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ABSTRACT

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

The passage of landmark government regulation is often the culmination of evolving social pressure and incremental policy change. During this process, firms may preemptively adjust behavior in anticipation of impending regulation, making it difficult to quantify the overall economic impact of the legislation. This study leverages newly digitized data on the operation of virtually every fossil-fuel power plant in the United States from 1938-1994 to examine the economic impacts of the 1970 Clean Air Act (CAA) on the power sector. This unique long panel provides us an extended pre-regulation benchmark, allowing us to account for both *anticipatory behavior* by electric utilities in the years leading up to the Act's passage and reallocative effects of the CAA across plant vintages. We find that the CAA led to large and persistent decreases in output and productivity, but only for plants that opened before 1963. The timing aligns with the passage of the original 1963 CAA, which provided the federal government with the authority to "control" air pollution, sending a strong signal to firms of impending federal regulation. We provide historical evidence of anticipatory responses by utilities in the design and siting of plants that opened after 1963. We also find that the aggregate productivity losses of the CAA borne by the power sector were substantially mitigated by the reallocation of output from older less efficient power plants to newer plants.

JEL Classification: K32, N52, Q52

Keywords: power plants, electricity generation, total factor productivity, clean air act, air quality regulations, NAAQS

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1 Introduction

Government regulation permeates all aspects of the modern economy. It affects a range of outcomes from worker safety to air quality to the provision of housing and medical care. Landmark policies, such as the Housing Act of 1949, Medicare and Medicaid in 1965, and the Clean Air Act of 1970, have fundamentally altered major sectors of the economy. Although transformative, these policies are often the culmination of evolving social pressure and incremental policy change.[1] During this lengthy process, economic agents may update their expectations over the likelihood of future regulation and take anticipatory actions to facilitate the transition to a post-regulatory regime.

Anticipatory behavior makes it difficult to empirically estimate the full effects of landmark regulations, since outcomes in the years leading up to enactment may not provide a valid benchmark against which post-regulation outcomes can be compared. Moreover, differences in producers' abilities to preemptively respond can have important distributional consequences with potentially first order impacts on aggregate outcomes.

This paper studies the impacts of the 1970 Clean Air Act (CAA) on the power sector. The CAA is the centerpiece of local air pollution regulation in the United States and a model for environmental policy around the world. It constitutes a prime example of landmark regulation that emerged after an extended period of incremental policy change. During this process, polluting plants may have preemptively adjusted behavior, since the Act's passage was largely foreseeable in the years leading up to its enactment.[2]

We leverage newly digitized data on the operation of virtually every fossil-fuel power plant in the United States from 1938-1994 to examine the impacts of the 1970 CAA on electricity producers. This setting provides an exceptional opportunity to account for both *anticipatory behavior* by electric utilities in the years preceding the Act's passage, and reallocative effects of the CAA across older and newer plants. The long time horizon allows us to establish a pre-regulatory benchmark, and estimate effects of the CAA across

[1]The Housing Act of 1949 was passed 15 years after the creation of the Federal Housing Administration, Medicare and Medicaid were signed into law 20 years after being proposed by President Truman, and the 1970 Clean Air Act was passed 22 years after the deadly Donora Smog of 1948.

[2]However, the precise timing and regulatory details of the 1970 CAA were largely unexpected (see Section 2). For example, there was a large and abrupt change in public opinion in favor of environmental protection around 1970. In May 1969, only one percent of the population included "pollution/ecology" as one the most important domestic problems in the United States. In May 1971, 25 percent did so, and that category was second only to "inflation/cost of living/taxes" (ACIR, 1981, p.19).

plant vintages that were more or less able to preemptively mitigate the consequences of the regulation. Because power plants are immobile and have extended lifespans, there is little concern regarding the relocation or exit of firms as is often the case in long-run analyses.[3] Detailed data on plant operations allow us to estimate annual plant-level "pollution-unadjusted" total factor productivity (PU-TFP).[4] We use these measures to estimate the direct effects of the CAA on plant productivity and assess the indirect productivity effects driven by the reallocation of output across older versus newer plants.[5]

Our empirical approach utilizes the geographic and temporal variation in environmental regulation built into the CAA, which designated counties to be either in attainment or nonattainment based on standards set forth by the National Ambient Air Quality Standards (NAAQS).[6] Whereas producers in attainment counties were subject to limited regulation, power plants located in nonattainment counties were forced by state and local regulators to take potentially costly actions to reduce pollution levels. Pollution emissions reductions were typically achieved by decreasing output, switching to "cleaner" fuels, or installing pollution abatement technology. We adopt a difference-in-differences strategy that compares the changes in outcomes of plants located in counties in versus out of attainment, before and after enforcement went into place. Event study graphs that motivate the regression analyses support the parallel trends assumption.

We find that county nonattainment designations under the CAA had negative effects on output and productivity, but only for plants built before 1963.[7] The productivity losses incurred by pre-1963 plants are economically large and persistent, suggesting that

[3]The typical lifespan of a fossil-fuel power plant was 40 years in our period of analysis. Rate-of-return regulation in the industry limited the incentive to relocate operations and ensured that monopoly producers faced virtually no risk of bankruptcy.

[4]Our measure focuses on the productivity losses incurred by plants ignoring the external costs of pollution borne by society at large. We estimate PU-TFP using the method specified by Ackerberg, Caves and Frazer (2015). Importantly, the estimation does not require the use of balance sheet data, which could be biased due to changes in market power in output and input markets. See, for example, Foster, Haltiwanger and Syverson (2008), Hsieh and Klenow (2009), and De Loecker (2011) for discussions of the advantages of productivity estimation based on input and output quantities (TFP-Q) rather than revenue and input costs (TFP-R).

[5]When markets are efficient, reallocative effects will not impact aggregate productivity (Solow, 1957). However, in the power sector, there were large productivity differences by power plant vintage, consistent with electric utilities operating as local monopolies during our sample period. As a result, distributional effects of regulation may have first order impacts on aggregate outcomes.

[6]The NAAQS initially covered five different criteria pollutants: carbon monoxide, particulate matter, nitrogen dioxide, ozone, and sulfur dioxide. Annual county-level nonattainment designations were based on whether air pollution concentrations exceeded the federal standard for the criteria pollutant.

[7]These plants responded to nonattainment status primarily by decreasing output and substituting towards higher cost low-sulfur coal.

these plants were unable to adapt to environmental regulation even in the long run. In contrast, the effects of the CAA on plants that opened from 1963 to 1971 are small and statistically insignificant. The timing of these patterns aligns with the passage of the original 1963 CAA, which provided the federal government with the authority to “control” air pollution, signalling impending environmental regulations. Plants that opened after this key year were largely unaffected by subsequent regulatory requirements.

What explains the absence of productivity effects for plants that opened immediately prior to the passage of the 1970 CAA? Both historical and empirical evidence suggest that electric utilities were able to take anticipatory actions to mitigate the effects of nonattainment status in the post-1972 period for their plants built between 1963 and 1971. Historical sources document preemptive design changes after 1963, including increases in plant stack height and the use of pollution abatement technology. We document a sharp increase in patenting related to power systems between 1963-1971. We also find a post-1963 shift in siting plants away from counties with pollution monitors. Taken together, both the historical narrative and descriptive evidence point to anticipation playing a key role in the eventual costs of complying with the CAA.

The aggregate productivity effects of the CAA were substantially mitigated by the reallocation of output away from older, less productive power plants. We estimate that the declines in output from plants built before 1963 in nonattainment counties were largely offset by increased output from new fossil fuel plants that opened in the post-1972 period. Since these plants have substantially higher average PU-TFP levels, the reallocative response of the CAA led to an increase in aggregate productivity. A simple calculation that accounts for this regulatory-induced shift in production across plants implies that the CAA imposed annual productivity losses of $3.5 billion (2020 dollars) in the power sector. Notably, we estimate that roughly half of the aggregate long-run losses were offset by the reallocation of production across plants.

Lastly, we show that an extended pre-regulatory period is crucial to capturing the full impacts of the 1970 CAA. We find that the magnitude of the nonattainment effects decline as we artificially increase the earliest year included in the sample – for example, estimating on 1940-1997 versus 1950-1997. The estimated effects are insignificant for samples that begin after 1965. Moreover, we find that the estimated effects were driven by the initial 1972 attainment designations and that post-1972 changes in attainment status had small and statistically insignificant effects on plant output and PU-TFP. Similarly, decompositions based on Goodman-Bacon (2018) show that the empirical identification of our primary nonattainment effects comes from the initial 1972 county nonattainment designations. These patterns are consistent with anticipatory responses to environmental regulation, since post-1972 changes in attainment status were largely determined by known trends in county-level pollution.

This paper makes three main contributions to the literature. First, it provides the first causal estimates of the impacts of the 1970 Clean Air Act (CAA) that account for anticipatory behavior. Our findings support Malani and Reif (2015)'s analysis demonstrating the potential for anticipatory behavior to substantially alter policy impact estimates. In a related context, Keiser and Shapiro (2019*a*,*b*) also document that water pollution declined more rapidly before the passage of the landmark 1972 Clean Water Act than after it. Because federal legislation pertaining to water pollution control was also enacted prior to 1972, anticipatory behavior may have played a role in that setting as well.[8]

Second, our findings indicate that distributional impacts of regulation can attenuate first order effects on aggregate outcomes through reallocative responses (e.g., Kline and Moretti, 2014; Hornbeck and Rotemberg, 2019). In the context of the CAA, the within-firm efficiency costs borne by older producers were substantially mitigated by reallocative efficiency gains, as output was directed towards more productive plants. These results also suggest that the potential external costs of delayed plant upgrade and/or exit under the CAA's grandfathering provisions (e.g., List, Millimet and McHone, 2004; Stavins, 2006) may have been alleviated by reallocative responses across producers.

The third contribution regards the critical importance of a long time horizon to assess the effects of transformative changes, especially when they involve nearly irreversible investments such as large power plants (e.g., Bleakley and Lin, 2012; Hornbeck, 2012; Hornbeck and Keniston, 2017). There is an extensive literature documenting the impacts of the CAA on firm behavior (see reviews by Currie and Walker, 2019; Aldy et al., Forthcoming),[9] but most of the prior studies have relied on post-1972 variation in attainment

[8]Indeed, a 1981 report from the U.S. Advisory Commission on Intergovernmental Relations (ACIR) states that "[t]he history of federal water pollution control initiatives from 1948 to 1966 is a vivid example of government action through incremental changes. (...) [F]ederal spending (...) increased from a small loan program funded at about $1 million per year to a grant-in-aid outlay of $3.55 billion over five years. In the same period, Congress moved from a posture of denying federal authorities any enforcement powers to requiring the enactment of national water quality standards" (ACIR, 1981, p.12).

[9]For impacts on manufacturing, see, for example, Henderson (1996); Becker and Henderson (2000);

status, and none have included data from before 1963. We show that an extended pre-treatment period is crucial for estimating the full economic impact of the CAA, because of the anticipatory adjustments made in the years leading up to the Act's passage.

The remainder of the paper is organized as follows. Section 2 presents background information on how the Clean Air Act might have affected the electricity industry. Section 3 outlines our conceptual framework for how plants choose inputs and output with versus without the Clean Air Act. Section 4 describes the data sources and summary statistics, and introduces our difference-in-differences approach to estimate the effect of nonattainment with NAAQS on plant outcomes. Section 5 reports and discusses the main findings, along with robustness checks and further heterogeneity analyses. Section 6 presents back-of-the-envelope calculations on the nationwide effects of the 1970 CAA on PU-TFP in the power sector. Lastly, Section 7 concludes.

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, when it was clear that further regulation was coming. The 1963 legislation gave the federal government the ability to intervene in specific settings. By 1965, the federal government had started to take enforcement actions – called conference proceedings – against the worst polluters and groups of polluters where interstate pollution was an issue. The third phase was from 1972 onward when the 1970 CAA legislation took effect. Subsequent amendments in 1977 and 1990 further strengthened the national pollution control regulatory framework.

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

Greenstone (2002); Gray and Shadbegian (2003); Greenstone, List and Syverson (2012); Ryan (2012); Kahn and Mansur (2013); 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); Sheriff, Ferris and Shadbegian (2019).

London smog (Clay, 2018). These events received international publicity, raised public awareness about 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 air pollution monitoring network. Although initially small, by 1962 the network included 270 monitors in 205 counties. The 1955 Act authorized a modest research budget and left the responsibility of prevention and control of air pollution to the states, although by 1960 there were no state air quality standards (Stern, 1982). 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).

2.2 1963-1971

The Clean Air Act of 1963 (1963 CAA) signalled an important shift in the role of the federal government in combating air pollution. This was the first federal legislation that gave the federal government the authority to "control" air pollution. The 1963 CAA included a conference procedure in section 115. In 1965, the Federal government held the first two abatement conferences involving interstate polluters, a pulp mill and a rendering plant (EPA, 1973). A total of 11 abatement conferences would be held through 1971.[11] The 1965 Amendment to the 1963 CAA addressed motor vehicles, the 1967 Air Quality Act strengthened federal enforcement powers. By 1966, ten states had set ambient air quality standards (Stern, 1982).[12]

A number of pieces of evidence suggest that electric utilities altered behavior after 1963 in anticipation of further regulation. The 1966 "Steam-Electric Plant Construction Cost and Annual Production Expenses" report dedicates, 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 major social-economic issues

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

[11] Interestingly, these procedures were not new. Similar procedures were included in the 1956 Federal Water Pollution Control Act and had been used beginning in 1957 (EPA, 1973).

[12] In the empirical analysis, we assess the role of these state-level standards on power plant outcomes.

affecting the electric power industry" (FPC, 1967, p.ix).[13] The 1968 reports adds 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 the selection of coal and oil fuels of lower sulfur content" (FPC, 1969, p.ix). The 1970 reports finally states that "[e]nvironmental factors are now a major, and often dominant, consideration in the siting and design of new steam-electric generating facilities. (...) All coal-fired units will employ electrostatic precipitators, wet scrubbers, or other efficient methods for controlling particulate emissions and many will be designed for later application of stack systems for removal of sulfur oxides which are now under development" (FPC, 1972, p.x).

The characteristics of power plants that opened in the post-1963 period are consistent with anticipatory behavior by electric utilities. Appendix Figure A.1 shows an increase in average smokestack height in the late 1960s that does not align with the more gradual increase in generator size. Appendix Figure A.2 shows that installation of flue gas particulate (FGP) collectors was already common before 1970. Finally, Appendix Figure A.3 shows a sharp increase in the number of patents granted for power systems in the mid- and late-1960s. These patterns may reflect the increased incentive for technological change in response to anticipated regulatory requirements following the passage of the 1963 CAA.[14]

Appendix Table A.1 shows a change in the siting of plants that opened between 1963 and 1971 that is consistent with preemptive avoidance behavior by electric utilities. In comparison to pre-1963 plants, newer plants were systematically less likely to be located in a county with an air pollution monitor. Interestingly, we find no pre-1972 differences in the probability of siting plants in future nonattainment counties, suggesting that the regulatory details of the CAA regarding which counties would ultimately be targeted

[13] 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" (FPC, 1967, pp. ix-x).

[14] Unfortunately, the aggregate data do not permit a finer decomposition of the sources of these new patents.

were largely unexpected.

These preemptive changes by electric utilities may partly account for the increase in construction costs of coal plants around 1966 (see Appendix Figure A.4). In a discussion of these trends, Joskow and Rose (1985) state that 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 rising costs were paid for by rate increases, which were approved in public utility commission hearings.[15]

2.3 1972 onward

The 1970 Clean Air Act (CAA) marked the first federal effort to regulate air quality on a large scale. The U.S. EPA was established and directed to set National Ambient Air Quality Standards (NAAQS) for certain criteria air pollutants: total suspended particles (TSP) or particulate matter (PM), carbon monoxide (CO), sulfur dioxide (SO_2), nitrogen dioxide (NO_2), and ozone (O_3). Lead was later added as a criteria pollutant and standards were established for other pollutants. Beginning in 1972, each county received an annual designation of nonattainment or attainment for each of the criteria pollutants.[16] This designation was dependant on whether air concentrations exceeded the federally mandated standards.

Each state was required to submit a state implementation plan (SIP) outlining how any noncompliant regions would be brought into compliance with the NAAQS. Typically states totaled up estimated stationary source emissions in each nonattainment area, divided it by an estimate of total emissions needed to achieve attainment status, and ordered plants to reduce emissions by that ratio (Roberts and Farrell, 1978). All states, territories, and the District of Columbia submitted SIPs by the end of 1972 (EPA, 1973).[17]

[15]Between 1963-1968 operating costs generally decreased and rates of return were higher than in the recent past. In line with this, there were between two and five cases a year. By 1969, inflation, increases in fossil fuel prices, and environmental factors had begun to drive up cost. The number of cases rose from 16 in 1969 to 53 in 1972. Environmental groups began to be active in rate cases as well.

[16]The *Code of Federal Regulations* (CFR) started to publish a list of nonattainment counties only in 1978. Following Greenstone (2002), we consider a county nonattainment for a pollutant over the period 1972-1977 if it had a pollution monitor reading that exceeded the relevant federal standard in 1972.

[17]The documentary record on SIPs is complicated by the fact that parts of SIPs were frequently being modified or litigated. Still, the EPA was able to write in late 1974 that "[w]ith a few notable exceptions

Thus, existing power plants in nonattainment counties faced greater constraints on emissions than plants in attainment counties. To achieve emissions targets, plants could reduce annual net generation or burn more expensive, lower sulfur coal. Alternatively, they could install flue gas desulfurization (FGD) systems – colloquially known as "scrubbers." Nevertheless, these installations were costly and the risked subjecting the plant to New Source Performance Standards (NSPS), which required that any substantial investments or modifications to existing plants be accompanied by installation of pollution abatement equipment.[18] Despite these concerns, scrubber installations increased after 1970 (see Appendix Figures A.2 and A.5).

Environmental regulation under the 1970 CAA led to a sharp drop in emissions by power plants. By 1975, the EPA reported that 261 of the 394 coal-fired power plants were in compliance with SIP emission limitations or abatement schedules. Consistent with this, the EPA found that TSP and SO_x emissions at coal-fired steam electric power plants had fallen (EPA, 1976*b*). TSP emissions fell from 4.2 million tons in 1970 to 2.9 million tons in 1974, and SO_x emissions fell from 15.4 million tons to 13.6 million tons.[19]

Measures of total suspended particulates (TSP) fell at monitors in counties that would ever be in nonattainment after 1972. Appendix Figure A.6 plots the estimated coefficients of a regression of TSP on year fixed effects interacted with attainment status, controlling for pollution monitor fixed effects.[20] Both nonattainment and attainment had declines in measured TSP over time, although the absolute reductions were larger in nonattainment counties. It is notable that these downward trends preceded the passage of the 1970 CAA.

(e.g. sulfur oxide emission limitations in the State of Ohio) all States now have fully enforceable emission limits affecting stationary sources" (EPA, 1975, p.12).

[18]In nonattainment counties, these abatement technologies had to meet the "lowest achievable emissions rate" regardless of costs, whereas in attainment counties, plants were required to install the "best available control technologies" with consideration over the costs. The 1977 amendments required the use of scrubbers for coal-fired plants built after 1978.

[19]Of the 133 plants not in compliance, 102 were located in Ohio (47), Indiana (29), and Illinois (26). In these states, there had been significant delay and litigation around SO_x control plans (EPA, 1976*a*). Of remaining 31 plants not in compliance, ten were part of the Tennessee Valley Authority and were the subject of a consent decree (see Appendix Table A.2); SIP revisions were underway for 7 plants; and the remaining plants were in litigation or otherwise subject to EPA action.

[20]Some caution should be taken in interpreting these trends, given the expansion of the monitoring network over the time period.

3 Conceptual Framework

This section provides a conceptual framework for understanding the margins of adjustment to the Clean Air Act for plants built prior to 1963, between 1963-1971, from 1972 onward. We relegate the full mathematical formulation corresponding to this framework to Appendix B. This appendix section and Appendix C.2 also describes how we measure annual plant-level total factor productivity.

In this conceptual framework, each plant i produces electricity output O_{it} in each year t using the following three inputs: capacity K_{it}, labor L_{it}, and input heat energy E_{it}. Generating capacity takes a longer time to adjust than either labor or energy while labor takes a longer time to adjust than energy. Indeed, we think of energy as a perfect complement to the other inputs: holding energy fixed, output cannot be increased by increasing either labor or capital.

Pollution P_{it} is also emitted as a consequence of burning fossil fuels in order to produce output O_{it}. Plants can reduce emissions by decreasing output, burning cleaner fuel such as coal with lower sulfur content, or installing pollution abatement technology (see, for example, Appendix Table A.2). Each of these actions come with environmental benefits for the public and costs for power plants. This paper focuses solely on the costs incurred by power plants. For example, consider a plant that reduces output in response to environmental regulations. It is unable to reduce its capacity, and it may not be able to decrease its number of employees because of fixed staffing requirements. This plant produces less output for the same level of inputs; *pollution-unadjusted* total factor productivity (PU-TFP) thus falls as a consequence of the environmental regulation. We emphasize pollution-unadjusted because the environmental benefits associated with reduced output (and thus decreased pollution emissions) are not captured in our quantification of annual plant-level productivity.[21,22]

We hypothesize that plants built up to 1962, from 1963 to 1971, and from 1972 onward will respond differently to the stricter environmental regulations associated with county-level nonattainment. Plants built before 1963 can decrease emissions by reducing output,

[21]As stated by Currie and Walker (2019), "if a regulation induces firms to use less pollution (that is, fewer unmeasured inputs), then it may look like total factor productivity declines when in fact the 'true' regulation-induced productivity change remains elusive" (p.15).

[22]See Muller, Mendelsohn and Nordhaus (2011); Muller (2014, 2019) for measurements of GDP that adjust for pollution damages.

burning cleaner fuel or making modifications to the plant. However, making modifications to the plant such as installing pollution abatement technology is expensive. Further, making "major modifications" can subject plants built prior to 1972 to the stricter set of environmental regulations applied to new plants (i.e.: the "New Source Performance Standards").[23] Given this combination of incentives, we hypothesize that plants built before 1963 will be unlikely to respond to nonattainment status by installing pollution abatement technology unless this is their last resort. Instead, plants built before 1963 are more likely to decrease emissions by some combination of reducing output and burning cleaner fuels. To the extent that the plant is unable to perfectly adjust their other inputs to match this reduction in output or change in fuel, the plant's PU-TFP will fall.[24]

In contrast to plants built up to 1962, we expect that plants built starting in 1963 and especially plants starting in 1972 will be much less affected by nonattainment status. Plants built from 1963-1971 that anticipate further environmental regulation can make siting and design decisions to reduce the likelihood of being located in more polluted counties that could be subject to more stringent environmental regulations in the future. All of the plants built after 1972 are subject to the NSPS; plants built after 1978 were required to install scrubbers under the NSPS. It is unlikely that nonattainment forces substantial reductions in pollution emissions from plants built after 1972 because: (1) all of these plants are already subject to the stricter NSPS policy and (2) these plants were sited and designed with full knowledge that the NAAQS were in place.

4 Data and Empirical Strategy

4.1 Data Description

This paper uses annual plant-level data for the vast majority of fossil fuel fired power plants in the United States for the period 1938-1994.[25] The Federal Power Commission

[23]That being said, it was only in the late 1990s that the EPA announced sweeping enforcement action against 46 power plants for violations of the New Source Review (NSR) – see Keohane, Mansur and Voynov (2009).

[24]These plants may run longer to compensate for the reduction in output, as reported in Appendix Table A.3.

[25]We end our sample period in 1994 because the market-based components of the Clean Air Act of 1990 were implemented in 1995. Moreover, some U.S. states decided to shift the provision of electricity generation from output price regulation to electricity market mechanisms beginning in 1998 ("electricity

(FPC), later renamed Federal Energy Regulatory Commission (FERC), began publishing detailed plant-level information in 1948.[26] The initial volume included retrospective data beginning in 1938. We digitized the data for 1938-1981, and use similar data collected by FERC for 1982-1994.[27] Further details on the data construction process are provided in Appendix C.

Our primary specifications focus on the impact of nonattainment with the National Ambient Air Quality Standards (NAAQS) on the operations of fossil-fuel-fired power plants. There are about 1,000 fossil-fuel-fired plants in our data, and they are located in approximately 700 U.S. counties, as displayed in Appendix Figure C.2. We differentiate between "existing" plants that were built before 1972 and "new" plants that were built after 1972 because only plants built after 1972 were subject to the New Source Performance Standards. Appendix Table C.1 presents the number of existing and new plants in our data that were always in attainment versus ever in nonattainment between 1972-1994. The table also shows that the share of plants that were in always attainment counties rose from 0.34 before 1963 to 0.40 from 1963-1971 to 0.44 after 1972. Attainment status is persistent: conditional on being in attainment (nonattainment) in year $t-1$, the empirical probability of being in attainment (nonattainment) in year t is over 0.9 (Appendix Table C.2). The vast majority of temporal variation in nonattainment status stems from the initial impact of the CAA as opposed to post-1972 changes.

We assess how nonattainment impacts a range of annual plant-level outcomes, including electricity output (in MWh), electricity generating capacity (in MW), number of employees, fuel use (in mmBTU), and fuel prices. We also use these data on inputs and output electricity to estimate pollution-unadjusted total factor productivity (PU-TFP). Appendix Table C.3 reports summary statistics over the period 1938-1994.[28] The average plant in our sample has approximately 135 employees, 528 MW in nameplate capacity, and generates roughly 2,300 GWh of electricity each year.

Figure 1 plots annual total electricity generation for three vintages of plants (pre-

restructuring"). Market-based plants face both a different set of incentives and a different set of reporting requirements.

[26] Appendix Figure C.1 displays a page of the 1957 report as an example.

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

[28] Details on the estimation of PU-TFP are provided in Appendix B and Appendix C.2. The estimated parameters of the production function are reported in Appendix Table C.4.

1963, 1963-1971, and post-1971) in nonattainment and attainment counties.[29] From this figure, we see that electricity generation from fossil fuel plants grew at a faster rate in ever-nonattainment counties relative to always-attainment counties prior to 1972. After 1972, production from "existing" fossil fuel plants built before 1972 decreased in ever-nonattainment counties but remained stable for existing plants in always-attainment counties. In contrast, we see a precipitous rise in production from new power plants built after 1972 in always-attainment counties along with a slower increase in production from new power plants in ever-nonattainment counties.[30]

Appendix Figure C.4 documents annual total electricity generating capacity over our sample period. This figure shows that coal capacity grew up through 1990. In contrast, oil and natural gas capacity increased up to roughly 1980 before declining from 1980-1994. This trend is due in large part to Congress passing a bill forcing electric utilities to convert oil and natural gas capacity to coal in response to the oil embargo of 1973-1974.[31] Nuclear capacity grew beginning around 1965 while hydro capacity remained roughly flat throughout our sample period. These trends are consistent with the decline in fossil fuel production in nonattainment counties having been offset by increased production by new fossil fuel and nuclear plants. In the empirical analysis, we directly explore these relationships.

4.2 Empirical Strategy

We use a difference-in-differences approach to examine how different annual plant-level outcomes Y_{it} vary across counties in versus out of attainment with pollutant standards set

[29]Specifically, we define "nonattainment" counties as those that ever went out of attainment during the post-1971 period and attainment counties as those that never went out of attainment. Appendix Figure C.3 plots the annual proportion of fossil fuel fired electricity generation produced in ever-nonattainment counties, separately for existing versus new plants. The top panel considers nonattainment with any pollutant while the bottom panels plots nonattainment by pollutant.

[30]Similar descriptive plots broken down by vintage group and the number of years a plant faced nonattainment are displayed in Appendix Figure C.5. The corresponding plots for PU-TFP are displayed in Appendix Figures C.6 and C.7. The distribution of the number of years of a county in nonattainment is displayed in Appendix Figure C.8.

[31]The oil price shocks occurred in 1973 and 1979. Regarding natural gas, "[i]n reaction to the oil embargo of 1973-74, Congress (...) mandated the implementation of a national program to conserve petroleum products and natural gas and increase the use of coal by major fuel consumers. (...) [It] directs FEA [Federal Energy Administration] to prohibit certain powerplants and authorizes FEA to prohibit certain major fuel burning installations from burning natural gas or petroleum products as a primary energy source. Such prohibitions effectively mandate the use of coal" (EPA, 1977, p.19).

forth by the National Ambient Air Quality Standards (NAAQS). Equation (1) estimates the effect of nonattainment with any pollutant standard on the plant outcome of interest:

$$log(Y_{it}) = \alpha_i + \delta_{ft} + \lambda_{vt} + \theta_{st} + \beta Nonattain_{ct} + \epsilon_{it} \quad (1)$$

where i indexes a plant located in county c in state s, and t indexes year-of-sample. We include plant fixed effects α_i, fuel-type-by-year fixed effects δ_{ft}, vintage-group-by-year fixed effects λ_{vt}, and state-by-year fixed effects θ_{st}. This structure of fixed effects controls for a variety of time-constant and time-varying unobserved heterogeneity. For example, it accounts for the technology to generate electricity and control pollution available at the time each plant was built, statewide energy and pollution control policies that might have been implemented before or after the CAA, fuel price shocks such as the oil and natural gas shocks in the 1970s, and improvements in power plant and emission control technology that becomes available for each vintage group over time. Based on the passage of the 1963 Clean Air Act, we consider two vintage groups in our main analysis: plants built before 1963, and plants built from 1963 to 1971.[32]

The independent variable of interest in Equation (1) is $Nonattain_{ct}$, an indicator that takes on the value one if the county is out of attainment with the NAAQS for any pollutant. Because of the variation in the timing of the treatment, we report and discuss the Goodman-Bacon decomposition in the results section (Goodman-Bacon, 2018). Event study analysis that motivate this difference-in-differences approach is also reported in the results section and supports the parallel trends assumption. When examining heterogeneity of our overall effects, we interact $Nonattain_{ct}$ with other variables of interest such as vintage groups and number of years a county has been in nonattainment. Unless otherwise noted, all our estimated coefficients are accompanied by standard errors that are two-way clustered by county and year (Cameron, Gelbach and Miller, 2011).

[32]The post-1971 vintage group is only incorporated in the analysis of the adoption of emission control technologies, and when we compare our main results with estimates from approaches and sample periods considered in prior studies.

5 Impacts of the CAA on Power Plant Outcomes

5.1 Impacts on Power Plant Output, Inputs, and PU-TFP, and Evidence of Anticipatory Effects

We begin by presenting event study graphs to motivate the regression analyses that follow. These graphs are derived from the estimation of versions of Equation (1) that take the first year in nonattainment as year zero in event time, and allows the coefficients to vary from $t \in \{-7, +10\}$ in event time. The figures plot these coefficients and their 95 percent confidence intervals. Event studies are presented for two outcomes, output and pollution-unadjusted total factor productivity (PU-TFP), and for three plant vintage groups – all plants built before 1972, plants before 1963, and plants built from 1963 to 1971.

Figure 2 highlights three key points. First, all panels show little evidence of differential trends in the years preceding the first year in nonattainment. Second, changes in the county attainment status lead to output and PU-TFP declines for existing plants in the years following nonattainment. Third, the declines appear to be driven by plants built before 1963. The coefficients of both output and PU-TFP of plants built from 1963 to 1971 look relatively flat around zero, suggesting that those plants might have made adjustments ahead of the impending air quality regulations.

Table 1 presents the estimates of β from Equation (1) for various plant-level outcomes. Panel A reports the average effects. Panel B reports the heterogeneous effects across plants built before and after 1963.

Panel A shows that power plants located in nonattainment counties experienced relative decreases in output and PU-TFP (cols. 1, 2). The effects are statistically significant and large in magnitude. We also find that plants in nonattainment counties experienced relative decreases in inputs (cols. 3-5). We estimate significant negative effects of nonattainment status on energy inputs (BTUs) and capacity. Meanwhile, the effects on employment are negative but small in magnitude and not statistically significant.

The negative effects of nonattainment status on plant PU-TFP are driven by the large declines in plant output that were not offset by proportional decreases in inputs. These patterns are consistent with the challenges of adjustment to power plant inputs.

Plant capacity could not be reduced in response to regulatory requirements and the number of employees required for plant operations was largely independent of output levels.[33] Meanwhile, power plants forced to reduce their output due to environmental regulations may have required more fuel per MWh of electricity production because they are producing at technically suboptimal levels, and because they are likely being forced to start up or ramp up production more often.

Table 1, Panel B, shows that negative effects on output and PU-TFP were driven entirely by power plants built before 1963. The heterogeneity in these effects is striking. For plants built before 1963, the coefficient estimates are large and statistically significant. For plants built from 1963 to 1971, the estimates are negative, but small in magnitude and not statistically significant.[34]

The divergent effects across plants built before 1963 and plants built from 1963-1971 is consistent with historical evidence on the role of the 1963 CAA in signaling future environmental regulation. Indeed, there is substantial historical evidence suggesting that power plants that opened in the post-1963 period were already incorporating anticipated regulatory requirements into plant design and locational decisions (see Section 2.1). This anticipatory behavior appears to have substantially mitigated the ultimate impact of subsequent impacts of nonattainment status on plant outcomes.

Robustness Checks. In Appendix Table D.2, we show that the estimated impacts of nonattainment on power plant output and PU-TFP remain statistically similar if we: (i) include utility fixed effects rather than plant fixed effects, (ii) focus on larger plants, (iii) consider only plants that primarily burn coal, (iv) drop gas-fired plants, and (v) exclude states that had set air quality standards by 1966.[35] Appendix Table D.3

[33] The negative effects on capacity reported in column 5 reflect a decrease in the rate of growth in nonattainment relative to attainment counties. Meanwhile, plant managers in nonattainment counties may actually have required additional workers whose roles were geared towards environmental compliance.

[34] Appendix Table D.1 presents estimates of the impacts of nonattainment separately for plants built between 1938-1954, 1955-1962, 1963-1966, 1967-1969 and 1970-1971. These estimates suggest that the bulk of the impacts stem from plants built before 1955, suggesting in turn that even plants built after the 1955 might have been able to partially anticipate impending environmental regulations. That being said, the estimated reduction in PU-TFP due to nonattainment for plants built between 1955-1962 is statistically significant and negative.

[35] There was great reluctance by states to set air quality standards until forced to do so by the National Ambient Air Quality Standards (NAAQS). Prior to 1960 there were no state 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

demonstrates that the findings are also robust to balancing the panel prior to estimating the specifications; thus, our results do not seem to be driven by plant entry or exit in response to nonattainment. Finally, Appendix Table D.4 provides evidence that the estimated reduction in PU-TFP due to nonattainment remain similar across a variety of different ways to estimate productivity.

Heterogeneity Analysis. Appendix Table D.5 presents estimates of the impact of nonattainment on outcomes separately for plants whose primary fuel type is coal, oil, versus natural gas. The effects are largest for natural gas, followed by coal, with no statistical effects of nonattainment on outcomes for oil-fired plants. Though gas does not emit much local pollution relative to coal or oil, burning gas can emit carbon monoxide. Moreover, natural gas was expensive during our sample period and gas-fired plants tended to be small. The FPC report of 1970 indeed states that the "[u]se of natural gas for new generating units, although desirable from a pollution standpoint, is being strongly discouraged because of the short supply"(FPC, 1972, p. xi). Therefore, utilities may have scaled down production by natural gas plants, replacing it with other sources, in response to county-level nonattainment.

Appendix Table D.6 reports estimates of the impacts of nonattainment on outcomes separately for the pollutant standards that the existing plants may experience county-level noncompliance. The table documents that the majority of the effects in our primary specifications may be driven by noncompliance with the standards associated with ambient ozone and nitrogen dioxide, which is strongly tied to ozone formation. This pattern may reflect the fact that the share of output from plants located in counties in nonattainment with these pollutants was the highest for most of our sample period, as plotted in Appendix Figure C.3.

5.2 Evidence of (Lack of) Adaptation By Existing Plants to Air Quality Standards

Do innovation and adaptation among existing plants mitigate the detrimental impacts of environmental regulation over time? The striking heterogeneity in effects *across* plants of different vintages suggests that anticipatory behavior mitigated the impact of nonattain-

total of 14 substances, and for deposited matter (Stern, 1982).

ment status among plants that opened in the post-1963 period. Nevertheless, it is unclear the extent to which existing producers – either those that opened pre- or post-1963 – were able to alter production processes and adapt to regulatory requirements imposed under the CAA. In this section, we exploit the extended lifespan of power plants to explore the evolving impacts of the CAA on existing producers.

Figure 2 (a, d) shows no evidence that existing plants adapted to environmental regulation. Estimated decreases in output and PU-TFP grow larger in size over the first 5-6 years after the county first goes into nonattainment before leveling off. Decomposing these effects across plants that opened pre-1963 (b, e) and post-1963 (c, f), we find that the long-run decreases in output and PU-TFP were driven by older vintage plants. There are no negative effects of nonattainment status on newer vintage plants in either the short, medium, or long run.

Table 2 reports the coefficient estimates from a generalized version of Equation (1), in which we allow the effects of current nonattainment status to vary according to the cumulative years of nonattainment (≤ 5, 6-10, and >10). We estimate these regressions separately for plants built prior to 1963 and those built from 1963 to 1971.

Panel A shows no evidence of adaption among older vintage power plants. Estimated losses in output and PU-TFP are substantial and persistent. For plants in counties that were out of attainment for more than 10 years, estimated output losses are 40 percent and estimate PU-TFP losses are 27 percent, substantially larger than the initial effects of nonattainment status. Although the effects of nonattainment status on inputs magnify with cumulative exposure, the decreases are not commensurate with the output declines, which explains the compounding effects on PU-TFP.

In contrast, Panel B shows no impact of nonattainment status on the operations of new vintage power plants in the short, medium, or long-run. The coefficient estimates are small and statistically insignificant.

What explains the persistent negative effects on pre-1963 plants? The initial expansion in effects may be due in part to evolving enforcement. Indeed, following a nonattainment designation, states were permitted 18-36 months to submit a State Implementation Plan (SIP) to reduce pollution levels, and state regulators typically gave plants some time to implement the compliance strategy.

The results in Table 2 show no evidence of adaptation among existing producers in response to environmental regulatory requirements. These persistent effects of the CAA regulations on firm outcomes contrast with prior research suggesting that innovation may respond to CAA regulatory pressure (e.g., Popp, 2003, 2006). Given the limited scope to adjust power plant operations and the high retrofit cost to install pollution abatement technology, however, existing plants were likely unable to take advantage of these new innovations. Instead, adaptation occurred primarily *across* producers, as newer vintage plants seemed to anticipate future regulatory requirements and took steps to mitigate their eventual impact.

5.3 The Importance of Data From Before the 1970 CAA on the Estimated Impacts on Plant Outcomes

All of the results thus far have focused on existing plants built before 1972, and have used data spanning 1938-1994. However, the vast majority of studies examining the impacts of the National Ambient Air Quality Standards (NAAQS) utilize data beginning after the enactment of the Clean Air Act (CAA) of 1970. To assess the importance of data from before 1972 for the identification of the impacts of nonattainment with the NAAQS on firm outcomes, we re-estimate our primary specifications using data on existing plants from 1972-1994 in column 2 of Table 3. For convenience, the estimated impacts of nonattainment on output and PU-TFP using the full sample are reproduced in column 1.

The difference in the estimates reported in columns 1 and 2 of Table 3 highlight the importance of having baseline data from before the implementation of the CAA. If a researcher only had access to data from after the implementation of the CAA, they would conclude that existing plants *increased* rather than decreased output and PU-TFP in response to nonattainment. Intuitively, studies using data beginning after 1972 utilize only variation from counties that alternate between attainment and nonattainment status. Nevertheless, only half of the power plants in our sample are located in counties that switch attainment status between 1972 and 1994; the remainder either always face attainment or always face nonattainment between 1972-1994. By using data from 1938-1994, we are able to capture the effect of nonattainment on outcomes using variation from plants located in counties that moved from attainment to nonattainment in 1972 but never switched back to attainment during our sample period. In fact, this might be one of the reasons why the 11% relative reduction in PU-TFP in nonattainment counties found in Table 1 is over twice as large as those found in Greenstone, List and Syverson (2012). Naturally, fossil-fuel power plants are large emitters even relative to other large, stationary point sources such as manufacturing plants, which are the focus of their study.[36] Notwithstanding, the fact that their sample period is 1972-1993 may preclude them from obtaining estimates that take into account the pre-regulation baseline.

Figure 3 plots the nonattainment effects on output and PU-TFP by first year of data in the sample, and reinforces the importance of pre-1970 data. The estimates are negative and stable if the sample starts in 1938 or any following year until approximately 1955. The effects diminish slightly if the sample begins in the late 1950s and early 1960s, and converge rapidly towards zero if it starts in the period post-1963. Given that most of the previous studies in the literature have information starting after 1963, it is likely that their estimated impacts are biased towards zero. Appendix Figure D.1 breaks these results down by plant vintage groups. Not surprisingly, the changes in the estimated nonattainment effects occur primarily for the pre-1963 plants.

One may be concerned that the difference in the magnitude of the effect when estimating the models for the sample period 1938-1994 versus 1972-1994 is driven by plants shutting down early in response to facing nonattainment. This does not seem to be the case from examining the trends in total capacity across counties that ever versus never face nonattainment between 1972-1994 (see Figure 1b). Appendix Table A.3 also provides descriptive evidence that the number of years that a plant is in operation is *positively* associated with either ever facing nonattainment between 1972-1994 or the number of years facing nonattainment between 1972-1994. The plants built before 1963 are even more strongly associated with a longer lifespan. This positive association suggests that, if anything, electric utilities are running plants built before 1972 in nonattainment counties longer to avoid having to build new fossil-fuel plants that would be subject to the stricter New Source Performance Standards regardless of the county attainment status.

We provide two additional pieces of evidence that having pre-regulation data is crucial. First, we show that the bulk of our estimated reductions in output and PU-TFP stem

[36] In 1976, for example, "the 688 large coal- and oil-fired plants in the U.S. emit nearly 60% of the total national emissions of sulfur oxides and are heavy contributors to ambient particulate loadings" (EPA, 1977, p. 12).

from existing plants that first faced nonattainment between 1972-1977. Appendix Table D.7 presents estimates of the impact of nonattainment on outcomes separately for existing plants that first faced nonattainment between 1972-1977, 1978-1983, or 1984-1994. Given that most of the effects are for 1972-1977, it would be difficult to identify the effect of nonattainment without baseline data from prior to 1972.

Second, we use a Goodman-Bacon (2018) decomposition to show that the majority of the estimated effects stem from a comparison of plants that have versus have never faced nonattainment. Appendix Table D.3 decomposes our overall difference-in-differences estimates into the three components proposed by Goodman-Bacon (2018): (i) the effect of first-nonattainment on outcomes using plants that never faced nonattainment as the control group, (ii) the effect for plants first facing nonattainment earlier in the sample using plants first facing nonattainment later in the sample as the control group, and (iii) the effect for plants first facing nonattainment later in the sample using plants first facing nonattainment earlier in the sample as the control group.[37] Previous work using data from after the implementation of the CAA relies on switches in attainment status over time, i.e., the last two categories listed above. Yet, the results of the Goodman-Bacon decomposition indicate that the majority of the estimated effects of first-nonattainment on outcomes stem from a comparison of plants that have versus have never faced nonattainment, rather than from differential timing in changes in attainment status. Approximately 7 percent of the existing plants faced nonattainment in every year between 1972-1994; the counties where they were located switched from attainment to nonattainment only once during our sample period – in the year 1972, when the CAA was implemented. On the other hand, about 35 percent of existing plants were located in counties that were always in attainment over the period 1972-1994. We can leverage the key variation generated by those counties only because we have historical data from before 1972.

When we estimate the specification using data from new plants built after 1972 in column 3 of Table 3, the effects of nonattainment on output and PU-TFP are somewhat smaller than our main estimates – and not statistically significant. This is not surprising because most, if not all, fossil-fuel power plants built after the enactment of the 1970

[37]To conform to the specification considered in Goodman-Bacon (2018), we define treatment to be the first nonattainment rather than time-varying nonattainment, and we construct a balanced panel, as discussed in the notes of Appendix Table D.3.

CAA Amendments faced technology mandates aiming at minimizing or eliminating emissions. As part of the stricter New Source Performance Standards, plants located both in attainment and nonattainment counties all had to comply with such standards to avoid air quality deterioration. Plants built after the 1977 CAA Amendments, in particular, all had to install flue gas desulfurization devices, also known as "scrubbers," which are the most costly technologies to reduce emissions.

5.4 Alternate Margins of Adjustment to the CAA

5.4.1 No Evidence of Production Spillovers from Plants in Nonattainment to Attainment Counties

It is possible that electric utilities respond to the CAA by shifting generation from plants in nonattainment counties to those operating under less stringent regulation in attainment counties. The relative decrease in output among plants in nonattainment counties may partly reflect this shift in operations (see columns 1 and 2 of Appendix Table D.2). In the short-run, however, these adjustments may be limited by existing excess generating capacity among plants in attainment counties. There was little scope for these plants to expand capacity without facing additional regulatory burden under the New Source Review.

To explore cross-county shifts in electricity generation, we assess whether the output of plants in attainment counties was affected by the nonattainment status potentially faced by nearby plants. We estimate the following equation for output Y_{it} for power plants located in counties that were always in attainment over the sample period 1938-1994:

$$log(Y_{it}) = \alpha_i + \delta_{ft} + \lambda_{vt} + \beta PropNonAttain_{st} + \epsilon_{it}, \qquad (2)$$

where i represents a plant from vintage group v, burning primary fuel f, and located in state s; as before, t indexes year-of-sample. The equation includes plant fixed effects α_i, fuel-type-by-year fixed effects δ_{ft}, and vintage-group-by-year fixed effects λ_{vt}.

We measure plant i's exposure to nonattainment, $PropNonAttain_{st}$, in three different ways. The first measure is the annual state-level proportion of fossil-fuel-fired electricity generating capacity in nonattainment counties. The second measure is the proportion of fossil-fuel-fired capacity in nonattainment counties owned by the same utility in the year. Finally, for each plant i in county c in year t, we calculate the proportion of fossil-fuel-fired capacity in nonattainment in year t among neighboring counties.

Table 4 reports the results and shows no evidence of local shifts in production towards attainment counties. If anything, the point estimates, while noisy, are consistently negative across the various measures of local exposure. The absence of cross-border spillovers in electricity generation contrasts with previous work showing large effects of nonattainment on the geographic patterns of industrial activity (Henderson, 1996; Becker and Henderson, 2000; Gibson, 2019). Our findings likely reflect the various geographic constraints facing electric utilities. First, unlike other sectors, power plants are immobile because of the interdependency with the placement of the power grid, and the well-defined service territory delineated by the state public utility commission. Second, short-run adjustments were severely constrained by the generating capacity of existing plants in attainment counties, which may have already been producing near peak load. Third, there was little scope for plants in attainment counties to expand capacity without the threat of regulatory intervention under the New Source Review.

Instead, Figure 1 and Appendix Figure C.4 suggest that an increasing share of electricity demand was met by new fossil fuel and nuclear plants built in the 1970s. In fact, Appendix Table D.8 provides suggestive evidence that new fossil fuel and nuclear power plants were more likely to be built in states with a larger annual proportion of the state's population living under nonattainment.

5.4.2 Fuel Switching and Scrubbers

Power plants may also adjust to nonattainment status by switching to "cleaner" fuels and/or adopting emission control technologies. By switching from bituminous coal with high sulfur and heat contents to sub-bituminous coal with lower sulfur and heat contents, existing coal-fired plants can reduce emissions levels. Existing plants can also respond to nonattainment by installing pollution abatement technology. Our analysis focuses on the adoption of flue gas desulfurization (FGD) units, colloquially known as "scrubbers." This technology reduces oxides of sulfur emissions by over 90 percent. Because the New Source Performance Standards (NSPS) mandates the installation of FGD units in all new plants, especially those built after the 1977 CAA Amendments, the analysis below aims at examining how nonattainment with the NAAQS and the NSPS impact the decision to install scrubbers.

Table 5 indicates that coal-fired power plants in nonattainment counties incur higher coal prices per mmBTU than plants in attainment counties. The estimates are obtained by replacing the dependent variable in Equation (1) with logged coal prices. 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 higher than Appalachian bituminous coal, both because transportation costs are typically higher from PRB to the plant and because PRB coal has a lower heat content, i.e., less heat in mmBTU per ton of coal.[38] In column 1, the sample with all coal power plants built before 1972, the increase in coal prices is of 3.5 percent. This estimated impact seems to be driven by coal plants built before 1963, as reported in column 2, although the imprecise estimate for plants built from 1963-1971 is quantitatively similar. The impact seems to increase with the cumulative number of years of exposure to nonattainment, as reported in column 3, corroborating the lack of adaptation to environmental regulation discussed in subsection 5.2.

To examine the installation of scrubbers, we estimate the following equation using all plants over our entire sample period 1938-1994:

$$\begin{aligned} 1[IS_i \leq t] = \delta_{ft} + \theta_{st} + \gamma 1[FirstNonAttain_c \leq t] \\ +\beta_1 1[Existing\_Prior1963_i] + \beta_2 1[Existing\_1963\_1971_i] \\ +\delta_1(1[FirstNonAttain_c \leq t] \times 1[Existing\_Prior1963_i]) \\ +\delta_2(1[FirstNonAttain_c \leq t] \times 1[Existing\_1963\_1971_i]) + \epsilon_{it}, \end{aligned} \quad (3)$$

where i indexes plant burning fuel f located in county c of state s; as before, t indexes year. The variable IS_i is equal to the year that the plant first installed a scrubber, and

[38] As mentioned by the 1968 FPC report, "[w]hile domestic reserves of coal containing one percent sulfur are large, they are mostly located in the west, and are not economically available for supplying eastern power plants. East the Mississippi River, the limited supplies of low-sulfur coal have good coking qualities and electric utilities must compete at relatively high prices with metallurgical industries and export markets for such supplies" (FPC, 1969, pp. ix-x). Ultimately, "[t]he cost of reducing oxides of sulfur emissions—through the use of higher cost 'cleaner' fuels (...)—is having a decided effect on the competitive position of coal (...) for electric power generation" (FPC, 1969, p. x).

the dependent variable $1[IS_i \leq t]$ is an indicator variable equal to one if the plant i first installed a scrubber prior to year t. The variable $FirstNonAttain_c$ is equal to the first year that county c went out of attainment with the NAAQS; if county c never went out of attainment during our sample period, the indicator variable $1[FirstNonAttain_c \leq t]$ is always equal to zero. The indicator variable $1[Existing\_Prior1963]_{it}$ is equal to one if plant i was built before 1963; similarly, the indicator variable $1[Existing\_1963\_1971]_{it}$ is equal to one plant i was built from 1963-1971. The omitted category is new plants – those built after 1972. Consequently, this specification estimates the impact of first-nonattainment on FGD adoption separately for existing plants built before 1963 and existing plants built from 1963-1971 relative to new plants built after 1972. We include fuel-type-by-year fixed effects and state-by-year fixed effects.[39] Finally, as in our main analysis, standard errors are two-way clustered by county and year.

Table 6 documents that existing plants are less likely to install scrubbers than new plants. Columns 1 and 3 consider all plants while columns 2 and 4 consider only plants that primarily burn coal. Scrubbers remove sulfur oxides from gases released due to the burning of fossil fuels. Thus, we hypothesize that the results are most pronounced for coal-fired plants because burning coal emits far more sulfur oxides than burning either fuel oil or natural gas. Columns 1 and 2 reveal that existing plants are less likely to install scrubbers than new plants, without meaningful differences regarding when they were built. In particular, the estimates presented in Column 2 indicate that existing coal-fired plants in attainment counties are about 30 percent less likely to install scrubbers than new coal-fired plants. This is likely because only new plants are subject to the stricter NSPS. Indeed, as alluded to above, plants built after 1978 were obligated to install a scrubber, irrespective of whether they were built in attainment or nonattainment counties. Existing plants, on the other hand, may only be forced to face NSPS if they make "significant upgrades," which can include installing a scrubber. Thus, existing plants may forgo installing FGD units in order to avoid the need to comply with the stricter NSPS. They might only consider scrubbers as the last resort to comply with the NAAQS.

Columns 2 and 4 of Table 6 indicate that coal plants built between 1963 and 1971 may have made some adjustments in anticipation of the impending regulations. In column

[39] We do not include plant fixed effects because we want to estimate the impact of being built before versus after 1972 on the decision to install pollution abatement technology.

2, the interaction coefficient on *First NA* x *Built Before 1963* suggests that these plants may have had no other less costly way to comply with air quality standards. In contrast, the interaction coefficient on *First NA* x *Built From 1963-1971* is smaller and statistically insignificant, indicating that they may have made some adjustments in anticipation of the impending regulations, avoiding the need to install scrubbers later on. The differences between plants built before 1963 and from 1963 to 1971 remain when coal plants built after 1972 are dropped from the analysis in column 4.

6 Aggregate Effects of the 1970 CAA on PU-TFP

In this section, we explore the national-level effects of the National Ambient Air Quality Standards (NAAQS) on pollution-unadjusted total factor productivity (PU-TFP) in the power sector. In any year t, we can calculate average PU-TFP across U.S. power plants as a simple output-weighted average:

$$\overline{PU\text{-}TFP}_t = \frac{\sum_i output_{it} \cdot \text{PU-TFP}_{it}}{\sum_i output_{it}}$$

we calculate the difference between output-weighted PU-TFP with versus without the 1970 CAA in each year between 1972-1994 using our estimates to construct the counterfactual levels of PU-TFP and output that would have prevailed if the NAAQS wasn't implemented. We denote the counterfactual PU-TFP and output for plant i in year t PU-TFP^C and Output^C respectively. To calculate counterfactual PU-TFP and output, we increase observed output and PU-TFP for plants built before 1963 in nonattainment counties using the estimates from Table 2. We do not adjust observed PU-TFP and output levels for plants built between 1963-1971 given that: (1) the effects listed in Table 2 are small and not statistically significant for plants built between 1963-1971, and (2) Table 4 suggests that output does not shift from existing plants in nonattainment counties to plants in attainment counties. We also do not adjust PU-TFP in the counterfactual for plants built after 1972 because the estimate from column 3 of Table 3 suggests that the impact of nonattainment on PU-TFP for these plants is very small. That being said, we adjust the output levels for plants built after 1972 down in the counterfactual based on the simplifying assumption that output from post 1972 plants increased to compensate for output reductions from pre-1963 plants in nonattainment counties.[40,41]

Our back-of-the-envelope calculation of the impact of the NAAQS on aggregate productivity is based on the following equation:

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

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 respectively with the NAAQS versus without the NAAQS. Equation (4) shows that the NAAQS can affect national productivity via two channels. The first channel, $\frac{\text{Output}_{i,t}}{\sum_i \text{Output}_{i,t}} \cdot \Delta\text{PU-TFP}_{it}$, is a *within-plant efficiency* effect: existing plants in nonattainment counties may have lower productivity due to increased regulatory requirements. The second channel, $\sum_i \Delta s\_output_{it} \cdot PU\text{-}TFP_{it}$, is a *cross-plant reallocative effect*, which arises from regulatory-induced shifts in output from older plants in nonattainment to newer plants.

Figure 4 plots the annual changes with versus without the NAAQS in output-weighted PU-TFP, within-plant efficiency, and across-plant reallocation. This figure documents that the NAAQS led to an annual average national decline in PU-TFP of 6 percent over the period 1972-1994. This corresponds to annual productivity losses of \$3.5 billion in 2020 dollars.[42] Although sizeable, this economic cost is substantially smaller than the health benefits from improved air quality attributable to the CAA (Currie and Walker, 2019; Aldy et al., Forthcoming). Moreover, the estimated productivity losses appear to diminish with time, falling to less than 5 percent in the latter half of the sample period.

The aggregate impact of the NAAQS on PU-TFP in Figure 4 is the result of two offsetting effects. The dashed red line shows the negative *within-plant efficiency* effect over the post-1972 period. The magnitude of these aggregate productivity losses increase until 1979 but decrease thereafter. These nonuniform trends reflect several competing

[40]Appendix Table D.8 provides suggestive evidence in favor of this assumption.

[41]We assume that, under the NAAQS, reductions in output by pre-1963 plants in nonattainment counties in each year were reallocated proportionally to power plants that opened after 1972 in the same census division.

[42]We obtain this aggregate cost estimate by multiplying the PU-TFP effect by the total revenue earned by steam electric utilities in 1970 (Federal Power Commission, 1971).

forces. On the one hand, the productivity losses should magnify because: (1) more counties fall out of attainment over the post-1972 period, and (2) the estimated impacts on PU-TFP increase with number of years in nonattainment. On the other hand, as older plants in nonattainment counties reduce output over time, their contribution to national PU-TFP diminishes.

The dotted blue line shows the positive *cross-plant reallocation* effect over the post-1972 period. The CAA induced plants built before 1963 in nonattainment counties to gradually reallocate production to newer plants that opened in the post-1972 period. Since these newer plants were typically more efficient (see Appendix Figures A.7 and C.7), this reallocation contributed to an increase in average national PU-TFP in the power sector. This effect becomes larger over our sample period as pre-1963 plants reduced their output further. That being said, the cross-plant reallocation never becomes larger enough to fully offset the within-plant losses.

Together, our results demonstrate how reallocation across producers can substantially mitigate the aggregate economic costs of environmental regulation. Although our analysis focuses on the power sector, these patterns may carry over to a wide array of sectors and industries. To the extent that pollution is often concentrated among older and less efficient entrenched incumbents, 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 economic impacts of the 1970 Clean Air Act (CAA) on firm behavior. The long panel allows for a benchmark period without regulation, and for anticipatory responses by electric utilities. We find that the CAA caused relatively large reductions in output and pollution-unadjusted total factor productivity. These effects were concentrated among plants that opened before 1963, when there was little scope to anticipate future regulatory requirements. In contrast, we find no negative effects on plants that opened in the post-1963 period. These results indicate that firms may be able to acquire information during the process leading up to the passage of a landmark legislation, and preemptively take actions to reduce the costs of regulatory compliance.

We also find no evidence that the impacts of nonattainment status for older plants diminished with time. These results suggest that the long-run economic impacts of environmental regulation are likely to be offset primarily through industry churn as opposed to *within-producer* adaptation and innovation. Newer entrants were able to incorporate pre-emptive investments in plant design and choose locations strategically. Hence, they may have incurred limited economic costs from subsequent environmental enforcement.[43]

Our findings highlight key political economy challenges for environmental regulation. As emphasized by Stigler (1971), governments are able to create rents, and regulation often generates winners and losers. To the extent that entrenched incumbent producers bear the economic costs of regulatory compliance and have disproportionate political influence, environmental policy may be enacted slowly and carve out exemptions for certain emitters (Stavins, 2006; Revesz and Lienke, 2016).

The aggregate economic costs of the Clean Air Act borne by the electricity supply sector are small in comparison to the health gains associated with improved air quality. Nevertheless, these costs are unevenly distributed across plants, and ultimately incurred by local residents through higher prices in certain utility service areas. The historical U.S. experience highlights the challenge for environmental policy design in developing countries, where policymakers often must balance the need to curb extreme levels of air pollution with the objective of promoting widespread access to affordable energy services.

[43]Other efforts to reduce the impacts of government oversight may include industry self-regulation (DeMarzo, Fishman and Hagerty, 2005; Charoenwong, Kwan and Umar, 2019), lobbying and grandfathering (Stavins, 2006; Kang, 2016), and strategic and tactical actions that affect the regulation effectiveness (Lim and Yurukoglu, 2018; Abito, 2019).

References

Abito, Jose Miguel. 2019. "Measuring the Welfare Gains from Optimal Incentive Regulation." *Review of Economic Studies*, 87(5): 2019–2048.

ACIR, U.S. Advisory Commission on Intergovernmental Relations. 1981. "The Federal Role in the Federal System: The Dynamics of Growth." Protecting the Environment: Politics, Pollution, and Federal Policy: Washington, DC: U.S. Advisory Commission on Intergovernmental Relations.

Ackerberg, Daniel A., Kevin Caves, and Garth Frazer. 2015. "Identification Properties of Recent Production Function Estimators." *Econometrica*, 83(6): 2411–2451.

Aldy, Joseph E., Maximilian Auffhammer, Maureen L. Cropper, Arthur G. Fraas, and Richard Morgenstern. Forthcoming. "Looking Back at Fifty Years of the Clean Air Act." *Journal of Economic Literature*.

Atkinson, Scott E., and Robert Halvorsen. 1976. "Interfuel Substitution in Steam Electric Power Generation." *Journal of Political Economy*, 84(5): 959–978.

Barzel, Yoram. 1963. "Productivity in the Electric Power Industry, 1929–1955." *Review of Economics and Statistics*, 45(4): 395–408.

Becker, Randy, and Vernon Henderson. 2000. "Effects of Air Quality Regulations on Polluting Industries." *Journal of Political Economy*, 108(2): 379–421.

Bleakley, Hoyt, and Jeffrey Lin. 2012. " Portage and Path Dependence ." *Quarterly Journal of Economics*, 127(2): 587–644.

Boisvert, Richard N. 1982. "The Translog Production Function: Its Properties, Its Several Interpretations and Estimation Problems." *Mimeo.*

Cameron, Colin A., Jonah B. Gelbach, and Douglas L. Miller. 2011. "Robust inference with multiway clustering." *Journal of Business & Economic Statistics*, 29(2): 238–249.

Carlson, Curtis, Dallas Burtraw, Maureen Cropper, and Karen L. Palmer. 2000. "Sulfur Dioxide Control by Electric Utilities: What Are the Gains from Trade?" *Journal of Political Economy*, 108(6): 1292–1326.

Charoenwong, Ben, Alan Kwan, and Tarik Umar. 2019. "Does Regulatory Jurisdiction Affect the Quality of Investment-Adviser Regulation?" *American Economic Review*, 109(10): 3681–3712.

Christensen, Laurits R., and William H. Greene. 1976. "Economies of Scale in U.S. Electric Power Generation." *Journal of Political Economy*, 84(4, Part 1): 655–676.

Clay, Karen. 2018. "The Environment in American Economic History." *The Oxford Handbook of American Economic History, vol. 2*, 349.

Currie, Janet, and W. Reed Walker. 2019. "What Do Economists Have to Say about the Clean Air Act 50 Years after the Establishment of the Environmental Protection Agency?" *Journal of Economic Perspectives*, 33(4): 3–26.

Curtis, E. Mark. 2018. "Who Loses under Cap-and-Trade Programs? The Labor Market Effects of the NOx Budget Trading Program." *Review of Economics and Statistics*, 100(1): 151–166.

De Loecker, Jan. 2011. "Product Differentiation, Multi-Product Firms and Estimating the Impact of Trade Liberalization on Productivity." *Econometrica*, 79(5): 1407–1451.

DeMarzo, Peter M., Michael J. Fishman, and Kathleen M. Hagerty. 2005. "Self-Regulation and Government Oversight." *Review of Economic Studies*, 72(3): 687–706.

EIA, Energy Information Administration. 1992. "Electric Plant Cost and Power Production Expenses 1990." Washington, DC: U.S. Department of Energy.

EIA, Energy Information Administration. 2021. "Monthly Energy Review – February 2021." Washington, DC: U.S. Department of Energy.

EPA, U.S. Environmental Protection Agency. 1973. "Progress in the Prevention and Control of Air Pollution in 1972: Annual Report of the Administrator of the Environmental Protection Agency to the Congress of the United States." Washington, DC: U.S. Environmental Protection Agency.

EPA, U.S. Environmental Protection Agency. 1975. "EPA Enforcement: Two Years of Progress, December 1972 to November 1974 – Air, Water, and Pesticides." Washington, DC: U.S. Environmental Protection Agency.

EPA, U.S. Environmental Protection Agency. 1976*a*. "EPA Enforcement: A Progress Report, December 1974 to December 1975 – Air, Noise, Pesticides, and Water." Washington, DC: U.S. Environmental Protection Agency.

EPA, U.S. Environmental Protection Agency. 1976*b*. "Summary of Particulate and Sulfur Oxide Emission Reductions Achieved Nationwide for Selected Industrial Categories, 1970-1974." Washington, DC: U.S. Environmental Protection Agency, Office of General Enforcement.

EPA, U.S. Environmental Protection Agency. 1976*c*. "Tall Stacks and the Atmospheric Environment." Research Triangle Park, NC: U.S. Environmental Protection Agency, Office of Air and Waste Management – Office of Air Quality Planning and Standards (EPA-450/3-76-007).

EPA, U.S. Environmental Protection Agency. 1977. "EPA Enforcement: A Progress Report, 1976 – Air, Noise, Water, and Pesticides." Washington, DC: U.S. Environmental Protection Agency.

EPA, U.S. Environmental Protection Agency. 1984. "Project Summary Utility FGD Survey: October 1983 - September 1984." Washington, DC: U.S. Environmental Protection Agency, Office of Air Quality Planning and Standards (EPA-340/1-85-014).

Fabrizio, Kira R., Nancy L. Rose, and Catherine D. Wolfram. 2007. "Do Markets Reduce Costs? Assessing the Impact of Regulatory Restructuring on US Electric Generation Efficiency." *American Economic Review*, 97(4): 1250–1277.

Ferris, Ann E., Ronald J. Shadbegian, and Ann Wolverton. 2014. "The Effect of Environmental Regulation on Power Sector Employment: Phase I of the Title IV SO2 Trading Program." *Journal of the Association of Environmental and Resource Economists*, 1(4): 521–553.

Foster, Lucia, John Haltiwanger, and Chad Syverson. 2008. "Reallocation, Firm Turnover, and Efficiency: Selection on Productivity or Profitability?" *American Economic Review*, 98(1): 394–425.

FPC, Federal Power Commission. 1966. "Steam-Electric Plant Construction Cost and Annual Production Expenses: 1965." Washington, DC: U.S. Government Printing Office.

FPC, Federal Power Commission. 1967. "Steam-Electric Plant Construction Cost and Annual Production Expenses: 1966." Washington, DC: U.S. Government Printing Office.

FPC, Federal Power Commission. 1969. "Steam-Electric Plant Construction Cost and Annual Production Expenses: 1968." Washington, DC: U.S. Government Printing Office.

FPC, Federal Power Commission. 1972. "Steam-Electric Plant Construction Cost and Annual Production Expenses: 1970." Washington, DC: U.S. Government Printing Office.

GAO, U.S. Government Accountability Office. 1980. "TVA's Clean Air Settlement with EPA (EMD-80-49)." Washington, DC: U.S. Government Accountability Office, Energy and Minerals Division.

Gibson, Matthew. 2019. "Regulation-Induced Pollution Substitution." *Review of Economics and Statistics*, 101(5): 827–840.

Gollop, Frank M., and Mark J. Roberts. 1983. "Environmental regulations and productivity growth: The case of fossil-fueled electric power generation." *Journal of Political Economy*, 91(4): 654–674.

Gollop, Frank M., and Mark J. Roberts. 1985. "Cost-Minimizing Regulation of Sulfur Emissions: Regional Gains in Electric Power." *Review of Economics and Statistics*, 67(1): 81–90.

Goodman-Bacon, Andrew. 2018. "Difference-in-differences with variation in treatment timing." National Bureau of Economic Research.

Gray, Wayne B, and Ronald J Shadbegian. 2003. "Plant vintage, technology, and environmental regulation." *Journal of Environmental Economics and Management*, 46(3): 384–402.

Greenstone, Michael. 2002. "The Impacts of Environmental Regulations on Industrial Activity: Evidence from the 1970 and 1977 Clean Air Act Amendments and the Census of Manufacturers." *Journal of Political Economy*, 110(6): 1175–1219.

Greenstone, Michael, John A. List, and Chad Syverson. 2012. "The Effects of Environmental Regulation on the Competitiveness of U.S. Manufacturing." *NBER Working Paper No. 18392.*

Henderson, J. Vernon. 1996. "Effects of Air Quality Regulation." *American Economic Review*, 86(4): 789–813.

Hornbeck, Richard. 2012. "The Enduring Impact of the American Dust Bowl: Short- and Long-Run Adjustments to Environmental Catastrophe." *American Economic Review*, 102(4): 1477–1507.

Hornbeck, Richard, and Daniel Keniston. 2017. "Creative Destruction: Barriers to Urban Growth and the Great Boston Fire of 1872." *American Economic Review*, 107(6): 1365–98.

Hornbeck, Richard, and Martin Rotemberg. 2019. "Railroads, Reallocation, and the Rise of American Manufacturing." *NBER Working Paper #26594.*

Hsieh, Chang-Tai, and Peter J. Klenow. 2009. "Misallocation and Manufacturing TFP in China and India." *Quarterly Journal of Economics*, 124(4): 1403–1448.

Joskow, Paul L., and Nancy L. Rose. 1985. "The Effects of Technological Change, Experience, and Environmental Regulation on the Construction Cost of Coal-Burning Generating Units." *RAND Journal of Economics*, 16(1): 1–27.

Kahn, Matthew E., and Erin T. Mansur. 2013. "Do Local Energy Prices and Regulation Affect the Geographic Concentration of Employment?" *Journal of Public Economics*, 101: 105–114.

Kang, Karam. 2016. "Policy Influence and Private Returns from Lobbying in the Energy Sector." *Review of Economic Studies*, 83(1): 269–305.

Keiser, David A., and Joseph S. Shapiro. 2019*a*. "Consequences of the Clean Water Act and the Demand for Water Quality." *Quarterly Journal of Economics*, 134(1): 349–396.

Keiser, David A., and Joseph S. Shapiro. 2019*b*. "US Water Pollution Regulation over the Past Half Century: Burning Waters to Crystal Springs?" *Journal of Economic Perspectives*, 33(4): 51–75.

Keohane, Nathaniel O., Erin T. Mansur, and Andrey Voynov. 2009. "Averting Regulatory Enforcement: Evidence from New Source Review." *Journal of Economics & Management Strategy*, 18(1): 75–104.

Kline, Patrick, and Enrico Moretti. 2014. "Local Economic Development, Agglomeration Economies, and the Big Push: 100 Years of Evidence from the Tennessee Valley Authority." *Quarterly Journal of Economics*, 129(1): 275–331.

Lim, Claire S. H., and Ali Yurukoglu. 2018. "Dynamic Natural Monopoly Regulation: Time Inconsistency, Moral Hazard, and Political Environments, journal = Journal of Political Economy." 126(1): 263–312.

List, John A., Daniel L. Millimet, and Warren McHone. 2004. "The Unintended Disincentive in the Clean Air Act." *Advances in Economic Analysis & Policy*, 4(2): Article 2.

Malani, Anup, and Julian Reif. 2015. "Interpreting pre-trends as anticipation: Impact on estimated treatment effects from tort reform." *Journal of Public Economics*, 124: 1–17.

Muller, Nicholas Z. 2014. "Boosting GDP Growth by Accounting for the Environment." *Science*, 345(6199): 873–874.

Muller, Nicholas Z. 2019. "Long-Run Environmental Accounting in the US Economy." *Environmental and Energy Policy and the Economy, Volume 1*, 158–191. University of Chicago Press.

Muller, Nicholas Z., Robert Mendelsohn, and William Nordhaus. 2011. "Environmental Accounting for Pollution in the United States Economy." *American Economic Review*, 101(5): 1649–75.

Nelson, Randy A., and Mark E. Wohar. 1983. "Regulation, Scale Economies, and Productivity in Steam-Electric Generation." *International Economic Review*, 24(1): 57–79.

Nelson, Randy A., Tom Tietenberg, and Michael R. Donihue. 1993. "Differential Environmental Regulation: Effects on Electric Utility Capital Turnover and Emissions." *Review of Economics and Statistics*, 75(2): 368–373.

Nerlove, Marc. 1963. "Returns to Scale in Electricity Supply." In *Measurement in Economics – Studies in Mathematical Economics and Econometrics in Memory of Yehuda Grunfeld*, ed. Carl F. Christ. Stanford, CA:Stanford University Press.

Popp, David. 2003. "Pollution Control Innovations and the Clean Air Act of 1990." *Journal of Policy Analysis and Management*, 22(4): 641–660.

Popp, David. 2006. "International innovation and diffusion of air pollution control technologies: the effects of NOX and SO2 regulation in the US, Japan, and Germany." *Journal of Environmental Economics and Management*, 51(1): 46–71.

Revesz, Richard L., and Jack Lienke. 2016. *Struggling for Air: Power Plants and the "War on Coal"*. New York, NY: Oxford University Press.

Roberts, Marc J, and Susan O Farrell. 1978. "The political economy of implementation: The Clean Air Act and stationary sources." *Approaches to controlling air pollution*, 152: 156–60.

Ryan, Stephen P. 2012. "The Costs of Environmental Regulation in a Concentrated Industry." *Econometrica*, 80(3): 1019–1061.

Sheriff, Glenn, Ann E. Ferris, and Ronald J. Shadbegian. 2019. "How Did Air Quality Standards Affect Employment at US Power Plants? The Importance of Timing, Geography, and Stringency." *Journal of the Association of Environmental and Resource Economists*, 6(1): 111–149.

Solow, Robert M. 1957. "Technical Change and the Aggregate Production Function." *Review of Economics and Statistics*, 39(3): 312–320.

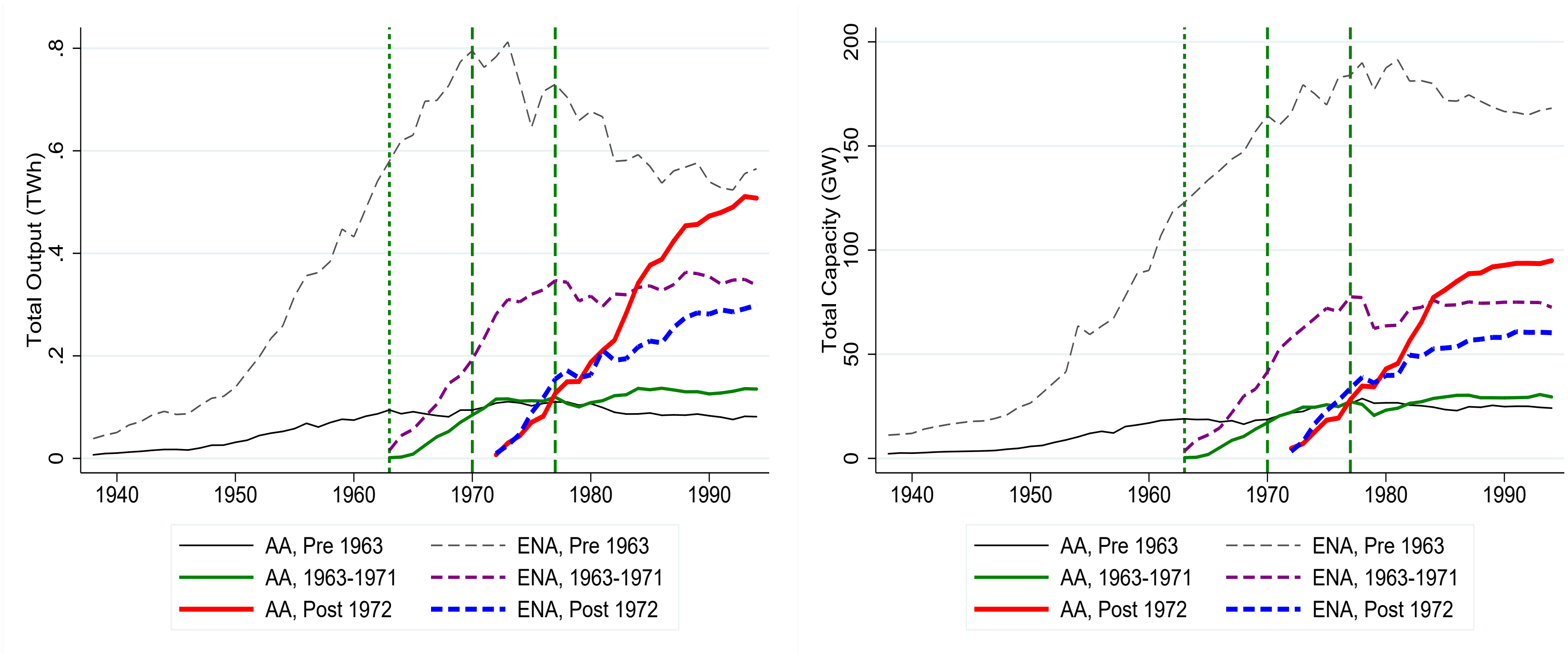
Stavins, Robert N. 2006. "Vintage-Differentiated Environmental Regulation." *Stanford Environmental Law Journal*, 25(1): 29–63.

Stern, Arthur C. 1982. "History of Air Pollution Legislation in the United States." *Journal of the Air Pollution Control Association*, 32(1): 44–61.

Stigler, George J. 1971. "The Theory of Economic Regulation." *The Bell Journal of Economics and Management Science*, 2(1): 3–21.

Figures and Tables

Figure 1: Annual Total Electricity Generation and Capacity from Fossil-Fuel Power Plants By Vintage and Attainment Status

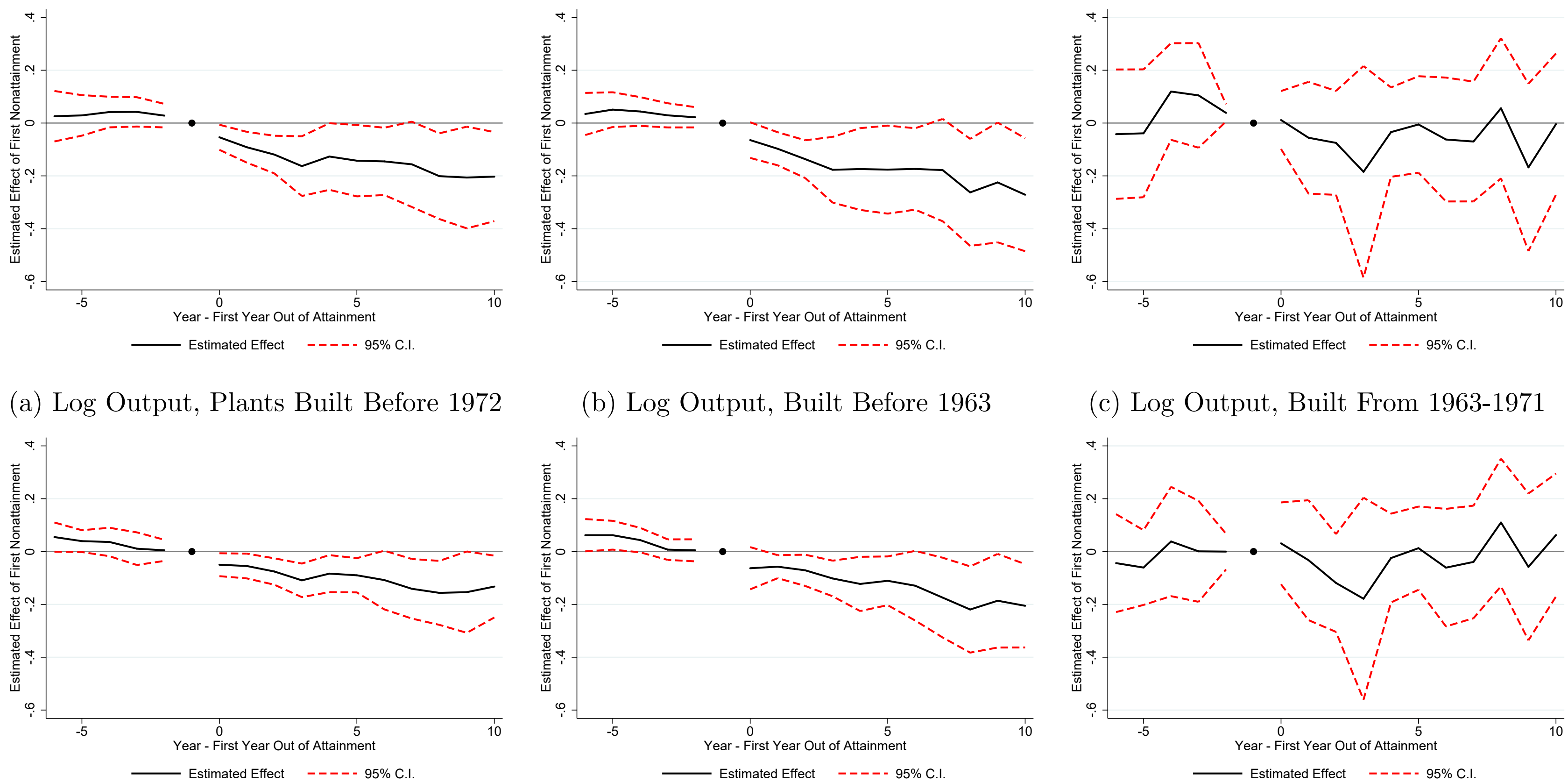


(a) Total Output

(b) Total Capacity

Notes: This figure documents annual total electricity generation produced by fossil-fuel-fired plants in the United States. 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 over that period of analysis. 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 2: Event Study Analysis of the Impacts of First Year in Nonattainment on Power Plant Outcomes

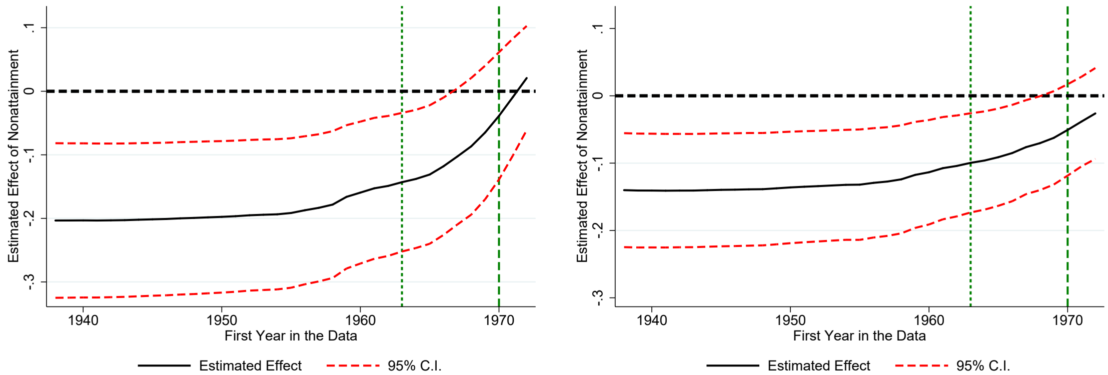


(a) Log Output, Plants Built Before 1972 (b) Log Output, Built Before 1963 (c) Log Output, Built From 1963-1971

(d) Log PU-TFP, Plants Built Before 1972 (e) Log PU-TFP, Built Before 1963 (f) Log PU-TFP, Built From 1963-1971

Notes: This event study figure plots the estimated effect of first nonattainment on log output and 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, state-by-year fixed effects, fuel-type-by-year fixed effects, and vintage-by-group fixed effects; plants built before 1963 are in vintage group 1 while plants built between 1963-1971 are in vintage group 2. The 95% confidence intervals reported in these figures are based on standard errors that are two-way clustered by county and year. The two leftmost panels are estimated using plants built before 1972, the middle two panels consider plants built before 1963, and the rightmost two panels focus on plants built between 1963-1971.

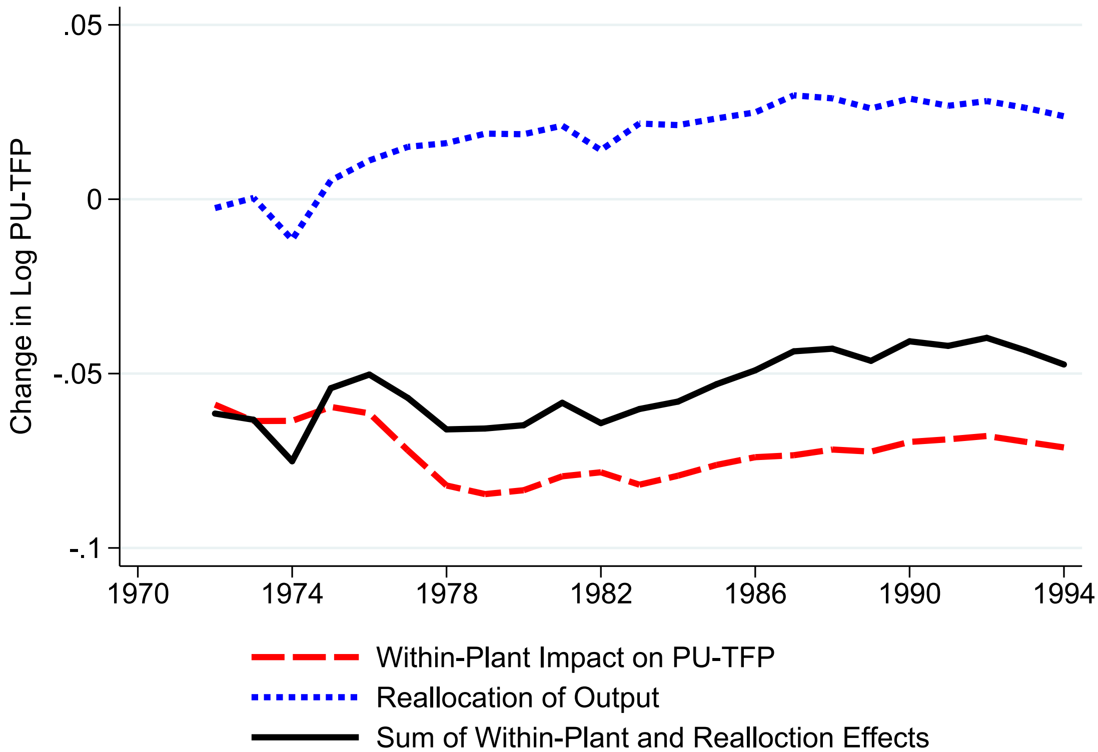
Figure 3: Impacts of Nonattainment on Plant Operations by Initial Sample Year



(a) Estimated Effects on Log Output (b) Estimated Effects on Log PU-TFP

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

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



Notes: This figure depicts the estimated nationwide effects of the 1970 CAA on power plant productivity based on the methodology described in Section 6. The aggregate impact of the CAA on pollution-unadjusted total factor productivity (PU-TFP), represented by the solid black line, is a result of two offsetting effects. The long-dashed red line shows the negative *within-plant efficiency effect* over the post-1972 period, which reflects the fact that pre-1963 "existing" plants in nonattainment counties may have lower productivity due to increased regulatory requirements (see Table 2, Panel A, column 2). The short-dashed blue line shows the positive *cross-plant reallocative effect* over the post-1972 period, which arises from regulatory-induced shifts in output across plants with different productivity levels (see Appendix Table D.8). Some of the reductions in output of existing plants may have been shifted to post-1972 "new" plants, which were usually more productive (see Appendix Figures A.7 and C.7).

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

Dep. Var. (in Logs):	(1) Output	(2) PU-TFP	(3) Fuel Use	(4) No. Employees	(5) Capacity
Panel A. Average Effects					
Nonattainment	-0.203***	-0.140***	-0.115*	-0.033	-0.102**
	(0.062)	(0.043)	(0.058)	(0.031)	(0.039)
R^2	0.819	0.616	0.751	0.864	0.914
Panel B. Effects by Plant Vintage					
NA × 1[Before 1963]	-0.230***	-0.163***	-0.138**	-0.033	-0.119***
	(0.069)	(0.050)	(0.065)	(0.035)	(0.044)
NA × 1[1963-1971]	-0.063	-0.019	0.012	-0.030	-0.015
	(0.089)	(0.070)	(0.085)	(0.055)	(0.049)
R^2	0.819	0.616	0.751	0.864	0.914
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 By Year FE	Y	Y	Y	Y	Y
Mean Dep. Var.	6.736	-0.621	9.168	4.498	5.474
Number of Obs.	22,134	22,134	22,134	22,134	22,134
Number of Plants	686	686	686	686	686

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 plants that were built before 1972. Panel A estimates how annual plant-level outcomes change with the annual 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 from 1963-1971. For all specifications, "nonattainment" is defined as the county being out of attainment with the NAAQS for any pollutant in the year. 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. PU-TFP stands for pollution-unadjusted total factor productivity, and NA for nonattainment. Standard errors in parentheses are two-way clustered by county and year. *** denotes statistical significance at the 1% level, ** at the 5% level, and * at the 10% level.

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

	(1)	(2)	(3)	(4)	(5)
Dep. Var. (in Logs):	Output	PU-TFP	Fuel Use	No. Employees	Capacity
Panel A. Effects for Plants Built Before 1963					
Years in NA ≤ 5	-0.100	-0.141***	0.003	0.068	-0.030
	(0.084)	(0.051)	(0.082)	(0.044)	(0.054)
Years in NA $\in [6, 10]$	-0.248**	-0.221***	-0.030	0.013	-0.127*
	(0.118)	(0.079)	(0.113)	(0.057)	(0.066)
Years in NA > 10	-0.370**	-0.285***	-0.212	0.010	-0.243***
	(0.140)	(0.095)	(0.133)	(0.076)	(0.085)
R^2	0.799	0.614	0.724	0.858	0.903
Mean of Dep. Var.	6.608	-0.665	9.053	4.491	5.357
Number of Obs.	19,063	19,063	19,063	19,063	19,063
Number of Plants	559	559	559	559	559
Panel B. Effects for Plants Built From 1963-1971					
Years in NA ≤ 5	-0.066	0.018	-0.041	-0.048	-0.044
	(0.122)	(0.097)	(0.102)	(0.071)	(0.061)
Years in NA $\in [6, 10]$	-0.025	0.109	0.013	-0.075	-0.080
	(0.129)	(0.099)	(0.122)	(0.088)	(0.077)
Years in NA > 10	-0.116	0.032	-0.012	-0.106	-0.037
	(0.174)	(0.144)	(0.162)	(0.114)	(0.094)
R^2	0.903	0.679	0.890	0.929	0.961
Mean of Dep. Var.	7.596	-0.345	9.960	4.591	6.259
Number of Obs.	2,714	2,714	2,714	2,714	2,714
Number of Plants	121	121	121	121	121
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 By Year FE	Y	Y	Y	Y	Y

Notes: This table report 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 plants built before 1963 in the top panel while the bottom panel considers plants built between 1963-1971. 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. PU-TFP stands for pollution-unadjusted total factor productivity, and NA for nonattainment. Standard errors in parentheses are two-way clustered by county and year. *** denotes statistical significance at the 1% level, ** at the 5% level, and * at the 10% level.

Table 3: Comparison of Estimates for Existing and New Plants
Using Sample Periods 1938-1994 versus 1972-1994

	(1)	(2)	(3)
Panel A. Effects of Nonattainment on Log Output			
Nonattainment	-0.203***	0.021	-0.042
	(0.062)	(0.042)	(0.110)
R^2	0.819	0.891	0.950
Mean of Dep. Var.	6.736	7.050	7.650
Panel B. Effects of Nonattainment on Log PU-TFP			
Nonattainment	-0.140***	-0.026	-0.010
	(0.043)	(0.034)	(0.079)
R^2	0.616	0.717	0.825
Mean of Dep. Var.	-0.621	-0.736	-0.509
Number of Obs.	22,134	10,584	2,221
Number of Plants	686	580	185
Plant FE	Y	Y	Y
State By Year FE	Y	Y	Y
Fuel Type By Year FE	Y	Y	Y
Vintage By Year FE	Y	Y	Y
Type of Plant	Existing	Existing	New
Sample Period	1938-1994	1972-1994	1972-1994

Notes: This table reports the estimated impacts of nonattainment on the outcomes of existing and new plants over alternative periods of analysis. Panel A reports the impact of nonattainment on the log of output while Panel B reports the impact on the log of pollution-unadjusted total factor productivity (PU-TFP). The unit of observation for the regressions in this table is plant-year. For all specifications, "nonattainment" is defined as the county being out of attainment with the NAAQS for any pollutant in the year. Column 1 of both panels is estimated for the sample period 1938-1994 considering all "existing" plants built before 1972. Column 2 of both panels is estimated for the sample period 1972-1994 focusing on all "existing" plants. Column 3 of both panels is estimated for the sample period 1972-1994 focusing on all "new" plants built after 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, plants built between 1963-1971 are in vintage group 2, and plants built after 1972 are in vintage group 3. Standard errors in parentheses are two-way clustered by county and year. *** denotes statistical significance at the 1% level, ** at the 5% level, and * at the 10% level.

Table 4: Impact of Nonattainment on Log Output: Spillovers

Dep. Var.: Log Output	(1) Cap-Weighted	(2) Utility-Level	(3) Adjacency
Spillover Nonattainment	0.039	0.032	-0.204
	(0.255)	(0.276)	(0.193)
R^2	0.826	0.830	0.820
Mean of Dep. Var.	6.049	6.107	6.014
Number of Obs.	5,437	5,087	5,598
Number of Plants	231	227	232
Plant FE	Y	Y	Y
Fuel Type By Year FE	Y	Y	Y
Vintage Group By Year FE	Y	Y	Y

Notes: This table reports estimates testing whether the output of plants in attainment counties varies with measures of annual county-level nonattainment in nearby counties. The unit of observation for all regressions is plant-year, considering only 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 in Column 1 is the proportion of fossil-fuel-fired electricity generating capacity in nonattainment counties in the state in the year. In Column 2, we consider the proportion of fossil-fuel-fired capacity in nonattainment counties owned by the same utility in the year. Finally, Column 3 focuses on the proportion of fossil-fuel-fired capacity in nonattainment counties adjacent to the county in the year. All specifications include plant 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 two-way clustered by county and year. *** denotes statistical significance at the 1% level, ** at the 5% level, and * at the 10% level.

Table 5: Impact of Nonattainment on Log Coal Prices

Dep. Var.: Log Coal Price	(1)	(2)	(3)
Nonattainment	0.029		
	(0.018)		
NA × 1[Before 1963]		0.025	
		(0.020)	
NA × 1[1963-1971]		0.051	
		(0.038)	
Years in NA ≤ 5			0.047**
			(0.020)
Years in NA $\in$ [6,10]			0.054*
			(0.029)
Years in NA >10			0.121***
			(0.038)
R^2	0.719	0.719	0.719
Mean of Dep. Var.	-0.789	-0.789	-0.789
Number of Obs.	11,160	11,160	11,160
Number of Plants	342	342	342
Plant FE	Y	Y	Y
State By Year FE	Y	Y	Y
Fuel Type By Year FE	Y	Y	Y
Vintage Group By Year FE	Y	Y	Y

Notes: This table presents the estimated impact of nonttainment on the log of coal prices. The unit of observation for the regressions in this table are plant-year, focusing only on plants built before 1972 and considering only years in which the plant purchased coal. 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. In Column 2, we interact nonattainment with two indicators denoting whether the plant was built before 1963 versus built between 1963-1971. In Column 3, we consider nonattainment interacted with three indicators denoting whether the cumulative number of years up to the year-of-sample that plant has faced nonattainment was less than 5 years, between 6-10 years, or more than 10 years. Standard errors in parentheses are two-way clustered by county and year. *** denotes statistical significance at the 1% level, ** at the 5% level, and * at the 10% level. The unit of observation for these regressions is a plant-year.

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

Dep. Var: 1[FGD]	(1)	(2)	(3)	(4)
1[1963-1971]	0.025	0.033	0.016	0.037
	(0.017)	(0.029)	(0.016)	(0.028)
1[After 1972]	0.254***	0.302***		
	(0.050)	(0.060)		
First NA	0.032**	0.055**	0.019	0.055***
	(0.015)	(0.025)	(0.012)	(0.020)
First NA × 1[1963-1971]	-0.043	-0.091**	-0.035	-0.103**
	(0.026)	(0.042)	(0.025)	(0.041)
First NA × 1[After 1972]	-0.153**	-0.208***		
	(0.059)	(0.074)		
R^2	0.373	0.446	0.264	0.307
Mean of Dep. Var.	0.050	0.087	0.023	0.035
Number of Obs.	25,107	14,295	22,134	12,123
Number of Plants	899	504	686	346
State By Year FE	Y	Y	Y	Y
Fuel Type By Year FE	Y	Y	Y	Y
Vintage Group By Year FE	Y	Y	Y	Y
Fuel Type	All	Coal	All	Coal
Includes Plants Built After 1972	Y	Y	N	N

Notes: This table presents regression results measuring whether the installation of flue gas desulfurization (FGD) technology is impacted by attainment status. The unit of observation for these regressions is a plant-year. For all specifications, "nonattainment" is defined as the county being out of attainment with the NAAQS for any pollutant in the year. The dependent variable is an indicator variable that is equal to one if the plant has at least one FGD system installed in the year. Columns 1 and 3 consider all plants while Columns 2 and 4 consider only plants that primarily burn coal. All specifications include state-by-year fixed effects, fuel-type-by-year fixed effects, and vintage group by year; plants built before 1963 are in vintage group 1, plants built between 1963-1971 are in vintage group 2, and plants built after 1972 are in vintage group 3. Standard errors in parentheses are two-way clustered by county and year. *** denotes statistical significance at the 1% level, ** at the 5% level, and * at the 10% level.

Online Appendix (Not For Publication)

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

Karen Clay, Akshaya Jha,

Joshua Lewis, and Edson Severnini[*]

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

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

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

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

A.1 Additional Background Figures and Tables

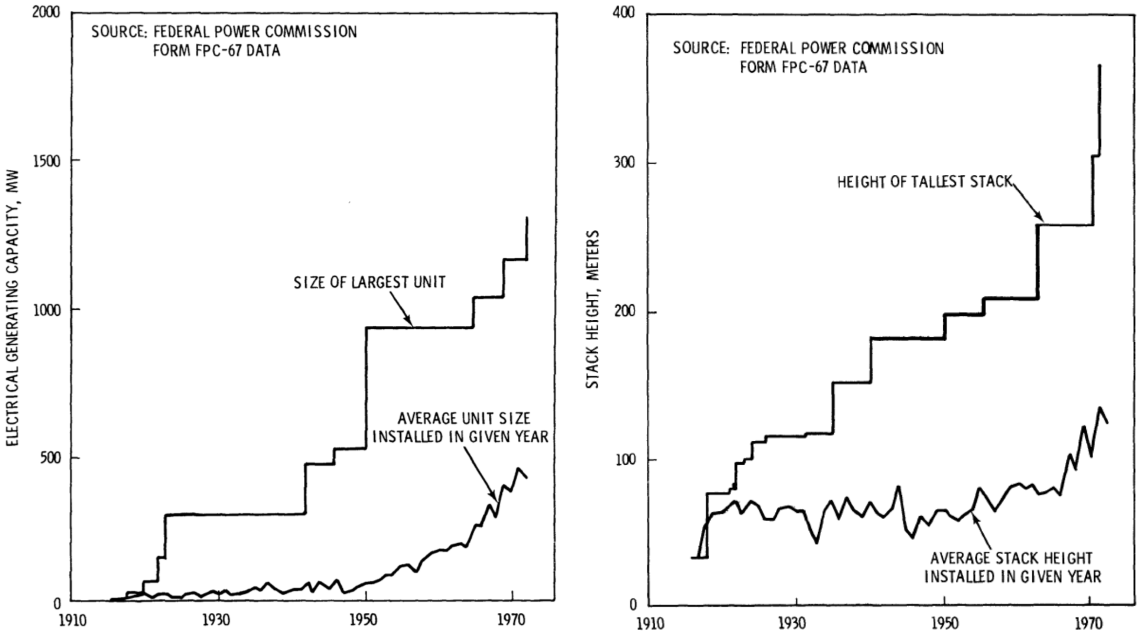
The figures and tables in this appendix subsection provide information on a variety of actions taken by the electric utilities aimed at reducing pollution concentration around power plant sites. Appendix Figure A.1 shows the power plants were becoming larger after 1950, and installing taller and taller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

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

A.2 Tennessee Valley Authority: An Example

To illustrate the variety of strategies used by electric utilities to reduce emissions, we present the case of the ten coal-fired power plants from the Tennessee Valley Authority (TVA). Those plants were built before 1972, but only complied with the CAA regulations after TVA and EPA reached a settlement in 1979-80 (GAO, 1980). Appendix Table A.2 shows that many plants ended up switching to a cleaner fuel: either medium or low sulfur coal. Several plants combined that strategy with coal washing, electrostatic precipitators, baghouses, and scrubbers. The U.S. Government Accountability Office (GAO)'s estimated that the total cost of the consent decree over the life span of the projects was substantial: over $14 billion (2019 USD). Capital costs comprised 14% of that amount, operating and maintenance costs 30%, and the incremental fuel costs 56%.

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

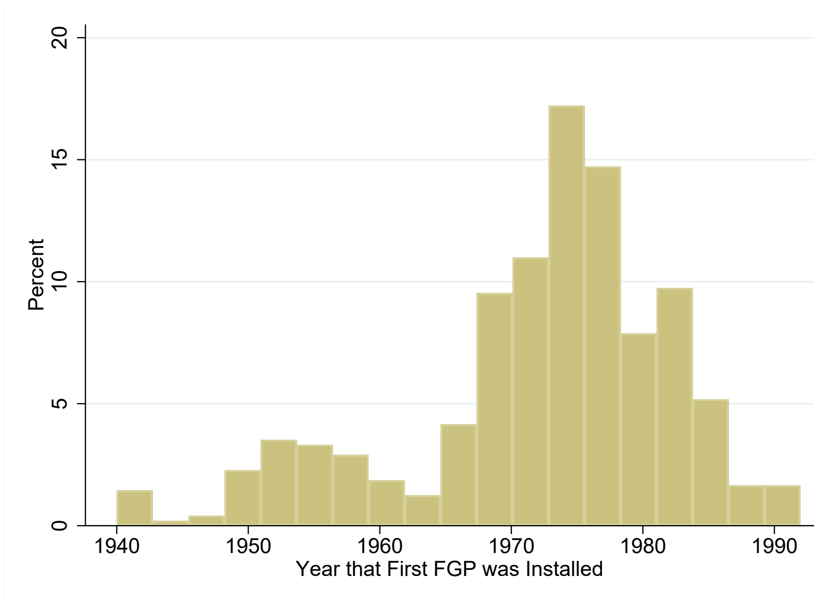


(a) Trends in Plant Size

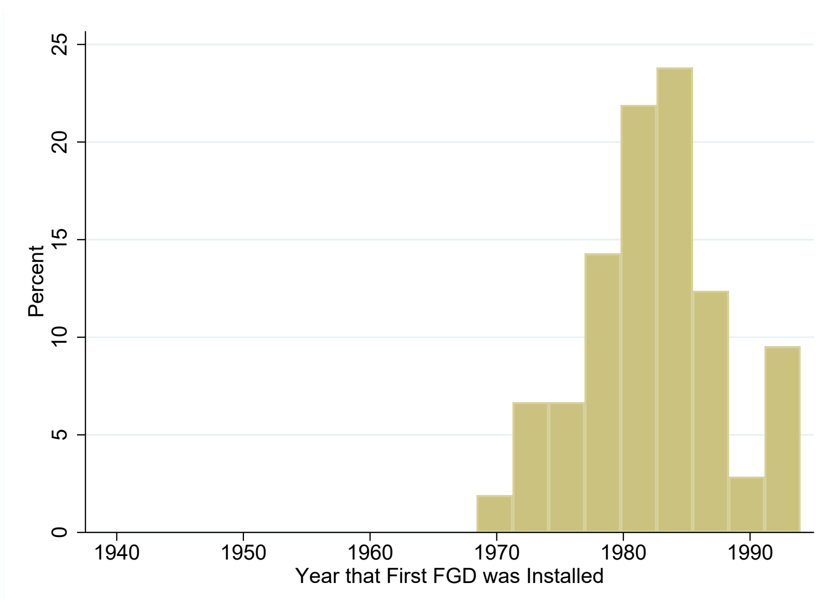
(b) Trends in Smokestack Height

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

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



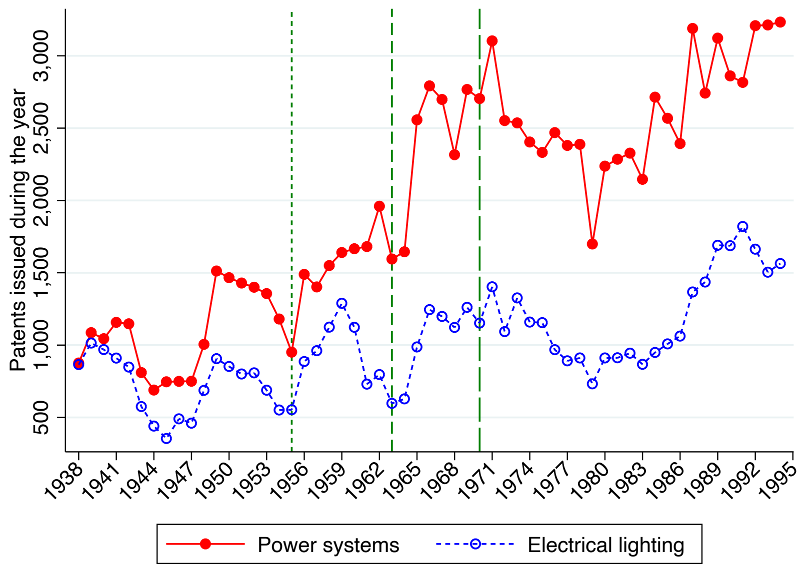
(a) FGP Adoption



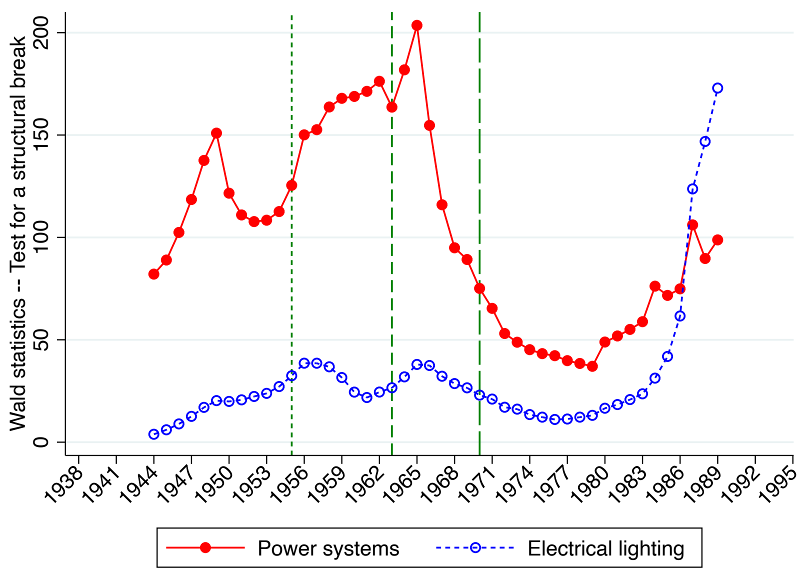
(b) FGD Adoption

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

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



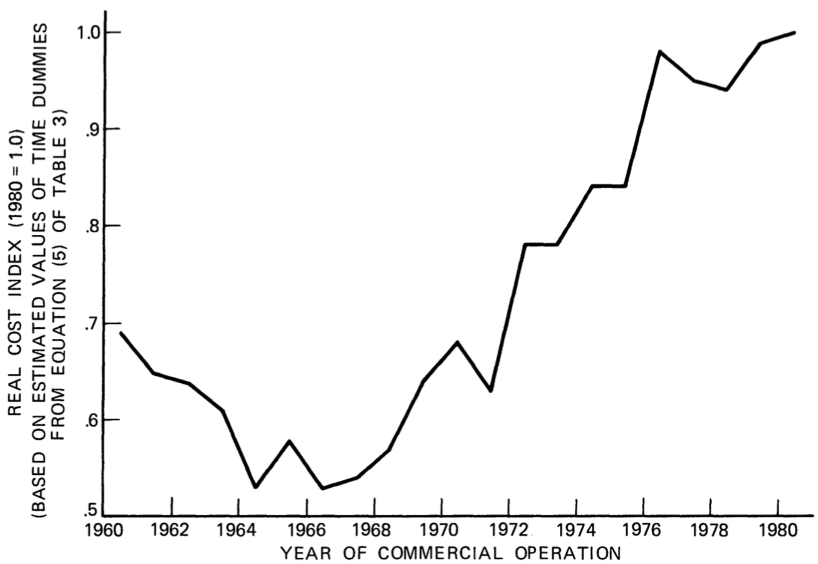
(a) Trends in the Number of Issued Patents



(b) Wald Statistics for Tests of Unknown Structural Break

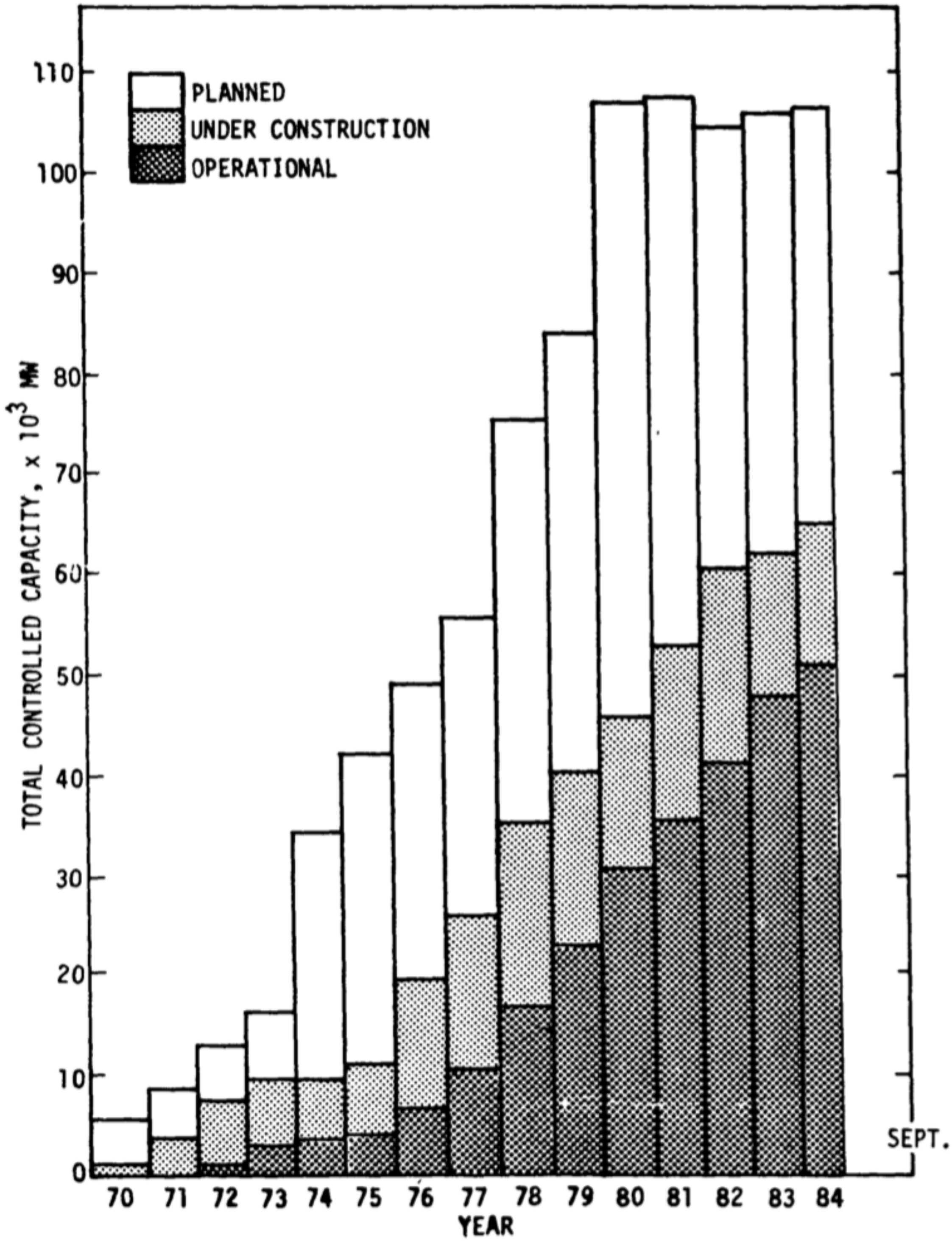
Notes: This figure displays trends in patents for categories related to electricity. Panel (a) plots the number of patents issued per year for two broad categories: (i) "power systems," which includes power plants, electrical generator, and single generator systems, and (ii) "electrical lighting," which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

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



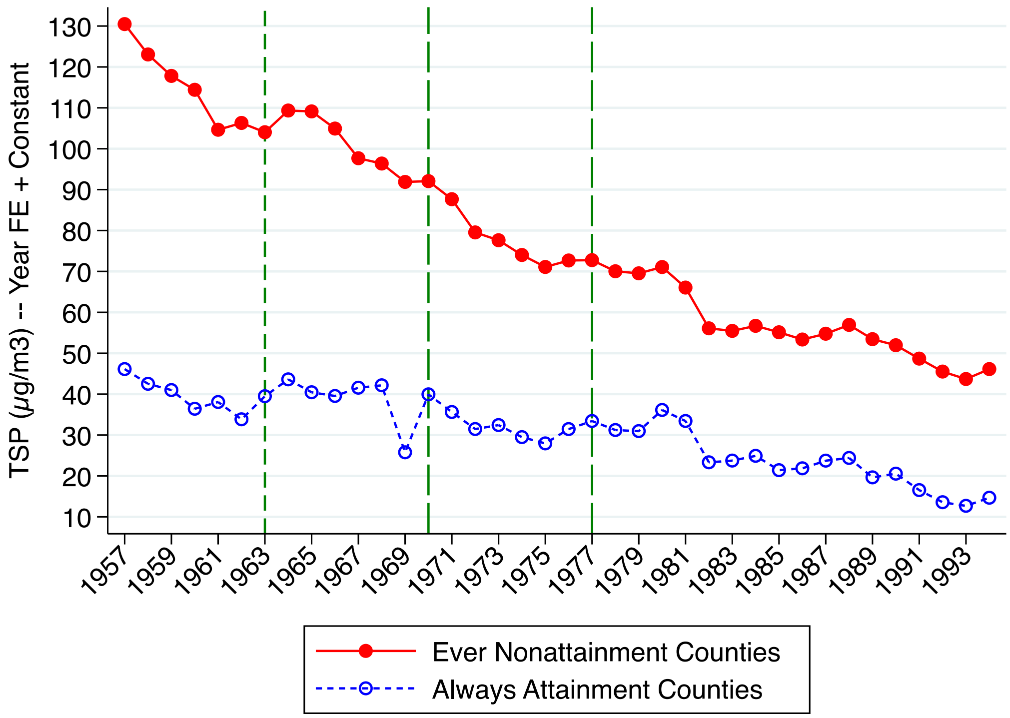
Notes: This figure reproduces Figure 2 from Joskow and Rose (1985). It plots the index of real costs per kilowatt of installed capacity associated with the construction of coal-burning electricity generating units. Notice that it declines during the early 1960s, stabilizes in the mid 1960s, and then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

Figure A.5: Trends in Scrubber Adoption



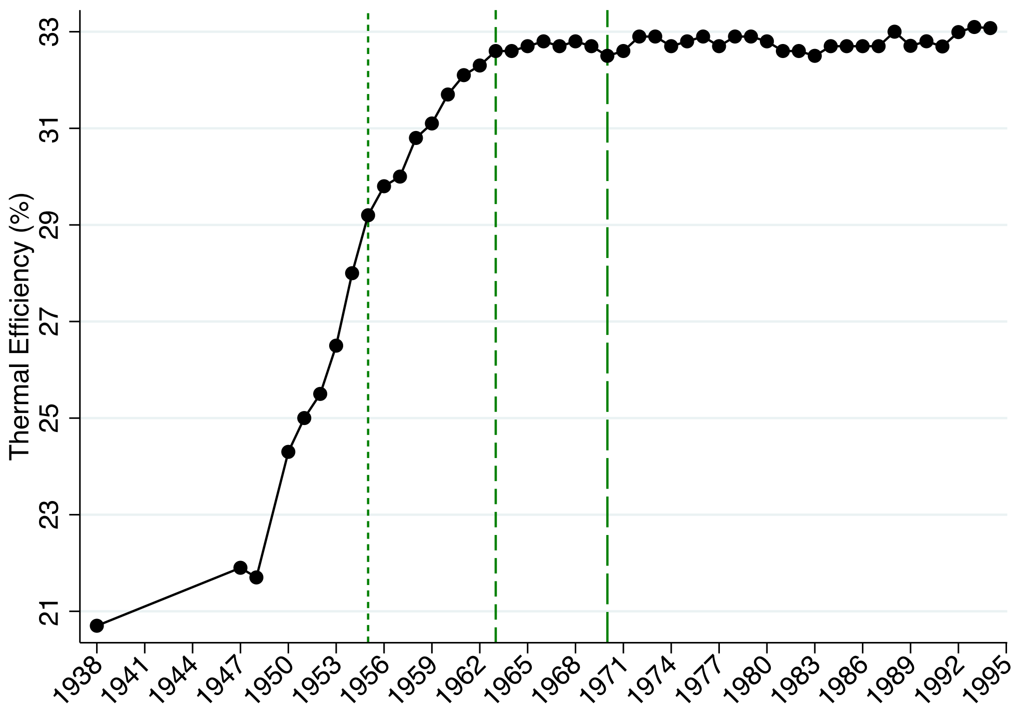
Notes: This figure presents a historical breakdown of utility status reports for operational, under construction, and planned flue gas desulfurization (FGD) capacity – December 1970 through September 1984. *Source*: Figure 2, EPA (1984).

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



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

Figure A.7: Trends in Power Plant Thermal Efficiency



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

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

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

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

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

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

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

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

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

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

B Details on the Conceptual Framework

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

B.1 Two-Period Cost Minimization Problem

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

The plant's pollution "production function" is

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

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

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

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

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

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

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

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

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

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

C Data Construction and Data Description

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

C.1 Data Construction

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

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

These are the titles of the FPC reports:

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

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

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

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

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

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

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

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

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

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

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

C.2 Estimation of Total Factor Productivity

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

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

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

C.3 Additional Descriptive Figures and Tables

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

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

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

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

CHANGES OR ADDITIONS IN 1957

TURBO - GENERATOR CHARACTERISTICS

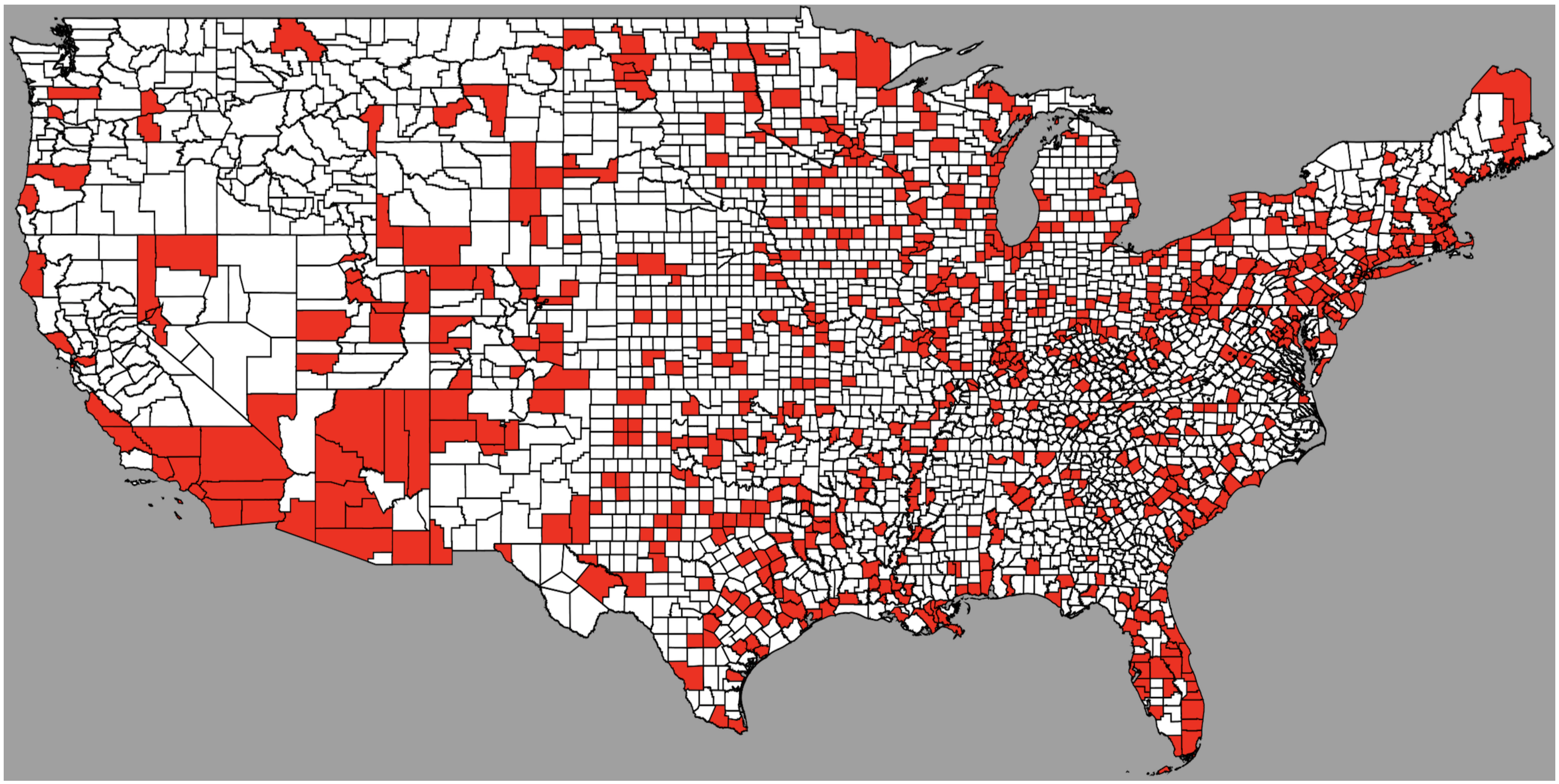
Units	MW	P.F.	P.S.I.	R.P.M.	Kv.	Year
1	156.2	85	2,000 (Added	3,600 - March,	18.0 1957)	1957

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.

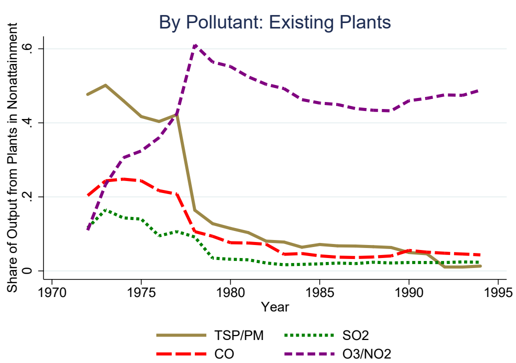
Figure C.2: Map of Counties with Fossil-Fuel-Fired Power Plants in Our Sample



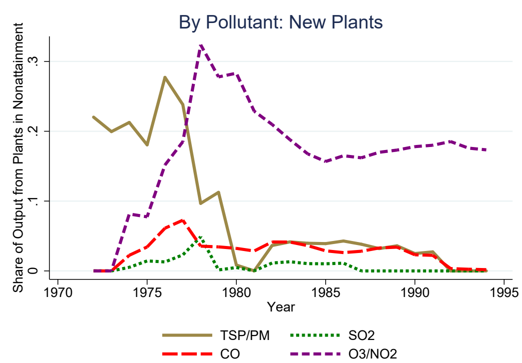
Notes: This figure displays which counties had fossil-fuel power plants at any point during our period of analysis 1938-1994. The counties shaded in red were home to at least one fossil-fuel plant in our sample. There were no power plants in any year of our sample in the counties shaded in white.

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

(a) Share of Electricity Generation in Nonattainment Counties



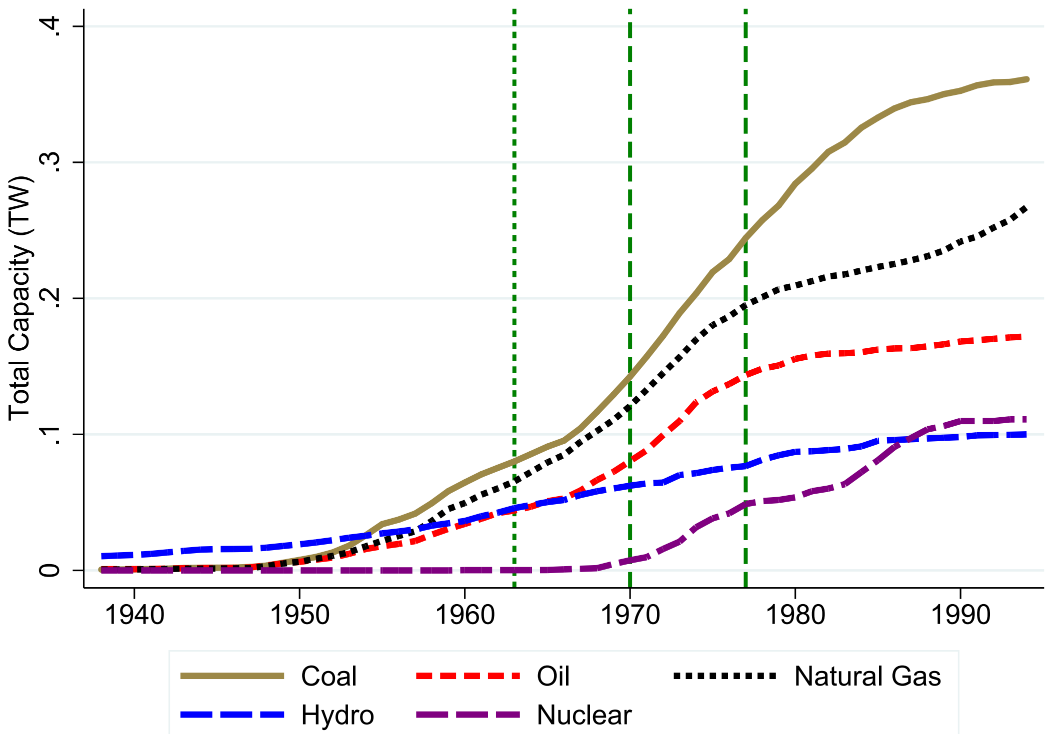
(b) Share of Generation in Nonattainment by Pollutant – Existing Plants



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

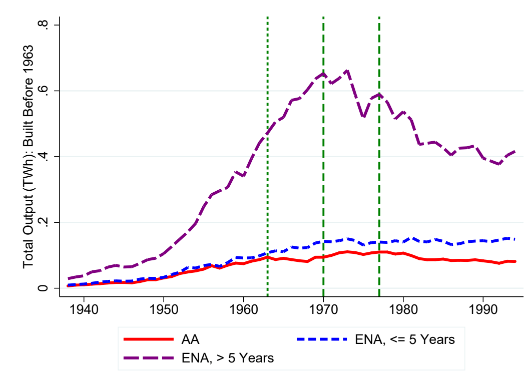
Notes: The top panel of this figure documents the aggregate proportion of electricity production from plants in counties out of attainment with NAAQS for any pollutant for the sample period 1972-1994. The bottom panels document the aggregate proportion of electricity production from "existing" (pre-1972)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

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

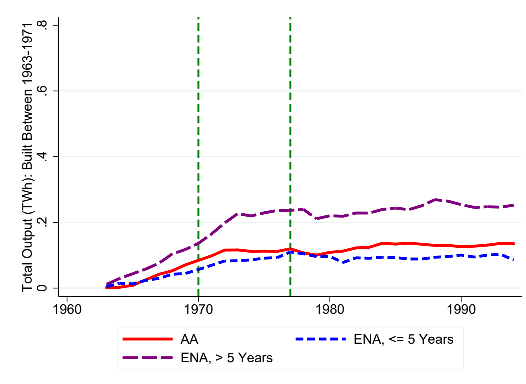


Notes: This figure documents annual national total electricity production capacity by fuel type. The data underlying this figure come from the EIA Form 767. The thin dashed vertical green line represents the Clean Air Act of 1963 while the thicker green vertical lines represent the 1970 Clean Air Act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

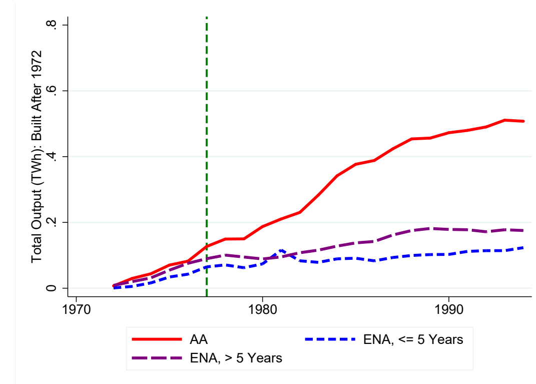
Figure C.5: Annual Total Electricity Generation and Capacity from Fossil-Fuel Power Plants by Vintage and Years in Nonattainment



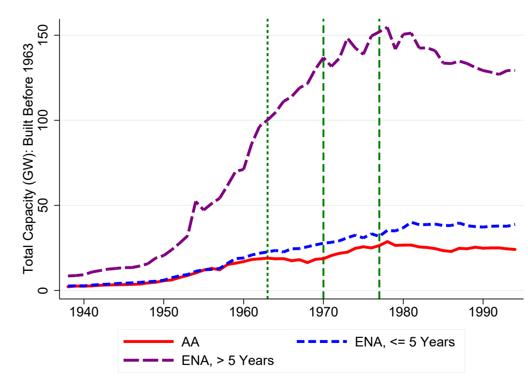
(a) Generation – Pre-1963 Plants



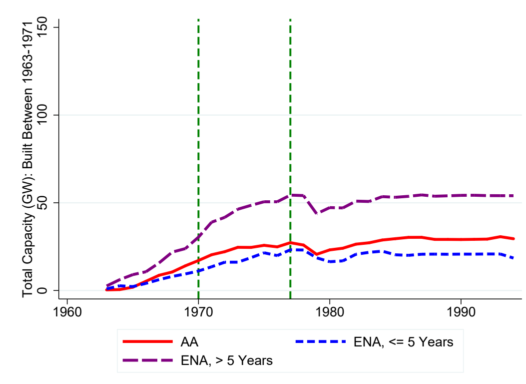
(b) Generation – 1963-1971 Plants



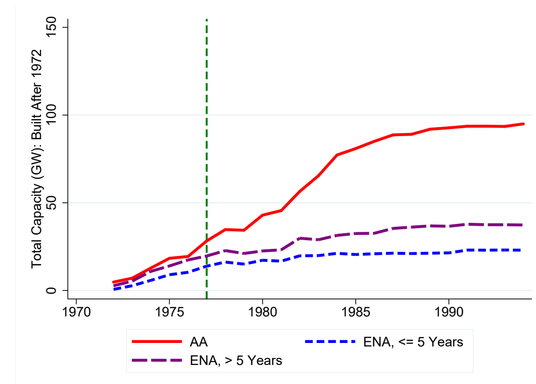
(c) Generation – Post-1972 Plants



(d) Capacity – Pre-1963 Plants



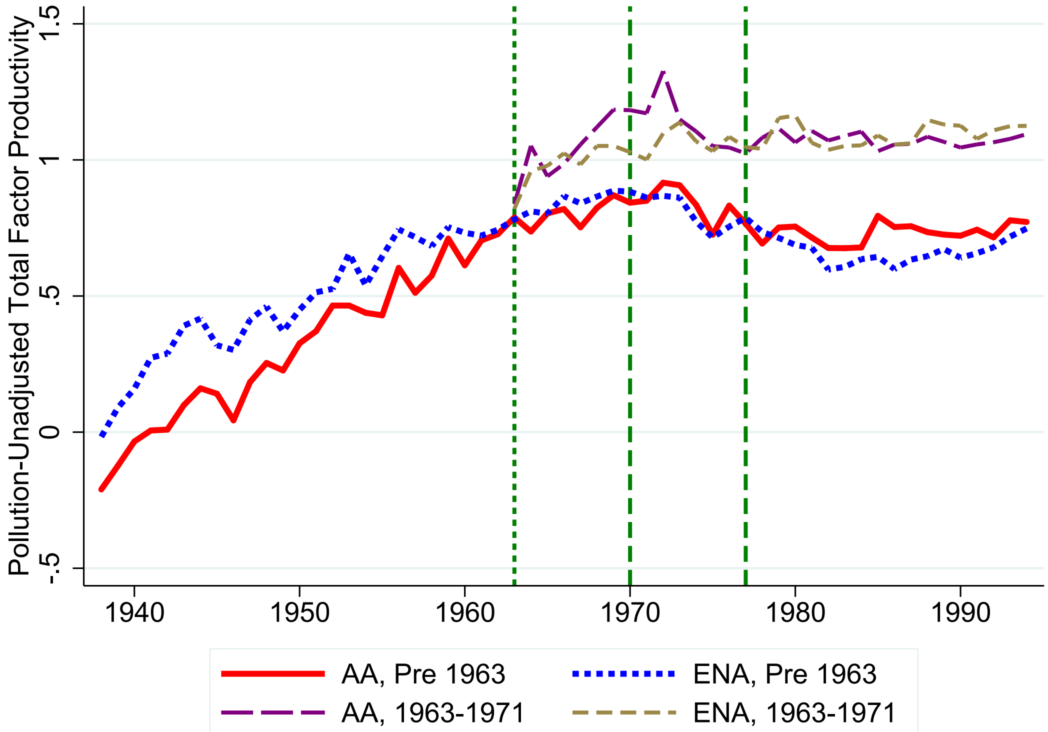
(e) Capacity – 1963-1971 Plants



(f) Capacity – Post-1972 Plants

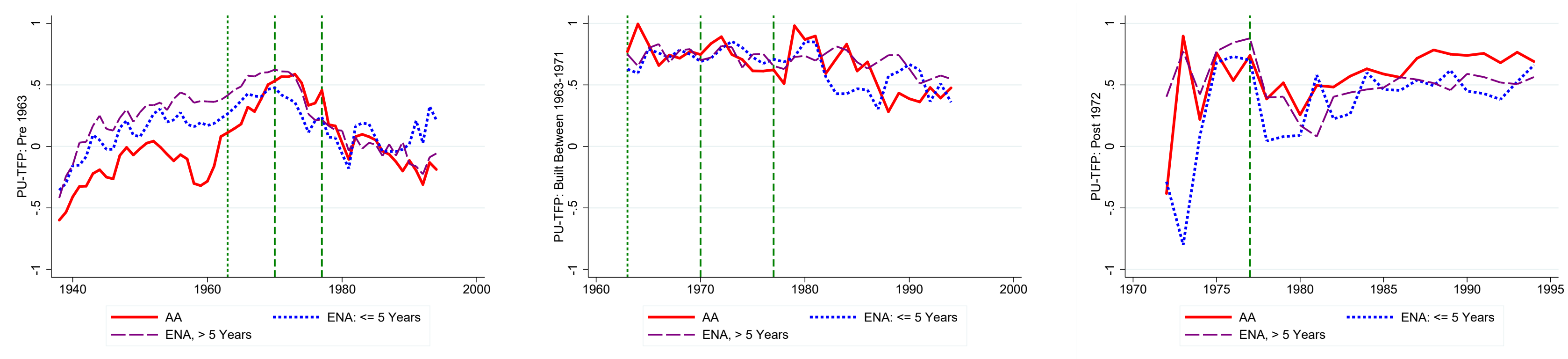
Notes: This figure documents annual total electricity generation and electricity-generating capacity by fossil-fuel-fired plants in the United States. We consider three vintage categories: plants built before 1963, 1963-1971, and post-1972. We consider three regulatory status categories: "always-attainment"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

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



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

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



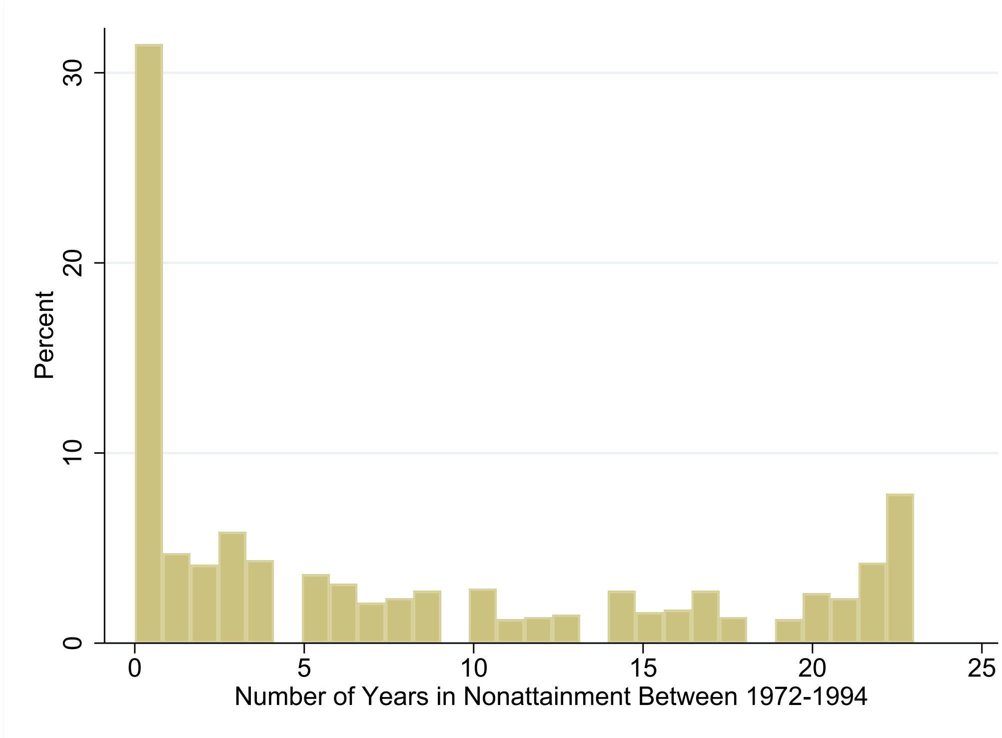
(a) PU-TFP – Pre-1963 Plants

(b) PU-TFP – 1963-1971 Plants

(c) PU-TFP – Post-1972 Plants

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

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



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

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

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

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

Table C.2: Attainment Status versus Lagged Attainment Status

Panel A. Number of Observations From 1972-1994		
	Attainment in Year t	Nonattainment in Year t
Attainment in Year *t-1*	6,594	615
Nonattainment in Year *t-1*	348	5,455
Panel B. Conditional Probability		
	Attainment in Year t	Nonattainment in Year t
Attainment in Year *t-1*	0.91	0.09
Nonattainment in Year *t-1*	0.06	0.94

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

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

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

Notes: This table presents summary statistics for our difference-in-differences regressions relating NAAQS attainment status and different plant-level outcome variables. We estimate plant-year level PU-TFP based on a translog production function with capital (the plant's capacity), labor (average number of employees), and fuel (the heat input in billions of BTU of fuel burned) using the estimation procedure developed by Ackerberg, Caves and Frazer (2015).

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

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

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

D Additional Results

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

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

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

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

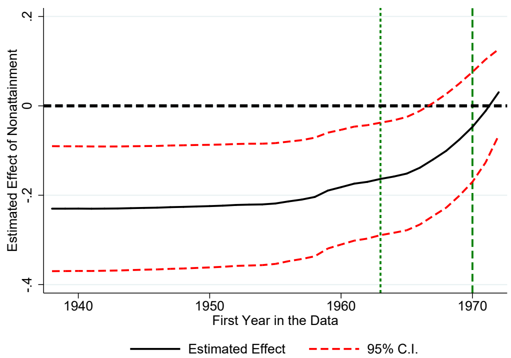
Appendix Table D.7 reports heterogeneous impacts of nonattainment by the first year a county is in nonattainment, shedding light on which transitions to nonattainment matter the most for the main findings. Appendix Table D.8 examines how statewide electricity generating capacity by fuel type responds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

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

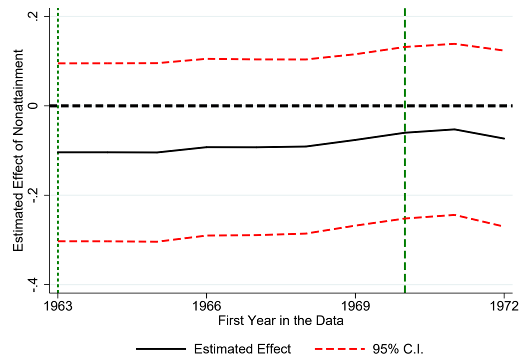
- Figure D.1. Impacts of Nonattainment on Power Plant Outcomes by Vintage and Initial Sample Year

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

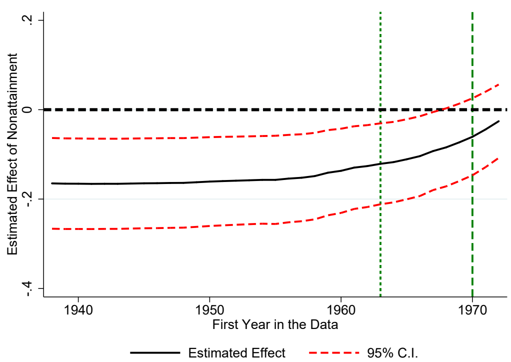
Figure D.1: Impacts of Nonattainment on Power Plant Outcomes by Vintage and Initial Sample Year



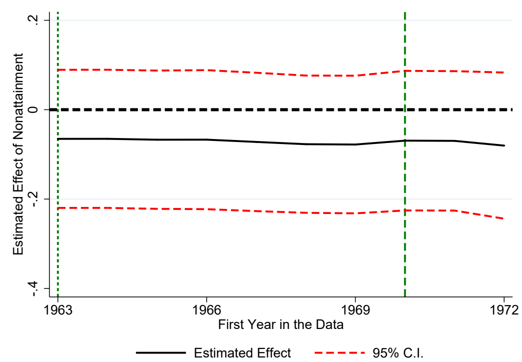
(a) Effects on Log Output – Pre-1963 Plants



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



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



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

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

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

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

Number of Plants in Each Group: There are 402 plants built before 1955, 168 plants built between 1955 and 1962, 66 plants built between 1963 and 1967, and 60 plants built between 1967 and 1971.

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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