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IMPACTS OF THE CLEAN AIR ACT ON THE POWER SECTOR FROM 1938-1994: ANTICIPATION AND ADAPTATION

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ABSTRACT

This paper provides the first assessment of the plant-level productivity impacts of the 1970 Clean Air Act (CAA) that accounts for anticipatory responses. A simple theoretical framework is used to illustrate how credible signals of future regulatory actions can induce firms to make anticipatory investments in cleaner technologies, mitigating the subsequent impacts of environmental regulation. Drawing on newly digitized data on virtually every fossil-fuel power plant in the United States from 1938-1994, the paper uses a difference-in-differences approach to examine the impacts of the Act's nonattainment designations on coal-fired power plants. We find that nonattainment designation led to a 20% reduction in productivity among plants built before 1963, but had no effect on plants built after the passage of the 1963 CAA. The 1963 CAA resulted in minimal regulatory enforcement but served as a strong signal of impending federal air pollution regulation. Empirical and historical evidence suggests that electric utilities made anticipatory investments following the passage of the 1963 CAA. As a result, plants that opened after 1963 were better able to adapt to subsequent regulatory enforcement under the 1970 CAA. The aggregate productivity losses from the 1970 CAA were also substantially mitigated by the reallocation of output away from older, less productive power plants. These productivity losses would be substantially underestimated without utilizing data that extends well before the 1970 CAA.

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1 Introduction

The evaluation of landmark regulations is complicated by the possibility that firms may take actions in anticipation of regulation. For example, the 1970 Clean Air Act (CAA) is the centerpiece of local air pollution regulation in the United States and its effects have been widely studied. However, the 1970 CAA was the culmination of evolving social pressure and incremental policy efforts. The 1963 CAA in particular was the first legislation that authorized the federal government to "control" air pollution. Although the 1963 CAA resulted in minimal regulatory enforcement, it ushered in a period of sustained legislative activity in the 1960s that served as a strong signal of impending federal air pollution regulation. After the 1963 CAA, firms may have updated their beliefs about the likelihood of future regulation when making expensive long-term investments such as power plants. This anticipation complicates efforts to estimate the effects of the 1970 CAA without data that extend well before 1970.

This paper provides the first assessment of the plant-level productivity impacts of the 1970 CAA that accounts for anticipatory responses. A simple theoretical framework is used to illustrate the conditions under which firms make anticipatory investments in cleaner technology following an information shock. The model makes clear that anticipatory responses are likely to occur in settings where capital expenditures are large, durable, and expensive to modify. The framework also shows that anticipatory adjustments to investment choices may occur for two reasons. First, adjustment may occur suddenly in response to a new information shock such as the 1963 CAA that alters expectations over the probability and stringency of future regulation (the "information channel"). Second, adjustment may occur gradually across plant vintages depending on when regulation is expected over the plant's lifespan (the "lifecycle channel"). These preemptive investments, in turn, influence the ultimate productivity impacts of environmental regulation across different plant vintages.

Drawing on newly digitized data on virtually every fossil-fuel power plant in the United States from 1938-1994, the paper uses a difference-in-differences approach to examine the impacts of the 1970 Clean Air Act's nonattainment designations on coal-fired power plants that opened before and after 1963.[1] The 1970 CAA established the National Ambient Air Quality Standards (NAAQS), which classifies areas as in versus out of attainment for several criteria pollutants. Such designations depend on whether pollution levels are below or above the relevant standard. Our primary analysis is based on plants built before 1972, and compares those located in attainment versus non-attainment counties.[2] Plants located in attainment counties are subject to limited regulation. In contrast, plants located in nonattainment counties are pressured by state and local regulators to take costly actions to reduce pollution levels. The fact that our data series starts in 1938 allows us to account for anticipatory investments and to utilize variation generated both by the initial nonattainment designations in 1972 and by subsequent changes in attainment status.[3]

The paper has three main findings. First, nonattainment designation led to a 20% reduction in productivity among plants built before 1963, but had no effect on plants built after 1963.[4,5] This is consistent with the "information channel" in the theoretical framework. Namely, our estimates suggest a change in firm beliefs following the passage of the 1963 CAA, rather than gradual cross-vintage differences in anticipatory investments due to differing lifecycle incentives. Empirical and historical evidence suggests that electric utilities updated their beliefs about the likelihood of regulation following the passage of the 1963 CAA. Compared to plants that opened before 1963, plants that opened between 1963-1971 were built with taller smokestacks, and were more likely to be sited away from pollution monitors, to use less polluting coal, and to install pollution abatement technology.

Second, the distributional impacts of the 1970 CAA substantially mitigated the ag-

[1] We also estimate event study models using the methodology from Callaway and Sant'Anna (2021). This methodology accommodates arbitrary heterogeneity in treatment effects when estimating the average treatment effects on the treated when the timing of treatment is staggered.

[2] We exclude plants built after 1972, since they are also subject to a separate component of the 1970 CAA – the stricter New Source Performance Standards that apply regardless of attainment status under the NAAQS.

[3] For the years 1972-1977, we use the attainment status designations specified in Greenstone (2002). The difference-in-differences and event-study results remain similar if the designations assigned to air quality control regions as mapped into counties by Cropper et al. (2023) are used instead.

[4] Our measure of productivity focuses on how input quantities translate to output electricity, without incorporating the external costs of pollution borne by society at large. We estimate "pollution-unadjusted" total factor productivity (PU-TFP) using the method developed by Ackerberg, Caves and Frazer (2015).

[5] The results remain similar if we account for major generating capacity upgrades (e.g., installing a boiler) when estimating productivity, defining plant vintage, and including fixed effects.

gregate productivity losses from the regulation. Aggregate average productivity between 1972-1994 decreased by roughly 4% due to the NAAQS, resulting in annual total productivity losses of about $4.4 billion (2020 USD). While plants built before 1963 in nonattainment counties suffered a 20% reduction in productivity, plants built after 1963 did not experience productivity losses. In addition, a significant portion of the aggregate productivity losses incurred by pre-1963 plants was offset by productivity gains from the CAA-induced reallocation of output away from older plants to newer plants that opened after 1972.

Third, without data that extends well before 1970, researchers would substantially underestimate the effects of the 1970 CAA on power plant productivity. The magnitude of the main estimates diminish as the pre-regulation sample period is artificially shortened. The results are not statistically significant for samples beginning in the mid-1960s.

Together, these findings offer general insights for the evaluation of landmark regulations. Major regulatory actions such as the 1970 CAA do not arise in a vacuum but typically emerge from an extended period of government legislative efforts. Policy interventions that at first glance appear largely symbolic and ineffective, such as the 1963 CAA, may ultimately have large impacts if they shift beliefs over the probability of future regulatory action. Ignoring these previous policy efforts when constructing a pre-regulation benchmark will result in under-estimates of the effects of the regulation.

This paper makes four contributions to existing literature. The first contribution is to the literature studying anticipatory behavior prior to the passage of regulations. Previous work has documented anticipatory responses to a wide range of policies (Lueck and Michael, 2003; Di Maria, Lange and van der Werf, 2014; Malani and Reif, 2015; Lemoine, 2017; Keiser and Shapiro, 2019).[6] We contribute to this literature by providing evidence on the key role that improvements in information played in generating anticipatory responses that ultimately mitigated the costs of regulatory compliance under the 1970 CAA.

Second, the findings contribute to existing work demonstrating that the distributional

[6] A related literature on the "green paradox" suggests that firms may shift polluting production forward in anticipation of increases in the stringency of future climate policy (see reviews by Jensen et al., 2015; Van der Ploeg and Withagen, 2015). This is not feasible for power plants because long-duration electricity storage is currently prohibitively expensive and electricity demand is close to perfectly inelastic.

impacts of government policy can have first-order effects on aggregate outcomes through reallocative responses (Kline and Moretti, 2014; Hornbeck and Rotemberg, 2019). This paper shows that policy-induced reallocation of output away from older, less productive plants substantially mitigates the aggregate productivity losses from the 1970 CAA.[7]

Third, the paper contributes to the extensive literature documenting the impacts of the 1970 CAA on firm outcomes (see reviews by Currie and Walker, 2019; Aldy et al., 2022).[8] Almost all of these prior studies have relied on post-1972 variation in attainment status, and none have included data from before 1963. By leveraging newly digitized data on plant operations from 1938-1994, this paper provides the first causal estimates of the impact of the 1970 CAA on plant productivity that account for anticipatory investments in the years leading up to the Act's implementation.

Fourth, the paper complements a growing literature in economic history that relies on extended historical time horizons to study the external costs of polluting activities (Beach and Hanlon, 2018; Hanlon, 2020; Heblich, Trew and Zylberberg, 2021; Clay, Lewis and Severnini, 2024). The analysis draws on detailed data on power plant operations spanning seven decades to provide new insights on the economic impacts of environmental regulation. The evidence suggests that the productivity costs of the 1970 CAA borne by the U.S. power sector—one of the largest sources of pollution emissions (Tschofen, Azevedo and Muller, 2019)—are small relative to the public health benefits from regulation-induced reductions in air pollution.[9]

The remainder of the paper is organized as follows. Section 2 presents background information on the evolution of environmental policy in the United States. Section 3 highlights the theoretical conditions under which firms engage in anticipatory behavior. Section 4 describes the data sources, presents summary statistics, and introduces the difference-in-differences approach to estimating the effects of nonattainment on power plant operations. Section 5 reports the main findings, along with robustness checks and

[7] These reallocative effects may have also helped to mitigate the costs of provisions in the 1970 CAA that imposed more stringent regulations on plants built after 1972 (List, Millimet and McHone, 2004).

[8] For impacts on manufacturing, see, for example, Henderson (1996); Becker and Henderson (2000); Greenstone (2002); Gray and Shadbegian (2003); Greenstone, List and Syverson (2012); Ryan (2012); Kahn and Mansur (2013); and Curtis (2018). For impacts on the power sector, see, for example, Gollop and Roberts (1983, 1985); Nelson, Tietenberg and Donihue (1993); Carlson et al. (2000); Ferris, Shadbegian and Wolverton (2014) and Sheriff, Ferris and Shadbegian (2019).

[9] The US Environmental Protection Agency estimates that the 1970 CAA generated more than $22 trillion in public health benefits from 1970 to 1990 (USEPA, 1997).

heterogeneity analyses. Section 6 presents a back-of-the-envelope calculation of the effect of the 1970 CAA on aggregate productivity in the U.S. power sector. Lastly, Section 7 concludes by discussing the policy implications of our findings.

2 Background

This section describes three phases of air pollution regulation in the United States. The first phase was up to 1962, when most of the federal efforts were directed towards data collection. The second phase was 1963-1971. It begins with the passage of the 1963 CAA and ends in 1971, the last year before the 1970 CAA took effect. The third phase was from 1972 onward when the 1970 CAA legislation took effect.

2.1 Up to 1962

The modern clean air movement arose in the postwar period following a number of high profile incidents of extreme air pollution, notably the 1948 Donora smog and the 1952 London smog (Clay, 2018). These events received international publicity, raised public awareness of the relationship between air quality and health, and created the impetus for federal action.[10]

Federal legislation under the 1955 Air Pollution Control Act provided funding for research and technical assistance related to air pollution control. One outcome of this legislation was the creation of the air pollution monitoring network. Although initially small, the network included 270 monitors in 205 counties by 1962. The 1955 Act authorized a modest research budget and left the responsibility of prevention and control of air pollution to the states. A report by the U.S. Advisory Commission on Intergovernmental Relations offers an assessment of the impact of the 1955 Air Pollution Control Act: "It legislated little and, correspondingly, accomplished little." (ACIR, 1981, p.12)

[10]Around the same time, severe ongoing smog problems in Los Angeles led California's state officials to begin lobbying for federal legislation.

2.2 1963-1971

The Clean Air Act of 1963 (1963 CAA) signaled an important shift in the role of the federal government in combating air pollution. The 1963 CAA was the first legislation to give the federal government the authority to "control" air pollution. Namely, the 1963 CAA allowed the initiation of abatement conferences to address air pollution threatening public health and provided for federal enforcement in court if conditions did not improve. Prior to its passage, it was unclear whether the 1963 Act would grant the federal government the authority to regulate air pollution (Orford, 2021). Indeed, two versions of the bill were introduced in 1963, one that granted federal authority and one that did not. Ultimately, the first bill passed into law.[11] Thus, by granting the federal government the authority to compel stationary polluters to reduce emissions, the 1963 CAA represented a sharp and unexpected change in the federal government's role in combating air pollution.

Despite the change in regulatory authority, enforcement under the 1963 CAA was virtually nonexistent. Only a handful of requests for federal intervention were made between 1963 and 1967, and the Secretary of Health, Education, and Welfare (HEW) initiated just five abatement conferences to address complaints about specific facilities, such as pulp mills, a rendering plant, a ferroalloy plant, an open burning dump, and various processing plants. In his article "History of Air Pollution Legislation in the United States," Stern (1982) writes (p. 52): "very little air pollution abatement was actually accomplished by these procedures, which were later abandoned."

By 1967, debates over national pollution emissions standards were in full swing. However, such standards were not included in the final Air Quality Act of 1967 and would not be passed until 1970 (Stern, 1982). The 1967 Act did, however, mark a significant step forward, allowing the HEW to establish regional air quality standards and undertake abatement actions based on these standards. The Act required the establishment of air quality control regions and clean air criteria, with states responsible for implementing these criteria. Three years later, however, "only 21 states had submitted implementation plans, none of which had been approved in Washington. This, of course, made enforcement impossible" (ACIR, 1981, p.23).[12] The 1967 Act represented a critical evolution in

[11]This bill was modeled on the Federal Water Pollution Control Act of 1956.

[12]While there was little enforcement to curb stationary source emissions through the 1960s, the federal government did take action to reduce pollution from mobile sources over this period. Specifically, the passage of 1965 legislation empowered the Secretary of HEW to set automobile emission standards.

federal air pollution control, paving the way for more comprehensive and effective regulation in the years to come. Together, the historical evidence underscores the ineffectiveness of early federal interventions in addressing air pollution concerns.

Despite the limited achievements of the 1963 and 1967 Acts, they played a crucial role in laying the groundwork for future, more robust, federal air pollution control efforts (Orford, 2021). Observers viewed federal air quality enforcement as likely. For example, Professor Zimmerman (1969) wrote in the *Journal of Urban Law* that "although the federal government had not preempted air pollution abatement except for automotive emissions... if state and local governments fail to solve the air pollution problem, it is reasonable to anticipate that a future Congress will approve President Johnson's recommendation... to appoint regional air quality commissions which would be authorized to establish emission levels to be enforced."[13] In retrospect, the 1963 Act was viewed as a "foot in the door" towards establishing a comprehensive national air pollution enforcement program (Orford, 2021).

Qualitative evidence from the 1960s suggests polluting firms were anticipating legislation and seeking to minimize the costs of complying. In 1966, the Federal Power Commission "Steam-Electric Plant Construction Cost and Annual Production Expenses" report dedicated, for the first time, a section on "environmental influences on plant design, construction, and operation." It points out that, among other factors, air pollution was "emerging as a major social-economic issue affecting the electric power industry" (Federal Power Commission, 1967, p.ix).[14] During a 1967 senate hearing on air pollution, Senator Muskie questioned Dr. John Middleton, the director of the National Center for Air Pollution Control, about firms' responses to the need to limit air pollution. Dr. Middleton stated "I think also the industry, in view of your comments earlier about the relative costs, percent increases in control, would like to anticipate this need [for greater emissions control] as much as possible. I think a further point needs to be mentioned and that is that the sooner national emission standards can be employed, the better industry

[13]In 1969, a state senator in North Dakota similarly presaged impending federal legislation, stating: "Those states without pollution statutes or enforcement means will have the void filled by the federal government (Zimney, 1970)."

[14]The report also states that "[t]echnology for the removal of particulate matter has been available for some time; however, the demand for very high efficiency (99 percent+) electrostatic precipitators is growing rapidly. Commercial devices for the removal of oxides of sulfur from the flue gases are not yet available (...) In the meantime, (...) higher boiler stacks are being installed to attain greater dispersion" (Federal Power Commission, 1967, pp. ix-x).

will be because it is much cheaper to build a plant with these constraints than it is to have them added after the construction" (United States Congress, 1967).

Changes in the design of power plants that opened after 1963 are also consistent with anticipatory behavior by electric utilities. The 1968 Federal Power Commission Report notes that "[u]tilities are giving increasing attention to the location and design of new plants and to lessening the impact of these facilities on the environment. (...) Most new coal and oil fired plants include high efficiency electrostatic precipitators to remove particulate matter from stack discharges. (...) High stacks are frequently used to obtain greater dispersion and reduce ground level concentration of oxides of sulfur, and greater attention is being given to the selection of coal and oil fuels of lower sulfur content" (Federal Power Commission, 1969, p.ix). Consistent with this, Appendix Figure A.1 shows an increase in average smokestack height in the late 1960s. Appendix Figure A.2 documents a sharp increase in the number of patents granted for power systems beginning in the mid-1960s, potentially reflecting the increased incentive for innovation.[15] Finally, in Section 5.3, we present additional descriptive evidence on power plant siting, heat content of coal burned, and the installation of pollution abatement technology consistent with anticipatory behavior.

2.3 1972 onward

The 1970 Clean Air Act (CAA) marked the first federal effort to regulate air pollution on a national scale. It emerged after an extended period of mounting public pressure for federal action on air pollution. Nevertheless, the exact timing and scope of the regulation came as somewhat of a surprise. A confluence of high profile events – the 1969 Cuyahoga River Fire, a massive oil spill off the coast of Santa Barbara in 1969, and the first Earth Day in the spring of 1970 – triggered a groundswell of public sentiment favoring environmental action. Despite his anti-regulatory tendencies, President Nixon supported the 1970 CAA to outflank Senators Muskie and Jackson, two pro-environment legislators

[15]The data do not permit a more disaggregate decomposition of either the holders of the new patents or the innovations underlying these patents. We are able, however, to provide a few examples: (i) the Pennsylvania Electric Company obtained a patent in 1967 to optimize the operation of a coal-fired power plant and generate metals from the collected ash; and (ii) the Babcock & Wilcox Company, New York, obtained a patent in 1966 for a combined cycle power plant where the second steam generator uses as fuel the particulate matter emitted when burning coal to power the first generator.

who were widely considered his strongest rivals for the 1972 presidency (ACIR, 1981).[16]

The 1970 CAA established the National Ambient Air Quality Standards (NAAQS) for five criteria air pollutants: particulate matter, carbon monoxide, sulfur dioxide, nitrogen dioxide, and ambient ozone.[17] Beginning in 1972, each county received an annual designation of nonattainment or attainment for each criteria pollutant, depending on whether air pollution concentrations exceeded the federally mandated standard. Each state was required to submit a state implementation plan (SIP) outlining how any nonattainment areas would be brought into compliance with the NAAQS. All states, territories, and the District of Columbia submitted SIPs by the end of 1972 (USEPA, 1973).[18]

New plants built after 1970 were also subject to New Source Performance Standards (NSPS). In addition, power plants that underwent "significant modifications" would be subject to the NSPS. Norhaus (2012) in his discussion of the 1970 Clean Air Act noted (p. 373): "The approach adopted in 1970 was to focus federal technology-based performance standards on new or 'modified' facilities on the theory that advanced pollution control equipment could be most economically installed when the facility is constructed or is otherwise undergoing major changes." NSPS required these plants to implement the best available pollution control technologies to limit the emissions of sulfur dioxide (SO_2), nitrogen oxides (NO_x), and other pollutants. The 1977 amendments to the 1970 CAA strengthened the NSPS, requiring the use of scrubbers for coal-fired plants built after 1977.

Although not subject to the New Source Performance Standards, power plants built before 1972 were included as part of the SIPs, which typically required emissions reductions for plants in nonattainment counties (Revesz and Lienke, 2016).[19] In fact,

[16]As mentioned in ACIR (1981): "[t]hroughout the period, lobbying was intense from both industry and environmental groups, but public attention to the debate made industry the sure loser" (p.23). In fact, a 1970 Gallup poll inquired: *Which three of these national problems would you like to see government devote most of its attention to?* In contrast to a 1967 poll, "53% of the polled population named reducing air and water pollution as [one of the three] most serious national problem[s], second only to crime"(p.18).

[17]Airborne lead was later added as a criteria pollutant.

[18]The documentary record on SIPs is complicated by the fact that the SIPs were frequently modified or litigated. Still, in 1974, the EPA noted that "[w]ith a few notable exceptions (e.g., sulfur oxide emission limitations in the State of Ohio) all States now have fully enforceable emission limits affecting stationary sources" (USEPA, 1975, p.12).

[19]Joskow and Schmalensee (1998) note: "Pre-1970 plants were still subject to controls under State Implementation Plans (SIPs) required by the Clean Air Act to ensure that each state came into compliance with national ambient air quality standards" (p. 43).

by 1975, the EPA reported that 261 of the 394 coal-fired power plants in the United States were in compliance with SIP emission limitations or abatement schedules.[20] Bleicher (1975) discussed the practical difficulties with SIPs. "The process of SIP development is basically one of load allocation, i.e., determining the total tonnage of emissions that may be allowed without violating NAAQS, and allocating it among the sources in the geographic area in question" (p. 325). In its discussion of the 1970 Clean Air Act, the U.S. Citizens' Advisory Committee on Environmental Quality (1971) highlighted: "Typically, environmental standards are implemented by setting approximate levels of abatement for each source. Usually these limits call for uniform or proportionate reductions by all dischargers. That is, if the total discharges exceed the ambient standards, each source is required to reduce discharges in proportion to its contribution to the total (p. 136)."

Regardless of vintage, power plants in nonattainment counties faced greater constraints on emissions than plants in attainment counties. One way for plants to meet regulatory requirements was to decrease output. Indeed, Appendix Figure C.1 shows a large drop in output among plants built before 1963 located in nonattainment counties after the passage of the 1970 CAA. This decline in output seems to be driven by utilities scaling back production at older plants rather than shuttering capacity, which remained stable in the post-1972 period. Reductions in output from pre-1963 plants were offset primarily by increases in production from new plants built after 1972.

To reduce emissions, existing plants in nonattainment counties could also burn more expensive, lower sulfur coal or install pollution abatement technology – either flue gas desulfurization (FGD) systems or flue gas particulate collectors (FGP). However, installing a FGD system was costly and risked subjecting the plant to the stricter New Source Performance Standards that applied to the plant regardless of its county's attainment status.[21] Despite these concerns, both FGP and FGD installation rates increased after 1970 (see Appendix Figure A.3).

[20]Of the 133 plants not in compliance, 47 were located in Ohio, 29 were located in Indiana, and 26 were located in Illinois. In these states, there was significant delay and litigation around SO_x control plans (USEPA, 1976a). Of the remaining 31 plants not in compliance, ten were part of the Tennessee Valley Authority and were subject to a consent decree (see Appendix Table A.1); SIP revisions were underway for 7 plants; and the remaining plants were in litigation or otherwise subject to EPA action.

[21]In nonattainment counties, abatement technologies had to meet the "lowest achievable emissions rate" regardless of costs. In contrast, plants in attainment counties were required to install the "best available control technology", which allowed for the consideration of costs.

The 1970 CAA led to a sharp drop in emissions from power plants. During the first three years of the CAA, total suspended particle (TSP) emissions fell from 4.2 million tons in 1970 to 2.9 million tons in 1974, and sulfur oxide (SO_x) emissions fell from 15.4 million tons to 13.6 million tons (USEPA, 1976b). These reductions in pollution emissions accelerated a downtrend trend in monitored TSP concentration levels that pre-dated the Act's passage (see Appendix Figure A.4).

3 Conceptual Framework

In this framework, we outline the conditions under which anticipation of future environmental regulation will induce producers to preemptively shift activity to cleaner production technologies.

Assume that at the time a power plant opens, managers must decide how to allocate the share of generating capacity, θ, across two production technologies: a dirty technology $F_D(\theta, V_D)$ and a clean technology $F_C(1-\theta, V_C)$, where V denotes variable inputs (labor and fuel).[22] This setup reflects the fact that plants have access to multiple different technologies that have different levels of pollution emissions per unit of output.[23]

The plant then operates for two periods, where $a \in \{1, 2\}$ denotes the age of the plant (young and old). In each period, managers choose variable inputs V_D and V_C to maximize per-period profit from each technology, $\Pi_D(\theta)$ and $\Pi_C(1-\theta)$. Future profits are discounted by a constant discount factor β.[24]

In each period $a \in \{1, 2\}$, the plant may be subject to a new environmental regulation. This regulation permanently lowers the relative profitability of the dirty technology, so that $\Pi_D(\theta)$ decreases to $\delta\Pi_D(\theta)$ in every period, where $\delta \in (0, 1)$. Following the enactment of regulation, the plant can choose to pay a one-time nonrecoverable fixed cost, c, to reallocate capacity across the production technologies. Intuitively, c can be interpreted

[22]We assume production functions that are differentiable and concave, allowing us to focus on interior solutions. Qualitatively similar results would hold if the initial equilibrium were a corner solution in which plants installed either fully dirty technology or clean technology.

[23]For example, a plant can include multiple boilers that have different design characteristics or that use different types of coal as inputs. Alternatively, utilities may choose to install pollution abatement technology that covers only a fraction of the plant's total generating capacity.

[24]We assume that producers face a constant inelastic demand for electricity, and do not model the initial decision about whether to open a plant or subsequent decisions to expand total generating capacity.

as the cost of retrofitting dirty generating capacity with pollution abatement technology.

Prior to building the plant, electric utilities form expectations over the likelihood that environmental regulation will be enacted over the plant's lifespan. Denote λ_1 and λ_2 as the subjective probabilities that legislation will be enacted in each period of operation, and let $(1-\delta)$ denote the expected stringency of enforcement.[25]

Given this setup, we can derive optimal responses to regulation for existing plants over their lifecycle, $a \in \{1, 2\}$, and through backwards induction solve for the initial capacity investment share in dirty generation, θ.

3.1 Decisions to retrofit power plants at ages $a \in \{1, 2\}$

Following the enactment of environmental regulation, per-period profits under the initial capacity allocation, θ^*, are reduced to $\Pi(\theta^*) = \delta\Pi_D(\theta^*) + \Pi_C(1-\theta^*)$. As a result, managers must decide whether to continue operations under this inefficient allocation or pay a one-time cost to retrofit dirty generating capacity with pollution abatement technology. This decision will depend on the fixed cost of retrofitting, c, the relative per-period profitability of the plant with and without abatement technology, and the age of the plant when regulation is passed. Specifically, managers will choose to re-optimize and shift capacity away from the dirty technology if and only if the following inequality holds:

$$\Pi\big(\hat{\theta}\big) - \Pi\big(\theta^*\big) \geq \begin{cases} \frac{c}{1+\beta} & \text{if regulation passes at } a = 1 \\ c & \text{if regulation passes at } a = 2 \end{cases} \tag{1}$$

where $\hat{\theta} < \theta^*$ denotes the optimal investment choice after re-optimizing,[26] and where the difference between adjusted and unadjusted profits is given by

$$\Pi(\hat{\theta}) - \Pi(\theta^*) = \int_{\hat{\theta}}^{\theta^*} [\Pi'_C(1-x) - \delta\Pi'_D(x)]dx \approx \frac{1}{2}(\theta^* - \hat{\theta})(1-\delta)\Pi'_D(\theta^*).$$

Intuitively, the per-period gain from adjustment is the difference in marginal profits

[25] We further assume that, once enacted, environmental legislation is never revoked, and is permanently enforced over the plant's lifespan.

[26] If managers choose to re-optimize capacity, they will choose the $\hat{\theta}$ that solves $\delta\Pi'_D(\hat{\theta}) = \Pi'_C(1-\hat{\theta})$.

across all capacity that is reallocated.[27]

The probability of adjustment increases with the stringency of the regulation, $(1-\delta)$, and the gap between the plant's existing versus desired capacity allocation under regulation, $(\theta^* - \hat{\theta})$. Meanwhile, higher fixed costs, c, reduce the likelihood that the plant will reallocate capacity. The constraint is less binding at age $a = 1$ than $a = 2$, reflecting the fact that plants should be more willing to pay the fixed cost to adjust capacity when young since the benefits accrue over a longer time horizon.[28]

3.2 Initial investments in plant capacity and expectations over future environmental regulation

Managers make initial investment in plant capacity taking into account both their beliefs over the likelihood and stringency of future environmental regulation, as well as their ex-post retrofit decisions should regulation be enacted. The optimal initial investment in dirty capacity, θ^*, differs based on which of three potential ex-post responses to environmental regulation would be chosen. Optimal investment in dirty capacity under each of the three scenarios is:

$$\theta^* = \begin{cases} \theta^*_{AR} & \text{s.t.} \quad \Pi'_D(\theta^*_{AR}) = \Pi'_C(1-\theta^*_{AR}) \quad \text{iff} \quad \Pi(\hat{\theta}) - \Pi(\theta^*) \geq \frac{c}{1+\beta} \\ \theta^*_{NR} & \text{s.t.} \quad \left[1 - \lambda_1(1-\delta) - \lambda_2(1-\delta)\frac{\beta}{1+\beta}\right]\Pi'_D(\theta^*_{NR}) = \Pi'_C(1-\theta^*_{NR}) \quad \text{iff} \quad c > \Pi(\hat{\theta}) - \Pi(\theta^*) \\ \theta^*_{SR} & \text{s.t.} \quad \left[1 - \frac{\lambda_2}{1-\lambda_1}(1-\delta)\frac{\beta}{1+\beta}\right]\Pi'_D(\theta^*_{SR}) = \Pi'_C(1-\theta^*_{SR}) \quad \text{iff} \quad \Pi(\hat{\theta}) - \Pi(\theta^*) \in [c, \frac{c}{1+\beta}) \end{cases}$$

where θ^*_{AR} denotes the optimal initial allocation for plants that will *always retrofit* if regulation is enacted at either age $a = 1$ or $a = 2$; θ^*_{NR} denotes the optimal initial allocation for plants that will *never retrofit* if regulation is passed at either age; and θ^*_{SR} denotes the optimal initial allocation for plants that will *sometimes retrofit*, so that they will retrofit if regulation is passed at age $a = 1$ but not at age $a = 2$.

In **Case 1**, the fixed costs of retrofitting are small relative to the profit gains from

[27] The last approximation is obtained by taking a first-order Taylor expansion of each marginal profit function around θ^*.

[28] Once a plant is built, it is never optimal to adjust current capacity in anticipation of future regulation. That is, changes in the probability of regulation in period 2 (i.e., λ_2) have no influence on decision-making at $t = 1$. This result contrasts with a framework with endogenous environmental regulation, in which plants may strategically decrease emissions in an effort to reduce the stringency of future regulation.

capacity adjustment, so plants will always retrofit if regulation is passed (i.e., $\Pi(\hat{\theta}) - \Pi(\theta^*) \geq \frac{c}{1+\beta}$). In this scenario, the initial capacity investment, θ^*_{AR}, does not depend on the likelihood of future regulation, so that $\frac{\partial \theta^*_{AR}}{\partial \lambda_1} = \frac{\partial \theta^*_{AR}}{\partial \lambda_2} = 0$. Intuitively, because managers know that these plants will retrofit in the event that regulation is enacted, the initial optimal choice between dirty and clean technologies will not depend on the possibility of future regulatory action.

In **Case 2**, the fixed costs of retrofitting are large, so managers will never choose to retrofit plants if regulation is enacted (i.e., $c > \Pi(\hat{\theta}) - \Pi(\theta^*)$). As a result, the initial capacity investment, θ^*_{NR}, will depend on the likelihood of future regulatory action. Managers will preemptively allocate capacity away from the dirty production technology, so that $\theta^*_{NR} < \theta^*_{AR}$.[29]

An increase in the perceived likelihood of future environmental regulation in either period will lead to a preemptive shift away from dirty capacity: $\frac{\partial \theta^*_{NR}}{\partial \lambda_1} < 0$ and $\frac{\partial \theta^*_{NR}}{\partial \lambda_2} < 0$. This is because an increase in the likelihood of regulation reduces the expected profitability of the dirty technology. Moreover, the responsiveness of these initial investments to future regulatory action depends on *when* the regulation is anticipated over the plant's lifecycle. Because regulation passed when a plant is young has a larger impact on lifetime profitability, initial capacity investments will be more responsive to anticipated regulation that occurs earlier in the plant's lifecycle: $\frac{\partial \theta^*_{NR}}{\partial \lambda_1} < \frac{\partial \theta^*_{NR}}{\partial \lambda_2} < 0$.

In **Case 3**, the costs of adjustment are moderate, so managers will choose to retrofit only if regulation is passed when the plant is young (i.e., $c \leq \Pi(\hat{\theta}) - \Pi(\theta^*) < \frac{c}{1+\beta}$). The initial capacity investment, θ^*_{SR}, will depend on the likelihood of future regulatory action in both periods.[30] Again, managers will preemptively allocate capacity away from the dirty production technology, so that $\theta^*_{SR} < \theta^*_{AR}$.[31]

As in **Case 2**, an increase in the perceived likelihood of future environmental regulation in either period will lead to a preemptive shift away from dirty capacity: $\frac{\partial \theta^*_{SR}}{\partial \lambda_1} < 0$

[29] This result is due to the fact that the term $\left[1 - \lambda_1(1-\delta) - \lambda_2(1-\delta)\frac{\beta}{1+\beta}\right]$ in the first order condition is less than one.

[30] Because managers will retrofit if regulation is passed when the plant is young ($a = 1$), λ_1 affects the ex-ante decision-making only indirectly, by increasing the conditional probability that the plant will be regulated in $a = 2$ provided that regulation does not pass in $a = 1$.

[31] Provided that λ_2 is not more than twice as large as λ_1, the preemptive shift in capacity will be smaller than in **Case 2**: $\theta^*_{NR} < \theta^*_{SR} < \theta^*_{AR}$. This is because, in **Case 3**, regulation only affects plant profitability if it is passed in $a = 2$. In **Case 2**, regulation passed in either $a = 1$ or $a = 2$ affects profitability.

and $\frac{\partial \theta^*_{SR}}{\partial \lambda_2} < 0$. In this scenario, initial investment in clean capacity will be more responsive to changes in perceived likelihood of regulation that are expected *later* in the plant's lifecycle: $\frac{\partial \theta^*_{SR}}{\partial \lambda_2} \leq \frac{\partial \theta^*_{SR}}{\partial \lambda_1} < 0$. Intuitively, since managers know that they will simply retrofit plants if regulation is passed early in the plant's lifecycle, changes in λ_1 have a smaller impact on initial capacity investments.

3.3 Empirical Predictions

The 1970 Clean Air Act reduced the profitability of polluting technologies. Our simple framework highlights how anticipation of future regulatory actions in the years preceding the 1970 CAA might induce producers to preemptively shift towards cleaner production technologies. These anticipatory responses are particularly likely to occur in settings such as ours where the costs of ex-post retrofitting are large.

Our framework also demonstrates that anticipatory responses may have differed across plants built before versus after 1963 for two reasons. First, differences in initial investments across pre- and post-1963 plants may have arisen from an *informational channel*. The 1963 CAA signaled an increased likelihood of future regulatory action. For plants that were built after 1963, utilities likely updated their beliefs over the probabilities that plants would face regulation over their lifespan (i.e., λ_1 and λ_2 are higher for post-1963 plants). As a result, the model predicts that utilities would have shifted capacity towards cleaner production technologies when building plants after 1963, in an effort to increase plant productivity in a post-regulation environment (i.e., θ^* is lower for post-1963 plants).

Second, even if the 1963 CAA did not alter beliefs about the likelihood of future regulation, preemptive investments in clean technologies may have differed across pre- and post-1963 plants due to the *lifecycle channel*. Suppose that utilities held the same beliefs over the timing and stringency of future environmental regulation before and after 1963. Even in this case, pre-1963 plants would be expected to face regulation later in their lifespan than post-1963 plants. Due to this difference in the expected timing of regulation over the plant's lifespan and the large costs of retrofiting, anticipatory responses should be smaller among pre-1963 plants.[32]

[32] This is because, in practice, the retrofit costs for power plants are very large, so that few power plants choose to install pollution abatement technology after opening (Case 2). In contrast, if the costs of retrofiting were moderate (Case 3), the *lifecycle channel* would predict *larger* preemptive responses among pre-1963 plants.

Our framework predicts that the information shock arising from the 1963 CAA should have led to a shift towards cleaner production technologies among plants built after 1963. As a result, these plants were better suited to comply with regulation following the subsequent passage of the 1970 CAA. Thus, the productivity losses from enforcement under the 1970 CAA should be smaller for plants built after 1963. If this *informational channel* dominates, we should not expect to observe differences in the effects of the 1970 CAA across different vintages of plants built before 1963, which held similar beliefs regarding the likelihood of future regulatory action.

The *lifecycle channel* also predicts that anticipatory responses should have been larger among post-1963 plants, which were expected to face regulation over a greater fraction of their lifespan. Nevertheless, because this mechanism depends continuously on expected lifetime exposure to regulation, the size of these anticipatory investments should increase monotonically with plant vintage, with no discernible change in the relationship for plants that opened before and after 1963. Thus, if the *lifecycle channel* dominates, the productivity effects of future regulation should differ by plant vintage more broadly, not just across plants built before versus after 1963. We investigate these competing hypotheses in the empirical analysis.

4 Data and Empirical Strategy

4.1 Data Description

The analysis uses annual plant-level data that covers virtually every fossil-fuel-fired power plant in the United States and spans the period 1938-1994.[33] The Federal Power Commission (FPC), later renamed the Federal Energy Regulatory Commission (FERC), began publishing detailed plant-level information in 1948.[34] The initial volume included retrospective data beginning in 1938. We digitized the data for 1938-1981, and use similar

[33]Our sample ends in 1994 because the market-based components of the 1990 Clean Air Act Amendments were implemented in 1995. Moreover, some U.S. states decided to shift the provision of electricity generation from cost-of-service regulation to market mechanisms beginning in 1998 (Fowlie, 2010; Cicala, 2015). Market-based plants face both a different set of incentives and a different set of reporting requirements than price-regulated plants.

[34]As an example, Appendix Figure C.2 displays a page from the 1957 report.

data collected by FERC for 1982-1994.[35]

Our annual plant-level data provide detailed information on a range of outcomes, including electricity output, electricity generating capacity, number of employees, input fuel use, and fuel prices. Appendix Table C.1 provides summary statistics for the variables utilized in the analysis. Further details on the data construction process are provided in Appendix Section C.

There are 784 fossil-fuel-fired power plants in the data, located in 565 U.S. counties (see Appendix Figure C.3). Our main sample focuses on the 371 "existing" coal-fired plants that opened before 1972.[36,37] In auxiliary analysis, we also include the 123 "new" coal plants built after 1972, which were subject to more stringent regulation under the New Source Performance Standards regardless of their attainment status under the National Ambient Air Quality Standards (NAAQS).

We assign each county an annual nonattainment status based on whether the county was in noncompliance with the standards associated with any of the five regulated criteria pollutants – particulate matter, carbon monoxide, sulfur dioxide, nitrogen dioxide, and ambient ozone. These designations are obtained from the *Code of Federal Regulation* (CFR) for the period 1978-1994. For the period 1972-1977, we follow Greenstone (2002) and classify a county as nonattainment if it had a monitor reading in the year that exceeded the federal standard. However, the findings remain similar when we instead use the attainment status designations for 1972-1977 based on air quality control regions constructed by Cropper et al. (2023).

Appendix Table C.2 presents the number of existing and new coal plants in our data that never versus ever faced nonattainment between 1972-1994. The share of plants that never faced nonattainment between 1972-1994 is 0.27 for plants built before 1963 and 0.38 for plants built between 1963-1971. In contrast, plants built after 1972 were substantially

[35]Part of the digitization for 1938-1981 was done with resources from the NSF grant SES 1627432. We thank Ron Shadbegian, Carl Pasurka, and other researchers at the USEPA for providing the data for 1982-1994.

[36]For each plant and fuel type, we calculate the aggregate total heat input (in MMBtu) generated from burning the fuel in the plant's first five years of operation. The plant is assigned the fuel type corresponding to the largest total heat input across the three fuel types (coal, oil, and natural gas).

[37]We focus on coal plants in part because Congress authorized the Federal Energy Administration (FEA) to prohibit certain power plants from burning natural gas or petroleum products as a primary energy source in response to the oil embargo of 1973. In some cases, the FEA explicitly mandated the use of coal (USEPA, 1977). We explore the effects of nonattainment on oil- and gas-fired plants in sensitivity analyses.

more likely to be built in "always-attainment" counties (i.e., counties that never faced nonattainment between 1972-1994).

Attainment status is persistent. Conditional on facing attainment (nonattainment) in year $t-1$, the empirical probability that a coal plant faces attainment (nonattainment) in year t is 0.92 (0.94) (see Appendix Table C.3). Thus, the vast majority of variation in nonattainment status stems from the initial designations set forth in 1972 rather than post-1972 switches in attainment status.

4.2 Estimation of Pollution-Unadjusted Total Factor Productivity

We combine data on input and output quantities to estimate annual plant-level productivity. Our measures of capital, labor, and fuel are the annual total generating capacity of the power plant (in MW), annual total number of employees at the plant, and annual total heat input energy (in MMBtu). Our measure of productivity focuses on how these three inputs combine to produce annual total electricity sold (in MWh).[38] Since we do not model plant pollution emissions as either an input or an output in our production function, we term our measure "pollution unadjusted" total factor productivity.

Building on the approach of Greenstone, List and Syverson (2012), we exclude the capital costs associated with "compliance-related" investments, such as installing pollution abatement technology. These investments do not directly contribute to electricity production. For example, consider a plant that installs a scrubber but does not operate it. This plant can still produce and sell the same amount of electricity using its productive inputs – capacity, labor, and fuel – just as it did prior to installing the scrubber.[39] To explore the effects of the 1970 Clean Air Act on compliance-related capital, we perform separate analyses where we document changes in plant investment and equipment costs across plant vintages and estimate the effect of first nonattainment on the adoption of pollution abatement technology.

[38]An advantage of our quantities-based approach is that our measure of productivity is unaffected by policy-induced changes in capital prices, wages, and fuel prices (Foster, Haltiwanger and Syverson, 2008; Hsieh and Klenow, 2009; De Loecker, 2011).

[39]Operating scrubbers requires the use of on-site electricity, which lowers the total amount of electricity sold by the plant. This effect is included in our measure of productivity: the *operation* of scrubbers lowers our measure of productivity since the same inputs results in less electricity *sold*.

We estimate productivity using two methods that build on Olley and Pakes (1996). Our main approach follows Ackerberg, Caves and Frazer (2015), but the results remain similar when we apply the Levinsohn and Petrin (2003) method instead. Both methodologies rely on assumptions about the timing of capital, labor, and energy input decisions relative to productivity and idiosyncratic shocks. They both construct moments using polynomials of lagged input choices and their interactions as instruments.

Following Fabrizio, Rose and Wolfram (2007), we assume that energy is a perfect complement to capacity and labor in the production function, and that energy demand increases monotonically with productivity. This allows us to invert the energy demand function to control for unobserved productivity shocks in the second-stage equation. For our main specifications, we use a translog production function for capital and labor, but the results are quantitatively and qualitatively similar when using the simpler Cobb-Douglas function. Further details on our productivity estimation process can be found in Appendix Section C.2.[40]

4.3 Empirical Strategy

We use the following difference-in-differences specification to study the effects of nonattainment on power plant operations:

$$Y_{it} = \alpha_i + \lambda_{vt} + \theta_{st} + \beta Nonattain_{ct} + \epsilon_{it} \tag{2}$$

where i indexes a plant in vintage group v located in county c in state s, and t indexes year. In our primary specifications, the vintage groups are pre-1963 plants, 1963-1971 plants, and post-1972 plants (if applicable to the specification). Equation (2) includes plant fixed effects, α_i, to control for time-invariant plant characteristics. The term λ_{vt} represents vintage group by year fixed effects that allow for differential evolution in operations across different cohorts of plants.[41] Finally, our primary specifications include state by year fixed effects, θ_{st}, to account for any state-level energy or pollution control policies implemented either before or after the introduction of the 1970 CAA.

[40] The production function parameter estimates are reported in Appendix Table C.4.

[41] Our primary specifications focus on coal plants built before 1972. For sensitivity analyses that include plants of all fuel types, we include fuel type by year fixed effects that account for input price shocks that might differentially impact plants that burn different types of fuel (i.e., coal, oil, or gas).

The independent variable of interest is $Nonattain_{ct}$, an indicator that is equal to one if the county is out of attainment with the National Ambient Air Quality Standards for any pollutant in year t. We also estimate a generalized version of Equation (2) that allows the effects of nonattainment to differ by vintage group. Unless otherwise noted, our coefficient estimates are accompanied by standard errors that are clustered by county.

For our primary specifications, we estimate Equation (2) via ordinary least squares. However, our event study estimates remain similar if we instead use the methodology from Callaway and Sant'Anna (2021) that excludes potentially problematic comparisons between already-treated plants first treated in different years.

5 Impacts of the CAA on Power Plant Operations

5.1 Impacts on Outcomes, Overall and by Vintage

5.1.1 Main results

Panel A of Table 1 indicates that power plants located in nonattainment counties experienced a 16% decrease in pollution-unadjusted total factor productivity (PU-TFP) and a 23% decrease in output relative to plants located in attainment counties.[42] The negative and statistically significant effect of nonattainment on PU-TFP is due to the fact that declines in plant output were not fully offset by adjustments in inputs. In practice, investment in plant generating capacity is essentially irreversible.[43] Similarly, the number of employees required to operate a plant is largely independent of output levels.[44] Meanwhile, reductions in plant output may have increased input fuel use per MWh of generation because the new production levels are technically sub-optimal or because plants facing nonattainment may be forced to adjust output levels more frequently.

Panel B of Table 1 shows that nonattainment designation led to a 20% reduction in productivity and a 27% decrease in output among plants built before 1963, but had

[42]In line with the findings in Greenstone, List and Syverson (2012), Appendix Table D.1 shows that the effect of nonattainment on productivity is driven primarily by noncompliance with ambient ozone and nitrogen dioxide standards.

[43]The negative effect of nonattainment on capacity reflects a decrease in the rate of growth of installed capacity for plants located in nonattainment counties *relative* to plants located in attainment counties.

[44]In nonattainment counties, plants may have actually required additional workers whose roles were geared towards environmental compliance (Sheriff, Ferris and Shadbegian, 2019).

no effect on plants built after 1963. This suggests that anticipatory investments among plants built after 1963 may have significantly mitigated the subsequent impacts of nonattainment on plant operations.

Figure 1 provides further evidence consistent with our hypothesis that the 1963 CAA constituted a large information shock. Namely, this figure presents separate effects of nonattainment for plants built before 1955, built between 1955-1962, built between 1963-1966, and built between 1967-1971.[45] These four periods align with the 1955 Air Pollution Control Act, the 1963 Clean Air Act, the 1967 Air Quality Act, and the implementation of the 1970 Clean Air Act in 1972 respectively. For pre-1963 vintages, we estimate large and negative effects of nonattainment on PU-TFP. In contrast, the corresponding effect for plants built between 1963-1966 is close to zero while the effect for plants built between 1967-1971 is positive. Neither of these post-1963 estimates are statistically significant.

This pattern in post-1963 effects is consistent with the *information channel*: the signal provided by the 1963 CAA led to changes in the design of plants built after this year. The similarity in effect size across different cohorts of pre-1963 plants runs counter to the *lifecycle channel* from the conceptual framework in Section 3. If the lifecycle channel was operative, we would predict that the effects of nonattainment should increase monotonically across all plant vintage groups.[46] Instead, we find no heterogeneity in effects across plants built before 1955 versus those built between 1955-1962.

The uneven distributional impacts across plant vintage groups also point to the potential for first-order reallocative effects. In particular, reductions in output due to nonattainment are concentrated among pre-1963 plants, noting that pre-1963 plants operated at lower average productivity levels than newer plants (see Appendix Figure C.4). As a result, the aggregate productivity losses borne by older plants may have been partially offset by the productivity gains from the reallocation of output away from these older, less productive plants. Section 6 explores the quantitative implications of this shift in output on the aggregate productivity cost of the 1970 CAA.

[45]The corresponding regression results are presented in column 1 of Appendix Table D.2.

[46]These findings also suggest that the 1955 Air Pollution Control Act had little impact on utility investment decisions.

5.1.2 Event study analyses

In this subsection, we exploit the extended lifespan of power plants to explore the longer-run impacts of nonattainment on the operations of older versus newer plants. Namely, Figure 2 presents event study estimates for our primary outcome – productivity – separately for plants built before 1963 and plants built between 1963-1971. These graphs are based on a version of Equation (2) that treats the first year in nonattainment as year zero in event time. The left and right panels of Figure 2 present event study graphs based on estimation via ordinary least squares and the Callaway and Sant'Anna (2021) method respectively.[47,48] For both methods, the pre- and post-treatment event study estimates are interpretable as effects relative to the year before first nonattainment.

Across all panels, Figure 2 provides evidence in favor of the common trends assumption needed for our difference-in-differences empirical approach. Namely, the pre-treatment estimates are close to zero, not statistically significant in almost all cases, and display no discernible upward or downward trends. This is true regardless of the vintage considered (either plants built before 1963 or between 1963-1971) or the method utilized (either ordinary least squares or Callaway and Sant'Anna (2021)).

Productivity declines for plants built before 1963 in the years following first nonattainment and these declines in productivity appear to be persistent. In contrast, the post-treatment estimated effects for plants built between 1963-1971 are small in magnitude and are not statistically significant. This suggests that utilities adapted primarily through changes in the design and siting of plants built after 1963 rather than changes in plant operations among plants built prior to 1963.

The results from Table 2 indicate that, for pre-1963 plants that have faced nonattainment for more than 10 years cumulatively, the estimated reductions in PU-TFP and output due to nonattainment are 38% and 58% respectively. Both of these reductions are substantially larger than the short-run impacts. Older plants in nonattainment counties did gradually reduce fuel use relative to their counterparts in attainment counties. Further, their capacity grew more slowly. However, older plants facing nonattainment were

[47] When estimating via ordinary least squares, we follow convention and include two "endpoint restrictions" indicator variables that capture all event years before and all event years after those displayed in the figure respectively (see Kline, 2012).

[48] Appendix Figure D.1 documents that the results remain similar when the event study specifications are estimated excluding state by year fixed effects.

unable to significantly reduce the number of workers employed at the plant site, which explains the persistent negative effects on productivity. In contrast, nonattainment does not affect productivity, output, or inputs for plants built between 1963-1971 in either the short, medium, or long run.

What explains the persistent negative effects of nonattainment on plants built before 1963? These findings seemingly contrast with prior research suggesting that innovation and adaptive responses by polluting producers helped mitigate the economic costs of the 1970 CAA over time (e.g., Popp, 2003, 2006). Unlike producers in many other sectors, however, existing power plants are severely constrained in their ability to adjust operations. Given the long lifespan of equipment such as boilers and turbines, power plants are difficult to modify after being built, even over the span of decades (Aminov, Shkret and Garievskii, 2016). In addition, retrofit installations of pollution abatement technology are especially costly for existing plants, and "major modifications" risk subjecting these plants to stricter environmental regulation under the New Source Performance Standards (Stavins, 2006; Revesz and Lienke, 2016). Instead, our findings suggest that adaptation occurred primarily through the siting and design of plants built after the 1963 CAA.

5.2 Mechanisms

Power plants facing nonattainment can reduce their pollution emissions in three ways. First, as documented above in Table 1, they can reduce output levels. Second, power plants can switch to burning coal with lower sulfur and ash contents. Finally, they can install expensive pollution abatement technology. In this section, we provide evidence on the latter two margins of adjustment.

Coal plants can respond to environmental regulations by switching to "cleaner" fuels. Plants can switch from burning lower-cost bituminous coal with higher sulfur and heat contents to higher-cost sub-bituminous coal with lower sulfur and heat contents.[49] We assess the importance of this margin of adjustment by estimating the effect of first nonattainment on the log of the annual average coal price paid by the power plant. We focus on first nonattainment rather than nonattainment because in order to switch the

[49]The primary source of sub-bituminous coal in the United States is the Powder River Basin (PRB) in Montana and Wyoming. The delivered price per MMBtu of PRB coal is typically higher than Appalachian bituminous coal, both because transportation costs are typically higher from PRB to the plant and because PRB coal contains less heat energy per ton of coal.

type of coal burned, plants typically must sign new long-term coal supply contracts and may make irreversible changes to their boilers (Joskow, 1987).

Column 1 of Table 3 shows that first nonattainment led to increases in the price paid per MMBtu of coal among plants built before 1963. The effect of first nonattainment on coal prices is not statistically significant for plants built between 1963-1971. This suggests that plants built between 1963-1971 were less likely to switch the type of coal burned in response to first nonattainment, perhaps because these plants were already built with environmental compliance in mind.

Plants may also respond to nonattainment by installing pollution abatement technology – flue gas particulate (FGP) collectors or flue gas desulfurization (FGD) units. FGP collectors, such as electrostatic precipitators and fabric filters (colloquially called "baghouses"), remove fly ash from the combustion gases associated with burning coal. FGD units, colloquially called "scrubbers", remove sulfur dioxide emissions from the exhaust of fossil-fuel plants. Since the bulk of FGDs were installed after 1972, we can estimate the impact of first nonattainment on subsequent retrofit installations of FGDs among plants built before 1972. In contrast, since some FGPs were installed well before the 1970 CAA, the pre-1972 plants without FGP technology as of 1972 may constitute a selected sample of plants.

Column 2 of Table 3 indicates that plants built before 1963 were 5% more likely to retrofit and install a scrubber in response to first nonattainment. The corresponding effect for plants built between 1963-1971 is negative and not statistically significant. This is consistent with some pre-1963 plants having no recourse other than to install costly FGD technology in order to bring pollution levels into compliance with the NAAQS.[50] In contrast, 1963-1971 plants were likely designed and sited with future environmental regulation in mind, and thus may have had other less costly means to reduce pollution levels in response to first nonattainment.

[50] Assuming that scrubbers have a 40-year lifespan, we calculate that the annualized cost of installing and operating a scrubber incurred by the average plant built between 1978-1994 is $8.0 million (2020 USD). As a point of comparison, we estimate that first nonattainment led to a 4.1% increase in coal prices across all plants built before 1972, corresponding to an increase in annual fuel costs of $1.3 million (2020 USD). This suggests that the requirement under the New Source Performance Standards that plants built after 1978 must install scrubbers imposed significant costs on utilities relative to reducing emissions by switching the type of coal burned.

5.3 Anticipation

This subsection provides additional evidence consistent with anticipation. It builds on the evidence presented in the background that electric utilities anticipated federal air pollution regulation after 1963.

First, we provide evidence that utilities were not able to predict which counties would be targeted under the 1970 CAA. Appendix Table A.2 shows that plants built between 1963 and 1971 were systematically less likely to be sited in counties with an air pollution monitor than plants built before 1963. Thus, utilities adjusted siting in response to current information. Interestingly, however, there are no cross-vintage differences in the likelihood that plants were sited in counties that would later face nonattainment, suggesting that electric utilities were unable to predict which counties would ultimately be targeted under the 1970 CAA.

Because utilities were unable to predict whether counties would be in nonattainment, we next explore average plant characteristics in the first year of operation across all coal plants of each vintage. Figure 3 presents capacity-weighted average coal heat content and the capacity-weighted proportion of plants with flue gas particulate collectors—a type of pollution abatement technology—across coal-fired power plants. This figure focuses on the years 1950-1980, because there are very few plants built in some years outside of this window.

Panel (a) documents that plants built after 1963 burned lower heat content coal in the first year of operation than plants built earlier. In the United States, coal with lower heat content typically also has lower sulfur content. Burning lower sulfur content coal results in less sulfur dioxide emissions per MWh of electricity produced. Heat content was highest among plants built between 1950-1962. The average heat content of the coal burned in the initial year of operation (in MMBtu/ton) began to fall after 1963, suggesting that utilities were installing boilers designed to burn lower heat content coal. Average heat content in the first year of operation declined even further after 1971.

Panel (b) shows that plants built after 1963 were more likely to be built with flue gas particulate collectors than plants built earlier. This figure presents the capacity-weighted proportion of coal-fired power plants built with flue gas particulate collectors (FGPs) for each plant vintage. Flue gas particulate collectors remove airborne pollution particles from the flue gas released when fossil fuels are burned. Roughly 10% of plants were built with a flue gas particulate collector (FGP) across coal-fired plants built between 1950-1962. We see a dramatic increase in the proportion of coal-fired plants built with an FGP from 1963-1971. By 1972, almost all plants are built with a FGP. Retrofitting an FGP is typically far more expensive than installing an FGP when the plant is built. Thus, the dramatic rise in plants built with an FGP between 1963-1971 suggests that utilities were increasingly building plants with air pollution control in mind.

The costs associated with changes in design and siting were passed on to consumers via regulatory rate increases. Beginning in the mid-1960s, coal plant construction costs increased (see Appendix Figure A.5).[51] These increases were likely driven in part by changes in siting and design. Since electric utilities were subject to rate-of-return regulation, plant construction costs as well as the costs of installing and operating pollution abatement technology were largely passed on to consumers through rate increases approved in public utility commission hearings (Fowlie, 2010).

5.4 Importance of an Extended Pre-Regulation Data

In the previous section, we presented evidence that utilities anticipated environmental regulation and took preemptive steps to respond prior to the passage of the 1970 CAA. As a result, plant outcomes in the years immediately preceding the Act's passage may provide an invalid baseline to use to construct estimates of the productivity effects of the 1970 CAA.

To assess the importance of having extended pre-regulation data, we compare the main results to policy estimates based on artificially shortening the pre-regulatory sample period. Figure 4 plots the effect of nonattainment on productivity estimated using different pre-regulatory sample horizons. Each point on the x-axis denotes the initial sample year; the estimated effect for 1938, for example, coincides with the full sample. Moving rightwards along the x-axis shows how the effects change as we artificially shorten the pre-regulatory sample period used for estimation. For each initial sample year, Figure 4 presents the coefficient estimate and 95 percent confidence interval.

[51] Joskow and Rose (1985) comment that this trend in construction costs surprised them: they "expected to see the major increases appear later as a result of new plants' coming on line with state-of-the-art environmental control equipment in response to regulations introduced in the 1970s; but costs clearly begin to increase by the late 1960s" (p. 21).

The estimated impact of nonattainment on PU-TFP is negative and statistically significant for samples starting as late as 1962, but converge rapidly towards zero for samples beginning after 1963.[52] These patterns align with the timing of the 1963 CAA. Specifically, the diminishing estimated treatment effects when starting the sample after 1963 may stem from preemptive investment responses among plants built after the 1963 CAA, as utilities updated beliefs over the likelihood and stringency of future regulatory enforcement.

The patterns in Figure 4 suggest that we would substantially underestimate the productivity effects of the 1970 CAA without extended pre-regulation data. These patterns are striking, given that all prior research on the 1970 CAA has relied on sample periods beginning after 1963. Indeed, the vast majority of studies have relied on data that begin after the 1970 CAA's implementation in 1972. Identification in these studies relies on switches in the county's annual attainment status after 1972. Much of this variation stems from trends in county-level air quality that may have been largely foreseeable by local polluters (e.g., Grosset and Schlenker, 2022).[53,54]

5.5 Robustness and Spillovers

5.5.1 Robustness

This subsection discusses robustness checks and sensitivity analyses pertaining to our main estimates presented in Table 1. We assess robustness to a range of sample restrictions, the estimation of productivity, capacity upgrades, effects by fuel type, and alternative measures of nonattainment. Our main results are robust to these alternative specifications.

Appendix Table D.4 shows that the estimated impacts of nonattainment on PU-TFP

[52]Appendix Figure D.2 breaks these results down by plant vintage groups. The estimated effects of nonattainment by first year included in the sample look similar to those in Figure 4 for pre-1963 plants but are small and statistically insignificant for plants built between 1963-1971 regardless of first year included.

[53]Using the methodology from Goodman-Bacon (2021), Appendix Table D.3 documents that the difference-in-differences estimate implied by comparisons across ever-treated versus never-treated plants is substantially larger in absolute magnitude than the difference-in-differences estimate implied by comparisons across plants treated earlier versus later.

[54]Column 1 of Appendix Table D.4 documents that the estimated effect of nonattainment on productivity for plants built after 1972 is positive and not statistically significant.

are similar if we: (i) exclude smaller power plants, (ii) focus only on plants owned by a utility that owns no other coal plants (to address concerns of within-utility spillovers), or (iii) exclude states that had implemented air quality standards before 1967.[55] Appendix Table D.5 shows that the main estimates are not sensitive to alternative specifications for the production function used to estimate PU-TFP. We estimate different measures of PU-TFP based on Translog and Cobb-Douglas production functions, and for models that do and do not include plant materials as production inputs.

Appendix Table D.6 provides evidence that our primary findings are not driven by capacity upgrades at existing plant sites. Following Fabrizio, Rose and Wolfram (2007), if a power plant increased its capacity by either 40MW or 15% from the previous year, we consider it as entering a new "epoch". Productivity is estimated treating the cross-sectional unit as plant/epoch instead of plant, vintage is defined at the plant/epoch level, and plant/epoch fixed effects are included as part of this specification. The conclusions drawn from this specification remain the same: nonattainment led to sizable reductions in PU-TFP and output among pre-1963 plants, but had small and statistically insignificant effects on 1963-1971 plants.

Appendix Table D.7 shows that, in addition to coal plants, gas plants also appear to suffer a loss in productivity in response to nonattainment. This may be due to the forced switch from gas to coal mandated by the Federal Energy Administration (FEA) during the 1970s energy crisis.[56]

Appendix Table D.8 shows that the results are robust to using an alternative definition of nonattainment for years between 1972-1977. Our primary specifications are based on Greenstone (2002), which assigns county-level attainment status based on monitor

[55] Prior to 1960, there were no state-level air quality or deposited matter standards. By 1966, ten states – California, Colorado, Delaware, Missouri, Montana, New York, Oregon, Pennsylvania, South Carolina, and Texas – had adopted ambient air quality standards for a total of 14 substances, and for deposited matter (Stern, 1982).

[56] "In reaction to the oil embargo of 1973-74, Congress enacted the Energy Supply and Environmental Coordination Act (ESECA). ESECA, which became law on June 22, 1974, mandated the implementation of a national program to conserve petroleum products and natural gas and increase the use of coal by major fuel consumers. (...) Section 2 of ESECA (...) directs FEA to prohibit certain power plants (...) from burning natural gas or petroleum products as a primary energy source. *Such prohibitions effectively mandate the use of coal.* (...) On June 30, 1975, FEA issued prohibition orders to 74 generating units at 32 utilities" (USEPA, 1977, p.19-20, our highlight).

readings.[57] However, Cropper et al. (2023) note that the US EPA defined nonattainment from 1972-1977 based on Air Quality Control Regions (AQCRs), regions typically larger than counties. The estimated impacts of nonattainment on PU-TFP and output are similar when using the AQCR-based definition of nonattainment.

5.5.2 Spillovers

This subsection assesses whether output from existing plants in attainment counties is affected by nonattainment status in nearby counties. Electric utilities may have responded to the 1970 CAA by shifting output from existing plants in nonattainment counties to existing plants in attainment counties. The presence of this type of cross-county spillover might lead us to overestimate the effect of nonattainment on output, since this effect may partly reflect a relative rise in output among existing plants in attainment counties.

We estimate the following equation for coal plants built before 1972 located in counties that were always in attainment between 1972-1994:

$$log(Y_{it}) = \alpha_i + \lambda_{vt} + \beta PropNonAttain_{it} + \epsilon_{it}, \tag{3}$$

where Y_{it} is the output from plant i in year t. The equation includes plant fixed effects α_i and vintage group by year fixed effects λ_{vt}. The independent variable of interest, $PropNonAttain_{it}$, is the weighted share of counties "near" plant i facing nonattainment in year t. The results remain similar whether we define "nearby" based on: (1) counties in the same state as plant i, or (2) counties in the same state home to existing coal capacity owned by the same utility as plant i in year t. Moreover, the results remain similar whether the weights are defined based on coal-fired generating capacity or electricity output in 1954. We choose the year 1954 to avoid the weights reflecting any possible effect of federal air pollution regulations on coal-fired capacity or output.

Table 4 shows that there were not shifts in production from existing coal plants in nonattainment counties to *existing* coal plants in attainment counties. Indeed, the point estimates are small in absolute magnitude and are not statistically significant whether

[57] We focus on the Greenstone (2002) definition in the main text for three reasons: (1) to maintain comparability with previous literature, (2) to maintain consistency with defining attainment status at the county level (as was done post-1977), and (3) to present more conservative estimates of the impacts of nonattainment.

"nearby" counties are defined based on state or state and utility. Thus, it does not appear that the reductions in output from existing plants in nonattainment counties were offset by increased production from *existing* plants in attainment counties.

The available evidence suggests that decreases in output from existing plants facing nonattainment were instead offset by increased production from *new* plants that opened after 1972. Appendix Figure C.5 highlights the growth in production capacity across all major generation types except hydroelectric. Appendix Table D.9 provides suggestive evidence that fossil fuel and nuclear generating capacity was more likely to be built in states where a larger share of the population lived in nonattainment counties. Summarizing, CAA-induced shifts in output were primarily from *existing* plants in nonattainment counties to *new* plants that opened after 1972. Importantly, this type of spillover does not compromise our difference-in-differences estimation strategy, which relies solely on comparisons across plants built before 1972.

6 Aggregate Effects of the 1970 CAA on PU-TFP

Given the large differences in average productivity across plant vintages, the aggregate productivity losses from the 1970 CAA may be mitigated by the reallocation of output from older, less productive plants to newer, more productive plants. In this section, we calculate the aggregate productivity cost of the National Ambient Air Quality Standards (NAAQS), accounting for both plant-level productivity losses and cross-plant reallocation of output.

We start by calculating annual plant-level counterfactual PU-TFP and output for three plant vintage groups: plants built before 1963, plants built between 1963 and 1971, and plants built after 1972. For pre-1963 plants facing nonattainment, the counterfactual values are obtained by multiplying the observed value by the relevant estimate from the top panel of Table 2.[58] For plants built between 1963-1971 facing nonattainment, we assume that counterfactual output and PU-TFP are equal to their observed values, given the insignificant effects of nonattainment for these plants. We also assume that

[58]For example, consider a plant built before 1963 that we observe producing $\text{Output}_{i,t}$ with productivity $\text{PU-TFP}_{i,t}$ in year t. If this plant faced nonattainment in year t and had faced more than 10 years of nonattainment up to that year, its counterfactual output in a world without the NAAQS would be $O^C_{i,t} = (1{+}0.584) \times O_{i,t}$ and its counterfactual productivity would be $\text{PU-TFP}^C_{i,t} = (1{+}0.383) \times \text{PUTFP}_{i,t}$.

nonattainment-induced reductions in output from pre-1963 coal plants were not replaced by increases in output from *existing* coal plants in attainment counties, consistent with the evidence in Section 5.5.2. Instead, we assume that the decreases in output from pre-1963 plants in nonattainment counties were reallocated proportionally to coal plants built after 1972 within the same census division, based on the suggestive evidence in Appendix Table D.9.[59]

The impact of the NAAQS on aggregate productivity operates through two channels: (1) decreases in within-plant productivity concentrated among pre-1963 plants in nonattainment counties, and (2) the reallocation of output from pre-1963 plants in nonattainment counties to post-1972 plants. The change in annual output-weighted average productivity is calculated as follows:

$$\Delta\overline{\text{PU-TFP}}_t = \sum_i [\underbrace{\frac{\text{Output}_{i,t}}{\sum_i \text{Output}_{i,t}} \cdot \Delta\text{PU-TFP}_{it}}_{\text{Within-Plant Efficiency}} + \underbrace{\frac{\Delta\text{Output}_{i,t}}{\sum_i \text{Output}_{i,t}} \cdot \text{PU-TFP}_{it}}_{\text{Across-Plant Reallocation}}] \tag{4}$$

where $\Delta\text{PU-TFP}_{it} \equiv \text{PU-TFP}_{it} - \text{PU-TFP}^C_{it}$ and $\Delta\text{Output}_{it} \equiv \text{Output}_{it} - \text{Output}^C_{it}$ are the changes in PU-TFP and output with the NAAQS versus without the NAAQS. The first term in Equation (4) is the *within-plant efficiency* effect: existing plants in nonattainment counties have lower productivity due to increased regulatory requirements. The second term is the *across-plant reallocation* effect, which arises from regulatory-induced shifts in output from older plants facing nonattainment to newer plants.

The results of this back-of-the-envelope calculation indicate that the NAAQS led to an annual average productivity decline among coal plants of roughly 4% over the period 1972-1994. This corresponds to an annual aggregate productivity loss of $4.4 billion (2020 USD).[60] Although sizable, this economic cost is substantially smaller than the health benefits from improved air quality attributable to the 1970 CAA (see reviews by Currie and Walker, 2019; Aldy et al., 2022).

In Figure 5, we decompose annual output-weighted average differences in productivity with versus without the NAAQS into changes in within-plant efficiency and across-plant

[59]We reallocated within census division rather than within state because some states with coal plants built before 1963 do not also have coal plants built after 1972.

[60]We obtain this annual aggregate productivity cost by multiplying the annual average reduction in productivity due to nonattainment by the total revenue earned by steam electric utilities in 1970 (Federal Power Commission, 1971).

reallocation. The dashed red line shows the negative *within-plant efficiency* effect while the dotted blue line shows the positive *across-plant reallocation* effect.[61] Finally, the solid purple line depicts the impact of the NAAQS on aggregate PU-TFP: the sum of the within-plant efficiency effect and the across-plant reallocation effect.

Over 40% of the within-plant productivity losses from 1972-1994 were offset by the gains in productivity from across-plant reallocation. The trends in within-plant productivity losses and across-plant productivity gains reflect both an increase in the number of nonattainment counties over time and the growing effects of nonattainment on productivity and output documented in Table 2. Namely, pre-1963 plants in nonattainment counties faced decreases in productivity and reduced their output, with both effects growing with the number of years they faced nonattainment. Nonattainment-induced declines in output among these plants were offset by increases in output from plants built after 1972. Since newer plants were typically more productive (see Appendix Figure C.4), this nonattainment-induced reallocation of output increased average national PU-TFP in the power sector.

Together, these findings highlight how reallocation across producers can substantially mitigate the aggregate economic costs of environmental regulation. To the extent that older and less efficient entrenched incumbents emit higher levels of pollution, environmental regulation may accelerate the process of reallocation towards higher productivity entrants.

7 Conclusion

This paper leverages newly digitized data on power plant operations from 1938 to 1994 to examine the plant-level productivity impacts of the 1970 Clean Air Act (CAA). The long panel includes an extended period prior to regulation, allowing us to account for anticipatory responses by electric utilities. We find that nonattainment with the NAAQS led to large reductions in output and productivity, but only among plants built before 1963. Both the evolution of the treatment effects across vintages and complementary evidence suggest that the information shock generated by the 1963 CAA led utilities

[61] The within-plant efficiency effect is smaller than the estimates reported in Table 2 because it averages across both the plant-level losses incurred by pre-1963 plants in nonattainment counties and all remaining plants (again, assumed not to incur any productivity losses).

to take preemptive actions when building and siting plants after 1963. The aggregate productivity losses associated with regulatory compliance were mitigated by these anticipatory investments and by the policy-induced reallocation of output away from older, less productive plants to newer, more productive plants that opened after 1972. Annual total productivity losses between 1972-1994 were about $4.4 billion (2020 USD), which is much less than the estimated health benefits of the 1970 Clean Air Act.

Our analysis emphasizes that anticipatory behavior can emerge as a response to decreases in regulatory uncertainty, particularly when the expected costs of compliance are large.[62] This has relevance across a wide range of policy settings.[63] Notably, the historical U.S. experience may offer insights for future environmental and climate policy. Our analysis suggests that credible signals of future regulatory oversight can induce substantial and immediate adjustments among producers, especially when these decisions involve costly irreversible investments. This message may be particularly relevant for policymakers in low- and middle-income countries. Although governments in many of these countries have signaled shifting environmental priorities, there remains considerable uncertainty regarding the timing and details of future regulation (Jayachandran, 2022).

Lastly, our findings offer general lessons for the evaluation of major policy interventions such as the 1970 CAA. Empirical evaluations of landmark regulations typically treat them as discrete events that can be studied in a vacuum. However, major regulations are often the result of building social pressure and prior policy efforts, facilitating anticipatory actions by firms in the lead up to the passing of the legislation. In order to understand the full impacts of major policy interventions, it is crucial that researchers take these prior efforts and anticipatory actions into account when conducting policy evaluation.

[62] Other efforts to reduce the impacts of government oversight include industry self-regulation (DeMarzo, Fishman and Hagerty, 2005; Charoenwong, Kwan and Umar, 2019), voluntary regulation (Einav et al., 2022), lobbying for less stringent regulation for existing firms (Stavins, 2006; Kang, 2016), as well as actions that undermine the effectiveness of the regulation (Lim and Yurukoglu, 2018; Abito, 2019).

[63] For instance, the Federal Reserve and other central banks around the world often announce targets well in advance of policy actions. These announcements give time for individuals and firms to take anticipatory actions such as obtaining a mortgage or other loans.

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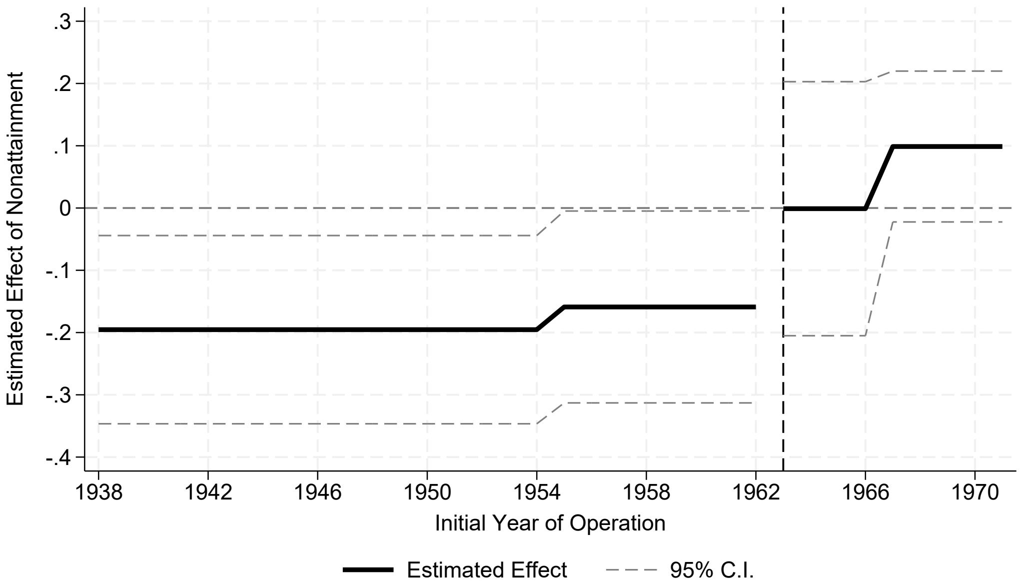
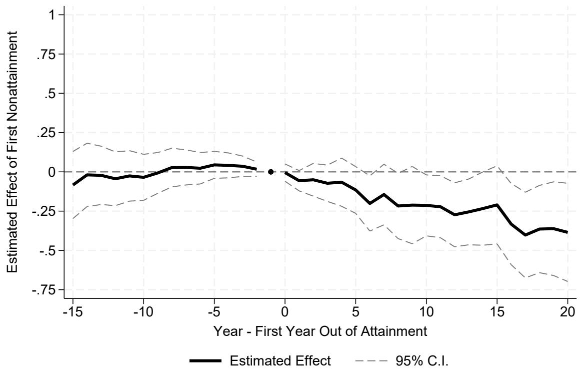
Figures and Tables

Figure 1: Estimated Effect of Nonattainment on PU-TFP by Initial Year of Operation

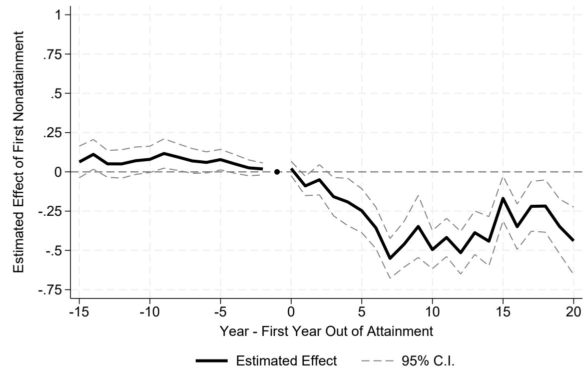


Notes: This figure plots the estimated effect of nonattainment on the log of pollution-unadjusted total factor productivity (PU-TFP) by initial year of plant operation. The estimation considers all coal plants that were built before 1972. We estimate separate effects of nonattainment for plants built before 1955, between 1955-1962, between 1963-1967, and after 1967; these four periods align with the 1955 Air Pollution Control Act, the 1963 Clean Air Act, the 1967 Air Quality Act, and the implementation of the 1970 Clean Air Act in 1972 respectively. The vertical dashed line represents the passage of the 1963 Clean Air Act, which resulted in minimal regulatory enforcement but served as a signal of impending federal regulation. We fail to reject the null hypothesis that the estimated effects of nonattainment are the same across plants built before 1955 versus built between 1955-1962 (p-value = 0.719); this provides evidence against the lifecycle channel for anticipatory investments. The estimates presented in this figure correspond to the regression results reported in Appendix Table D.2. The regression specification includes plant fixed effects, state by year fixed effects, and vintage group by year fixed effects; plants built before 1955, between 1955-1962, between 1963-1967, and after 1967 are in vintage groups 1, 2, 3, and 4 respectively. The 95% confidence intervals reported in this figure are based on standard errors that are clustered by county.

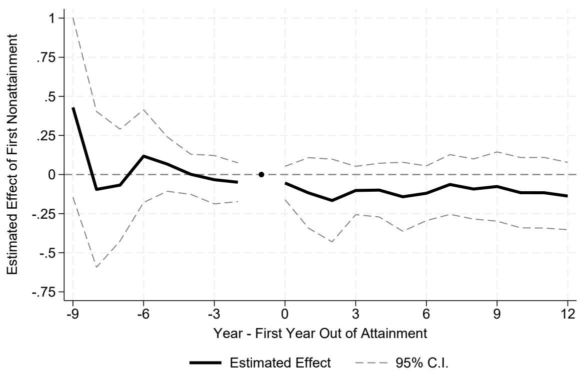
Figure 2: Event Study Analysis of the Impacts of First Year in Nonattainment on Power Plant Productivity



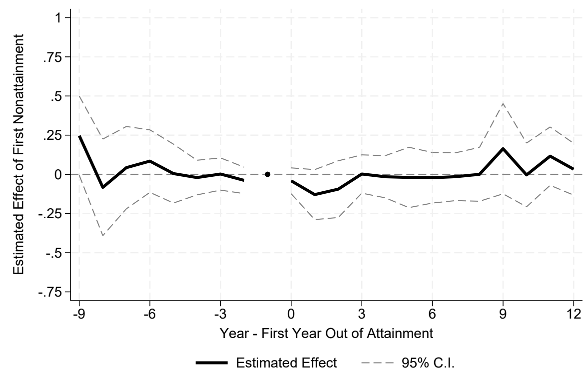
(a) TWFE, Before 1963



(b) Callaway-Sant'Anna, Before 1963



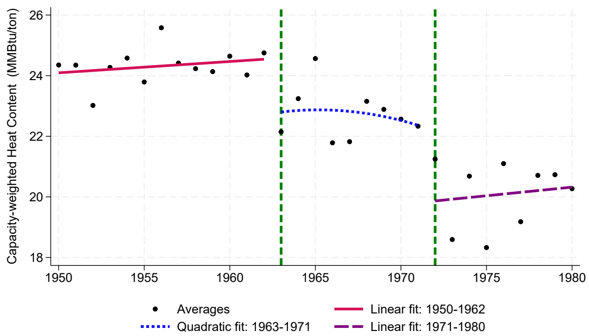
(c) TWFE, Between 1963-1971



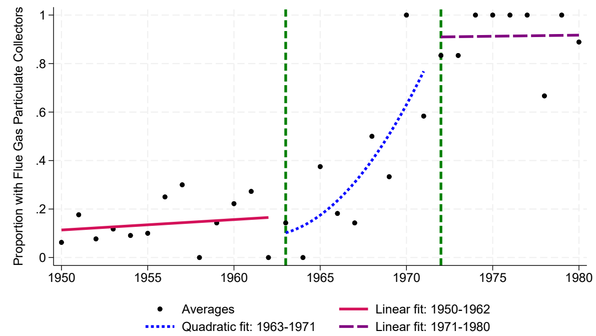
(d) Callaway-Sant'Anna, Between 1963-1971

Notes: This figure plots the estimated effect of first nonattainment on the log of pollution-unadjusted total factor productivity (PU-TFP) separately for each event year. The period of analysis is 1938-1994. All specifications include plant fixed effects and state by year fixed effects. The 95% confidence intervals reported in these figures are based on standard errors that are clustered by county. The top and bottom panels focus on coal plants built before 1963 and built between 1963-1971 respectively. In the left panels, we estimate effects via ordinary least squares. In the right panels, we use the Callaway and Sant'Anna (2021) methodology that accommodates arbitrary heterogeneity in treatment effects when estimating the average treatment effects on the treated when the timing of treatment is staggered.

Figure 3: Average heat content and FGP installation rates by plant vintage



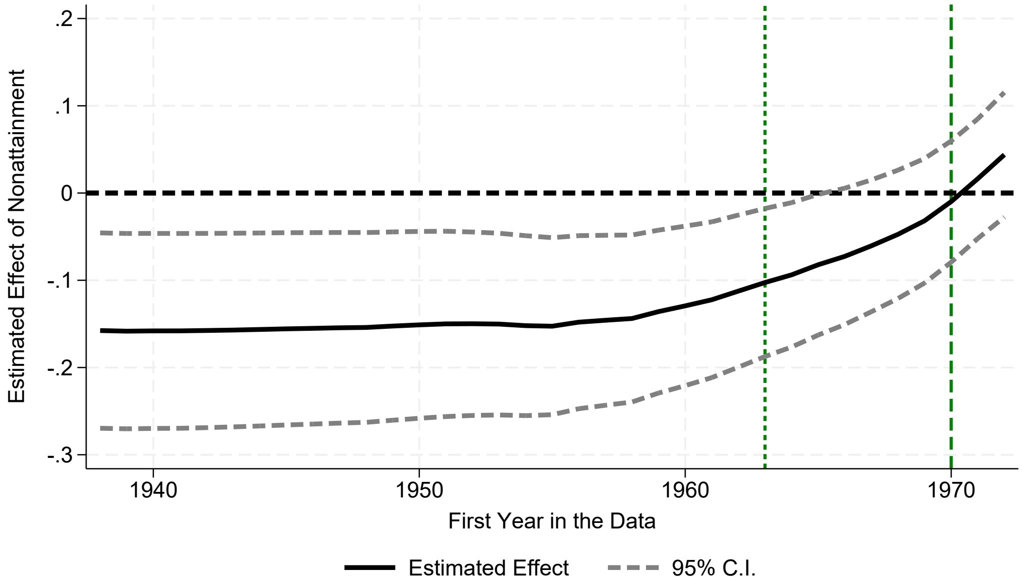
(a) Heat content (MMBtu/ton)



(b) Proportion w/ FGP

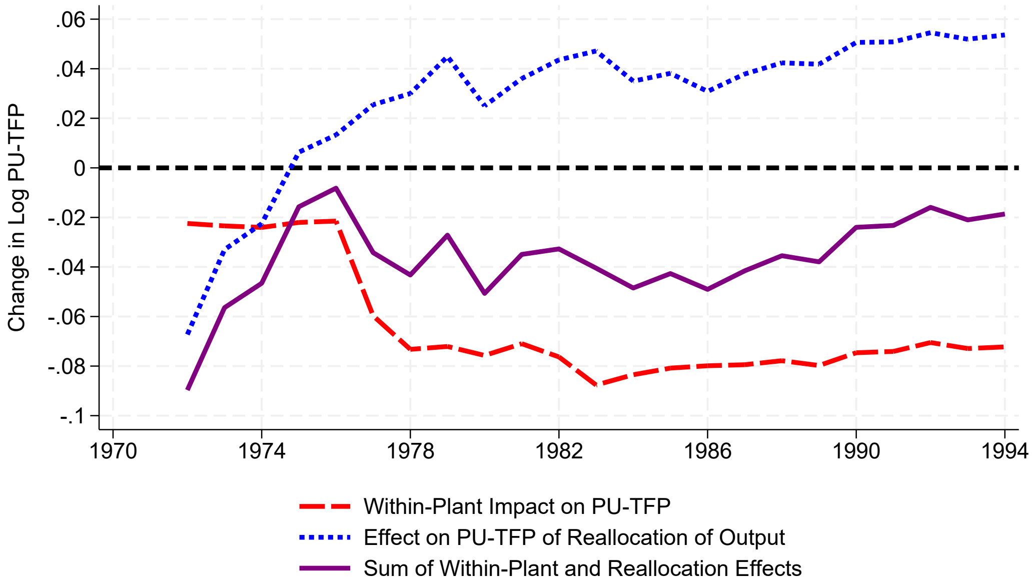
Notes: This figure plots the average outcome in the first year of operation across plants built in each year between 1950-1980 (i.e., the x-axis lists the year the plant was built). Panel (a) focuses on average heat content (in MMBtu/ton), while panel (b) considers the proportion of plants built with flue gas particulate collectors (FGPs). Both average heat content and proportion of plants with FGPs are capacity-weighted. We also include linear fit lines across the averages for plants built prior to 1963 and after 1972, with a quadratic fit line across the averages for the plants built between 1963-1971. Vertical dashed green lines denote the 1963 Clean Air Act and the implementation of the 1970 Clean Air Act in 1972 respectively.

Figure 4: Impacts of Nonattainment on PU-TFP by Initial Sample Year



Notes: This figure displays the estimated impacts of nonattainment on the log of pollution-unadjusted total factor productivity (PU-TFP) by initial sample year. Namely, for initial year X on the x-axis, we artificially restrict the sample period used to estimate the relevant effect to X-1994 (e.g., the effect for initial year 1950 is estimated using data from 1950-1994). We estimate these effects using only data from coal plants built before 1972. The short-dashed green vertical line represents the passage of the 1963 Clean Air Act and the dashed green vertical line represents the passage of the 1970 Clean Air Act. All specifications include plant fixed effects, state 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 the figure are based on standard errors that are clustered by county.

Figure 5: Effects of the 1970 CAA on Nationwide Power Plant Productivity



Notes: This figure depicts the estimated effects of the National Ambient Air Quality Standards (NAAQS) on aggregate power plant productivity calculated using the methodology described in Section 6. The impact of the NAAQS on the annual output-weighted average of the log of pollution-unadjusted total factor productivity (PU-TFP), represented by the solid purple line, is the sum of two offsetting effects. The long-dashed red line shows the negative *within-plant efficiency* effect, which reflects the fact that nonattainment reduces the productivity of plants built before 1963 (see Table 2, Panel A, column 1). The short-dashed blue line shows the positive *across-plant reallocation* effect, which arises from shifts in output from pre-1963 plants facing nonattainment to plants built after 1972 (see Appendix Table D.9).

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

	(1)	(2)	(3)	(4)	(5)
Dep. Var. (in Logs):	PU-TFP	Output	Fuel Use	No. Employees	Capacity
Panel A. Average Effects					
Nonattainment	-0.158***	-0.230***	-0.197***	-0.064	-0.138**
	(0.057)	(0.075)	(0.070)	(0.040)	(0.054)
R^2	0.711	0.827	0.756	0.853	0.901
Panel B. Effects by Plant Vintage					
NA × 1[Built Before 1963]	-0.197***	-0.269***	-0.236***	-0.071	-0.150**
	(0.064)	(0.085)	(0.079)	(0.044)	(0.061)
NA × 1[Built Between 1963-1971]	0.061	-0.010	0.023	-0.020	-0.076
	(0.064)	(0.085)	(0.088)	(0.062)	(0.064)
R^2	0.712	0.827	0.756	0.853	0.901
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.	1.325	7.011	16.328	4.789	5.632
Number of Obs.	12,935	12,935	12,935	12,935	12,935
Number of Plants	371	371	371	371	371

Notes: This table reports the impacts of nonattainment on power plant operations over the period 1938-1994. The unit of observation for the regressions in this table is plant-year, and the estimation considers all coal plants built before 1972. Panel A estimates how annual plant-level outcomes change with the attainment status of the county where the plant is located. Panel B estimates the impact of nonattainment on outcomes separately for plants built before 1963 versus plants built between 1963-1971. For all specifications, "nonattainment" is defined as the county being out of attainment with the National Ambient Air Quality Standards for any pollutant in the year. All specifications include plant fixed effects, state 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. PU-TFP stands for pollution-unadjusted total factor productivity, and NA for nonattainment. Standard errors in parentheses are clustered by county. *** denotes statistical significance at the 1% level, ** at the 5% level, and * at the 10% level.

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	-0.050	-0.114	-0.105	-0.028	-0.088
	(0.069)	(0.104)	(0.098)	(0.054)	(0.076)
Years in NA $\in [6, 10]$	-0.244**	-0.406***	-0.329**	-0.147*	-0.252**
	(0.103)	(0.147)	(0.139)	(0.076)	(0.103)
Years in NA > 10	-0.383***	-0.584***	-0.516***	-0.078	-0.363***
	(0.135)	(0.180)	(0.164)	(0.101)	(0.126)
R^2	0.688	0.805	0.730	0.842	0.888
Mean of Dep. Var.	1.243	6.867	16.194	4.776	5.511
Number of Obs.	11,307	11,307	11,307	11,307	11,307
Number of Plants	306	306	306	306	306
Panel B. Effects for Plants Built Between 1963-1971					
Years in NA ≤ 5	-0.144	-0.157	-0.055	-0.054	-0.006
	(0.088)	(0.110)	(0.123)	(0.083)	(0.080)
Years in NA $\in [6, 10]$	-0.023	-0.076	-0.027	-0.020	-0.038
	(0.103)	(0.133)	(0.147)	(0.129)	(0.118)
Years in NA > 10	-0.049	-0.112	-0.043	-0.023	-0.037
	(0.118)	(0.148)	(0.158)	(0.162)	(0.139)
R^2	0.866	0.940	0.907	0.943	0.960
Mean of Dep. Var.	1.886	8.017	17.269	4.912	6.489
Number of Obs.	1,628	1,628	1,628	1,628	1,628
Number of Plants	65	65	65	65	65
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

Notes: This table reports estimates of the impact of nonattaiment on power plant operations separately for bins defined by the cumulative number of years that a plant has faced nonattainment. The unit of observation for the regressions in this table is plant-year. For both panels, we interact the indicator for nonattainment with three bins defined by whether the plant has cumulatively faced nonattainment in five or fewer years, six to ten years, or more than ten years as of the year-of-sample. We focus on coal plants built before 1963 in the top panel while the bottom panel considers coal plants built between 1963-1971. All specifications include plant fixed effects and state by year fixed effects. PU-TFP stands for pollution-unadjusted total factor productivity, and NA for nonattainment. Standard errors in parentheses are clustered by county. *** denotes statistical significance at the 1% level, ** at the 5% level, and * at the 10% level.

Table 3: Impacts of First Nonattainment on Log Coal Prices and FGD Installation

	(1)	(2)
Dep. Var.:	Log Coal Price	FGD
First NA × 1[Built Before 1963]	0.042**	0.048***
	(0.021)	(0.017)
First NA × 1[Built Between 1963-1971]	0.036	-0.057
	(0.027)	(0.051)
R^2	0.886	0.596
Mean of Dep. Var.	0.474	0.031
Number of Obs.	11,681	12,935
Number of Plants	371	371
Plant FE	Y	Y
State By Year FE	Y	Y
Vintage Group By Year FE	Y	Y

Notes: This table presents the estimated impacts of first nonttainment on the log of coal prices per MMBtu and the installation of flue gas desulfurization (FGD) technology. In Column 2, the dependent variable is an indicator variable that is equal to one if the plant has at least one FGD system installed by the year-of-sample. The unit of observation for the regressions in this table is plant-year, focusing on coal plants built before 1972. All specifications include plant fixed effects, state 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. For both columns, we interact first nonattainment with two indicators denoting whether the plant was built before 1963 versus built between 1963-1971. Standard errors in parentheses are clustered by county. *** denotes statistical significance at the 1% level, ** at the 5% level, and * at the 10% level.

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

	(1)	(2)	(3)	(4)
Dep. Var.: Log Output				
Capacity-Weighted Spillover NA	-0.019	-0.061		
	(0.151)	(0.192)		
Output-Weighted Spillover NA			0.001	0.004
			(0.146)	(0.189)
R^2	0.859	0.843	0.859	0.843
Mean of Dep. Var.	6.422	6.353	6.422	6.353
Number of Obs.	2,764	2,307	2,764	2,307
Number of Plants	105	82	105	82
Plant FE	Y	Y	Y	Y
Vintage Group By Year FE	Y	Y	Y	Y
State Level Spillovers	Y		Y	
State-Utility Level Spillovers		Y		Y

Notes: This table tests whether the output of plants in attainment counties varies with measures of the annual nonattainment status of nearby counties. The unit of observation for all regressions is plant-year, considering only coal plants built before 1972 that never faced nonattainment between 1972-1994. The outcome considered in all columns is the log of annual plant-level output. The independent variable of interest is an annual weighted average share of nearby counties in nonattainment, focusing on counties: (1) in the same state (Columns 1 and 3), or (2) in the same state and home to an existing coal plant owned by the same utility (Columns 2 and 4). The weights are based on county-level coal-fired generating capacity in 1954 for Columns 1-2 and county-level coal-fired output in 1954 for Columns 3-4. All specifications include plant 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. Standard errors in parentheses are clustered by state. *** denotes statistical significance at the 1% level, ** at the 5% level, and * at the 10% level.

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 Section A* presents additional background information. *Appendix Section B* more fully develops the conceptual framework included in the paper. *Appendix Section C* provides further details on the data sources and construction of the final dataset, and presents additional descriptive figures and tables. *Appendix Section D* reports results from a variety of robustness checks and sensitivity analyses.

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A Additional Background Information

This appendix section provides further information supporting the description of the historical setting in Section 2. Appendix Section A.1 presents the figures and tables mentioned in the text while Appendix Section A.2 provides historical evidence on how one large electric utility responded to the 1970 Clean Air Act. This appendix section includes the figures and tables outlined below.

A.1 Additional Background Figures and Tables

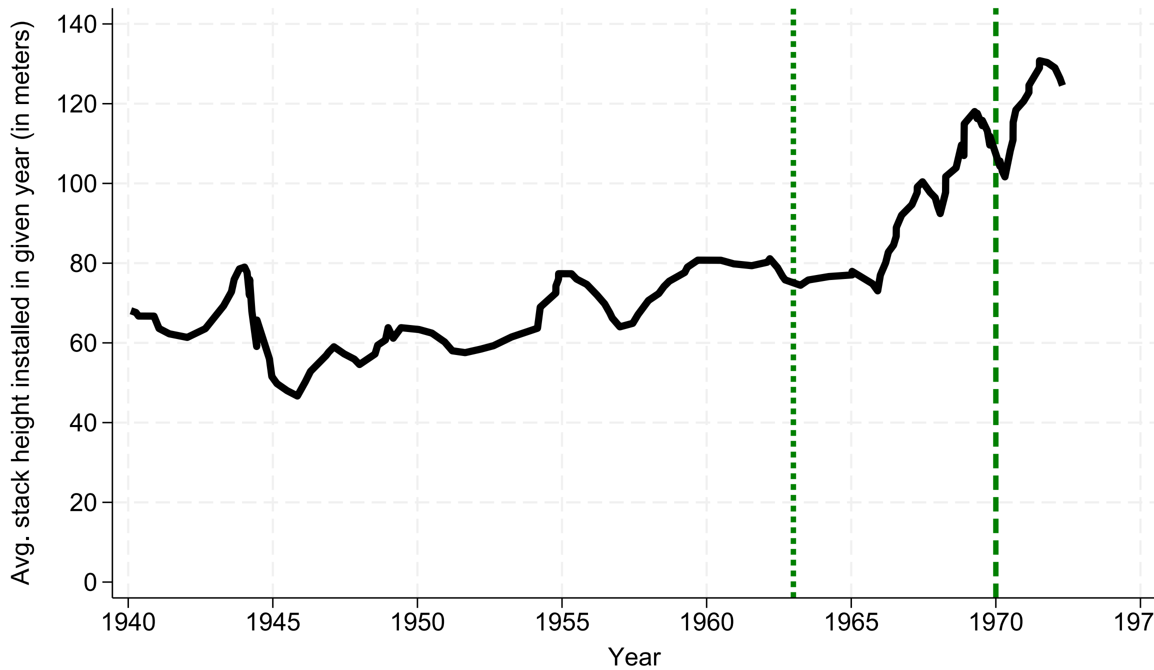
The figures and tables in this appendix subsection provide information on a variety of actions taken by electric utilities aimed at reducing pollution emissions from power plants. Appendix Figure A.1 shows that electric utilities increasingly put taller smokestacks on their plants to send emissions farther away. Appendix Figure A.2 provides evidence suggesting that the number of patents pertaining to power systems increases with the passage of the 1963 Clean Air Act. Appendix Figure A.3 depicts histograms of the year 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.4 displays trends in the concentration levels of total suspended particulates (TSP). Lastly, Appendix Figure A.5 depicts average capacity and measures of capital costs by plant vintage.

Appendix Table A.1 lists the different strategies to comply with the 1970 CAA employed by the Tennessee Valley Authority. The estimates in Appendix Table A.2 suggest that electric utilities chose to avoid locations with pollution monitors when siting fossil-fuel power plants after the passing of the 1963 CAA. Appendix Table A.3 provides descriptive evidence suggesting that electric utilities kept older plants facing nonattainment in operation longer to avoid building new generating capacity that would be subject to the stricter New Source Performance Standards regardless of attainment status.

A.2 Tennessee Valley Authority: An Example

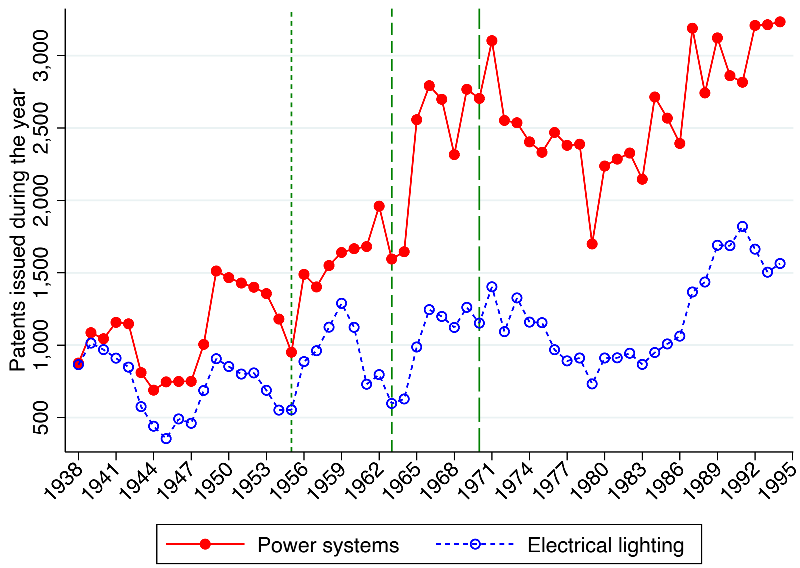
To illustrate the variety of strategies used by electric utilities to reduce pollution emissions, we present the case of the ten coal-fired power plants owned by the Tennessee Valley Authority (TVA). These plants were built before 1972, but only complied with the 1970 Clean Air Act (CAA) after TVA and EPA reached a settlement in 1979-80 (USGAO, 1980). Appendix Table A.1 shows that many plants ended up switching to coal with lower sulfur content. Several plants combined that strategy with coal washing, electrostatic precipitators, baghouses, and scrubbers. The U.S. Government Accountability Office estimated that the total cost of the consent decree over the lifespan of the projects was over \$14 billion (2020 USD). Capital costs comprised 14% of that amount, operating and maintenance costs 30%, and the incremental fuel costs 56%.

Figure A.1: Trends in Average Stack Height

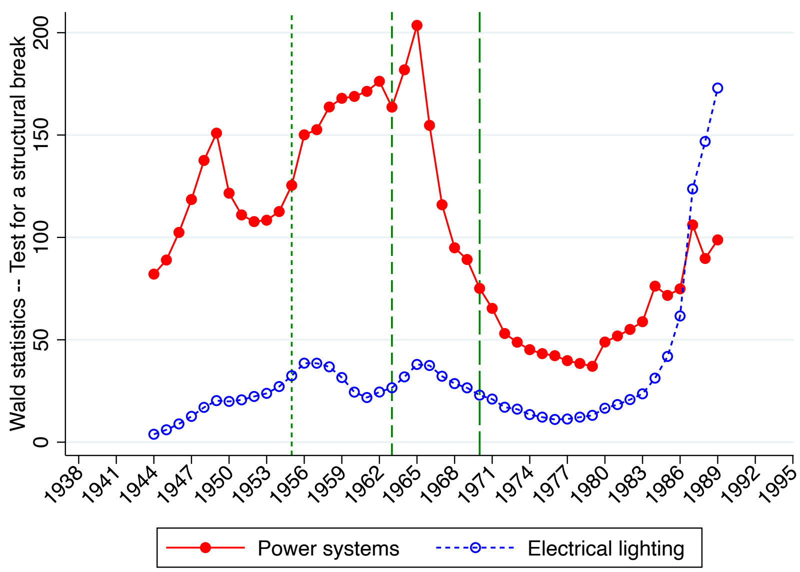


Notes: This figure displays trends in average smokestack height (in meters). It is reproduced from Figure 4 of USEPA (1976c), noting that the underlying source data are from Federal Power Commission Form FPC-67. Vertical dashed green lines denote the passing of the 1963 and 1970 Clean Air Acts.

Figure A.2: Patents Related to Power Systems and Electrical Lighting



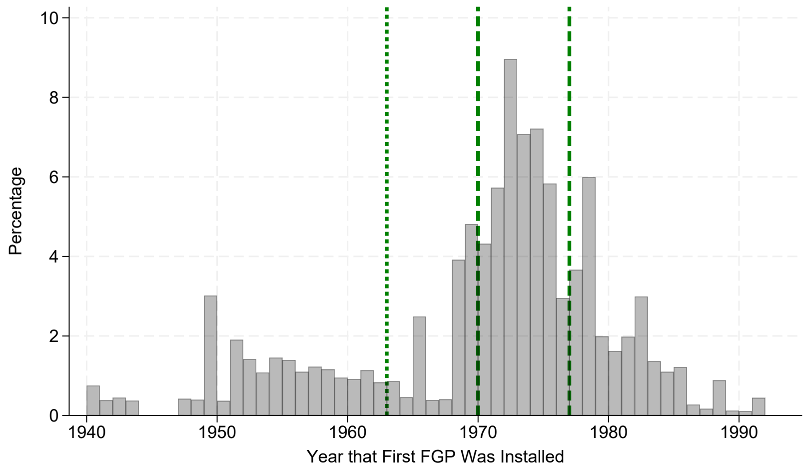
(a) Trends in the Number of Patents Issued



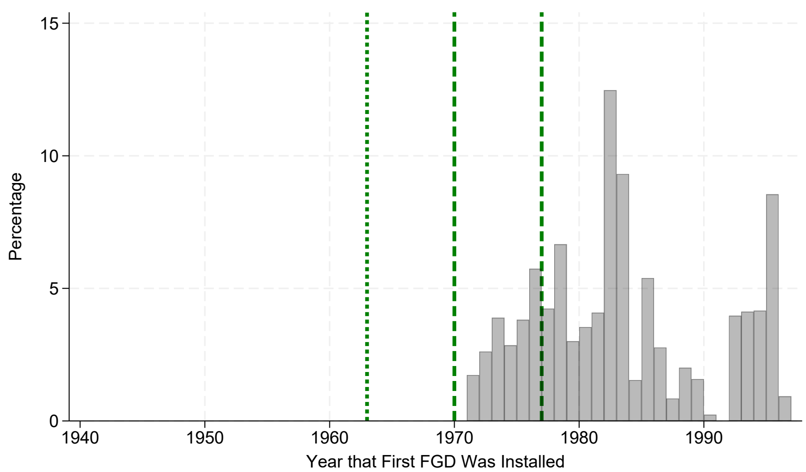
(b) Wald Statistics for Tests of Unknown Structural Break

Notes: This figure displays trends in patents for categories pertaining to electricity. Panel (a) plots the number of patents issued during the year for two 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 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 in 1989 for electrical light – the electrical lighting category appears to be a good "control group" for power systems. The short-dashed vertical green line refers to the Air Pollution Control Act of 1955, the dashed vertical green line refers to the Clean Air Act of 1963, and the long-dashed vertical green line refers to the Clean Air Act of 1970. *Data Source:* The Historical Patent Data Files from the U.S. Patent and Trademark Office, available at https://www.uspto.gov/learning-and-resources/electronic-data-products/historical-patent-data-files.

Figure A.3: Histogram of First Year with FGP or FGD



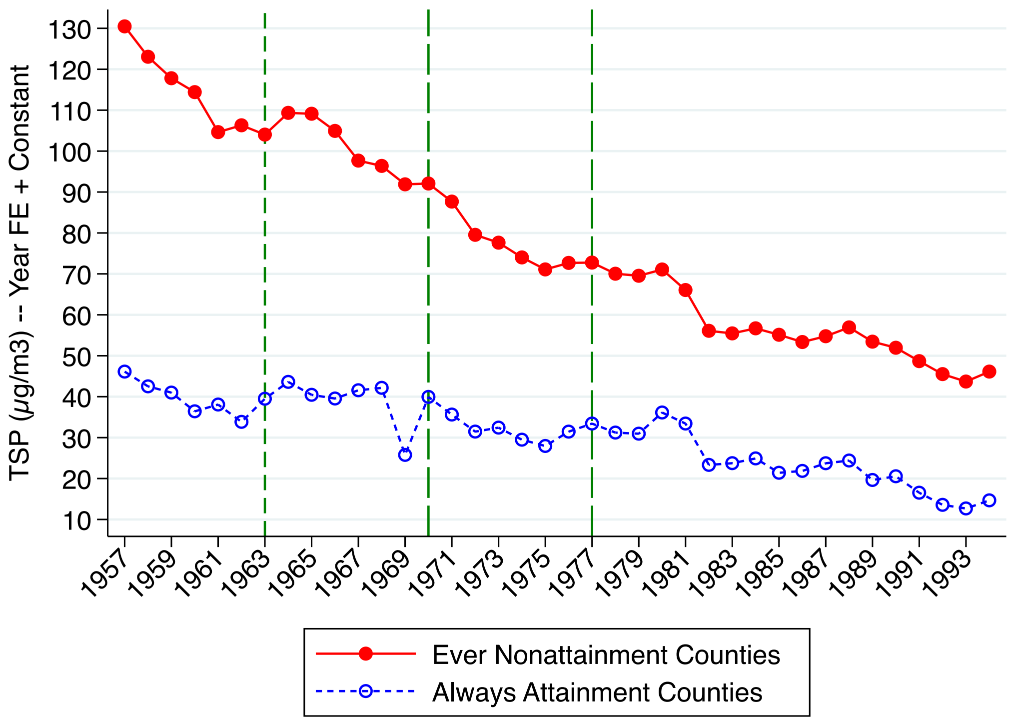
(a) FGP Adoption



(b) FGD Adoption

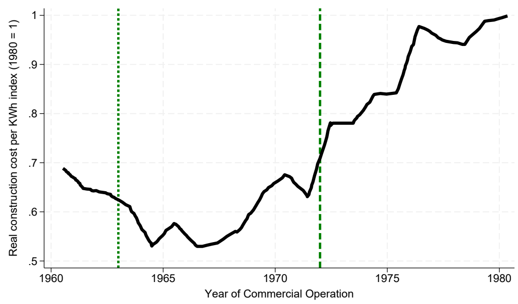
Notes: This figure displays the timeline of adoption of pollution abatement technology. Panel (a) plots the plant-level distribution of the year that the first flue gas particulate (FGP) collector was installed on the plant. Panel (b) plots the plant-level distribution of the year that the first flue gas desulfurization (FGD) system was installed on the plant. These histograms focus on coal plants. The short-dashed green line denotes the Clean Air Act (CAA) of 1963 while the two dashed green lines denote the 1970 CAA and its amendments in 1977 respectively. Data on the installation year of each FGP system and FGD system come from Form EIA-767 administered by the US Energy Information Administration.

Figure A.4: Trends in Total Suspended Particulates by County Attainment Status

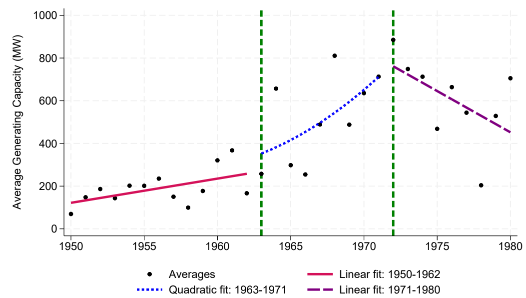


Notes: This figure displays trends in total suspended particulates (TSP) by county attainment status. Specifically, it plots the estimated coefficients from a regression of TSP on year fixed effects interacted with attainment status, controlling for pollution monitor fixed effects. A county is categorized as "ever nonattainment" if it was in nonattainment with the National Ambient Air Quality Standards for any pollutant in any year between 1972-1994; a county is categorized as "always attainment" if it never faced nonattainment between 1972-1994. The dashed green vertical line refers to the passage of the Clean Air Act of 1963, and the long-dashed green vertical lines to the Clean Air Act of 1970 and its amendments in 1977. Data on TSP concentration levels, which start in 1957, were provided by the US Environmental Protection Agency under a Freedom of Information Act request.

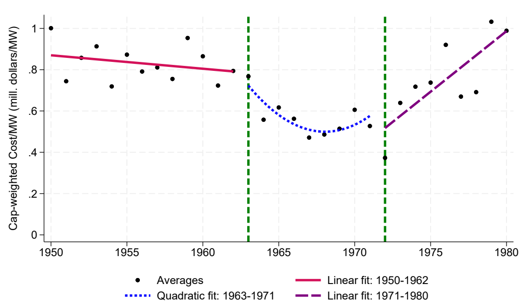
Figure A.5: Construction Costs and Capacity of U.S. Coal-Fired Power Plants



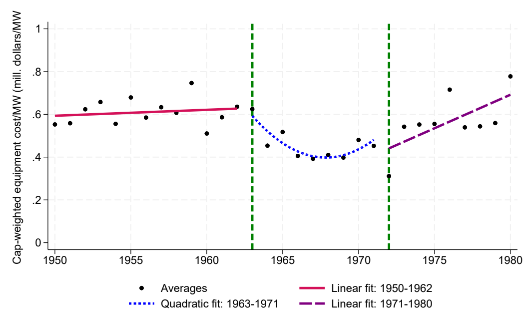
(a) Real construction cost index



(b) Production capacity (MW)



(c) Total cost per MW



(d) Equipment cost per MW

Notes: Panel (a) of this figure reproduces Figure 2 from Joskow and Rose (1985), plotting an index of construction costs per kilowatt for coal-fired electricity generating units. This index is based on the estimated values of time dummies from Equation (5) of Table 3 of Joskow and Rose (1985). Panels (b)-(d) of this figure plot the average outcome in the first year of operation across coal-fired power plants built in each year between 1950-1980 (i.e., the x-axis lists the year the plant was built). Panels (b), (c), and (d) focus on average production capacity (in MW), average total plant investment cost per MW (in million dollars/MW) and average total equipment investment cost per MW (in million dollars/MW). All averages in panels (b)-(d) are capacity-weighted. We also include linear fit lines across the averages for plants built prior to 1963 and after 1972, with a quadratic fit line across the averages for the plants built between 1963-1971. Vertical dashed green lines denote the 1963 Clean Air Act and the implementation of the 1970 Clean Air Act in 1972 respectively.

Table A.1: Pollution Abatement Strategies: The Case of the Tennessee Valley Authority

Coal Plant	County	State	Attainment in 1978	Compliance Method	Compliance Cost (millions of 2020 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 Units 1-6	Jackson	AL	No	Low Sulfur Coal	564.05
Widows Creek Units 7-8	Jackson	AL	No	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 owned by the Tennessee Valley Authority (TVA), as agreed upon in the clean air settlement between TVA and EPA in 1979-80. All ten plants were built before 1972, the year that the 1970 Clean Air Act was implemented. 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 lifespan of the projects. This table was compiled using information from USGAO (1980).

Table A.2: Where Electric Utilities Site Plants Before and After the Clean Air Act

	(1)	(2)	(3)
Dependent Variable	1[County has a Pollution Monitor Before 1963]	1[County has a Pollution Monitor Before 1963]	1[County Ever in Nonattainment (ENA)]
1[Built Between 1955-1962]	0.002	0.002	0.007
	(0.062)	(0.073)	(0.036)
1[Built Between 1963-1971]	-0.146***	-0.186***	-0.034
	(0.054)	(0.063)	(0.047)
1[Built Between 1972-1994]	-0.160***	-0.207***	0.008
	(0.051)	(0.063)	(0.070)
State FE	Y	Y	Y
ENA Counties Only		Y	
R^2	0.193	0.190	0.250
Mean of Dep. Var.	0.258	0.318	0.806
Number of Obs.	496	400	496

Notes: This table reports estimates from linear probability models that explore whether electric utilities are less likely to site their coal-fired power plants in counties that had a pre-existing pollution monitor (columns 1 and 2) or are more likely to face nonattainment in the future (column 3). We estimate separate effects for plants built between 1955-1962, 1963-1971, and 1972-1994; the (omitted) reference vintage group is plants built before 1954. The unit of observation for these regressions is a plant. In columns 1 and 2, the dependent variable is an indicator for whether the plant's county had at least one pollution monitor measuring air pollution within its boundaries before the passage of the 1963 Clean Air Act. Column 2 restricts the sample to counties that were ever out of attainment with the National Ambient Air Quality Standards (NAAQS) for any pollutant between 1972-1994. For reference, 128 coal plants that opened between 1938-1994 were built in counties that had at least one pollution monitor operating in at least one year during the baseline years 1957-1962. In column 3, the dependent variable is an indicator for whether the plant's county was ever in nonattainment with the NAAQS between 1972-1994. Information on the location of the network of pollution monitoring stations was obtained through a FOIA request submitted to the U.S. EPA. Standard errors in parentheses are clustered by state. *** denotes statistical significance at the 1% level, ** at the 5% level, and * at the 10% level.

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

Dep. Var.: Log of the Number of Years that the Plant Operates	(1)	(2)	(3)	(4)
Ever Nonattainment	0.024	0.672**		
	(0.074)	(0.320)		
ENA × 1[Built Before 1963]	0.498***	0.100		
	(0.058)	(0.306)		
Number of Years in Nonattainment			-0.001	0.078**
			(0.003)	(0.035)
# of Years in NA × 1[Built Before 1963]			0.025***	-0.022
			(0.003)	(0.034)
Capacity (GW)	0.059	0.950**	-0.061	0.649*
	(0.067)	(0.367)	(0.061)	(0.331)
Constant	3.202***	3.405***	3.366***	3.564***
	(0.057)	(0.103)	(0.043)	(0.086)
Mean of Dep. Var.	3.531	3.531	3.531	3.531
Number of Obs.	371	371	371	371
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 for any pollutant. The unit of observation for all of the regressions in this table is a power plant, considering all coal 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 the first year the plant is recorded as producing positive output plus one. 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 denoting plants built before 1963. All specifications control for the plant's capacity in its first year of operation. In Columns 1 and 3, we estimate the model via ordinary least squares. In Columns 2 and 4, we use 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 Theoretical Framework

This appendix section provides more details on the model presented in Section 3. When plants open, managers must decide the share of capacity, θ, to allocate across clean and dirty production technologies. This decision takes into account the probabilities that the plant will encounter future environmental regulation in periods $a = 1$ and $a = 2$, λ_1 and λ_2, as well as the expected stringency of the regulation, $(1 - \delta)$. Plants have full information regarding their future adjustment costs c if regulation is enacted. Depending on these parameters, plants make initial capacity investments with full knowledge that they will ex post respond to regulation in one of the three possible ways: (1) Always adjust (AA): Adjust capacity if regulation passes in $a = 1$ or $a = 2$; (2) Never adjust (NA): Do not adjust capacity if regulation passes in $a = 1$ or $a = 2$; (3) Sometimes adjust (SA): Adjust capacity if regulation passes at $a = 1$, but do not adjust capacity if regulation passes at $a = 2$.[1]

Case 1: *Always adjust (AA) – Adjust capacity if regulation passes at* $a = 1$ *or* $a = 2$

In this case, the plant chooses capacity share, θ, at $t = 0$ with full knowledge that capacity will be re-optimized (at cost c) if regulation is ever passed. The plant's initial allocation problem is:

$$\begin{aligned}
\max_{\theta} \quad & (1 - \lambda_1 - \lambda_2)(1 + \beta)\Big(\Pi_D(\theta) + \Pi_C(1 - \theta)\Big) \\
& + \lambda_1\Big[(1 + \beta)\Big(\delta\Pi_D(\hat{\theta}) + \Pi_C(1 - \hat{\theta})\Big) - c\Big] \\
& + \lambda_2\Big[\Pi_D(\theta) + \Pi_C(1 - \theta) + \beta\Big(\delta\Pi_D(\hat{\theta}) + \Pi_C(1 - \hat{\theta}) - c\Big)\Big]
\end{aligned}$$

With probability $(1 - \lambda_1 - \lambda_2)$, regulation will never pass. In this case, the initial capacity allocation, θ, determines profit levels for both $a = 1, 2$. Regulation is passed at $a = 1$ with probability λ_1, in which case the plant re-optimizes capacity to $\hat{\theta}$ and the choice of θ has no impact on profits. With probability λ_2, regulation is passed at $a = 2$. In this case, θ affects profits only at $a = 1$. The first order condition implies the following solution:

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

[1] For simplicity, we assume that the producer's initial choice of capacity allocation does not impact the probability they face regulation in $a = 1$ or $a = 2$.

From the first order condition, it is obvious that the initial capacity decision does not depend on the expected likelihood of regulation in either period, so that:

$$\frac{\partial \theta^*_{AR}}{\partial \lambda_1} = \frac{\partial \theta^*_{AR}}{\partial \lambda_2} = 0.$$

Case 2: *Never adjust (NA) – Do not adjust capacity if regulation passes at $a = 1$ or $a = 2$*

In this case, the plant chooses initial capacity θ with full knowledge that capacity will never be re-optimized if regulation is passed. The plant's initial allocation problem is:

$$\begin{aligned}\max_{\theta} \quad & (1-\lambda_1-\lambda_2)(1+\beta)\Big(\Pi_D(\theta)+\Pi_C(1-\theta)\Big) \\ & + \lambda_1(1+\beta)\Big(\delta\Pi_D(\theta)+\Pi_C(1-\theta)\Big) \\ & + \lambda_2\Big[(1+\beta\delta)\Pi_D(\theta)+(1+\beta)\Pi_C(1-\theta)\Big]\end{aligned}$$

In this case, the choice of θ determines the plant's profits regardless of whether and when regulation is passed. The first order condition implies the following solution:

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

From this first order condition, we can derive the comparative statics with respect to λ_1 and λ_2, which are given by:

$$\frac{\partial \theta^*_{NA}}{\partial \lambda_1} = \frac{(1-\delta)}{\Big(1-\lambda_1(1-\delta)-\lambda_2(1-\delta)\frac{\beta}{1+\beta}\Big)} \cdot \frac{\Pi'_D(\theta^*_{NA})}{\Pi''_D(\theta^*_{NA})+\Pi''_C(\theta^*_{NA})} < 0$$

$$\frac{\partial \theta^*_{NA}}{\partial \lambda_2} = \frac{(1-\delta)\frac{\beta}{1+\beta}}{\Big(1-\lambda_1(1-\delta)-\lambda_2(1-\delta)\frac{\beta}{1+\beta}\Big)} \cdot \frac{\Pi'_D(\theta^*_{NA})}{\Pi''_D(\theta^*_{NA})+\Pi''_C(\theta^*_{NA})} < 0$$

where it is clear that $\frac{\partial \theta^*_{NA}}{\partial \lambda_1} < \frac{\partial \theta^*_{NA}}{\partial \lambda_2} < 0$.

Case 3: *Sometimes adjust (SA) – Adjust capacity if regulation passes at $a = 1$, do not adjust capacity if regulation passes at $a = 2$*

In this case, the plant chooses initial capacity θ with full knowledge that capacity will be adjusted if regulation is passed at $a = 1$ but not if regulation is passed at $a = 2$. The plant's initial allocation problem is:

$$\begin{aligned}\max_{\theta} \quad & (1-\lambda_1-\lambda_2)(1+\beta)\Big(\Pi_D(\theta)+\Pi_C(1-\theta)\Big) \\ & + \lambda_1\Big[(1+\beta)\Big(\delta\Pi_D(\hat{\theta})+\Pi_C(1-\hat{\theta})\Big)-c\Big] \\ & + \lambda_2\Big[(1+\beta\delta)\Pi_D(\theta)+(1+\beta)\Pi_C(1-\theta)\Big]\end{aligned}$$

In this case, the choice of θ determines the plant's profits if regulation is never adopted and if regulation is adopted at $a = 2$. The first order condition implies the following solution:

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

From this first order condition, we can derive the comparative statics with respect to λ_1 and λ_2, which are given by:

$$\frac{\partial\theta^*_{SA}}{\partial\lambda_1} = \frac{\lambda_2(1-\delta)\beta}{(1-\lambda_1)\Big(1-\lambda_1(1+\beta)-\lambda_2(1-\delta)\beta\Big)}\cdot\frac{\Pi'_D(\theta^*_{SA})}{\Pi''_D(\theta^*_{SA})+\Pi''_C(\theta^*_{SA})} < 0$$

$$\frac{\partial\theta^*_{SA}}{\partial\lambda_2} = \frac{(1-\delta)\beta}{\Big(1-\lambda_1(1+\beta)-\lambda_2(1-\delta)\beta\Big)}\cdot\frac{\Pi'_D(\theta^*_{SA})}{\Pi''_D(\theta^*_{SA})+\Pi''_C(\theta^*_{SA})} < 0$$

From these two expressions, it is clear that $\frac{\partial\theta^*_{SA}}{\partial\lambda_2} \leq \frac{\partial\theta^*_{SA}}{\partial\lambda_1} < 0$, since $1 \geq \lambda_1 + \lambda_2$.

C Data Construction and Data Description

This appendix section provides further details on data sources, data construction, and data description, supporting the broad overview given in Section 4. Appendix Section C.1 discusses the digitization of historical information on fossil-fuel-fired power plants. Appendix Section 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 the production function. Appendix Section C.3 presents additional descriptive figures and tables. The outline of all of the figures and tables in this appendix section is below.

C.1 Data Construction

We digitized power plant level data from the Federal Power Commission (FPC) reports for the years 1938-1981.[2] Most of the digitization was funded by the NSF grant SES 1627432. We hired undergraduates and Master's students to manually enter 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 power plants. The number of power plants listed in the first report, which covers all years between 1938-1947, increases from 151 in 1938 to 200 in 1947. The number of plants listed in subsequent annual volumes is 277 in 1950, 528 in 1960, 553 in 1970, and 647 in 1980.[3]

The title of the FPC report for the years 1938-1947 is *Steam-Electric Plant Construction Cost and Annual Production Expenses, 1938-1947* (Single Volume). The title of the FPC report for each subsequent year between 1948 and 1978 is *Steam-Electric Plant Construction Cost and Annual Production Expenses* (Annual Supplements). Finally, the title of the relevant report for each year between 1979-1981 is *Thermal-Electric Plant Construction Cost and Annual Production Expenses* (Annual Supplements). As an example, we present a page from the 1957 report in Appendix Figure C.2.

Starting in 1982, the annual reports include only a small sample of steam-electric power plants. For this reason, we collect data from several other sources to construct an annual plant-level data-set from 1982-1994 that can be appended to the 1938-1981 data-set built by digitizing the annual reports from the FPC:

- Each plant's capacity in each year as well as each plant's latitude/longitude coordinates, state and county come from the eGrid database administered by the USEPA.[4]
  - *http://www.epa.gov/egrid/download-data*

[2] In 1977, Congress replaced FPC with the Federal Energy Regulatory Commission (FERC).

[3] The plants reported in 1938 accounted for 59% of the capacity and 75% of the generation of utility-owned, fossil-fuel-fired steam-electric plants in the United States. The corresponding percentage of capacity covered in the years 1947, 1950, 1960, 1970, and 1980 are 65%, 70%, 90%, 93%, and 92% respectively. The corresponding percentage of generation covered in the years 1947, 1950, 1960, 1970, and 1980 are 73%, 80%, 94%, 96%, and 91% respectively.

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

- Annual plant-level total generation and consumption by fuel type come from Form EIA-759 which later became Form EIA-906.
  – *http://www.eia.gov/electricity/data/eia923/eia906u.html*

- The year of installation of each flue gas desulfurization (FGD) technology and flue gas particulate (FGP) collector for each plant is from Form EIA-767.
  – *http://www.eia.gov/electricity/data/eia767/*

- Annual total quantity of fuel purchased by each plant and annual average fuel prices for each plant are from Form EIA-423.
  – *http://www.eia.gov/electricity/data/eia423/*

- Annual plant-level data on number of employees and nonfuel expenses come from FERC Form 1 (investor-owned utilities), EIA Form 412 (municipal and other government utilities), and RUS Forms 7 and 12 (electric cooperatives).[5]
  –*http://www.ferc.gov/industries-data/electric/general-information/electric-industry-forms/form-1-electric-utility-annual.*

  –*https://www.eia.gov/electricity/data/eia412/*

  –*https://www.rd.usda.gov/files/UEP_Support_DCS.pdf*

C.2 Estimation of Total Factor Productivity

We estimate pollution-unadjusted total factor productivity (PU-TFP) using the procedure developed by Ackerberg, Caves and Frazer (2015). We use data on each plant's output and inputs in each year. Our measure of output is annual plant-level net electricity generation in MWh. The first input, *capacity*, is the total nameplate capacity of the plant in the year in MW. The second input, *labor*, is a count of full-time equivalent employees at the plant in the year. The final input, *fuel*, is the quantity of fuel consumed

[5]Most of these 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.

by the plant in the year in MMBtu.[6]

In robustness checks, we also consider *nonfuel_costs* as an input when estimating PU-TFP. Nonfuel costs include all nonfuel operating 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 the materials used in the production process, both because it reflects expenditures rather than quantities, and because it includes the wage bill for the employees counted in *labor*. Namely, as nonfuel costs include payroll costs, both *nonfuel_costs* and *labor* would vary with changes in staffing.

We assume a Leontief production function as in Fabrizio, Rose and Wolfram (2007). In particular, fuel is assumed to be a perfect complement for a function of the other two inputs, capital and labor. We also follow the literature and assume that the function determining how capital and labor map to output 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.

Since we use the method developed by Ackerberg, Caves and Frazer (2015) to estimate PU-TFP, we are implicitly assuming that the plant first chooses capacity. At this point, it can also choose to install pollution abatement technology. Then, a productivity shock is realized, after which the plant chooses labor. Finally, fuel is chosen, after which an idiosyncratic shock is realized. This last shock captures a variety of different short-run shocks to the level of output sold by the plant. Examples include thermal efficiency shocks driven by variation in the type of coal burned or temperature, as well as unexpected variation in transmission line losses. This shock can also capture classical measurement error in log output.

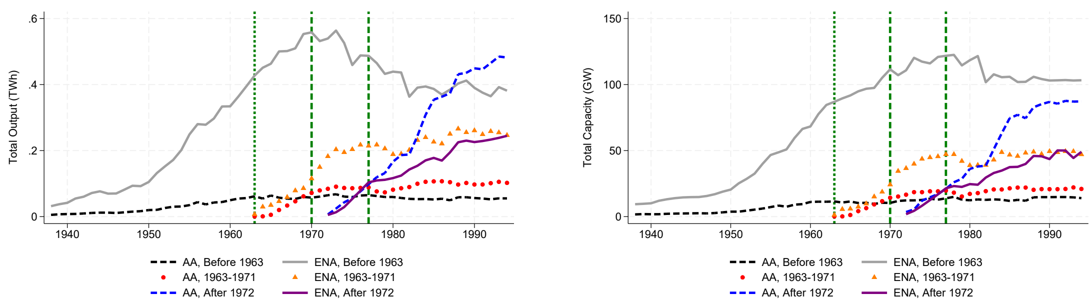
[6] de Roux et al. (2021) raise the issue that quantity-based TFP measures are potentially biased when there are quality differences in inputs or outputs. However, in our setting, electricity is a homogeneous output. The technology used to generate electricity is also quite similar across coal-fired power plants. The skills required for workers to operate a coal plant are also plausibly similar. The only input that differs in quality is fuel – high-sulfur, high-heat content versus low-sulfur, low-heat content coal. However, we measure input fuel use in units of heat (MMBtu) rather than units of weight (tons), so the aforementioned quality differences are less relevant for our estimation of productivity.

C.3 Additional Descriptive Figures and Tables

Appendix Figure C.1 presents annual total electricity generation and capacity by vintage and attainment status. Appendix Figure C.2 presents an example scan of the physical copy of the 1957 FPC report. Appendix Figure C.3 shows a map of the United States with all of the counties with at least one fossil-fuel power plant shaded in red. Appendix Figure C.4 displays trends in annual pollution-unadjusted total factor productivity by vintage and attainment status. Appendix Figure C.5 displays the annual total electricity generating capacity for each source type, including nuclear and hydro.

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

Figure C.1: Annual Total Electricity Generation and Capacity for Coal Power Plants By Vintage and Attainment Status



(a) Total Output (b) Total Capacity

Notes: The left panel of this figure documents the annual total electricity generation produced by coal plants in the United States. The right panel plots annual total coal-fired electricity generating capacity. Plants are located either in "ever-nonattainment" (ENA) counties that went out of attainment with the National Ambient Air Quality Standards (NAAQS) at least once during our 1938-1994 sample period or in "always-attainment" (AA) counties that never went out of attainment between 1938-1994. We consider three plant vintage groups: plants built before 1963, plants built between 1963-1971, and plants built after 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 passing of the Clean Air Act of 1970 and its amendments in 1977.

Figure C.2: 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

Line No.		Cannon Street		B. C. Cobb		Bryce E. Morrow		Saginaw River	
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	

Line No.		Cannon Street		B. C. Cobb		Bryce E. Morrow		Saginaw River	
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	

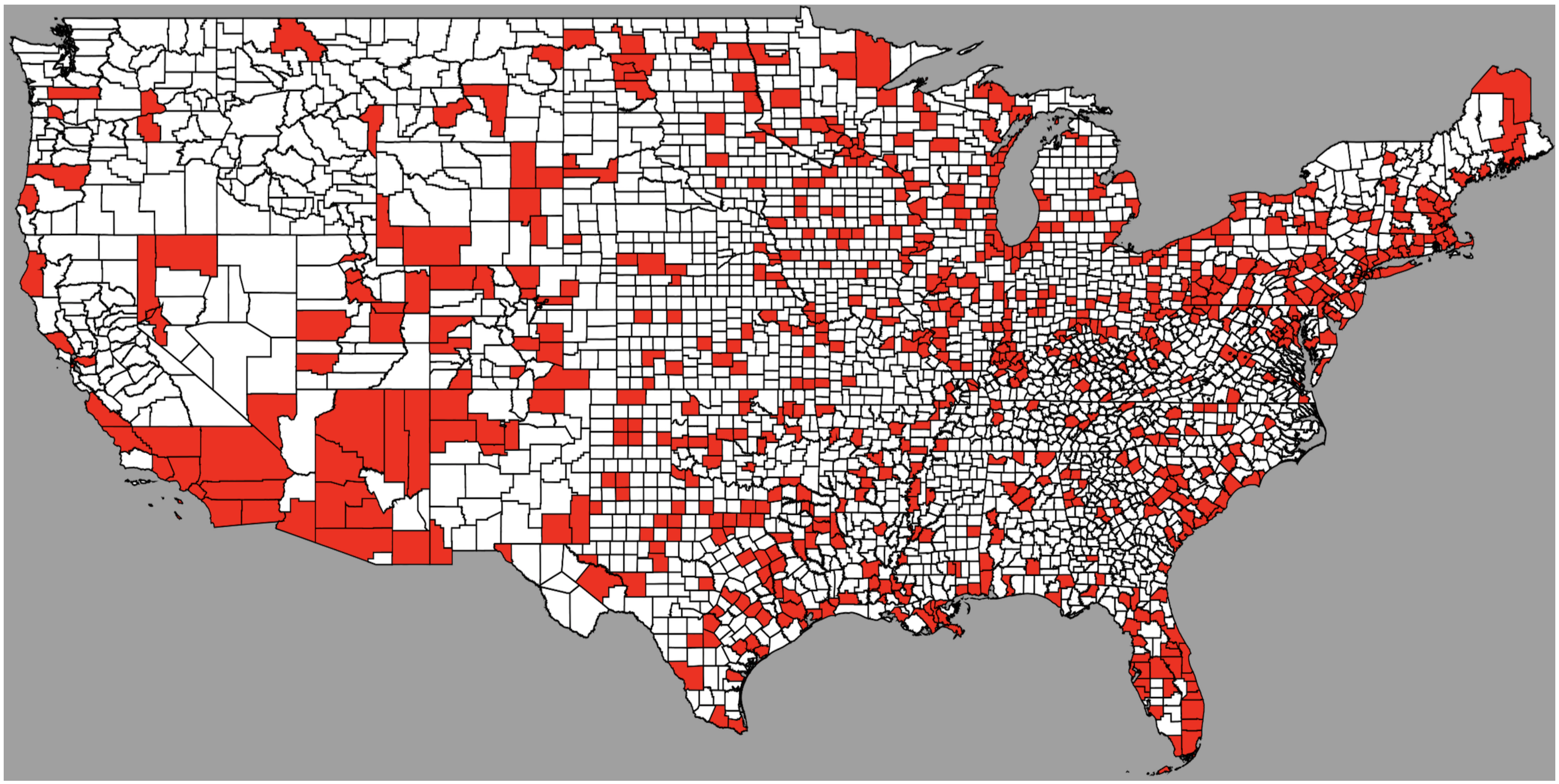
CHANGES OR ADDITIONS IN 1957

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

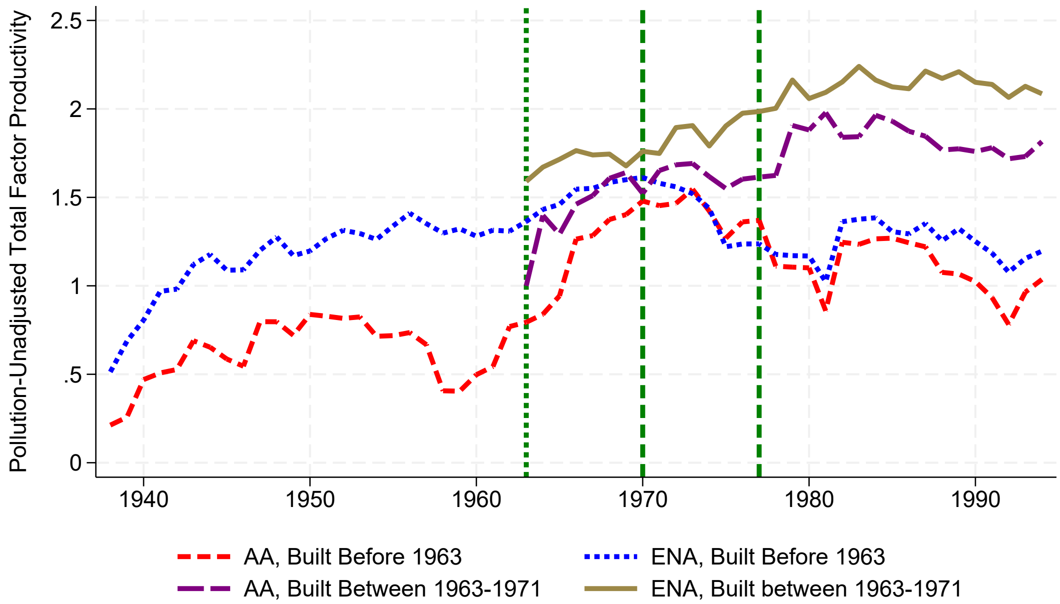
Source: Federal Power Commission Report "*Steam-Electric Plant Construction Cost and Annual Production Expenses – Tenth Annual Supplement*", 1957.

Figure C.3: Map of Counties with Fossil-Fuel-Fired Power Plants



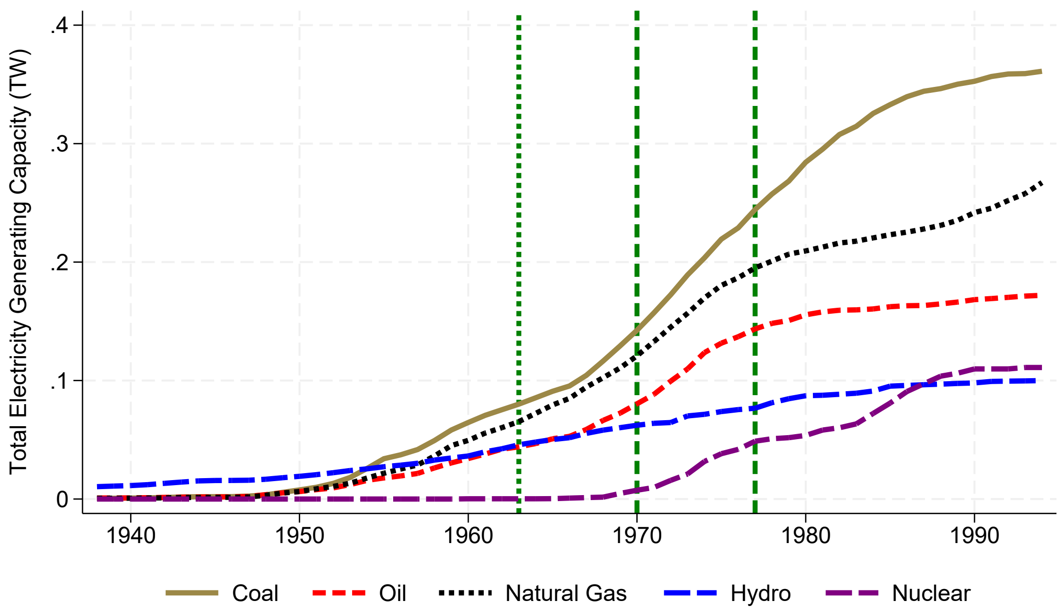
Notes: This figure displays which counties had fossil-fuel-fired power plants at any point between 1938-1994. The counties shaded in red were home to at least one fossil-fuel plant in our sample. There were no power plants in any year of our sample located in the counties shaded in white.

Figure C.4: Annual Average Total Factor Productivity for Coal Power Plants by Vintage and Attainment Status



Notes: This figure plots annual average pollution-unadjusted total factor productivity separately for coal 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 between 1972-1994 while "ENA" counties faced nonattainment at least once between 1972-1994. 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 Generating Capacity by Source Type



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

Table C.1: 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	12,935	1.33	0.82
Electricity Output (GWh)	12,935	2,186.96	2,540.94
Electricity Generating Capacity (MW)	12,935	483.07	510.71
Number of Employees	12,935	160.29	124.46
Fuel Burned (in Billion BTU)	12,935	22,655.14	24,812.00
Panel B: Indicator for NAAQS Noncompliance, Sample Period 1972-1994			
Variable	**No. of Obs.**	**Mean**	**Std. Dev.**
1[Out of Attainment with any NAAQS]	6,123	0.53	0.50
1[Out of Attainment with NAAQS: TSP or PM]	6,123	0.17	0.38
1[Out of Attainment with NAAQS: SO_2]	6,123	0.08	0.27
1[Out of Attainment with NAAQS: CO]	6,123	0.13	0.33
1[Out of Attainment with NAAQS: O_3 or NO_2]	6,123	0.42	0.49

Notes: This table presents summary statistics pertaining to our difference-in-differences regressions assessing the impacts of nonattainment on power plant operations. We estimate annual plant-level pollution-unadjusted total factor productivity based on a Leontiff function of: (1) a translog production function of capital (electricity generating capacity) and labor (average number of employees), and (2) fuel (heat input in billions of BTU of fuel burned) using the estimation procedure developed by Ackerberg, Caves and Frazer (2015).

Table C.2: 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	83	25	83
Ever Nonattainment	223	40	40
Total	306	65	123
Panel B. Proportion By Vintage			
	Built Before 1963	Built Between 1963-1971	Built After 1972
Always Attainment	0.27	0.38	0.67
Ever Nonattainment	0.73	0.62	0.33

Notes: The top panel of this table lists the number of coal power plants in our sample in each cell defined by the intersection of attainment status and vintage group. The bottom panel lists the proportion of coal plants in a given vintage group in each attainment status. The first row of each panel 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, second and third columns of each panel consider plants built before 1963, plants built between 1963-1971, and plants built after 1972 respectively.

Table C.3: 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*	3,782	341
Nonattainment in Year *t-1*	189	3,147
Panel B. Conditional Probability		
	Attainment in Year t	Nonattainment in Year t
Attainment in Year *t-1*	0.92	0.08
Nonattainment in Year *t-1*	0.06	0.94

Notes: The top panel of this table lists the number of observations in each of the four categories defined by attainment status in years t and $t-1$. The bottom panel lists the probabilities of being in attainment and nonattainment in year t conditional on being in attainment or nonattainment in year $t-1$. The unit of observation underlying this table is plant-year, considering all coal plants over the sample period 1972-1994.

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

Dep. Var.: Log Output	(1)	(2)	(3)	(4)
Panel A. Estimated Parameters				
Log Labor (l)	1.407***	1.605***	1.822***	2.246***
	(0.003)	(0.012)	(0.002)	(0.013)
Log Capacity (k)	0.510***	-0.191***	0.187***	-0.480***
	(0.002)	(0.011)	(0.002)	(0.014)
l × l	-0.089***	-0.049***	-0.205***	-0.154***
	(0.002)	(0.014)	(0.002)	(0.012)
l × k	-0.088***	-0.185***	0.047***	-0.164***
	(0.002)	(0.021)	(0.001)	(0.015)
k × k	0.034***	0.014	0.006*	-0.004
	(0.004)	(0.014)	(0.003)	(0.011)
Nonfuel Expenses		Y		Y
Fuel Types Considered	Coal	Coal	All	All
Number of Obs.	15,839	15,434	23,998	23,474
Number of Plants	532	530	841	839
Panel B. Post-Estimation Input Elasticities of Output				
Log Employees	0.12	-0.23	0.23	-0.06
Log Capacity	0.49	0.43	0.47	0.71
Log Nonfuel Expenses		0.94		0.50

Notes: This table reports the production function estimates that are used to construct pollution-unadjusted total factor productivity (PU-TFP). Panel A presents the estimated parameters of the production function with capital (electricity generating capacity), labor (average number of employees), and fuel (the heat input in MMBtu from the fuel burned) using the estimation procedure developed by Ackerberg, Caves and Frazer (2015). We consider specifications with and without nonfuel cost, which refers to all operating expenses other than those associated with fuel. We estimate productivity focusing only on coal plants in Columns 1 and 2 and pooling across coal, oil, and gas plants in Columns 3 and 4. Our preferred specification, which is the basis for the PU-TFP measure used in the main analysis, is presented in column 1. Panel B reports implied input elasticities of output. The unit of observation for all of these analyses is plant-year. *** denotes statistical significance at the 1% level, ** at the 5% level, and * at the 10% level. Standard errors in parentheses are calculated by bootstrapping.

D Additional Results

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

Appendix Figure D.1 presents event study estimates of the impacts of nonattainment on productivity including only plant fixed effects and year fixed effects (i.e., not including state by year fixed effects). These estimates are presented both for plants built before 1963 and between 1963-1971, using both the traditional two-way fixed effects approach and the methodology specified in Callaway and Sant'Anna (2021).

Appendix Figure D.2 examines how the estimated impacts of nonattainment on the productivity of plants of different vintages vary by the first year of data in the analysis. This figure highlights the importance of utilizing data from well before the Clean Air Act (CAA) of 1970.

Appendix Table D.1 investigates the effects of nonattainment with the standards for specific pollutants rather than focusing on nonattainment with any pollutant standard.

Appendix Table D.2 reports the estimated impacts of nonattainment on power plant outcomes for more granular vintage groups. For reference, the main analysis estimates separate effects only for plants built before 1963 versus plants built between 1963-1971.

Appendix Table D.3 reports the results of the Goodman-Bacon decomposition. These results indicate that the estimated impacts of first nonattainment on plant operations are far larger when utilizing comparisons across plants that ever versus never faced nonattainment between 1972-1994. This highlights again the importance of estimating the effects of nonattainment including data from before the implementation of the 1970 CAA in 1972.

Appendix Table D.4 documents robustness to alternative specifications and samples. Appendix Table D.5 checks whether the estimated impact of nonattainment on pollution-unadjusted total factor productivity (PU-TFP) changes if we estimate PU-TFP including a measure of input materials or consider alternative production functions.

Appendix Table D.6 reproduces the main estimates of the impacts of nonattainment on plant operations from Table 1 accounting for significant generating capacity upgrades such as installing a new boiler. Namely, if a power plant increased its capacity by either 40MW or 15% from the previous year, we consider it as entering a new "epoch". Vintage is defined at the plant/epoch level and plant/epoch fixed effects are included as part of this specification.

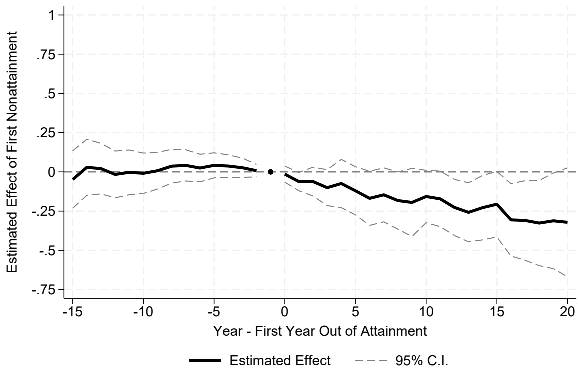
Appendix Table D.7 examines heterogeneity in the main estimates by the plant's primary fuel type. Appendix Table D.8 reproduces the main estimates of the impacts of nonattainment on plant operations from Table 1 using the definition of nonattainment between 1972-1977 based on Air Quality Control Regions constructed by Cropper et al. (2023).

Appendix Table D.9 examines how annual statewide electricity generating capacity by source responds to the proportion of counties in nonattainment in the state in the year.

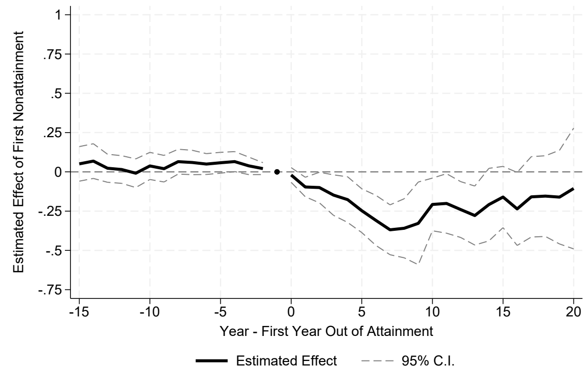
The outline of the figures and tables in this appendix section is below.

- Table D.6. Impacts of Nonattainment on Power Plant Operations from 1938-1994: Plant/Epoch Level
- Table D.7. Impacts of Nonattainment on Power Plant Outcomes by Primary Fuel Type
- Table D.8. Impacts of Nonattainment on Power Plant Operations from 1938-1994: AQCR-Based Attainment Status
- Table D.9. Impacts of the Proportion of Counties in Nonattainment on State-Level Capacity

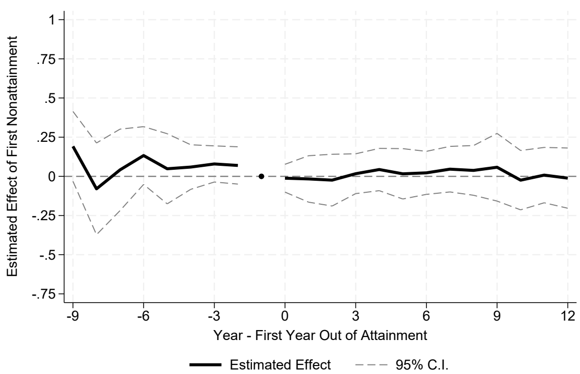
Figure D.1: Event Study Analysis of the Impacts of First Year in Nonattainment on Power Plant Productivity: No State-Year Fixed Effects



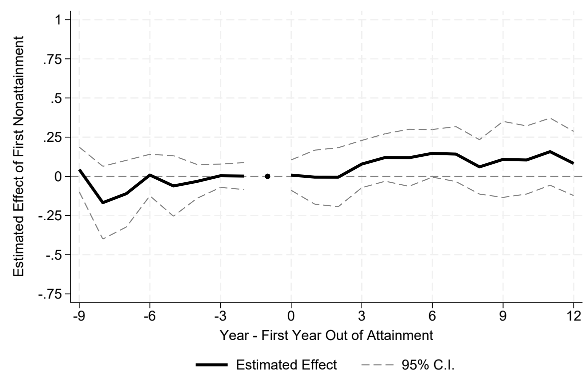
(a) TWFE, Before 1963



(b) Callaway-Sant'Anna, Before 1963



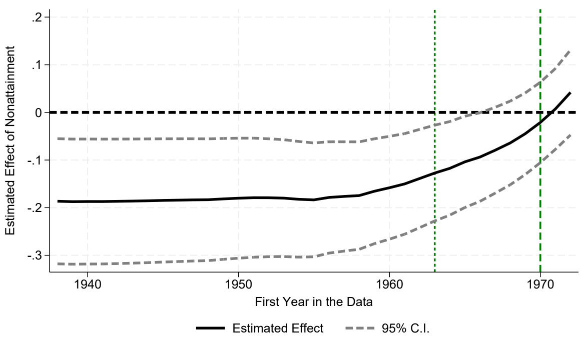
(c) TWFE, Between 1963-1971



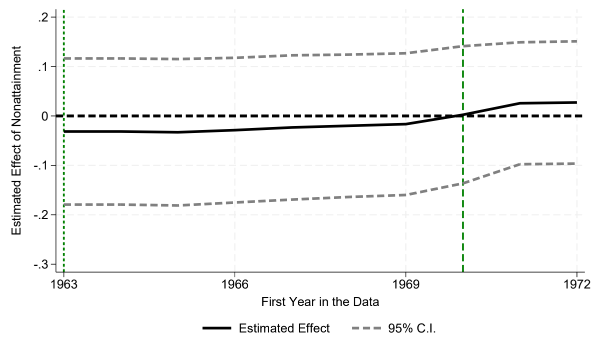
(d) Callaway-Sant'Anna, Between 1963-1971

Notes: In this figure, we plot the estimated effect of first nonattainment on the log of pollution-unadjusted total factor productivity (PU-TFP) separately for each event year. The period of analysis is 1938-1994. All specifications include plant fixed effects, but include year fixed effects rather than state by year fixed effects as in our primary specifications. The 95% confidence intervals reported in these figures are based on standard errors that are clustered by county. The top and bottom panels focus on coal plants built before 1963 and between 1963-1971 respectively. In the left panels, we estimate effects using ordinary least squares. In the right panels, we utilize the method in Callaway and Sant'Anna (2021) that accommodates arbitrary heterogeneity in treatment effects when estimating the average treatment effects on the treated when the timing of treatment is staggered.

Figure D.2: Impacts of Nonattainment on Power Plant Productivity by Vintage and Initial Sample Year



(a) Effects on Log PU-TFP – Built Before 1963



(b) Effects on Log PU-TFP – Built Between 1963-1971

Notes: This figure displays the estimated impacts of nonattainment on the log of pollution-unadjusted total factor productivity (PU-TFP) by initial sample year, separately for coal plants built before 1963 (left panel) and for coal plants built between 1963-1971 (right panel). Namely, for initial year X on the x-axis, we artificially restrict the sample period used to estimate the relevant effect to X-1994 (e.g., the effect for initial year 1950 is estimated using data from 1950-1994). The short-dashed green vertical line represents the passage of the Clean Air Act of 1963 and the dashed green vertical line represents the Clean Air Act of 1970. All specifications include plant fixed effects and state by year fixed effects. The 95% confidence intervals reported in these figures are based on standard errors that are clustered by county.

Table D.1: Impacts of Nonattainment on Power Plant Outcomes By Pollutant Standard

Dep. Var. (in Logs)	(1) PU-TFP	(2) Output	(3) Fuel Use	(4) No. Employees	(5) Capacity
NA: TSP or PM	-0.021	-0.013	0.005	-0.002	0.019
	(0.034)	(0.049)	(0.053)	(0.029)	(0.042)
NA: SO2	0.057	0.079	0.061	0.052	0.044
	(0.067)	(0.094)	(0.092)	(0.043)	(0.060)
NA: CO	-0.110	-0.229**	-0.198*	-0.161***	-0.244***
	(0.076)	(0.110)	(0.102)	(0.046)	(0.086)
NA: O_3 or NO_2	-0.169***	-0.207***	-0.174**	-0.029	-0.078
	(0.064)	(0.080)	(0.072)	(0.043)	(0.056)
R^2	0.713	0.828	0.756	0.854	0.902
Mean of Dep. Var.	1.325	7.011	16.328	4.789	5.632
Number of Obs.	12,935	12,935	12,935	12,935	12,935
Number of Plants	371	371	371	371	371
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 plant's county moves out of compliance with the National Ambient Air Quality Standards associated with each of four sets of pollutants: total suspended particulates or particulate matter (TSP or PM), sulfur dioxide (SO_2), carbon monoxide (CO), and nitrogen dioxide or ozone (NO_2 or O_3). There are separate standards for O_3 and NO_2, but we group these two standards together because the vast majority of counties that were in nonattainment for NO_2 were also in nonattainment for O_3. PU-TFP stands for pollution-unadjusted total factor productivity, and NA for nonattainment. The unit of observation for these regressions is plant-year, considering only coal plants built before 1972. Standard errors in parentheses are clustered by county. *** denotes statistical significance at the 1% level, ** at the 5% level, and * at the 10% level.

Table D.2: 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]	-0.195**	-0.255***	-0.220**	-0.074	-0.136**
	(0.077)	(0.098)	(0.092)	(0.046)	(0.066)
NA × 1[Built Between 1955-1962]	-0.159**	-0.228*	-0.201*	0.017	-0.123
	(0.078)	(0.121)	(0.109)	(0.084)	(0.107)
NA × 1[Built Between 1963-1966]	-0.001	-0.073	-0.028	-0.026	-0.065
	(0.104)	(0.134)	(0.139)	(0.094)	(0.100)
NA × 1[Built Between 1967-1971]	0.099	0.028	0.054	-0.015	-0.090
	(0.062)	(0.086)	(0.091)	(0.075)	(0.071)
R^2	0.721	0.834	0.762	0.866	0.905
Mean of Dep. Var.	1.325	7.011	16.328	4.789	5.632
Number of Obs.	12,935	12,935	12,935	12,935	12,935
Number of Plants	371	371	371	371	371
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 231 plants built before 1955, 75 plants built between 1955 and 1962, 31 plants built between 1963 and 1967, and 34 plants built between 1967 and 1971.

Notes: This table reports the impacts of nonattainment on power plant operations by vintage group. For reference, in the main analysis, we consider only two vintage groups: plants built before 1963 and plants built between 1963-1971. In contrast, the specifications in this table present separate estimates for vintage groups defined by whether the plant was built before 1955, between 1955-1962, between 1963-1966, or between 1967-1971. The unit of observation for the regressions in this table is plant-year, and the estimation considers all coal plants built before 1972. For all specifications, "nonattainment" (NA) is defined as the county being out of attainment with the National Ambient Air Quality Standards for any pollutant in the year. All specifications include plant fixed effects, state by year fixed effects, and vintage group by year fixed effects. Standard errors in parentheses are clustered by county. *** 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

Dep. Var. (in Logs)	(1) PU-TFP	(2) Output	(3) Fuel Use	(4) No. Employees	(5) Capacity
Overall DD Estimate	-0.112	-0.188	-0.236	-0.041	-0.088
DD Est.: T vs. Never Treated	-0.203	-0.378	-0.423	-0.126	-0.184
DD Est.: Timing Groups	-0.057	-0.122	-0.166	-0.054	-0.072
DD Est.: Within Residual Component	-0.054	0.013	-0.047	0.116	0.042
Weights: T vs. Never Treated	0.382	0.382	0.382	0.382	0.382
Weights: Timing Groups	0.382	0.382	0.382	0.382	0.382
Weights: Within Residual Component	0.236	0.236	0.236	0.236	0.236
Number of Obs.	2,961	2,961	2,961	2,961	2,961
Number of Plants	141	141	141	141	141

Notes: This table reports the results from running the Goodman-Bacon decomposition on panel regressions of first nonattainment on plant outcomes (Goodman-Bacon, 2021). The decomposition requires a strongly balanced panel. We consider only coal plants built before 1972. To construct the panel, we include only plants with consecutive observations for 10 years before and after 1972. Plant-year observations must have data listed for output, electricity generating capacity, number of employees, and input energy for the whole 21 year span in order to be included. The overall DD estimate is reported in the first row. The unit of observation in this analysis is plant-year, and the regressions include plant fixed effects, state by year fixed effects, and vintage group by year fixed effects; plants built before 1963 and plants built between 1963-1971 are in vintage groups 1 and 2 respectively. For all specifications, "first nonattainment" is an indicator variable that is equal to one for each year on or after the first year that the plant faced nonattainment with the National Ambient Air Quality Standards for any pollutant. The Goodman-Bacon method decomposes the overall difference-in-differences ("DD") effect of first nonattainment into three types of comparisons: (i) plants that ever face nonattainment using plants that never face nonattainment during our 1938-1994 sample period as controls ("T vs. Never Treated"), (ii) plants first facing nonattainment earlier (later), using plants first facing nonattainment later (earlier) as controls ("Timing Groups"), and (iii) a "within residuals" component. For each component, the decomposition provides both the DD estimate and the weight of this estimate in calculating the overall DD estimate.

Table D.4: Impacts of Nonattainment on Power Plant Productivity from Alternative Specifications and Samples

Dep. Var.: Log PU-TFP	(1) Post-1972 Plants	(2) Primary	(3) Larger	(4) One Plant Utilities	(5) No State Standard
Nonattainment	0.129	-0.158***	-0.137**	-0.226**	-0.172***
	(0.125)	(0.057)	(0.057)	(0.102)	(0.065)
R^2	0.907	0.711	0.685	0.861	0.715
Mean of Dep. Var.	1.843	1.325	1.577	1.179	1.308
Number of Obs.	1,429	12,935	9,685	1,011	11,068
Number of Plants	123	371	288	34	313
Plant FE	Y	Y	Y	Y	Y
State By Year FE	Y	Y	Y	Y	Y
Vintage Group by Year FE	N	Y	Y	Y	Y

Notes: This table presents estimates of the impact of nonattainment on the log of pollution-unadjusted total factor productivity (PU-TFP). The unit of observation for these regressions is plant-year. For all specifications, "nonattainment" is defined as the plant's county being out of attainment with the National Ambient Air Quality Standards for any pollutant in the year. Column 1 focuses on coal plants built after 1972, and includes plant fixed effects and state by year fixed effects. Columns (2)-(5) consider only coal plants built before 1972. All four of these specifications include plant fixed effects, state 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. For Column 2, we drop observations with capacity in the bottom 25% of the distribution of capacity. Column 3 focuses on utilities that own only one coal-fired plant built before 1972. Column 4 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 (Stern, 1982). Standard errors in parentheses are clustered by county. *** denotes statistical significance at the 1% level, ** at the 5% level, and * at the 10% level.

Table D.5: Impacts of Nonattainment on PU-TFP Estimated Using Alternative Production Functions and Specifications

Dep. Var.: Log PU-TFP	(1)	(2)	(3)	(4)
NA × 1[Built Before 1963]	-0.197***	-0.159**	-0.115**	-0.107**
	(0.064)	(0.062)	(0.054)	(0.053)
NA × 1[Built Between 1963-1971]	0.061	0.062	0.067	0.070
	(0.064)	(0.080)	(0.056)	(0.057)
R^2	0.712	0.656	0.569	0.586
Mean of Dep. Var.	1.325	-3.826	1.045	0.427
Number of Obs.	12,935	12,880	12,935	12,880
Number of Plants	371	371	371	371
Plant FE	Y	Y	Y	Y
State 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 estimates of the impact of nonattainment on pollution-unadjusted total factor productivity (PU-TFP). The unit of observation for these regressions is plant-year, considering only plants built before 1972. We estimate separate effects for plants built before 1963 and plants built between 1963-1971. For all specifications, "nonattainment" (NA) is defined as the plant's county being out of attainment with the National Ambient Air Quality Standards for any pollutant in the year. We estimate PU-TFP using the methodology developed by Ackerberg, Caves and Frazer (2015). The first two columns estimate PU-TFP assuming that the function relating capital and labor to output is translog while the next two columns are based on the assumption that this 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 without including any measure of materials. Standard errors in parentheses are clustered by county. *** denotes statistical significance at the 1% level, ** at the 5% level, and * at the 10% level.

Table D.6: Impacts of Nonattainment on Power Plant Operations from 1938-1994: Plant/Epoch Level

	(1)	(2)	(3)	(4)	(5)
Dep. Var. (in Logs):	PU-TFP	Output	Fuel Use	No. Employees	Capacity
NA × 1[Built Before 1963]	-0.329***	-0.347***	-0.280***	-0.078*	-0.055*
	(0.085)	(0.091)	(0.085)	(0.045)	(0.028)
NA × 1[Built Between 1963-1971]	-0.035	-0.041	-0.044	-0.010	-0.049
	(0.118)	(0.127)	(0.114)	(0.040)	(0.040)
R^2	0.873	0.922	0.838	0.950	0.989
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.	1.165	6.655	16.007	4.695	5.262
Number of Obs.	8,313	8,313	8,313	8,313	8,313
Number of Plants	318	318	318	318	318

Notes: This table reports the impacts of nonattainment on power plant operations over the period 1938-1994. The unit of observation for the regressions in this table is plant/epoch-year, and the estimation considers all coal plants that were built before 1972. We follow Fabrizio, Rose and Wolfram (2007) and define a plant as making a significant upgrade in generating capacity (i.e., entering a new epoch) if capacity in the year increases by either 40MW or 15% relative to the previous year. We estimate the impact of nonattainment on outcomes separately for plant/epochs with first year of operation before versus after 1963. For all specifications, "nonattainment" is defined as the county being out of attainment with the National Ambient Air Quality Standards for any pollutant in the year. All specifications include plant/epoch fixed effects, state by year fixed effects, and vintage group by year fixed effects; plant/epochs with first year of operation before 1963 are in vintage group 1 while plant/epochs with first year of operation between 1963-1971 are in vintage group 2. PU-TFP stands for pollution-unadjusted total factor productivity, and NA for nonattainment. Standard errors in parentheses are clustered by county. *** 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 Primary Fuel Type

	(1)	(2)	(3)	(4)	(5)
Dep. Var. (in Logs)	PU-TFP	Output	Fuel Use	No. Employees	Capacity
NA × 1[Coal Plant]	-0.154***	-0.218***	-0.195***	-0.063	-0.137**
	(0.057)	(0.075)	(0.071)	(0.040)	(0.053)
NA × 1[Oil Plant]	-0.035	0.055	0.071	0.131	0.050
	(0.114)	(0.141)	(0.217)	(0.097)	(0.090)
NA × 1[Gas Plant]	-0.310***	-0.355***	0.055	-0.014	-0.068
	(0.101)	(0.130)	(0.224)	(0.060)	(0.083)
R^2	0.678	0.819	0.695	0.866	0.907
Mean of Dep. Var.	0.663	6.768	15.793	4.507	5.484
Number of Obs.	19,965	19,965	19,965	19,965	19,965
Number of Plants	617	617	617	617	617
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 371 coal-fired plants, 71 oil-fired plants, and 175 gas-fired plants.

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 was coal, natural gas, or oil. We define each plant's fuel type by calculating the plant's aggregate total heat input from each fuel in its first five years of operation, picking the fuel corresponding to the largest aggregate heat input. For all specifications, "nonattainment" (NA) is defined as the plant's county being out of attainment with the National Ambient Air Quality Standards for any pollutant in the year. PU-TFP stands for pollution-unadjusted total factor productivity. The unit of observation for these regressions is plant-year, considering only plants built before 1972. 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. Standard errors in parentheses are clustered by county. *** denotes statistical significance at the 1% level, ** at the 5% level, and * at the 10% level.

Table D.8: Impacts of Nonattainment on Power Plant Operations from 1938-1994: AQCR-Based Attainment Status

	(1)	(2)	(3)	(4)	(5)
Dep. Var. (in Logs):	PU-TFP	Output	Fuel Use	No. Employees	Capacity
Panel A. Average Effects					
Nonattainment	-0.202***	-0.273***	-0.229***	-0.039	-0.142**
	(0.072)	(0.093)	(0.088)	(0.050)	(0.068)
R^2	0.712	0.827	0.756	0.853	0.901
Panel B. Effects by Plant Vintage					
NA × 1[Built Before 1963]	-0.256***	-0.333***	-0.292***	-0.053	-0.165**
	(0.080)	(0.103)	(0.098)	(0.055)	(0.076)
NA × 1[Built Between 1963-1971]	0.079	0.044	0.096	0.037	-0.025
	(0.072)	(0.095)	(0.097)	(0.078)	(0.076)
R^2	0.713	0.828	0.756	0.853	0.901
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.	1.325	7.011	16.327	4.789	5.631
Number of Obs.	12,901	12,901	12,901	12,901	12,901
Number of Plants	371	371	371	371	371

Notes: This table reports the impacts of nonattainment on power plant operations over the period 1938-1994. In contrast with Table 1, nonattainment from 1972-1977 is measured using the definitions based on Air Quality Control Regions constructed by Cropper et al. (2023). The unit of observation for the regressions in this table is plant-year, and the estimation considers all coal plants built before 1972. Panel A estimates how annual plant-level outcomes change with the attainment status of the county where the plant is located. Panel B estimates the impact of nonattainment on outcomes separately for plants built before 1963 versus plants built between 1963-1971. For all specifications, "nonattainment" is defined as the plant's county being out of attainment with the National Ambient Air Quality Standards for any pollutant in the year. All specifications include plant fixed effects, state 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. PU-TFP stands for pollution-unadjusted total factor productivity, and NA for nonattainment. Standard errors in parentheses are clustered by county. *** denotes statistical significance at the 1% level, ** at the 5% level, and * at the 10% level.

Table D.9: Impacts of the 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
	(2211.0)	(485.8)	(722.2)	(970.2)
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

Notes: This table presents estimates of the impact of annual state-level proportion of counties in nonattainment on annual state-level electricity generating capacity. Specifically, the independent variable of interest is the population-weighted proportion of counties in the state in nonattainment with the National Ambient Air Quality Standards for any pollutant in each year. The unit of observation for these regressions is state-year, excluding Alaska and Hawaii. 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 electricity generating capacity aggregating over fossil-fuel-fired sources using either steam turbines (ST) or internal combustion (IC), fossil-fuel-fired sources using either gas turbines (GT) or combined-cycle technology (CC), nuclear sources, and hydro sources respectively. Standard errors in parentheses are clustered by state. *** denotes statistical significance at the 1% level, ** at the 5% level, and * at the 10% level.