built greater than the 25% of the plant-level distribution of initial capacities. Column 4 focuses only on coal-fired plants while Column 5 is estimated dropping all plants that burn natural gas as their primary fuel. Finally, Column 6 drops plants located in the ten states that had state-level air quality standards by 1966 – California, Colorado, Delaware, Missouri, Montana, New York, Oregon, Pennsylvania, South Carolina, and Texas. These states had adopted ambient air quality standards for a total of 14 substances, and for deposited matter (Stern, 1982). The unit of observation for these regressions is a plant-year. Standard errors in parentheses are two-way clustered by county and year. *** denotes statistical significance at the 1% level, ** at the 5% level, and * at the 10% level.

Table D.3: Results of the Goodman-Bacon Decomposition for First Nonattainment

	(1)	(2)	(3)	(4)	(5)
Dep. Var. (in Logs)	Output	PU-TFP	Fuel Use	No. Employees	Capacity
Panel A. Strongly Balanced for 10 Years Before and After 1972					
Overall DD Estimate	-0.162	-0.052	0.010	-0.046	-0.121
DD Est.: T vs. Never Treated	-0.193	-0.056	0.032	-0.055	-0.148
DD Est.: Earlier T vs. Later C	-0.226	-0.063	-0.033	-0.106	-0.153
DD Est.: Later T vs. Earlier C	0.071	-0.018	-0.004	0.089	0.042
Weights: T vs. Never Treated	0.602	0.602	0.602	0.602	0.602
Weights: Earlier T vs. Later C	0.248	0.248	0.248	0.248	0.248
Weights: Later T vs. Earlier C	0.150	0.150	0.150	0.150	0.150
Number of Obs.	4,956	4,956	4,956	4,956	4,956
Number of Plants	236	236	236	236	236
Panel B. Strongly Balanced for 15 Years Before and After 1972					
Overall DD Estimate	-0.066	-0.007	-0.034	-0.001	-0.087
DD Est.: T vs. Never Treated	-0.113	-0.025	-0.074	0.004	-0.126
DD Est.: Earlier T vs. Later C	-0.140	-0.026	-0.051	-0.108	-0.091
DD Est.: Later T vs. Earlier C	0.233	0.097	0.157	0.130	0.081
Weights: T vs. Never Treated	0.641	0.641	0.641	0.641	0.641
Weights: Earlier T vs. Later C	0.208	0.208	0.208	0.208	0.208
Weights: Later T vs. Earlier C	0.151	0.151	0.151	0.151	0.151
Number of Obs.	4,495	4,495	4,495	4,495	4,495
Number of Plants	145	145	145	145	145

Notes: This table reports the output from running the Goodman-Bacon decomposition on panel regressions of first-nonattainment on outcomes (Goodman-Bacon, 2018). The unit of observation for these panel regressions is plant-year, and these regressions include plant fixed effects and year fixed effects; we consider only existing plants built before 1972. The Goodman-Bacon method decomposes the overall difference-in-differences ("DD") effect of nonattainment into three components: (i) counties that face nonattainment versus counties that never face nonattainment during our 1938-1994 sample period ("T vs. Never Treated"), (ii) counties that first face nonattainment earlier, using counties first facing nonattainment later as controls ("Earlier T vs. Later C"), and (iii) counties that first face nonattainment later, using counties first facing nonattainment earlier as controls ("Later T vs. Earlier C"). For each component, the decomposition provides both the DD estimate and the weight of this estimate in calculating the overall DD estimate. The overall DD estimate is reported in the first row of results in each panel. The decomposition requires a strongly balanced panel. To construct this, we include only plants with consecutive observations for 10 years or 15 years before and after 1972 in the top and bottom panels, respectively. We also only consider observations in the 10 years or 15 years before and after 1972 in the top and bottom panels, respectively. Plant-year observations must have data listed for output, electricity generating capacity, number of employees, and input energy for the whole 20 year span or 30 year span in order to be included.

Table D.4: Impact of Nonattainment on PU-TFP Estimated from Alternative Production Functions and Specifications

Dep. Var.: Log PU-TFP	(1)	(2)	(3)	(4)
Nonattainment	-0.136***	-0.136***	-0.099**	-0.104**
	(0.043)	(0.040)	(0.039)	(0.039)
R^2	0.615	0.624	0.609	0.607
Mean of Dep. Var.	-0.621	-1.328	0.469	0.674
Number of Obs.	22,134	21,886	22,134	21,886
Number of Plants	686	686	686	686
Plant FE	Y	Y	Y	Y
State By Year FE	Y	Y	Y	Y
Fuel Type By Year FE	Y	Y	Y	Y
Vintage Group By Year FE	Y	Y	Y	Y
Functional Form	Translog	Translog	CD	CD
Estimation Method	ACF	ACF	ACF	ACF
Includes Nonfuel Expenses		Y		Y

Notes: This table presents our regression results measuring how each plant's log of PU-TFP in a given year-of-sample changes when the county this plant is located in moves in and out of compliance with NAAQS associated any pollutant. The unit of observation for these regressions is a plant-year. We estimate pollution-unadjusted total factor productivity (PU-TFP) using the methodology developed by Ackerberg, Caves and Frazer (2015). The first two columns estimate TFP assuming that the production function is translog while the next two columns assume that the production function is Cobb-Douglas (CD). Finally, the even columns include nonfuel expenditures as a measure of materials when estimating PU-TFP while the odd columns estimate PU-TFP only considering capital and labor – i.e., no measure for materials is included. Standard errors in parentheses are two-way clustered by county and year. *** denotes statistical significance at the 1% level, ** at the 5% level, and * at the 10% level.

Table D.5: Impacts of Nonattainment on Power Plant Outcomes by Primary Fuel Type

	(1)	(2)	(3)	(4)	(5)
Dep. Var. (in Logs)	Output	PU-TFP	Fuel Use	No. Employees	Capacity
NA × 1[Coal Plant]	-0.201***	-0.133**	-0.136**	-0.033	-0.099**
	(0.073)	(0.050)	(0.066)	(0.036)	(0.047)
NA × 1[Oil Plant]	-0.170*	-0.154*	-0.037	0.030	-0.088
	(0.091)	(0.080)	(0.087)	(0.052)	(0.058)
NA × 1[Gas Plant]	-0.466**	-0.212	-0.399*	-0.285**	-0.232
	(0.230)	(0.140)	(0.212)	(0.109)	(0.153)
R^2	0.820	0.617	0.752	0.865	0.914
Mean of Dep. Var.	6.736	-0.621	9.168	4.498	5.474
Number of Obs.	22,134	22,134	22,134	22,134	22,134
Number of Plants	686	686	686	686	686
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

*Notes:*This table measures how annual plant-level outcomes change with nonattainment interacted with three bins associated with whether the primary fuel burned by the plant in its first three years of operation was coal, natural gas, oil, or a mix of these fuels. The fuel type is specified as "primary" only is the total heat input in mmBTUs from the fuel type divided by the total heat input in mmBTUs from all fuel types is greater than 0.75. For all specifications, "nonattainment" (NA) is defined as the county being out of attainment with the NAAQS for any pollutant in the year. PU-TFP stands for pollution-unadjusted total factor productivity. The unit of observation for these regressions is a plant-year. Standard errors in parentheses are two-way clustered by county and year. *** denotes statistical significance at the 1% level, ** at the 5% level, and * at the 10% level.

Table D.6: Impacts of Nonattainment For a Specific Pollutant on Power Plant Outcomes

	(1)	(2)	(3)	(4)	(5)
Dep. Var. (in Logs)	Output	PU-TFP	Fuel Use	No. Employees	Capacity
NA: TSP or PM	-0.036	-0.058*	-0.037	0.009	0.015
	(0.039)	(0.034)	(0.046)	(0.025)	(0.028)
NA: SO2	-0.044	-0.017	-0.010	-0.015	-0.032
	(0.080)	(0.052)	(0.076)	(0.037)	(0.047)
NA: CO	-0.152	-0.024	-0.076	-0.108**	-0.128**
	(0.095)	(0.060)	(0.087)	(0.044)	(0.054)
NA: O_3 or NO_2	-0.141**	-0.116**	-0.073	-0.005	-0.062
	(0.062)	(0.049)	(0.061)	(0.033)	(0.040)
R^2	0.819	0.616	0.751	0.865	0.914
Mean of Dep. Var.	6.736	-0.621	9.168	4.498	5.474
Number of Obs.	22,134	22,134	22,134	22,134	22,134
Number of Plants	686	686	686	686	686
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

Notes: This table presents our regression results measuring how annual plant-level outcomes change when the county this plant is located in moves in and out of compliance with NAAQS associated with each of four sets of pollutants: total suspended particulates or particulate matter (TSP or PM), sulfur dioxide (SO_2), carbon oxides (CO), and nitrogen oxides or ozone (NO_2 or O_3). There are separate standards for O_3 and nitrogen dioxide (NO_2), and in principle a county could meet one of these standards but not the other. However, O_3 is the result of a complicated chemical process that involves NO_2, and the vast majority of counties that were nonattainment for NO_2 were also nonattainment for O_3. As a result, we designated a county nonattainment for O_3 if the EPA labeled it nonattainment for either O_3 or NO_2. PU-TFP stands for pollution-unadjusted total factor productivity, and NA for nonattainment. The unit of observation for these regressions is a plant-year. Standard errors in parentheses are two-way clustered by county and year. *** denotes statistical significance at the 1% level, ** at the 5% level, and * at the 10% level.

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

	(1)	(2)	(3)	(4)	(5)
Dep. Var. (in Logs)	Output	PU-TFP	Fuel Use	No. Employees	Capacity
First NA in 1972-1977	-0.232***	-0.151***	-0.139**	-0.045	-0.124***
	(0.067)	(0.045)	(0.064)	(0.033)	(0.043)
First NA in 1978-1983	0.046	-0.074	0.114	0.092	0.088
	(0.134)	(0.118)	(0.112)	(0.084)	(0.106)
First NA in 1984-1994	0.038	0.111	0.040	-0.010	0.076
	(0.247)	(0.202)	(0.247)	(0.248)	(0.116)
R^2	0.819	0.616	0.751	0.865	0.914
Mean of Dep. Var.	6.736	-0.621	9.168	4.498	5.474
Number of Obs.	22,134	22,134	22,134	22,134	22,134
Number of Plants	686	686	686	686	686
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

Notes: This table measures how annual plant-level outcomes change with nonattainment interacted with three bins associated with whether the first year the county went out of nonattainment was in 1972-1977, 1978-1983 or 1978-1994. For all specifications, "nonattainment" is defined as the county being out of attainment with the NAAQS for any pollutant in the year. PU-TFP stands for pollution-unadjusted total factor productivity, and NA for nonattainment. The unit of observation for these regressions is a plant-year. Standard errors in parentheses are two-way clustered by county and year. *** denotes statistical significance at the 1% level, ** at the 5% level, and * at the 10% level.

Table D.8: Extensive Margin Response: State-Level Regressions of Capacity on Proportion of Counties in Nonattainment

	(1)	(2)	(3)	(4)
Dep. Var.: Capacity (in MW)	Fossil Fuel: ST	Fossil Fuel: GT or CC	Nuclear	Hydro
Prop. in Nonattainment	3785.0*	1165.3**	1334.9*	-411.1
	(2095.6)	(460.6)	(668.5)	(850.1)
R^2	0.679	0.575	0.527	0.704
Mean of Dep. Var.	4,019.1	567.1	571.4	1,026.3
Number of Obs.	2,907	2,907	2,907	2,907
Number of States	51	51	51	51
State FE	Y	Y	Y	Y
Year FE	Y	Y	Y	Y

Notes: This table presents estimates of the impact of state-level proportion of counties in nonattainment on state-level electricity generating capacity. Specifically, the independent variable of interest is the annual state-level population-weighted proportion of counties that in nonattainment with the NAAQS for any pollutant in each year. All specifications include state fixed effects and year fixed effects. The dependent variable considered in Columns 1, 2, 3 and 4 is the annual state-level capacity aggregating over fossil-fuel-fired sources using either steam turbines or internal combustion, fossil-fuel-fired sources using either gas turbines or a combined-cycle technology, nuclear sources, and hydro sources respectively. The unit of observation for these regressions is a state-year. Standard errors in parentheses are two-way clustered by state and year. *** denotes statistical significance at the 1% level, ** at the 5% level, and * at the 10% level.

Table D.9: Impacts of Nonattainment and Plant Vintage on the Adoption of FGP

Dep. Var.: 1[FGP]	(1)	(2)	(3)	(4)
1[1963-1971]	-0.049	-0.011		
	(0.041)	(0.044)		
1[After 1972]				
First NA	-0.198***	-0.102**	-0.075*	-0.074
	(0.045)	(0.049)	(0.040)	(0.051)
First NA × 1[1963-1971]	0.143**	0.044		
	(0.059)	(0.052)		
First NA × 1[After 1972]				
R^2	0.592	0.603	0.582	0.578
Mean of Dep. Var.	0.408	0.576	0.368	0.511
Number of Obs.	25,107	14,295	22,134	12,123
Number of Plants	899	504	686	346
State By Year FE	Y	Y	Y	Y
Fuel Type By Year FE	Y	Y	Y	Y
Vintage Group By Year FE	Y	Y	Y	Y
Fuel Type	All	Coal	All	Coal
Includes Plants Built After 1971	Y	Y	N	N

Notes: This table presents our regression results measuring how the installation of flue gas particulate (FGP) collectors change when the county this plant is located in moves in and out of compliance with the NAAQS for any pollutant. The dependent variable is an indicator variable that is equal to one if the plant has at least one FGP collector installed in the year. Columns 1 and 3 consider all plants while Columns 2 and 4 consider only plants that primarily burn coal. The unit of observation for these regressions is a plant-year. Standard errors in parentheses are two-way clustered by county and year. *** denotes statistical significance at the 1% level, ** at the 5% level, and * at the 10% level.