NBER WORKING PAPER SERIES

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

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Working Paper 28962
http://www.nber.org/papers/w28962

NATIONAL BUREAU OF ECONOMIC RESEARCH
1050 Massachusetts Avenue
Cambridge, MA 02138
June 2021, Revised July 2021

We are grateful for invaluable comments and suggestions from Becka Brolinson, Don Fullerton, Geoff Heal, Maggie Jones, Matt Kotchen, Arik Levinson, Chiara Lo Prete, Erin Mansur, Nick Muller, and Matthew Zaragoza-Watkins. We also appreciate feedback from seminars participants at Carnegie Mellon University, PERC, University of California { Berkeley, University of Illinois { Urbana-Champaign, University of Maryland, Université de Montréal, and the United States Environmental Protection Agency. Finally, we thank conference participants at the ASSA Annual Meetings, Occasional Workshop in Environmental and Resource Economics (University of California { Santa Barbara), Northeast Workshop on Energy Policy and Environmental Economics (Columbia University), Midwest Energyfest (Northwestern University), Annual Workshop on Empirical Methods in Energy Economics (EMEE), CEPR-EBRD-EoT-LSE Symposium on Environmental Economics and the Green Transition, the Annual Research Roundtable on Energy Regulation, Technology, and Transaction Costs, the 2021 Canadian Economic Association Meetings (CNEH), and the Berkeley-Harvard-Yale Environmental Economics Seminar. The authors also gratefully acknowledge financial support from the Center for Electricity Industry Studies, Heinz College, the Berkman fund at Carnegie Mellon University, National Science Foundation Grant SES-1627432, and the Université de Montréal. June 16, 2021. The views expressed herein are those of the authors and do not necessarily reflect the views of the National Bureau of Economic Research.

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NBER Working Paper No. 28962
June 2021, Revised July 2021
JEL No. K32,N52,N72,Q41,Q48,Q52,Q58

ABSTRACT

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 impacts of the 1970 Clean Air Act (CAA) on the power sector. This unique long panel provides 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. This timing aligns with the passage of the original 1963 CAA, which provided the federal government with limited authority to "control" air pollution, but signaled 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.

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An online appendix is available at http://www.nber.org/data-appendix/w28962

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 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 adapt to impending regulation can have important distributional consequences, with potentially first-order effects 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. Since regulation was largely foreseeable in the years leading up to the Act's passage, polluting electric utilities may have preemptively adjusted behavior in anticipation of the CAA.

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 unique data-set provides us with 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 the effects of the CAA for plant vintages that were more or less able to anticipate and

[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.

preemptively respond to regulation. Moreover, because power plants are immobile and have extended lifespans, there is little concern that plant relocation or exit will affect the estimates, as can often be the case in long-run analyses.[2] Finally, detailed data on plant operations allow us to estimate annual plant-level "pollution-unadjusted" total factor productivity (PU-TFP).[3] We use this measure of PU-TFP to estimate the direct effects of the CAA on plant productivity and to assess the indirect productivity effects driven by the reallocation of output from older plants to newer plants.[4]

Our empirical approach relies on geographic and temporal variation in environmental regulation. The CAA established the National Ambient Air Quality Standards (NAAQS), which set national standards for five criteria pollutants: carbon monoxide, particulate matter, nitrogen dioxide, ozone, and sulfur dioxide. In each year, each county is designated to be either in attainment or nonattainment depending on whether pollution levels are below or above the relevant standard. Power plants located in attainment counties are subject to limited regulation while plants in nonattainment counties are forced by state and local regulators to take potentially costly actions to reduce pollution levels. Power plants can reduce their pollution emissions by decreasing output, switching to "cleaner" fuels, or installing pollution abatement technology.

We adopt a difference-in-differences strategy that compares the operations of plants located in attainment versus nonattainment counties. Event study graphs support the parallel trends assumption. This is consistent with historical evidence that electric utilities anticipated some form of impending regulation, but were unable to predict the exact timing or details of the 1970 CAA.[5]

[2]During the sample period, the typical lifespan of a fossil-fuel power plant was 40 years. Rate-of-return regulation in the industry ensured that monopoly electric utilities faced virtually no risk of bankruptcy and were thus very unlikely to relocate or exit.

[3]Our measure of productivity focuses on how inputs translate to output electricity, without incorporating the external costs of pollution borne by society at large. We estimate PU-TFP using the method specified by Ackerberg, Caves and Frazer (2015). Our estimation is based on output and input quantities rather than revenue and costs from balance sheet data, so will not be biased by changes in market power in output or input markets (Foster, Haltiwanger and Syverson, 2008; Hsieh and Klenow, 2009; De Loecker, 2011).

[4]When markets are efficient, reallocative effects will not impact aggregate productivity (Solow, 1957). However, there were large productivity differences across power plants of different vintages, consistent with electric utilities operating as local monopolies during our sample period. As a result, the distributional impacts of regulation can have first-order effects on aggregate outcomes.

[5]Evolving pressure for environmental regulation culminated with a remarkable shift in public sentiment in favor of environmental protection at the end of the 1960s. In May 1969, only one percent of the population included "pollution/ecology" as one of the most important domestic problems in the United States. Two years later, that number had jumped to 25 percent (ACIR, 1981, p.19). In part, the 1970

We find that nonattainment led to reductions in output and productivity, but only for plants built before 1963. The productivity losses incurred by these older vintage plants are large and persistent, suggesting an inability to adapt to environmental regulation even in the long run. In contrast, the effects of nonattainment on plants that opened between 1963 and 1971 are small and statistically insignificant.

The heterogeneity in treatment effects across vintages aligns with the passage of the original 1963 CAA. This legislation provided the federal government with limited authority to "control" air pollution, but served as a strong signal of impending federal regulation to combat air pollution. Both historical and empirical evidence suggest that electric utilities took anticipatory actions following the 1963 CAA to mitigate the expected costs of future regulation. Historical sources document preemptive design changes among plants that opened after 1963, including increased stack height and installation of pollution abatement technology. We document a sharp increase in patenting related to power systems between 1963-1971. We also find that electric utilities were less likely to site plants in counties with pollution monitors after 1963. Taken together, this evidence points to anticipation having played a key role in reducing the productivity losses for newer vintage plants.

We find that the distributional impacts of the CAA substantially mitigated the aggregate productivity losses from the regulation. The declines in output from plants built before 1963 were largely offset by increased output from new fossil-fuel plants that opened after 1972. We estimate that roughly one third of the aggregate plant-level productivity losses from nonattainment were offset by the productivity gains implied by the reallocation of output from older plants to newer plants. A simple calculation that accounts for this regulatory-induced reallocation of output across plants implies that aggregate average productivity fell by 6% due to the CAA, resulting in annual total productivity losses of $4.0 billion (2020 USD).

Lastly, we show that, without data spanning well before the passage of the CAA, one would substantially *underestimate* the effects of nonattainment on plant output and productivity. We find that the magnitude of the main estimates diminish as the pre-regulatory sample period is artificially shortened, and are not statistically significant for samples beginning in the mid-1960s. We also find that the main coefficient estimates

CAA emerged from an effort by Nixon to outflank two pro-environment lawmakers – Senators Muskie and Jackson – who were widely considered his strongest political opponents in the 1972 presidential race.

are driven by the initial attainment designations in 1972 and that post-1972 variation in attainment status has small and statistically insignificant effects on plant output and PU-TFP.[6] Notably, these patterns also point to anticipatory behavior, since post-1972 changes in attainment status were largely determined based on 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 analysis demonstrates that anticipatory behavior can substantially affect the costs of regulatory compliance and meaningfully alter policy impact estimates. In related work, Keiser and Shapiro (2019*a*,*b*) document that water pollution started declining years before the passage of the landmark 1972 Clean Water Act. Anticipatory behavior may have played a role in that setting as well given that federal legislation pertaining to water pollution control was enacted well before 1972.[7] Our findings are also consistent with Malani and Reif (2015), who investigate the role of anticipatory behavior in the response to physician tort reform.

Second, our findings show that the distributional impacts of regulation can meaningfully alter the 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 productivity losses borne by older plants were substantially offset by the productivity gains associated with regulatory-induced reductions in output from older plants. This reallocative response also counteracted the air pollution costs associated with the CAA's grandfathering provisions, which imposed less stringent regulations on existing plants (e.g., List, Millimet and McHone, 2004; Stavins, 2006).

The third contribution relates to the critical importance of a long time horizon to assess the effects of transformative regulations, especially in settings with large irreversible investments (e.g., Bleakley and Lin, 2012; Hornbeck, 2012; Hornbeck and Keniston, 2017).

[6]Decompositions based on the Goodman-Bacon (2018) technique show that identification of the main estimates is based primarily on the comparison of plants that never versus ever faced nonttainment rather than switches in attainment status after 1972.

[7]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).

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).[8] However, most prior studies have relied on post-1972 variation in attainment status, and none have included data from before 1963. We show that an extended pre-regulatory period is essential for estimating the full economic impact of the CAA.

The remainder of the paper is organized as follows. Section 2 presents background information on the evolution of environmental policy in the United States. Section 3 outlines our conceptual framework for how plants choose inputs and output with versus without the Clean Air Act. Section 4 describes the data sources, presents summary statistics, and introduces our difference-in-differences approach to estimating the effect of nonattainment with the NAAQS on plant operations. Section 5 reports the main findings, along with robustness checks and further heterogeneity analyses. Section 6 presents a back-of-the-envelope calculation of the aggregate effect of the 1970 CAA on PU-TFP in the power sector. Lastly, Section 7 concludes by discussing the policy implications of our findings.

2 Background

This section describes three phases of air pollution regulation in the United States. The first phase was up to 1962, when most of the federal efforts were directed towards data collection. The second phase was 1963-1971, when the passing of the Clean Air Act (CAA) of 1963 provided a credible signal that comprehensive regulation was coming. The third phase was from 1972 onward when the 1970 CAA legislation took effect.

2.1 Up to 1962

The modern clean-air movement arose in the postwar period following a number of high profile incidents of extreme air pollution, notably the 1948 Donora smog and the 1952 London smog (Clay, 2018). These events received international publicity, raised public

[8]For impacts on manufacturing, see, for example, Henderson (1996); Becker and Henderson (2000); Greenstone (2002); Gray and Shadbegian (2003); Greenstone, List and Syverson (2012); Ryan (2012); Kahn and Mansur (2013); 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).

awareness of the relationship between air quality and health, and created the impetus for federal action.[9]

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

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. The 1963 CAA was the first federal legislation to give the federal government the authority to "control" air pollution.[10] Despite this transformation in the federal government's role in combating air pollution, the effective authority was limited. A total of just 11 "abatement conferences" were held through 1971, even as the 1967 Air Quality Act strengthened federal enforcement powers.[11,12]

Contemporary historical accounts document a change in the behavior of electric utilities following the 1963 legislation that is consistent with anticipation. For example, 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 a major social-economic issue affecting the electric power industry" (FPC, 1967, p.ix).[13] The 1968 reports adds that "[u]tilities are giving increasing attention to

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

[10] Namely, the 1963 CAA included a conference procedure in section 115.

[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] Between 1960 and 1966, ten states set their own air quality standards (Stern, 1982). Our primary specifications account for these state-level standards through the inclusion of state-year fixed effects. We also explore the impact of state-level standards in sensitivity analyses.

[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

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 state 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).

Changes in the design of power plants that opened after 1963 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 beginning in the mid-1960, potentially reflecting the increased incentive for regulatory-induced innovation.[14]

Changes in the siting of plants that opened after 1963 are also consistent with anticipatory behavior (Appendix Table A.1). In comparison to pre-1963 plants, plants built between 1963 and 1971 were systematically less likely to be sited in counties with an air pollution monitor. Interestingly, there are no cross-vintage differences in the likelihood that plants were sited in future nonattainment counties, suggesting that electric utilities were unable to predict which counties would ultimately be targeted under the CAA.

Preemptive changes by electric utilities may partly account for the increase in construction costs of coal plants beginning in the mid-1960s (see Appendix Figure A.4).[15]

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]The data do not permit a more disaggregate decomposition of the sources of the new patents.

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

Since electric utilities were subject to rate-of-return regulation, the costs of installing and operating environmental control equipment were largely passed on to consumers through rate increases approved in public utility commission hearings (Fowlie, 2010).

2.3 1972 onward

The 1970 Clean Air Act (CAA) marked the first federal effort to regulate air quality on a large scale. It emerged after an extended period of mounting public pressure for federal action on air pollution. Nevertheless, the timing and scope of the regulation came as somewhat of a surprise. A confluence of high profile events – the 1969 Cuyahoga River Fire, a massive oil spill off the coast of Santa Barbara in 1969, and the first Earth Day in spring 1970 – triggered a groundswell of public sentiment favoring environmental action. Despite his anti-regulatory tendencies, President Nixon supported the 1970 CAA to outflank Senators Muskie and Jackson, two pro-environment legislators who were widely considered his strongest rivals for the 1972 presidency (ACIR, 1981).

The 1970 CAA established the National Ambient Air Quality Standards (NAAQS) for five criteria air pollutants: particulate matter, carbon monoxide, sulfur dioxide, nitrogen dioxide, and ozone.[16] Beginning in 1972, each county received an annual designation of nonattainment or attainment for each criteria pollutant, depending on whether air pollution concentrations exceeded the federally mandated standard.[17]

Each state was required to submit a state implementation plan (SIP) outlining how any nonattainment regions would be brought into compliance with the NAAQS. Typically, states totaled up estimated emissions from all stationary sources of pollution in each nonattainment area, and divided this amount by an estimate of the maximum level of emissions that would ensure compliance with the NAAQS. Each plant was ordered to reduce emissions by this ratio (Roberts and Farrell, 1978). All states, territories, and the District of Columbia submitted SIPs by the end of 1972 (EPA, 1973).[18]

[16] Lead was later added as a criteria pollutant.

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

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

Power plants in nonattainment counties faced greater constraints on emissions than plants in attainment counties. One way for plants to meet regulatory requirements is to decrease output. Indeed, Appendix Figure C.5 shows a large drop in output among pre-1963 plants located in nonattainment counties after the passage of the CAA. This decline in output seems to be driven by utilities scaling back production at older vintage plants rather than shuttering capacity, which remained stable in the post-1972 period. Reductions in output from pre-1963 plants were offset primarily by increases in production from new plants built after 1972.[19]

To reduce emissions, existing plants in nonattainment counties could also burn more expensive, lower sulfur coal or install pollution abatement technology – either flue gas desulfurization (FGD) systems or flue gas particulate collectors (FGP). However, installing a FGD system was costly and risked subjecting the plant to the New Source Performance Standards (NSPS), a set of strict standards that applied to the plant regardless of attainment status.[20] Despite these concerns, both FGP and FGD installation rates increased after 1970 (see Appendix Figures A.2 and A.5).

The 1970 CAA led to a sharp drop in emissions from power plants. By 1975, the EPA reported that 261 of the 394 coal-fired power plants in the United States were in compliance with SIP emission limitations or abatement schedules.[21] During the first three years of the CAA, total suspended particle (TSP) emissions fell from 4.2 million tons in 1970 to 2.9 million tons in 1974, and sulfur oxide (SO_x) emissions fell from 15.4 million tons to 13.6 million tons (EPA, 1976*b*). These reductions in pollution emissions accelerated a downtrend trend in monitored TSP concentration levels that pre-dated the Act's passage (Appendix Figure A.6).

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

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

[21]Of the 133 plants not in compliance, 47 were located in Ohio, 29 were located in Indiana, and 26 were located in Illinois. In these states, there 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.

3 Conceptual Framework

This section provides a conceptual framework for understanding the different responses to the CAA for plants built prior to 1963, between 1963-1971, and after 1972. The mathematical formulation is presented in Appendix Section B, with the details on the procedure used to estimate productivity in Appendix Section C.2.

Each plant i produces electricity output O_{it} in each year t using the following three inputs: electricity generating capacity K_{it}, labor L_{it}, and input heat energy E_{it}. Capacity takes a longer time to adjust than either labor or energy while labor takes a longer time to adjust than energy. We follow Fabrizio, Rose and Wolfram (2007) in assuming a Leontief production function, where energy is a perfect complement to the other inputs: holding input energy fixed, output cannot be increased solely through increases in labor or capital.

Pollution P_{it} is emitted as a byproduct of fossil fuel combustion to produce output O_{it}. Plants can reduce emissions by decreasing output, burning cleaner fuel, or installing pollution abatement technology.[22] These actions are costly. For example, a plant that reduces output may be unable to fully adjust inputs, resulting in a decline in *pollution-unadjusted* total factor productivity (PU-TFP).[23] Of course, the benefits to society of lower emissions and thus reduced exposure to pollution are substantial. However, absent regulation, plants do not internalize these benefits in their decision-making.

The response to nonattainment may vary across plant vintages due to information asymmetries at the time of plant opening. Prior to 1963, electric utilities were less able to anticipate future federal environmental regulation. Plants that opened before 1963 were thus less likely to be designed with environmental compliance in mind. Instead, these plants could respond to nonattainment through retroactive adjustments in operations – decreasing output or switching to cleaner fuels – or retrofit installations of abatement technology.[24]

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[22] Appendix Table A.2 documents the compliance strategies utilized by plants owned by the Tennessee Valley Authority.

[23] Our PU-TFP measure does not account for the environmental benefits associated with reduced emissions that accrue to society at large. See Muller, Mendelsohn and Nordhaus (2011); Muller (2014, 2019) for measurements of GDP that adjust for pollution damages. 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).

[24] There was a risk that retrofit installations of pollution abatement technology would be considered a

Following the passage of the 1963 CAA, plants were better able to anticipate future environmental regulation. As a result, electric utilities were better able to incorporate future regulatory compliance into plant design decisions. The subsequent impacts of nonattainment on output and PU-TFP for plants built between 1963-1971 may have been mitigated by these anticipatory responses.[25]

Finally, a nonattainment designation should have limited impact on the operations of plants that opened 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

The analysis uses annual plant-level data for the vast majority of fossil fuel fired power plants in the United States for the period 1938-1994.[26] The Federal Power Commission (FPC), later renamed Federal Energy Regulatory Commission (FERC), began publishing detailed plant-level information in 1948.[27] 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.[28] Further details on the data construction process are provided in Appendix Section C.

There are 931 fossil-fuel-fired plants in the data, located in approximately 700 U.S. counties (see Appendix Figure C.2). Our main sample includes 687 "existing" plants

"major modification", which would subject the plant to stricter environmental regulation under the New Source Performance Standards (NSPS). Despite considerable uncertainty regarding what constituted a "major modification", it was only in the late 1990s that the EPA announced sweeping enforcement action against 46 power plants for violations (see Keohane, Mansur and Voynov (2009)).

[25]Electric utilities may also have responded by siting plants to avoid future regulatory requirements. However, Appendix Table A.1 suggests that utilities were unable to anticipate which counties would face nonattainment status.

[26]Our sample ends 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. Market-based plants face both a different set of incentives and a different set of reporting requirements than price-regulated plants.

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

[28]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.

that opened before 1972. The remaining 244 "new" plants were built after 1972 and were thus subject to more stringent regulatory standards under the NSPS.

We assign each county an annual nonattainment status based on whether the county was in noncompliance with the standards associated with any of the five regulated criteria pollutants. These designations are obtained from published lists from the *Code of Federal Regulation* (CFR) for the period 1978-1994. For the period 1972-1977, we follow Greenstone (2002) and classify a county as nonattainment if it had a monitor reading in the year that exceeded the federal standard. Appendix Table C.1 presents the number of existing and new plants in our data that never versus ever faced nonattainment between 1972-1994. The share of plants that never faced nonattainment between 1972-1994 is 0.35 for plants built before 1963 and 0.36 for plants built between 1963-1971.[29] This suggests that were no cross-vintage differences in the siting of existing plants across always-attainment versus ever-nonattainment counties. In contrast, "new" plants were systematically more likely to be built in always-attainment counties.

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). Thus, the vast majority of the variation in nonattainment status stems from the initial designations set forth in 1972 rather than post-1972 changes.[30]

Our annual plant-level data provide detailed information on a range of outcomes, including electricity output, electricity generating capacity, number of employees, input fuel use, and fuel prices. We model the plant production process as in Fabrizio, Rose and Wolfram (2007), combining data on inputs and output to estimate annual plant-level productivity. See Appendix Sections B and C.2 for the details on how we estimate productivity.[31] Appendix Table C.3 provides summary statistics for all of the key variables utilized in the analysis.

[29] Appendix Figure C.3 plots the annual proportion of fossil fuel fired electricity generation produced in 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] The distribution of the number of years that a county faced nonattainment between 1972-1994 is displayed in Appendix Figure C.9.

[31] The production function parameters are reported in Appendix Table C.4.

4.2 Empirical Strategy

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

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

where i indexes a plant located in county c in state s, and t indexes year. Equation (1) includes plant fixed effects, α_i, to control for time-invariant plant characteristics. The term δ_{ft} denotes a vector of fuel-type-by-year fixed effects that account for input price shocks that might differentially impact plants that burn different types of fuel (i.e. coal, oil, or gas). The term λ_{vt} represents a vector of vintage-group-by-year fixed effects that allow for differential evolution in operations across different cohorts of plants. Finally, we include state-by-year fixed effects, θ_{st}, to account for any state-level energy or pollution control policies that may have emerged either before or after the introduction of the CAA.

The independent variable of interest is $Nonattain_{ct}$, an indicator that takes on the value one if the county is out of attainment with the NAAQS for any pollutant in year t. We also estimate a generalized version of Equation (1) that allows the effects of nonattainment to differ by plant vintage (i.e.: plants built before 1963 versus between 1963-1971). Unless otherwise noted, our estimated coefficients are accompanied by standard errors that are two-way clustered by county and year (Cameron, Gelbach and Miller, 2011).

5 Impacts of the CAA on Power Plant Operations

5.1 Impacts on Output, Inputs, and Productivity, and Evidence of Anticipatory Effects

To motivate the regression analysis and assess the validity of the common trends assumption, we begin by presenting event study graphs. These graphs are based on a version of Equation (1) that treats the first year in nonattainment as year zero in event time, and allows the coefficients to vary from $\tau \in \{-7, +10\}$ in event time.[32] The figures plot

[32] We estimate the model including an indicator for observations with $\tau < -7$ and an indicator for observations with $\tau > 10$, but follow convention in not reporting the coefficient estimates for these

these coefficients and their 95 percent confidence intervals. We present event studies for two outcomes – output and productivity – and for three plant vintage groups – all plants built before 1972, plants built before 1963, and plants built between 1963-1971.

Figure 1 highlights three key points. First, in all panels there is no evidence of differential trends in the years preceding the first year in nonattainment. Second, output and PU-TFP decline for plants built before 1972 in the years following the plant first facing nonattainment. Third, the declines appear to be driven by plants built before 1963. The coefficients for both output and PU-TFP for plants built between 1963-1971 are small in magnitude and not statistically different from zero.

The absence of pre-trends may seem to be inconsistent with pre-emptive adjustments by electric utilities in anticipation of environmental regulation. Indeed, differential pre-trends can be a manifestation of anticipatory behavior (Malani and Reif, 2015). In our context, however, there is little evidence that producers could anticipate *which* jurisdictions would ultimately be subject to greater enforcement under the CAA (see Appendix Table A.1). Moreover, to the extent that anticipated regulation was incorporated into the initial design of post-1963 plants, these adjustments will be captured by the plant fixed effects. Thus, even if electric utilities made pre-emptive adjustments for plants that opened after 1963, we would not expect to see differential trends across attainment and nonattainment counties prior to the Act's passage.

Table 1 presents estimates of the impact of nonattainment on various annual plant-level outcomes from Equation (1). Panel A reports the average effects. Panel B reports heterogeneity in effects across plants built before 1963 versus those built between 1963-1971.

Power plants located in nonattainment counties experienced decreases in output and PU-TFP relative to plants located in attainment counties (Panel A, cols. 1, 2). The coefficient estimates are statistically significant and large in magnitude. We also find that plants in nonattainment counties reduced their inputs relative to plants in attainment counties (cols. 3-5). We estimate significant negative effects of nonattainment on fuel and generating capacity. The effect on employment is also negative, but small in magnitude and not statistically significant.

The negative effect of nonattainment on PU-TFP is due to the fact that declines in

"endpoint restrictions" (see Kline (2012)).

plant output were not fully offset by adjustments to inputs. This finding is consistent with large adjustment costs for plant inputs. Plant generating capacity is essentially irreversible in the short-run.[33] Similarly, the number of employees required for plant operations is largely independent of output levels.[34] Finally, plant output reductions may have increased input fuel use per MWh of generation because the new production levels were technically sub-optimal or because plants shifted from base load generation to more intermittent production.

The negative effects of nonattainment on output and PU-TFP are driven entirely by power plants built before 1963 (Table 1, Panel B). The heterogeneity in these effects is striking. For plants built before 1963, the estimated reductions in output and productivity are large and statistically significant. For plants built between 1963 and 1971, the estimates are small in magnitude and not statistically significant. Among older vintage plants, we estimate similarly large negative effects for plants built before 1955 and those built between 1955 and 1962 (Appendix Table D.1). Together, these findings suggest that the differential estimates across plants built before and after 1963 were not the result of gradual cross-cohort evolution in nonattainment impacts or changes in behavior among plants that opened after the passage of the 1955 Air Pollution Control Act.

The cross-vintage heterogeneity aligns with the timing of the 1963 CAA. This legislation sent a strong signal of future regulation, and electric utilities appear to have incorporated the likelihood of new regulatory requirements into the design and siting of plants built after 1963 (see Section 2.2). Our findings suggest that anticipatory behavior significantly mitigated the subsequent impacts of nonattainment on plant outcomes.

The uneven distributional impacts also point to potential first-order reallocative effects. In particular, reductions in output due to nonattainment are concentrated among older vintage plants that operated at lower average productivity levels (Appendix Figure C.7). As a result, the aggregate productivity losses borne by older vintage plants may have been partially offset by a reallocation of output away from these older plants. Section 6 explores the quantitative implications of this shift in production.

Robustness Checks and Heterogeneity Analysis

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

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

In Appendix Table D.2, we assess the robustness of the main findings to alternative specifications and samples. The estimated impacts of nonattainment on output and PU-TFP are similar if we: (i) exclude smaller power plants, (ii) restrict the sample to coal plants, (iii) replace the state-by-year fixed effects with utility-by-state-by-year fixed effects, and (iv) exclude states that had implemented air quality standards before 1967.[35]

The main effects cannot be attributed to differential plant exit across attainment and nonattainment counties after 1972. Instead, we find that plant lifespan is *positively* correlated with nonattainment status (Appendix Table A.3), consistent with the grandfathering provisions in the CAA that subjected older plants to less stringent regulations than plants built after 1972 (Stavins, 2006; Revesz and Lienke, 2016).

In Appendix Table D.4, we assess the sensitivity of the estimated effect of nonattainment on PU-TFP to alternate specifications for the production function used to estimate PU-TFP. We estimate different measures of PU-TFP based on Translog and Cobb-Douglas production functions, and for models that do and do not include plant materials as production inputs. The estimated impacts are similar across the various specifications.

In Appendix Table D.5, we explore how the nonattainment effects vary by the primary type of fuel burned by the plant: coal, oil, and gas. The estimates for output and PU-TFP are negative for all three fuel types. The reductions in output, inputs and PU-TFP due to nonattainment are largest for coal plants, and all of these reductions are statistically significant. This is consistent with the fact that coal generation was far more polluting than oil or gas generation.

Appendix Table D.6 reports estimates of the impacts of nonattainment on outcomes separately for different pollutant standards. The effects are driven primarily by noncompliance with ambient ozone, nitrogen dioxide, and carbon monoxide standards. The share of counties in noncompliance with the ozone and nitrogen dioxide standards in particular remained large through the sample period (see Appendix Figure C.3).

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

5.2 Evidence of Adaptation to the CAA Among Existing Plants

Did innovation and adaptation at existing plants mitigate the costs of environmental regulation over time? The insignificant estimates for post-1963 plants suggest that preemptive responses may have mitigated the impacts among newer vintage plants. In this subsection, we explore whether changes in operations at existing plants, including those that were less able to anticipate future federal regulation, mitigated the longer-run impacts of nonattainment. We exploit the extended lifespan of power plants to estimate the evolving impacts of nonattainment on plant-level outcomes.

The event study estimates show no evidence of plant-level adaptation to environmental regulation (Figure 1 a, d). Estimated decreases in output and PU-TFP increase in magnitude throughout the first six years following the initial nonattainment designation. After six years, the effect sizes remain large, negative, and fairly stable over time. The estimates for pre-1963 plants follow a similar pattern (b, e). In contrast, we find no significant effects of first nonattainment on post-1963 plants in the short-, medium-, or long-run (c, f).

Table 2 reports the coefficient estimates from a generalized version of Equation (1) that allows the effects of current nonattainment status to vary with the cumulative number of past years that the plant faced nonattainment. Among plants built before 1963, the estimated reductions in output and productivity are large and persistent (Panel A). For plants that were out of attainment for more than 10 years, the estimated reductions in output and PU-TFP from nonattainment are 40 percent and 32 percent, substantially larger than the short-run impacts. These older plants in nonattainment did gradually reduce fuel use and capacity relative to their counterparts in attainment counties. However, these input adjustments did not fully offset the decreases in output, which explains the persistent negative effects on productivity. In contrast, we find no impacts of nonattainment on output or productivity for plants built between 1963-1971 in either the short-, medium-, or long-run (Panel B).

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

5.3 The Importance of an Extended Pre-1972 Time Horizon

Our main policy estimates are based on plant-level data from 1938-1994 that span decades before and after the passage of the CAA. We have argued that the extended pre-regulatory sample period is crucial given the evidence of anticipation by electric utilities in the years leading up to the Act's passage. In this section, we directly test the sensitivity of the main estimates to differing pre-regulatory time horizons.

To begin, we compare the baseline results to estimates based solely on post-1972 data. The vast majority of research on the economic impacts of the CAA has relied on data that begin after its enactment in 1972. Identification in these studies is based on annual changes in county nonattainment status after 1972. Much of this variation stems from largely predictable trends in county-level air quality. Consequently, the results may be influenced by preemptive adjustments made by local polluters.

In Table 3, we compare estimates using the full 1938-1994 sample period to results based solely on post-1972 data. For reference, column 1 reports the baseline estimates. In column 2, we report the results based on data from 1938 to 1994 but restricted to plants that operated after 1972 (i.e., the same set of plants as used in column 3). In column 3, we report results from our primary specification, re-estimated using only data from the post-CAA period: 1972-1994. The estimated impacts of nonattainment on output and productivity based on the post-1972 time period are small and statistically insignificant. These findings contrast sharply with the large and statistically significant estimates reported in columns 1 and 2. Notably, the results in column 3 are based solely on post-1972 variation in county attainment status, which was arguably more predictable than the initial county designations in 1972. The striking difference between columns 2 and 3 highlight the importance of pre-1972 data for estimation.[36]

To further explore the importance of pre-1972 data, Appendix Table D.3 decomposes the 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] The results show that roughly 60 percent of the estimated impacts stem from comparisons across plants that ever versus never faced nonattainment as opposed to temporal variation in attainment status. These findings are consistent with the persistence of county attainment status documented in Appendix Figure C.9 and Appendix Table C.1. This variation across plants that never versus ever faced nonattainment could not be identified without data from before 1972.[38]

Having established the importance of pre-1972 data for identification, we next explore the extent to which the *length* of the pre-regulatory period in the data affects the policy estimates. Figure 2 plots the nonattainment estimates for different pre-regulatory sample horizons. Each point on the x-axis denotes the initial sample year; the estimated effect for 1938, for example, coincides with the full sample. Moving rightwards along the x-axis shows how the effects change as we shorten the pre-regulatory period. The results for output and PU-TFP are negative for samples starting as late as the mid-1950s. The effects diminish slightly for samples beginning in the late 1950s and converge rapidly towards zero for samples after 1963.[39]

The patterns in Figure 2 demonstrate the importance of an extended pre-regulatory benchmark period for capturing the full impact of the CAA. One would substantially

[36]We find similarly insignificant effects of nonattainment for plants built after 1972 (col. 4), consistent with the fact that all new plants were subject to NSPS regardless of attainment status.

[37]To conform to the specification considered in Goodman-Bacon (2018), we consider a plant as treated for all years after the plant first faced nonattainment ("first-nonattainment") rather than using annual county-level attainment status, and reports results based on a strongly balanced panel.

[38]Similarly, Table D.7 shows that the nonattainment impacts are driven by plants that first faced nonattainment between 1972-1977.

[39]Appendix Figure D.1 breaks these results down by plant vintage groups. Not surprisingly, the changes in the estimated effects of nonattainment by first year of the sample occur primarily for the plants built before 1963.

underestimate the negative impacts of nonattainment on plant outcomes without data that begin at least a decade before the Act's passage. These findings are notable since *all* of the prior research on the CAA has relied on data that begins after 1963.

5.4 Alternate Margins of Adjustment to the CAA

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

Electric utilities may have responded to the CAA by shifting generation from existing plants in nonattainment counties to existing plants in attainment counties. The presence of this type of cross-county spillover could lead us to overestimate the effects of nonattainment on output, since the effects may partly reflect a relative rise in output among existing plants in attainment counties.

In this section, we assess whether output from existing plants in attainment counties is affected by nonattainment status in nearby counties. We estimate the following equation for plants built before 1972 located in counties that were always in attainment between 1972-1994:

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

where Y_{it} is the output from plant i in year t. 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 construct several alternative measures for plant i's "exposure" to nonattainment plants, $PropNonAttain_{it}$: (1) the proportion of fossil-fuel capacity in nonattainment counties within the same state as plant i in year t, (2) the proportion of fossil-fuel capacity in nonattainment counties in the same state and owned by the same utility as plant i in year t, and (3) the proportion of fossil-fuel capacity in nonattainment counties that bordered plant i's county in year t.

Table 4 reports the results. We find no evidence of shifts in production from fossil-fuel plants in nonattainment counties to existing plants in attainment counties. If anything, the point estimates, while noisy, are consistently negative across the various measures of exposure to nonattainment. Thus, it does not appear that the reductions in output from existing plants in nonattainment counties were offset by increased production from *existing* plants in attainment counties.

We find some evidence that the decreased output from existing plants facing nonattainment was met by increased production from new plants that opened after 1972 (Appendix Figures C.4 and C.5). Appendix Table D.8 provides suggestive evidence that fossil fuel and nuclear generating capacity was more likely to be built in states where a larger share of the population lived in nonattainment counties. Together, the results are consistent with previous work suggesting that the CAA induced cross-border shifts in industrial activity (Henderson, 1996; Becker and Henderson, 2000; Gibson, 2019). In the electricity sector, the shift was primarily from existing plants in nonattainment counties to new plants that opened after 1972. Importantly, this type of spillover does not compromise our difference-in-differences estimation strategy, which relies solely on comparisons across *existing* plants.

5.4.2 Other Margins of Adjustment: Fuel Switching and Scrubbers

Plants can also respond to environmental regulations by switching to "cleaner" fuels. Plants can switch from burning lower-cost bituminous coal with higher sulfur and heat contents to higher-cost sub-bituminous coal with lower sulfur and heat contents.[40] We assess the importance of this margin of adjustment by estimating the effect of first nonattainment on the log of the annual average coal price paid by power plants.

Table 5 shows that first nonattainment led to increases in the price paid per mmBTU of coal. The effects are negative and statistically significant for plants built both before and after 1963 (col. 2). The magnitude of the effects do not diminish with cumulative number of years the plant faced nonattainment (col. 3), consistent with the evidence in Section 5.2 showing a lack of adaptation even in the long-run.

Plants may also respond to nonattainment by installing pollution abatement technology – flue gas particulate (FGP) collectors or flue gas desulfurization (FGD) units. We explore differences across vintages in the adoption of pollution abatement technology and assess how installation varied with nonattainment status.[41]

[40] 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 contains less heat energy per ton of coal.

[41] This analysis includes both existing plants and new plants that opened after 1972. We focus only

Columns 1 and 2 of Table 6 present cross-vintage differences in the adoption of FGP and FGD systems.[42] Plants built before 1963 were significantly less likely to install FGP systems than plants that opened between 1963 and 1971. Retrofit installation of an FGP collector on an existing plant is far costlier than installing an FGP collector as part of the construction of a new plant. Our findings are consistent with electric utilities preemptively installing FGP systems on new plants after the 1963 CAA.

Plants that opened after 1972 had substantially higher rates of adoption of FGD systems. This is largely because all new plants were subject to the stricter New Source Performance Standards (NSPS) regardless of attainment status. Plants built between 1963-1971 are no more likely to install a FGD than those built before 1963, consistent with the fact that this technology was not widely available before 1970.

Columns 3 and 4 of Table 6 report the effects of first facing nonattainment on FGP and FGD adoption for plants of different vintages. We find no evidence that plants responded to first nonattainment by installing abatement technology.[43] The coefficient estimates are mainly negative and generally not statistically significant. Given the high cost of retrofit installation of scrubbers in particular, it is not surprising that electric utilities preferred other methods to comply with environmental regulations for their existing plants.[44]

We close by performing a back-of-the-envelope calculation of the costs associated with a policy under NSPS that required plants that opened after 1978 to install a scrubber. We do so by comparing the average cost of installing and operating a scrubber to the estimated cost from switching to cleaner fuels due to first nonattainment. We estimate that first nonattainment led to a 6.6% increase in coal prices (Table 5, col. 1), corresponding to an increase in annual fuel costs of 1.9 million dollars (2020 USD). This is much smaller than the annualized cost of installing and operating a scrubber incurred by

on coal plants because burning coal emits far more local air pollution than burning either oil or natural gas (Jaramillo and Muller, 2016).

[42]The dependent variable is an indicator equal to one if plant i had installed the relevant technology by year t. The two coefficient estimates – 1[Built Between 1963-1971] and 1[Built After 1972] – capture adoption rates for each vintage group relative to pre-1963 plants.

[43]The findings should be interpreted with caution. These regressions identify within-plant variation in the installation of abatement technology. However, the majority of abatement technology was installed when the plant was built.

[44]The significant negative estimate for pre-1963 plants may reflect that state and local regulators did not perceive the installation of certain types of FGP systems as an effective means to significantly reduce pollution. Our evidence suggests that pre-1963 plants in nonattainment counties were forced to take potentially costlier actions such as drastically reducing their output levels or buying lower-sulfur coal.

the average plant built between 1978-1994 (which is 8.6 million dollars (2020 USD)).[45] Given this disparity in costs, it seems likely that many plants would have continued to be built without FGD systems in the absence of the 1978 NSPS requirements.

6 Aggregate Effects of the 1970 CAA on PU-TFP

In Section 5.1, we found significant negative effects of nonattainment on productivity and output, but only for plants built before 1963. Given the large differences in average productivity across plant vintages, the aggregate effects may differ from these plant-level estimates. In particular, the aggregate productivity losses from the CAA may be mitigated by the reallocation of output from older less productive plants to newer more productive plants.

In this section, we calculate the aggregate productivity cost of nonattainment, accounting for both plant-level productivity losses and cross-plant reallocation of output. We apply the cross-vintage nonattainment estimates from Section 5.1 to construct the counterfactual annual plant-level output and PU-TFP that would have prevailed in the absence of the NAAQS. The results of this back-of-the-envelope calculation show that the NAAQS led to an annual average productivity decline for fossil-fuel plants of 3.3 percent over the period 1972-1994. This corresponds to an annual aggregate productivity loss of $4.0 billion (2020 USD).[46] 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).

We calculate annual plant-level counterfactual PU-TFP and output for two plant vintage groups: plants built before 1963 and plants built between 1963 and 1971. For pre-1963 plants in nonattainment, the counterfactual values are obtained by multiplying the observed value by the relevant estimate from the top panel of Table 2.[47] For plants built between 1963-1971 in nonattainment, we assume that counterfactual output and PU-

[45] For simplicity, we assume that scrubbers have a 40 year lifespan.

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

[47] For example, consider a plant built before 1963 that we observe producing output $\text{Output}_{i,t}$ with productivity $\text{PU-TFP}_{i,t}$ in year t. If this plant faced nonattainment in year t and had faced more than 10 years of nonattainment up to that year, its counterfactual output in a world without the NAAQS would be $O^C_{i,t} = (1+0.404) \times O_{i,t}$ and its counterfactual productivity would be $\text{PU-TFP}^C_{i,t} = (1+0.318) \times \text{PUTFP}_{i,t}$.

TFP are equal to their observed values, given the insignificant effects of nonattainment for these plants. Similarly, we assume no spillover effects of nonattainment onto existing plants in attainment counties, consistent with the evidence in Section 5.4.1. Finally, we assume that the reductions in output from pre-1963 plants in nonattainment counties was reallocated proportionally to plants that opened after 1972 within the same census division, based on the suggestive evidence in Appendix Table D.8.

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

$$\Delta\overline{\text{PU-TFP}}_t = \sum_i [\underbrace{\frac{\text{Output}_{i,t}}{\sum_i \text{Output}_{i,t}} \cdot \Delta\text{PU-TFP}_{it}}_{\text{Within-Plant Efficiency}} + \underbrace{\frac{\Delta\text{Output}_{i,t}}{\sum_i \text{Output}_{i,t}} \cdot \text{PU-TFP}_{it}}_{\text{Across-Plant Reallocation}}] \tag{3}$$

where $\Delta\text{PU-TFP}_{it} \equiv \text{PU-TFP}_{it} - \text{PU-TFP}^C_{it}$ and $\Delta\text{Output}_{it} \equiv \text{Output}_{it} - \text{Output}^C_{it}$ are the changes in PU-TFP and output with the NAAQS versus without the NAAQS. The first term in Equation (3) is the *within-plant efficiency* effect: existing plants in nonattainment counties may have lower productivity due to increased regulatory requirements. The second term is the *across-plant reallocation* effect, which arises from regulatory-induced shifts in output from older plants facing nonattainment to newer plants.

Figure 3 plots annual output-weighted average changes in productivity due to changes in within-plant efficiency and across-plant reallocation. The dashed red line shows the negative *within-plant efficiency* effect over the period 1972-1994. This effect is smaller than the estimates reported in Table 2 because it averages the plant-level losses incurred by pre-1963 plants in nonattainment counties across all plants. The within-plant productivity losses increase through the 1970s. This trend reflects both an increase in the number of nonattainment counties and the evolving effects of nonattainment on productivity documented in Table 2. After 1982, the within-plant losses are fairly stable, decreasing slightly as the contribution of older vintage plants to total output declines.

The dotted blue line shows the positive *across-plant reallocation* effect from 1972-1994. Pre-1963 plants in nonattainment counties reduced their output. The shortfall in demand due to this nonattainment-induced decline in output was met by increases in output from plants that opened after 1972. Since newer plants were typically more efficient (see Appendix Figures A.7 and C.8), this reallocation contributed to an increase in average national PU-TFP in the power sector. This effect increases over time as pre-1963 plants in nonattainment further reduce output.

The solid black line depicts the aggregate impact of nonattainment on PU-TFP: the sum of the within-plant efficiency effect and the across-plant reallocation effect. The aggregate effects are negative throughout the sample period, but diminish considerably over time. By the end of the sample period, roughly one-third of the within-plant losses were offset by the reallocation of output.

Together, these findings highlight how reallocation across producers can substantially mitigate the aggregate economic costs of environmental regulation. To the extent that pollution is concentrated among older and less efficient entrenched incumbents, environmental regulation may accelerate the process of reallocation towards higher productivity entrants. Although our analysis focuses on the power sector, this intuition is likely to carry over to a wide array of industries.

7 Conclusion

This paper leverages newly digitized data on power plant operations from 1938 to 1994 to examine the impacts of the 1970 Clean Air Act (CAA) on the U.S. power sector. The long panel includes an extended benchmark period without regulation, allowing us to account for anticipatory responses by electric utilities. We find that nonattainment with the NAAQS led to relatively large reductions in output and productivity. These effects are 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 between 1963 and 1971. Our results suggest that firms may be able to acquire information during the process leading up to the passage of landmark legislation, and preemptively take actions to reduce the costs of regulatory compliance.[48]

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

The historical experience in the United States may offer guidance to policymakers in developing countries on the political economy challenges associated with implementing environmental regulation.[49] Our findings suggest that older plants were unable to adapt operations in response to new environmental regulation even in the long-run. Instead, the economic costs of regulation were mitigated primarily through the reallocation of output across plants. As emphasized by Stigler (1971), 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 existing emitters (Stavins, 2006; Revesz and Lienke, 2016).

[49]For example, He, Wang and Zhang (2020) finds that water quality regulation in China causes large declines in productivity, which emerge only after improvements in water quality were linked to political promotion.

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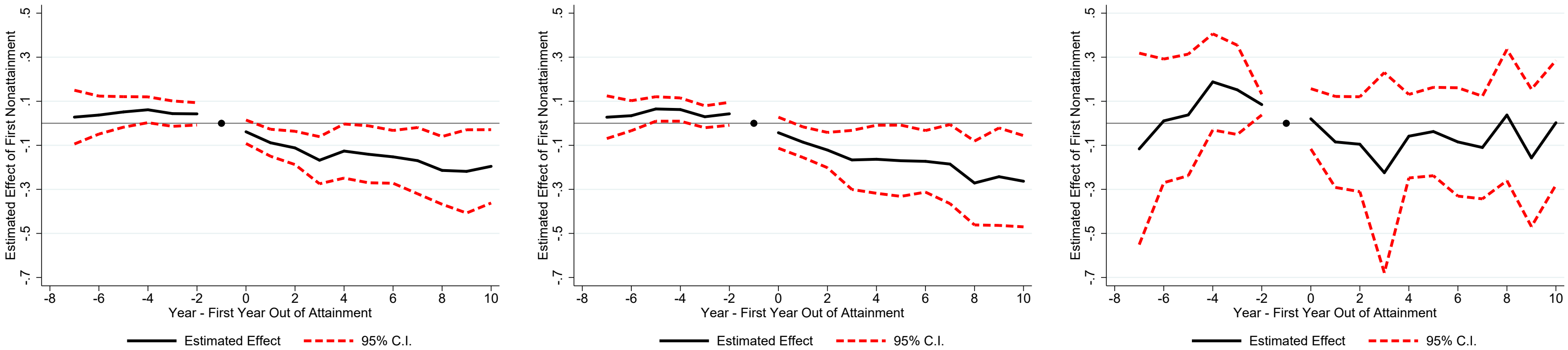
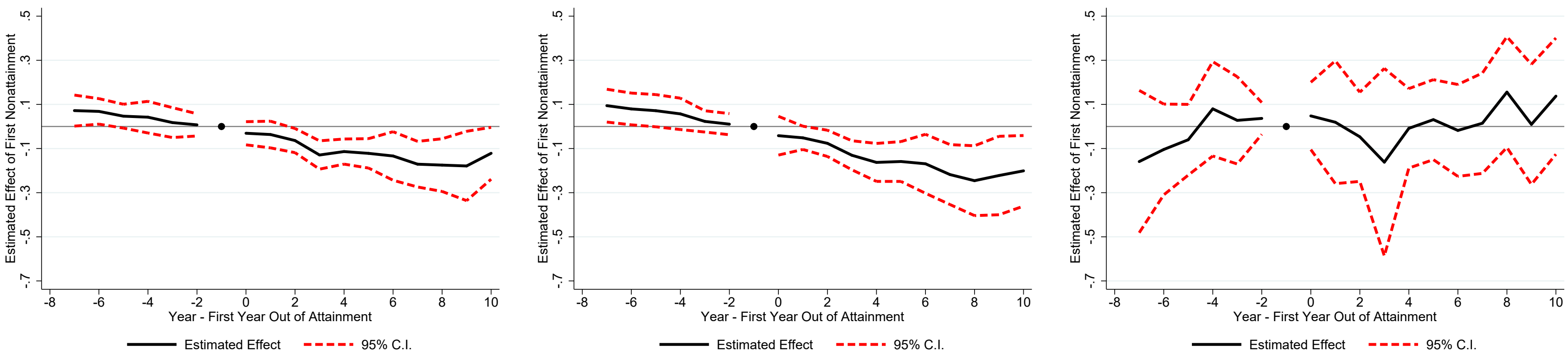
Figures and Tables

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



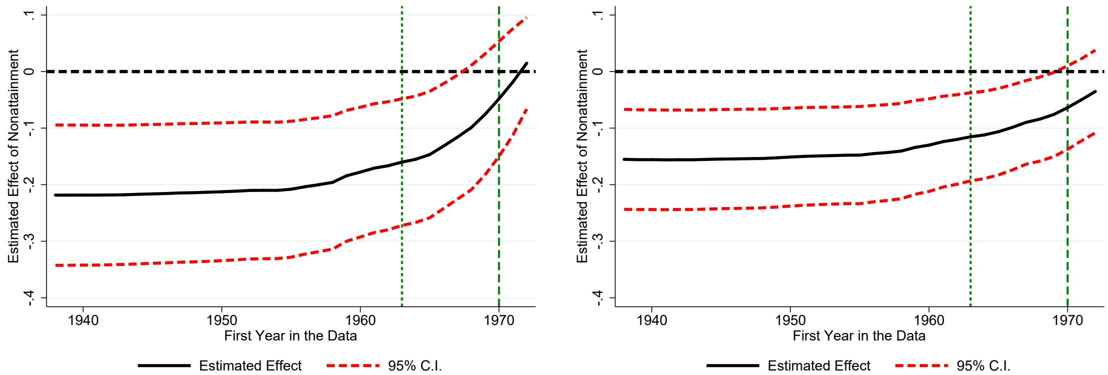
(a) Log Output, Plants Built Before 1972 (b) Log Output, Built Before 1963 (c) Log Output, Built Between 1963-1971



(d) Log PU-TFP, Plants Built Before 1972 (e) Log PU-TFP, Built Before 1963 (f) Log PU-TFP, Built Between 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-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. 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 2: Impacts of Nonattainment on Plant Operations by Initial Sample Year

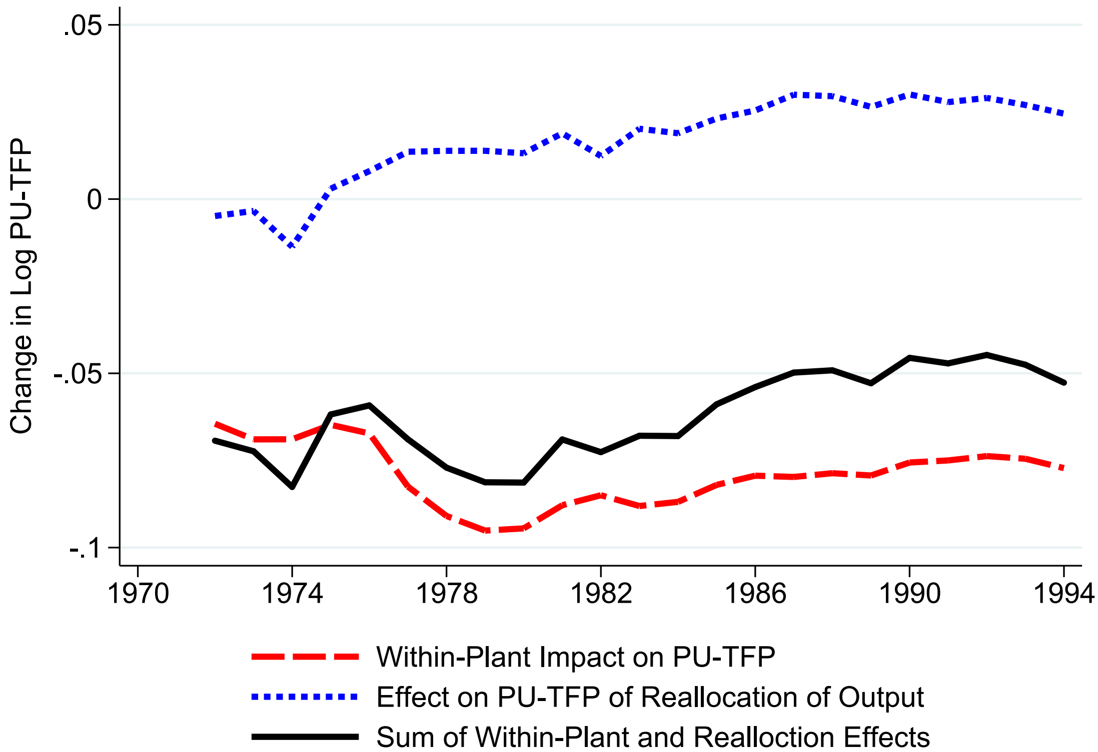


(a) Estimated Effects on Log Output

(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. Namely, for initial year X on the x-axis, we artificially restrict the sample period used to estimate the relevant effect to X-1994 (ex: the effect for initial year 1950 is estimated using data from 1950-1994). We estimate these effects using only data from plants 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 3: Nationwide Effects of the 1970 CAA on Power Plant Productivity



Notes: This figure depicts the estimated nationwide effects of the NAAQS on power plant productivity calculated using the methodology described in Section 6. The impact of the NAAQS on the annual output-weighted average of the log of pollution-unadjusted total factor productivity (PU-TFP), represented by the solid black line, is the sum of two offsetting effects. The long-dashed red line shows the negative *within-plant efficiency effect* over 1972-1994, which reflects the fact that nonattainment reduces the productivity of plants built before 1963 (see Table 2, Panel A, column 2). The short-dashed blue line shows the positive *across-plant reallocative effect*, which arises from shifts in output from pre-1963 plants facing nonattainment to plants built after 1972 (see Appendix Table D.8).

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

	(1)	(2)	(3)	(4)	(5)
Dep. Var. (in Logs):	Output	PU-TFP	Fuel Use	No. Employees	Capacity
Panel A. Average Effects					
Nonattainment	-0.219***	-0.155***	-0.124**	-0.029	-0.109***
	(0.063)	(0.045)	(0.060)	(0.031)	(0.040)
R^2	0.817	0.604	0.746	0.860	0.912
Panel B. Effects by Plant Vintage					
NA × 1[Built Before 1963]	-0.247***	-0.187***	-0.146**	-0.026	-0.119***
	(0.071)	(0.052)	(0.067)	(0.035)	(0.045)
NA × 1[Built Between 1963-1971]	-0.060	0.020	-0.008	-0.043	-0.054
	(0.091)	(0.074)	(0.087)	(0.056)	(0.048)
R^2	0.818	0.605	0.747	0.860	0.912
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
Mean Dep. Var.	6.730	-0.562	9.155	4.489	5.462
Number of Obs.	21,767	21,767	21,767	21,767	21,767
Number of Plants	687	687	687	687	687

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 attainment status of the county where the plant is located. Panel B estimates the impact of nonattainment on outcomes separately for plants built before 1963 versus plants built between 1963-1971. For all specifications, "nonattainment" is defined as the county being out of attainment with the 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

Dep. Var. (in Logs):	(1) Output	(2) PU-TFP	(3) Fuel Use	(4) No. Employees	(5) Capacity
Panel A. Effects for Plants Built Before 1963					
Years in NA ≤ 5	-0.099	-0.156***	0.022	0.086*	-0.018
	(0.083)	(0.054)	(0.083)	(0.045)	(0.055)
Years in NA $\in [6, 10]$	-0.266**	-0.261***	-0.013	0.040	-0.118*
	(0.115)	(0.079)	(0.114)	(0.059)	(0.065)
Years in NA > 10	-0.404***	-0.318***	-0.218	0.023	-0.245***
	(0.136)	(0.094)	(0.132)	(0.074)	(0.084)
R^2	0.798	0.603	0.720	0.853	0.901
Mean of Dep. Var.	6.604	-0.602	9.042	4.484	5.348
Number of Obs.	18,864	18,864	18,864	18,864	18,864
Number of Plants	560	560	560	560	560
Panel B. Effects for Plants Built Between 1963-1971					
Years in NA ≤ 5	-0.134	0.055	-0.146	-0.186**	-0.145**
	(0.118)	(0.097)	(0.099)	(0.079)	(0.061)
Years in NA $\in [6, 10]$	-0.124	0.083	-0.060	-0.155*	-0.144*
	(0.133)	(0.096)	(0.128)	(0.090)	(0.081)
Years in NA > 10	-0.187	0.067	-0.137	-0.226*	-0.143
	(0.179)	(0.150)	(0.163)	(0.118)	(0.096)
R^2	0.904	0.669	0.891	0.930	0.961
Mean of Dep. Var.	7.592	-0.309	9.940	4.573	6.238
Number of Obs.	2,903	2,903	2,903	2,903	2,903
Number of Plants	127	127	127	127	127
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 reports estimates of the impact of nonattaiment on power plant operations separately for bins defined by the cumulative number of years that a plant has faced nonattainment. The unit of observation for the regressions in this table is plant-year. For both panels, we interact the indicator for nonattainment with three bins defined by whether the plant has cumulatively faced nonattainment in five or fewer years, six to ten years, or more than ten years as of the year-of-sample. We focus on 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)	(4)
Panel A. Effects of Nonattainment on Log Output				
Nonattainment	-0.219***	-0.224***	0.015	-0.008
	(0.063)	(0.064)	(0.041)	(0.105)
R^2	0.817	0.790	0.891	0.954
Mean of Dep. Var.	6.730	6.868	7.042	7.471
Panel B. Effects of Nonattainment on Log PU-TFP				
Nonattainment	-0.155***	-0.158***	-0.035	0.023
	(0.045)	(0.045)	(0.037)	(0.077)
R^2	0.604	0.600	0.716	0.833
Mean of Dep. Var.	-0.562	-0.544	-0.687	-0.521
Number of Obs.	21,767	20,328	10,367	2,406
Number of Plants	687	579	579	215
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
Type of Plant	Existing	Existing	Existing	New
Sample Period	1938-1994	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 1938-1994 considering all "existing" plants that operated in at least one year between 1972-1994. Column 3 of both panels is estimated for the sample period 1972-1994 focusing on all "existing" plants. Column 4 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: Spillover Impacts of Nonattainment in Nearby Counties on Log Output

Dep. Var.: Log Output	(1) Cap-Weighted	(2) Utility-Level	(3) Adjacency
Spillover Nonattainment	-0.037	-0.206	-0.201
	(0.276)	(0.276)	(0.192)
R^2	0.826	0.826	0.822
Mean of Dep. Var.	6.055	6.055	6.055
Number of Obs.	5,617	5,617	5,617
Number of Plants	237	237	237
Plant FE	Y	Y	Y
Fuel Type By Year FE	Y	Y	Y
Vintage Group By Year FE	Y	Y	Y

Notes: This table tests whether the output of plants in attainment counties varies with measures of the annual nonattainment status of nearby counties. The unit of observation for all regressions is plant-year, considering only 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 annual proportion of fossil-fuel-fired capacity in nonattainment counties across plants in the same state owned by the same utility as the plant considered for the observation. 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 First Nonattainment on Log Coal Prices

Dep. Var.: Log Coal Price	(1)	(2)	(3)
First NA	0.066***		
	(0.022)		
First NA × 1[Built Before 1963]		0.054**	
		(0.025)	
First NA × 1[Built Between 1963-1971]		0.113**	
		(0.051)	
First NA × 1[Years in NA $\leq$ 5]			0.063***
			(0.021)
First NA × 1[Years in NA $\in$ [6,10]]			0.048*
			(0.028)
First NA × 1[Years in NA >10]			0.116***
			(0.037)
R^2	0.696	0.696	0.696
Mean of Dep. Var.	0.478	0.478	0.478
Number of Obs.	12,309	12,309	12,309
Number of Plants	400	400	400
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 first 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 plants whose primary fuel is coal. All specifications include plant fixed effects, state-by-year fixed effects, and vintage group by year fixed effects; plants built before 1963 are in vintage group 1 while plants built between 1963-1971 are in vintage group 2. In Column 2, we interact first nonattainment with two indicators denoting whether the plant was built before 1963 versus built between 1963-1971. In Column 3, we consider first nonattainment interacted with three indicators denoting whether the cumulative number of years that the plant has faced nonattainment up to the year-of-sample 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 plant-year.

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

	(1)	(2)	(3)	(4)
Dep. Var.	1[FGP]	1[FGD]	1[FGP]	1[FGD]
1[Built Between 1963-1971]	0.062*	0.023		
	(0.032)	(0.025)		
1[Built After 1972]	0.065**	0.258***		
	(0.029)	(0.042)		
First NA × 1[Built Before 1963]			-0.084**	0.021
			(0.037)	(0.021)
First NA × 1[Built Between 1963-1971]			-0.013	-0.039
			(0.061)	(0.028)
First NA × 1[Built After 1972]			-0.012	-0.047
			(0.111)	(0.040)
R^2	0.500	0.200	0.822	0.817
Mean of Dep. Var.	0.539	0.077	0.544	0.079
Number of Obs.	16,368	16,368	16,368	16,368
Number of Plants	596	596	596	596
Evernonattainment Indicator	Y	Y		
Year FE	Y	Y		
Plant FE			Y	Y
State By Year FE			Y	Y

Notes: This table presents regression results measuring whether the installation of flue gas particulate (FGP) collectors and flue gas desulfurization (FGD) technology is impacted by plant vintage and first nonattainment status. The unit of observation for these regressions is plant-year, focusing only on plants that primarily burn coal. The dependent variable for Columns 1 and 2 (Columns 3 and 4) is an indicator variable that is equal to one if the plant has at least one FGP (FGD) system installed by the year-of-sample. The indicator variable "First NA" is equal to one for any year on or after the first year that the plant faced nonattainment with the NAAQS for any pollutant. The specifications in Columns 1 and 2 control for year fixed effects and an indicator for whether the county ever faced nonattainment between 1972-1994, The specifications in Columns 3 and 4 include plant fixed effects and state-by-year fixed effects. 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 Section A* presents additional background information. *Appendix Section B* more fully develops the conceptual framework included in the paper. *Appendix Section C* provides further details on the data sources and construction of the final dataset, and presents additional descriptive figures and tables. *Appendix Section D* reports results from a variety of robustness checks and sensitivity analyses.

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A Additional Background Information

This appendix section provides further information supporting the description of the historical setting in Section 2. Appendix Section A.1 presents the figures and tables mentioned in the text while Appendix Section A.2 provides historical evidence on how one large electric utility responded to the 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 Total Suspended Particulates by County Attainment Status
- Figure A.7 Trends in Power Plant Thermal Efficiency

- Table A.1. Where Electric Utilities Site Plants 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

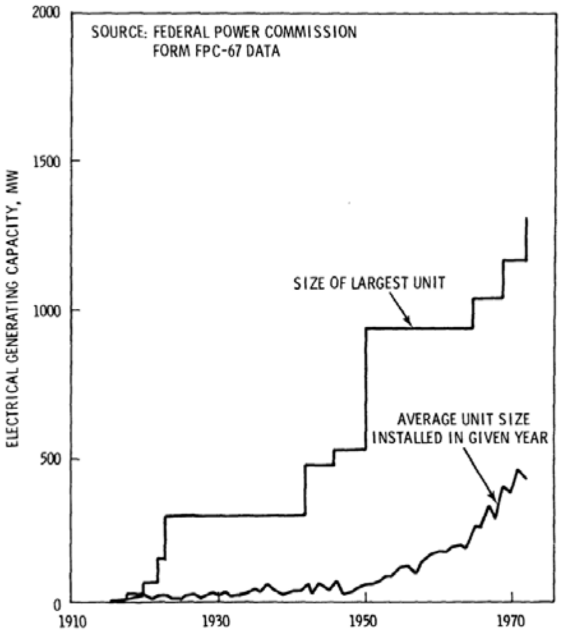
The figures and tables in this appendix subsection provide information on a variety of actions taken by electric utilities aimed at reducing pollution emissions from power plants. Appendix Figure A.1 shows that the electricity generating capacity of the average power plant grew beginning in 1950. Electric utilities also increasingly put taller smokestacks on their plants to send emissions further away over time. Appendix Figure A.2 depicts histograms of the year of adoption of flue gas particulate (FGP) collectors and flue gas desulfurization (FGD) technology. Several plants adopted FGP collectors even before 1950, but FGD technology only became commercially available in the early 1970s. Appendix Figure A.3 provides evidence suggesting that the number of patents pertaining to power systems increases with the passage of the Clean Air Act of 1963. 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 FGD technology (i.e. scrubbers) rapidly in the 1970s, after the passage of the 1970 CAA and its amendments in 1977. Appendix Figure A.6 displays trends in the concentration levels of total suspended particulates (TSP). Lastly, Appendix Figure A.7 displays the national average thermal efficiency of fossil-fuel steam-electric plants over 1938-1994.

The estimates in Appendix Table A.1 suggest that electric utilities chose to avoid locations with pollution monitors when siting fossil-fuel power plants after the passing of the 1963 CAA. Appendix Table A.3 provides descriptive evidence suggesting that electric utilities kept older plants in operation longer to avoid building new plants that would be subject to stricter environmental regulations regardless of attainment status.

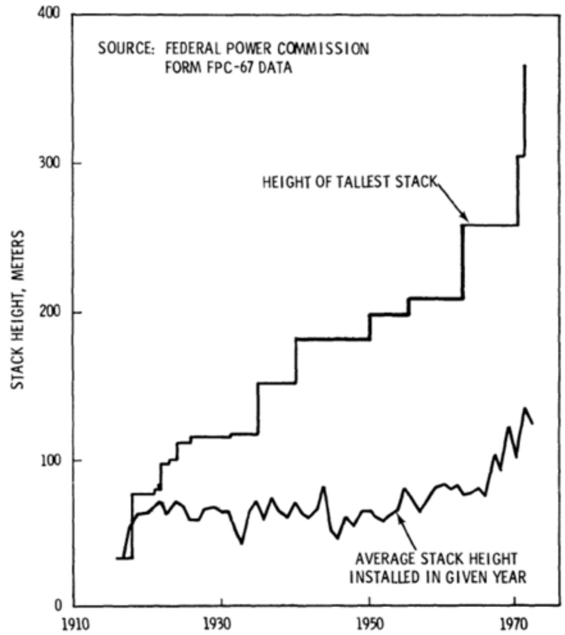
A.2 Tennessee Valley Authority: An Example

To illustrate the variety of strategies used by electric utilities to reduce emissions, we present the case of the ten coal-fired power plants owned by the Tennessee Valley Authority (TVA). These plants were built before 1972, but only complied with the 1970 Clean Air Act (CAA) after TVA and EPA reached a settlement in 1979-80 (GAO, 1980). Appendix Table A.2 shows that many plants ended up switching to coal with lower sulfur content. Several plants combined that strategy with coal washing, electrostatic precipitators, baghouses, and scrubbers. The U.S. Government Accountability Office estimated that the total cost of the consent decree over the life span of the projects was over $14 billion (2020 USD). Capital costs comprised 14% of that amount, operating and maintenance costs 30%, and the incremental fuel costs 56%.

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



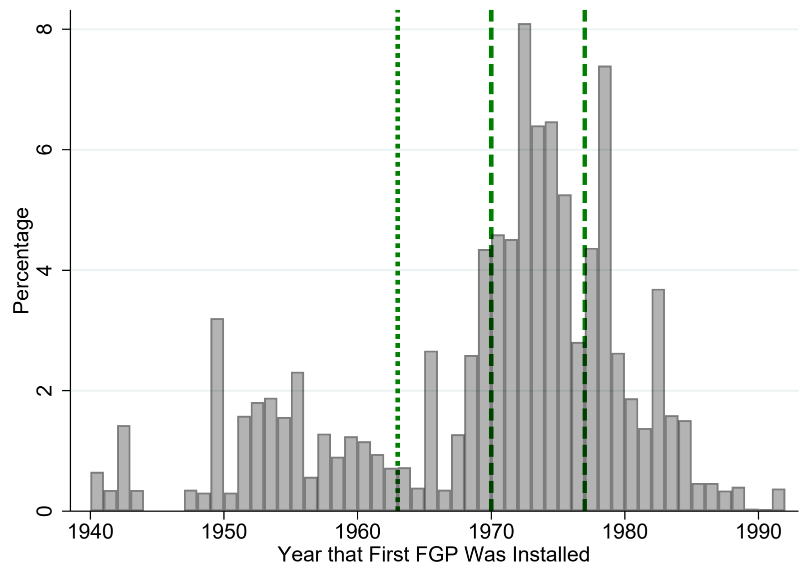
(a) Trends in Plant Size



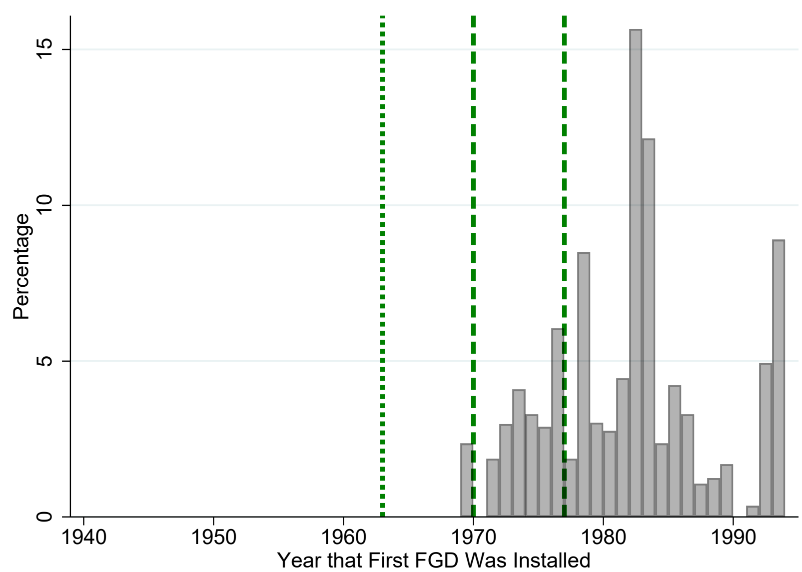
(b) Trends in Smokestack Height

Notes: This figure 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



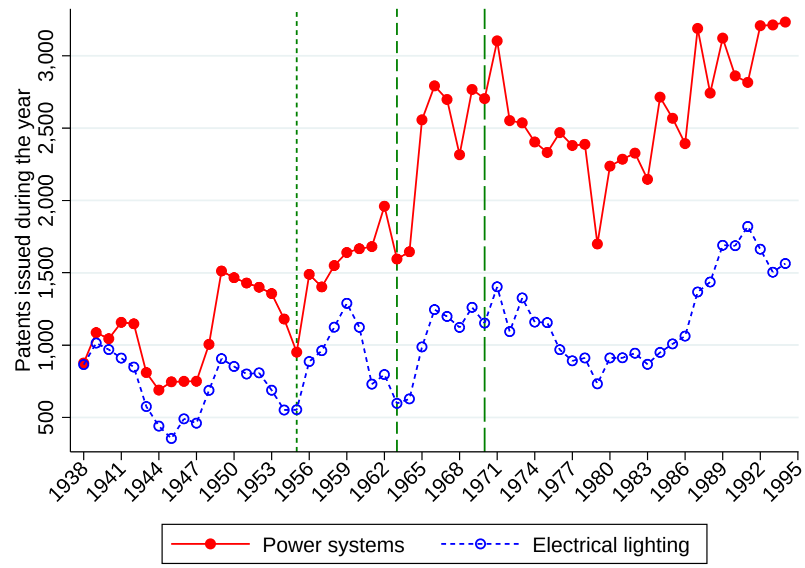
(a) FGP Adoption



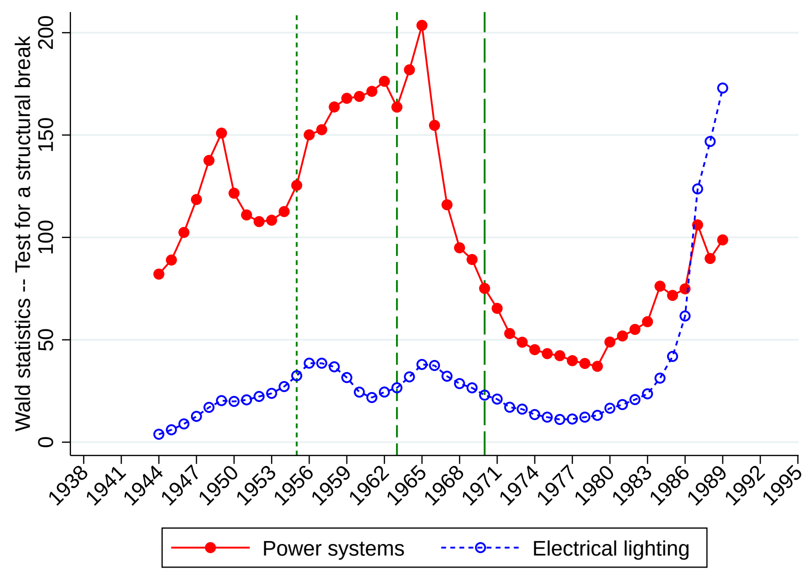
(b) FGD Adoption

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

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



(a) Trends in the Number of Patents Issued



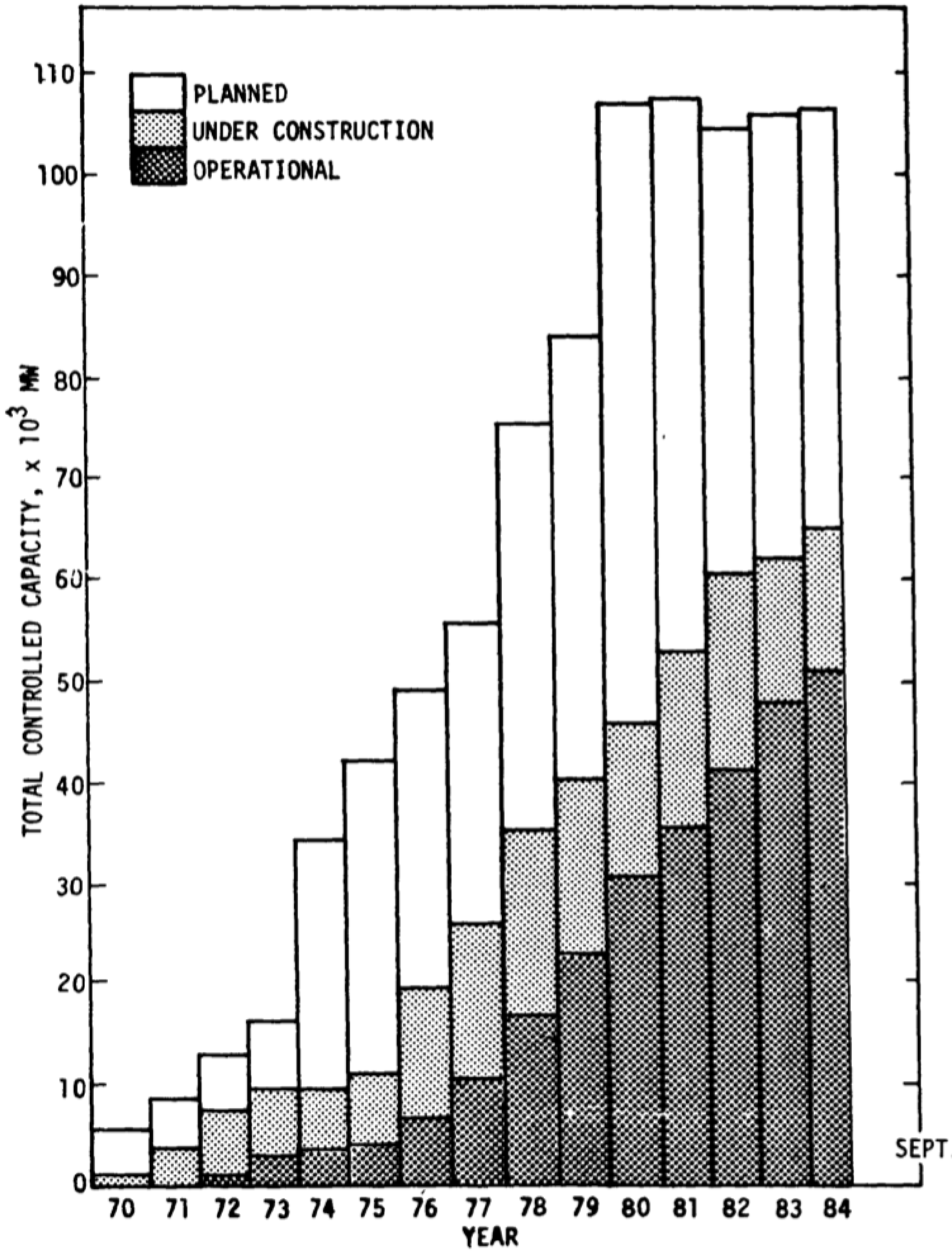
(b) Wald Statistics for Tests of Unknown Structural Break

Notes: This figure displays trends in patents for categories pertaining to electricity. Panel (a) plots the number of patents issued during the year for two 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 categories, visit https://historicip.com/nber/. Panel (b) plots the Wald statistics of tests for a structural break in time-series data with an unknown break date, with an equal left and right trimming percentage of ten percent. The break is estimated to happen in 1965 for power systems and in 1989 for electrical light – the electrical lighting category appears to be a good "control group" for power systems. The short-dashed vertical green line refers to the Air Pollution Control Act of 1955, the dashed vertical green line refers to the Clean Air Act of 1963, and the long-dashed vertical green line refers to the Clean Air Act of 1970. *Data Source:* The Historical Patent Data Files from the U.S. Patent and Trademark Office, available at https://www.uspto.gov/learning-and-resources/electronic-data-products/historical-patent-data-files.

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

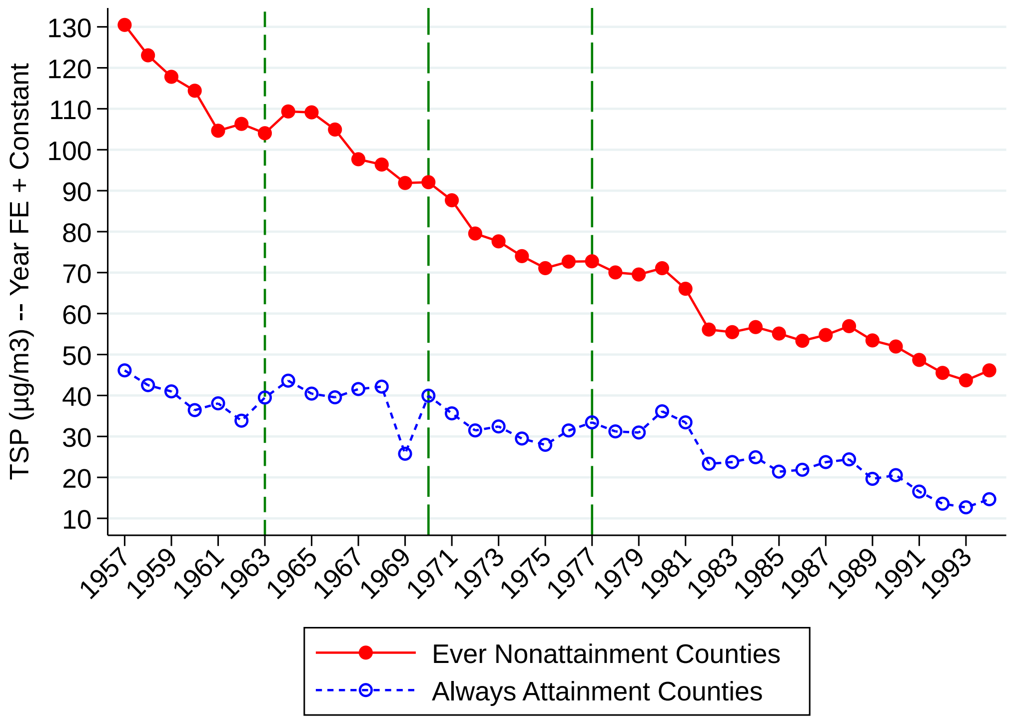
Notes: This figure reproduces Figure 2 from Joskow and Rose (1985). It plots an index of construction costs per kilowatt for coal-fired electricity generating units. Construction costs decline during the early 1960s, stabilize in the mid 1960s, and then increase starting around 1966 to a level that by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

Figure A.5: Trends in Scrubber Adoption



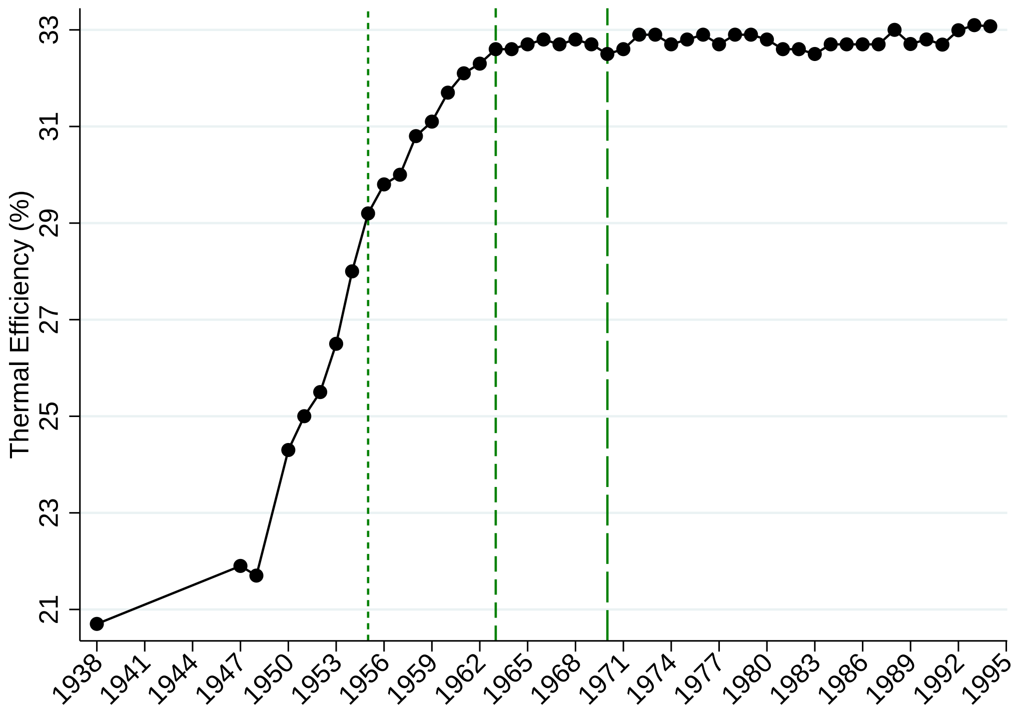
Notes: This figure presents the annual total amount of electricity generating capacity whose pollution emissions are "controlled" by flue gas desulfurization technology (i.e.: a scrubber), separately for generation units in operation, under construction, and planned. This figure spans the sample period December 1970 through September 1984. *Source*: Figure 2, EPA (1984).

Figure A.6: Trends in Total Suspended Particulates by County Attainment Status



Notes: This figure displays trends in total suspended particulates (TSP) by county attainment status. Specifically, it plots the estimated coefficients from a regression of TSP on year fixed effects interacted with attainment status, controlling for pollution monitor fixed effects. A county is categorized as "ever nonattainment" if it was in nonattainment with the NAAQS for any pollutant in any year between 1972-1994; a county is categorized as "always attainment" if it never faced nonattainment between 1972-1994. The green vertical dashed line refers 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 levels, which start in 1957, were provided by the 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 of fossil-fueled steam-electric plants from 1938-1994. 100% thermal efficiency corresponds to 3,412 BTU of heat input energy producing 1 kWh of electricity. The data sources for this figure are (i) for the period 1938-1955: 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. The short-dashed vertical green line represents the Air Pollution Control Act of 1955, the vertical dashed green line represents the Clean Air Act of 1963, and the long-dashed vertical green line represents the Clean Air Act of 1970.

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

	(1)	(2)	(3)
Dependent Variable	1[County has a Pollution Monitor Before 1963]	1[County has a Pollution Monitor Before 1963]	1[County Ever in Nonattainment (ENA)]
1[Built Between 1955-1962]	-0.026	-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 that explore whether electric utilities are less likely to site their fossil-fuel-fired power plants in counties that are more likely to face nonattainment in the future. We estimate separate effects for plants built between 1955-1962, 1963-1971, and 1972-1994; the (omitted) reference vintage group is plants built before 1954. The unit of observation for these regressions is a plant. In columns 1 and 2, the dependent variable is an indicator for whether the county where the plant was built 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 were ever out of attainment with the NAAQS for any pollutant between 1972-1994. For reference, 353 plants that opened between 1938-1994 were built in counties that had at least one pollution monitor operating in at least one year during the baseline years 1957-1962. In column 3, the dependent variable is an indicator for whether the county where the plant was built was ever in nonattainment with the NAAQS between 1972-1994. Information on the location of the network of pollution monitoring stations was obtained through a FOIA request submitted to the U.S. EPA. Standard errors in parentheses are clustered by state. *** denotes statistical significance at the 1% level, ** at the 5% level, and * at the 10% level.

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

Coal Plant	County	State	Attainment in 1978	Compliance Method	Compliance Cost (millions of 2020 USD)
Allen	Shelby	TN	No	Medium Sulfur Coal	271.46
Colbert	Colbert	AL	No	Medium Sulfur Coal	531.26
Cumberland	Stewart	TN	Yes	Coal Washing Electrostatic Precipitators	1,842.92
Gallatin	Sumner	TN	No	Medium Sulfur Coal Electrostatic Precipitators	421.89
Johnsonville	Humphreys	TN	No	Medium Sulfur Coal	1,107.55
Kingston	Roane	TN	No	Low Sulfur Coal	1,007.10
Paradise Unit 3	Muhlenberg	KY	No	Coal Washing and Partial Scrubbing Electrostatic Precipitators	3,715.81
Shawnee	McCracken	KY	No	Low Sulfur Coal, Baghouses	2,771.06
Watts Bar	Rhea	TN	Yes	Medium Sulfur Coal	Not Available
Widows Creek Units 1-6	Jackson	AL	No	Low Sulfur Coal	564.05
Widows Creek Units 7-8	Jackson	AL	No	Scrubbing and Medium Sulfur Coal	1,990.54
Total					14,223.67

Notes: This table provides the pollution abatement strategy of each of the ten coal-fired power plants owned by the Tennessee Valley Authority (TVA), as agreed upon in the clean air settlement between TVA and EPA in 1979-80. All ten plants were built before 1972, the year that the 1970 Clean Air Act was implemented. The costs in the last column were estimated by the U.S. Government Accountability Office (GAO), and refer to the total cost of the consent decree over the life span of the projects. This table was compiled using information from GAO (1980).

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

Dep. Var.: Log of the Number of Years that the Plant is Operating	(1)	(2)	(3)	(4)
Ever Nonattainment	0.132**	0.535***		
	(0.066)	(0.198)		
ENA × 1[Built Before 1963]	0.531***	0.528***		
	(0.045)	(0.180)		
Number of Years in Nonattainment			0.003	0.055***
			(0.003)	(0.019)
# of Years in NA × 1[Built Before 1963]			0.028***	0.024
			(0.002)	(0.019)
Capacity (GW)	0.145**	1.643***	0.021	1.316***
	(0.067)	(0.398)	(0.069)	(0.401)
1[Coal Plant]	0.000	0.068	0.032	0.159
	(0.058)	(0.138)	(0.062)	(0.143)
1[Gas Plant]	0.017	0.147	0.033	0.264*
	(0.066)	(0.152)	(0.070)	(0.155)
Constant	3.024***	3.089***	3.188***	3.195***
	(0.077)	(0.149)	(0.069)	(0.146)
Mean of Dep. Var.	3.427	3.427	3.427	3.427
Number of Obs.	687	687	687	687
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 NAAQS for any 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 and primary fuel type (the reference category is plants that primarily burn oil). 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 Section B.1 specifies the two-period expected cost minimization problem solved by plant managers. Appendix Section B.2 discusses how the CAA impacts this expected cost minimization problem for plants built before 1963, plants built between 1963-1971, and plants 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 shocks to the level of output required by the plant such as unexpectedly high electricity demand or binding transmission constraints limiting the amount of electricity that can flow from the plant to demand centers.

As in 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)).

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

where Q_t^A is the actual quantity of electricity produced by the plant. We include the $(1-X)^{I_t}$ term to reflect that X% of the plant's electricity is used to run the pollution abatement technology if $I_t = 1$.[2] We estimate total factor productivity 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).[3] 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.[4]

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:

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

[2]The percentage of electricity output used to run the pollution abatement technology varies substantially across plants, ranging from between 0.7% and 2.3% (Bellas and Lange, 2008).

[3]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).

[4]An S-shaped $g(E)$ implies that the heat rate curve as a function of output is U-shaped. Namely, the amount of input energy required to produce 1 additional MWh of electricity is large when the plant is producing either very small quantities of electricity or close to its capacity but small when the plant is producing close to its optimal level.

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.[5] The squared difference between labor in periods 1 and 2 – i.e.: $(L_2 - L_1)^2$ – 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), 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 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

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

[5]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.

where, for simplicity, we set emissions M_t equal to zero if the plant has installed pollution abatement technology (i.e: if $I_t = 1$). If $I_t = 0$, emissions are a function of heat energy E_t and characteristics of the fuel burned f_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 by reducing 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 pollution abatement technology.

However, the NSPS potentially distorts 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 the NSPS regardless of attainment status. 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. Consistent with our suggestive evidence on anticipation, we assume for this conceptual framework that the CAA is 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. Namely, 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 without decreasing output 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 environmental regulations to engineers who install and maintain 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. For example, a plant may switch from burning coal from Appalachia with higher heat and sulfur contents to low-sulfur coal from the Powder River Basin (PRB) that has less heat energy per ton. PRB coal is likely to have a higher price per mmBTU than Appalachian coal both because of its lower heat content and the higher transportation costs to deliver PRB coal from Montana/Wyoming to East coast plants (Busse and Keohane, 2007). In addition, boilers are typically tuned to burn a specific type of fuel; switching fuels is thus likely to come with thermal efficiency losses.

Plants built between 1963-1971 can also comply with nonattainment by reducing output, changing their 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 and design their plants in order to reduce the likelihood and costs of facing nonattainment.

Finally, both sets of plants built before 1972 might 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 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. 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 were 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 the 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. Second, we expect that nonattainment will result in little to no change in either output or heat energy per MWh for plants built between 1963-1971 because these plants were built and sited with knowledge that environmental regulations were forthcoming.

Third, "existing" plants built before 1972 are less likely to install pollution abatement technology than "new" plants built after 1972 because installing this technology might subject existing plants to the stricter environmental regulations associated with the New Source Performance Standards (NSPS). In contrast, every new plant is subject to the NSPS; based on this, our fourth hypothesis is that we should not expect substantial differences across new plants located in attainment versus nonattainment counties. Instead, 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 on data sources, data construction, and data description, supporting the broad overview given in Section 4. Appendix Section C.1 discusses the digitization of historical information on fossil-fuel-fired power plants. Appendix Section C.2 describes the variables used in the estimation of our measure of pollution-unadjusted total factor productivity (PU-TFP), and provides the estimates of the parameters of the production function. Appendix Section C.3 presents additional descriptive figures and tables. The outline of all figures and tables in this appendix section is below.

- Figure C.1. Sample Data for Four Power Plants from the 1957 FPC Report
- Figure C.2. Map of Counties with Fossil-Fuel-Fired Power Plants
- Figure C.3. Proportion of Electricity Generation Produced in Nonattainment Counties
- Figure C.4. Annual Total Electricity Generating Capacity by Source Type
- Figure C.5. Annual Total Electricity Generation and Capacity from Fossil-Fuel Power Plants By Vintage and Attainment Status
- Figure C.6. Annual Total Electricity Generation and Capacity for Fossil-Fuel Power Plants by Vintage and Years in Nonattainment
- Figure C.7. Annual Average Total Factor Productivity for Fossil-Fuel Power Plants by Attainment Status
- Figure C.8. Annual Average Total Factor Productivity for Fossil-Fuel Power Plants by Vintage and Years in Nonattainment
- Figure C.9. County-Level Distribution of the Number of Years Facing Nonattainment

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

- Table C.2. Attainment Status versus Lagged Attainment Status
- Table C.3. Summary Statistics: PU-TFP, Ouput, Inputs, and Attainment Status
- Table C.4. Production Function Estimates: Different Methods and Functional Forms

C.1 Data Construction

We digitized power plant level data from the Federal Power Commission (FPC) reports for the years 1938-1981.[6] Most of the digitization was funded by the NSF grant SES 1627432. We hired undergraduates and Master's students to manually enter the information from the historical reports. Then, a different set of students checked the accuracy of the information entered by the first group, and made corrections if needed.

Beginning in 1938, detailed annual data are available for large steam power plants. Steam power plants include coal-fired, gas-fired, and oil-fired power plants. The number of power plants listed in the first report, which covers all years between 1938-1947, increases from 151 in 1938 to 200 in 1947. The number of plants listed in subsequent annual volumes is 277 in 1950, 528 in 1960, 553 in 1970, and 647 in 1980.[7]

The title of the FPC report for the years 1938-1947 is *Steam-Electric Plant Construction Cost and Annual Production Expenses, 1938-1947* (Single Volume). The title of the FPC report for each subsequent year between 1948 and 1978 is *Steam-Electric Plant Construction Cost and Annual Production Expenses* (Annual Supplements). Finally, the title of the relevant report for each year between 1979-1981 is *Thermal-Electric Plant Construction Cost and Annual Production Expenses* (Annual Supplements). As an example, we present a page from the 1957 report in Appendix Figure C.1.

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

- Each plant's capacity in each year as well as each plant's latitude/longitude coordinates, state and county come from the eGrid database administered by the USEPA.[8]
  - *http://www.epa.gov/egrid/download-data*

[6]In 1977, Congress reorganized FPC as the Federal Energy Regulatory Commission (FERC).

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

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

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

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

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

- Annual plant-level data on number of employees and nonfuel expenses come from FERC Form 1.
  –*http://www.ferc.gov/industries-data/electric/general-information/electric-industry-forms/form-1-electric-utility-annual*.[9]

C.2 Estimation of Total Factor Productivity

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

In robustness checks, we also consider *nonfuel_costs* as an input when estimating TFP. Nonfuel costs include 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 the materials used in the production process, both because it reflects expenditures rather than quantities, and because it includes the wage bill for the employees counted in *labor*.

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

Namely, as nonfuel costs include payroll costs, both *nonfuel_costs* and *labor* would vary with changes in staffing.

As explained in Appendix Section B, we assume a Leontief production function as in Fabrizio, Rose and Wolfram (2007). In particular, 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 determining how capital and labor map to output is translog (Atkinson and Halvorsen, 1976; Christensen and Greene, 1976; Boisvert, 1982; Gollop and Roberts, 1983; Carlson et al., 2000). Appendix Table C.4 reports the estimates of the parameters of the production function.

C.3 Additional Descriptive Figures and Tables

Appendix Figure C.2 shows a map of the United States with all of the counties with at least one fossil fuel power plant shaded in red. Appendix Figure C.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 total electricity generating capacity for each source type, including nuclear and hydro. Appendix Figures C.5 and C.6 show the trends in annual electricity generation and electricity generating capacity by vintage and different bins defined by attainment status.

Appendix Figures C.7 and C.8 display trends in annual pollution-unadjusted total factor productivity by vintage and attainment status. Appendix Figure C.9 presents the county-level distribution of the number of years that 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. Appendix Table C.2 shows the empirical probabilities of transitioning 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

Line No.	PRODUCTION EXPENSES:		Cannon Street $1000	Cannon Street Mills Kwh	B. C. Cobb $1000	B. C. Cobb Mills Kwh	Bryce E. Morrow $1000	Bryce E. Morrow Mills Kwh	Saginaw River $1000	Saginaw River Mills Kwh
15	Operation Labor, Supervision and Engineering		424	.77	581	.21	388	.57	441	2.64
16	Operation Supplies and Expenses - Incl. Water		68	.12	136	.05	49	.07	43	.26
17	Maintenance (Labor, Material, and Expenses)		361	.65	465	.16	277	.41	377	2.26
18	Rents								2	.01
19	Steam from Other Sources or Steam Transferred		(23)	(.04)	(3)	-				
20	Joint Expenses		(10)	(.02)						
21	Total, Exclusive of Fuel		820	1.48	1.179	0.42	714	1.05	863	5.17
22	Fuel		3,424	6.16	8,801	3.16	2,918	4.30	1,089	6.52
23	Total Production Expenses		4,244	7.64	9,980	3.58	3,632	5.35	1,952	11.69
24	Production Expenses (except fuel) per Kilowatt	$	5.96		-		3.83		6.16	

Line No.	FUEL USED:		Cannon Street Quantity	Cannon Street Cost	B. C. Cobb Quantity	B. C. Cobb Cost	Bryce E. Morrow Quantity	Bryce E. Morrow Cost	Saginaw River Quantity	Saginaw River 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										

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

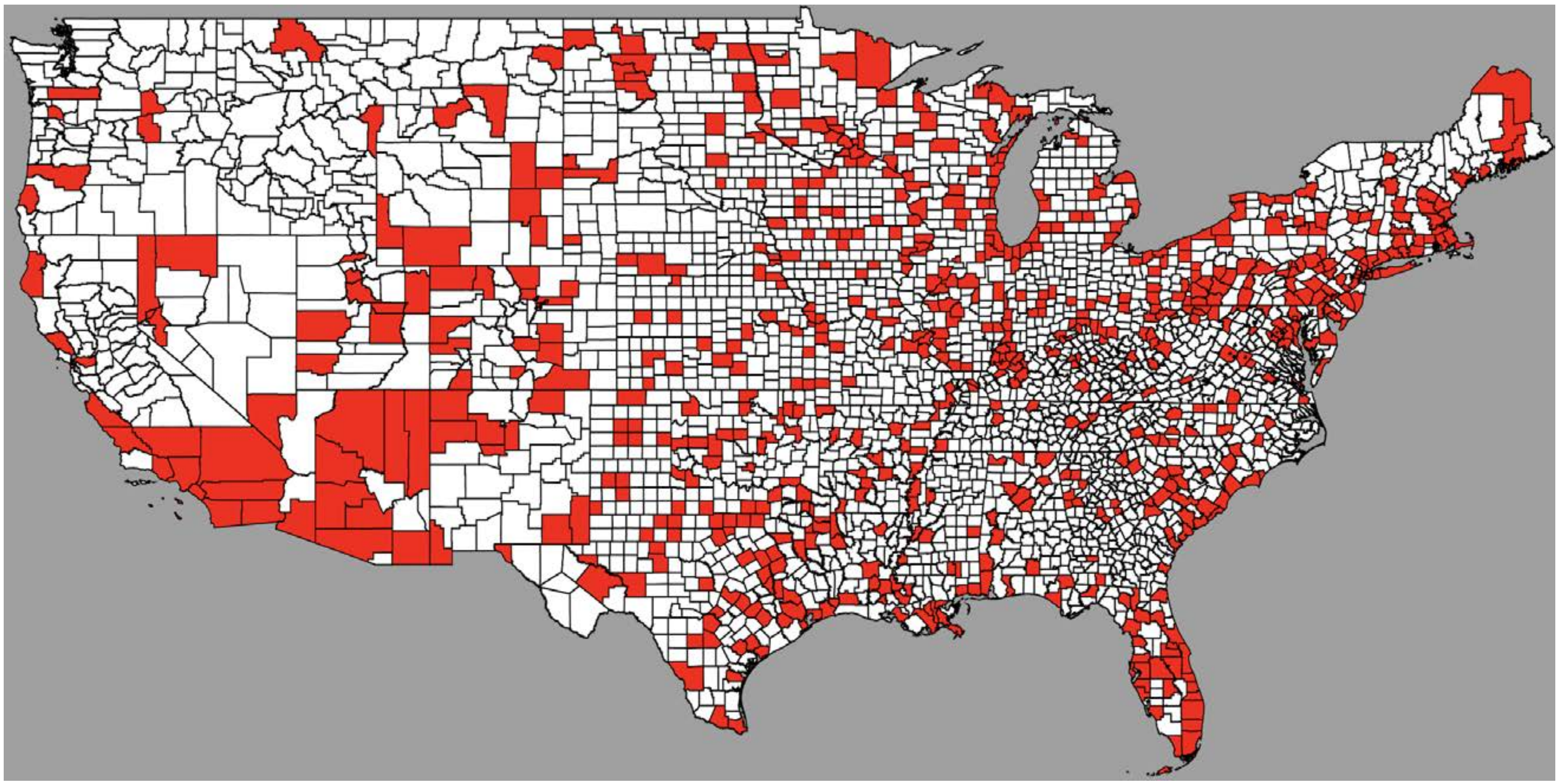
CHANGES OR ADDITIONS IN 1957

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

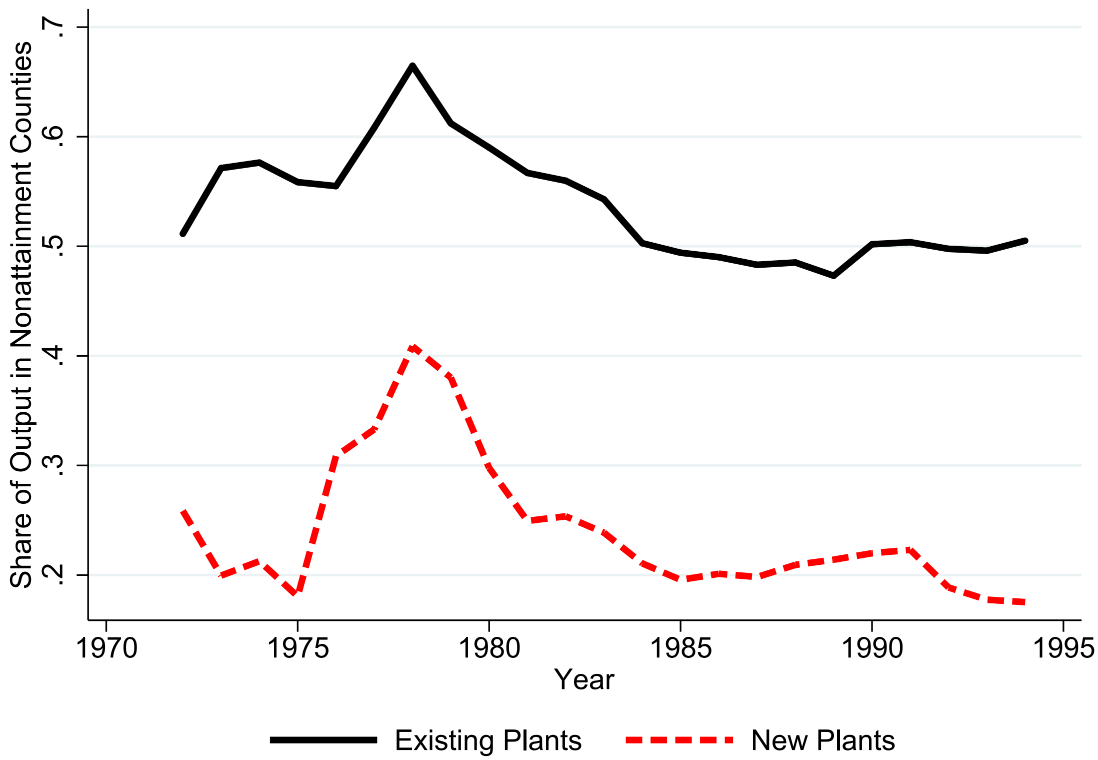
Source: Federal Power Commission Report "*Steam-Electric Plant Construction Cost and Annual Production Expenses – Tenth Annual Supplement*", 1957.

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

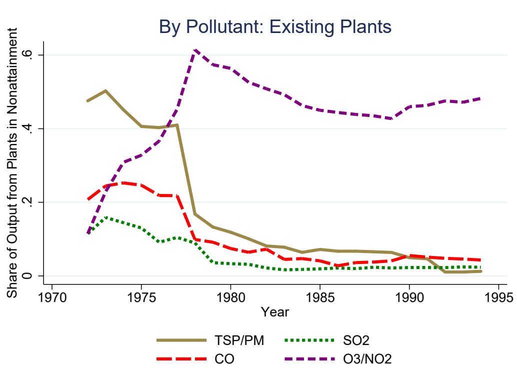


Notes: This figure displays which counties had fossil-fuel-fired power plants at any point between 1938-1994. The counties shaded in red were home to at least one fossil-fuel plant in our sample. There were no power plants in any year of our sample located in the counties shaded in white.

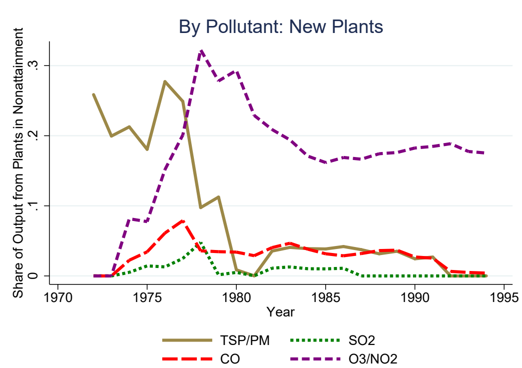
Figure C.3: Proportion of Electricity Generation Produced in Nonattainment Counties



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



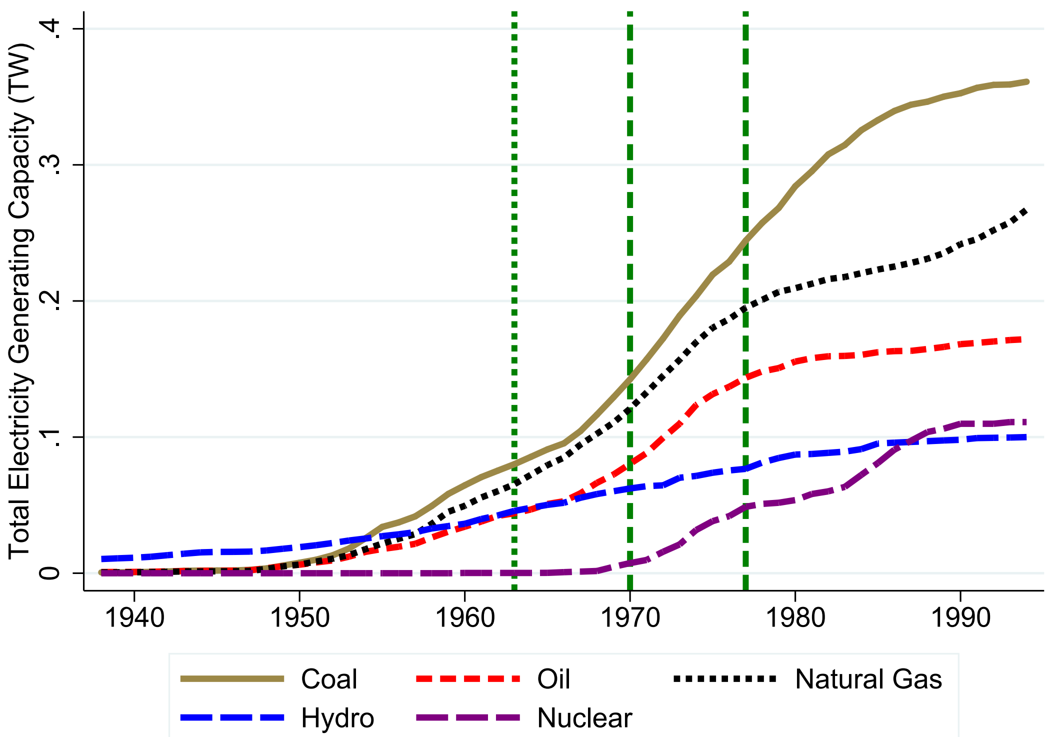
(b) Share of Output from Nonattainment Counties by Pollutant – Existing Plants



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

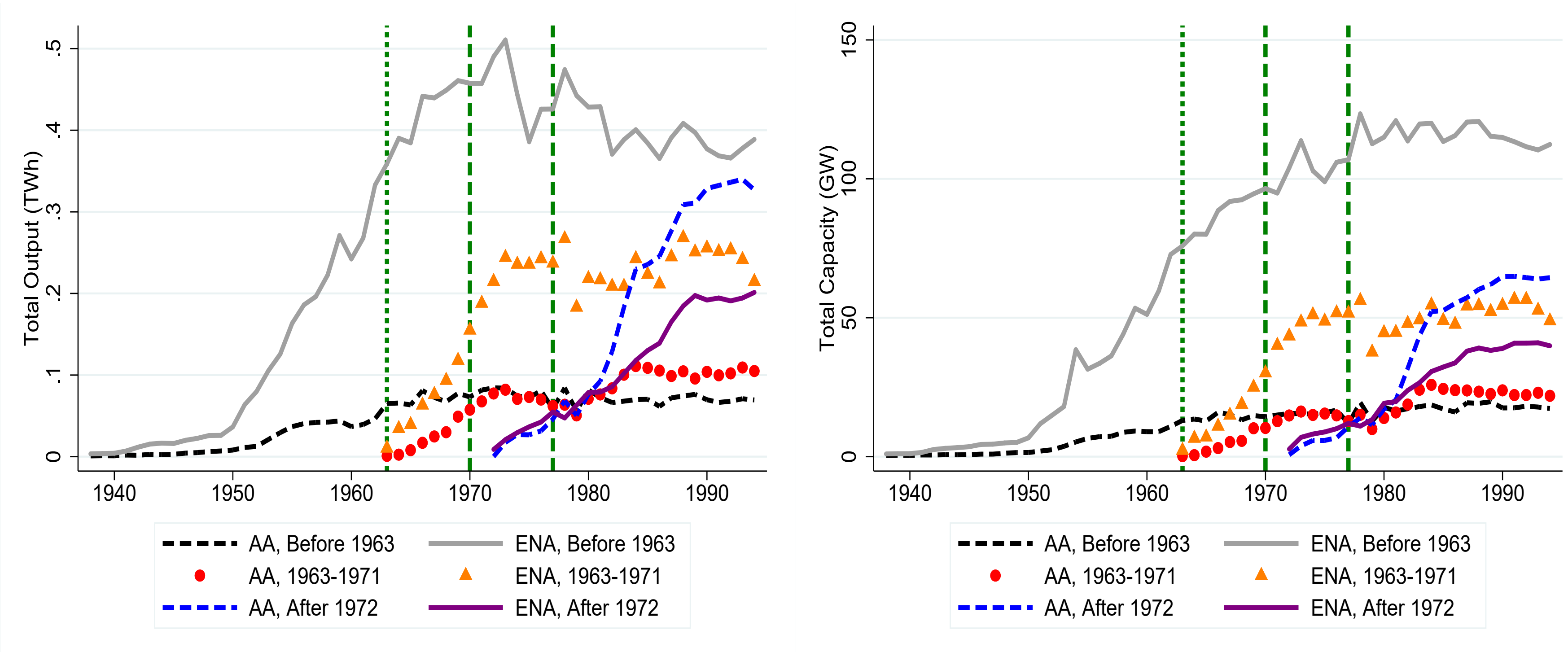
Notes: The top panel of this figure documents the annual aggregate proportion of electricity production from plants in counties out of attainment with the NAAQS for any pollutant. The bottom panels document the annual aggregate proportion of electricity production from plants in counties out of attainment with the NAAQS for each pollutant, separately for "existing" plants built before 1972 and "new" plants built after 1972. "TSP/PM" refers to standards pertaining to either total suspended particulates (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 Source Type



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

Figure C.5: Annual Total Electricity Generation and Capacity from Fossil-Fuel Power Plants By Vintage and Attainment Status

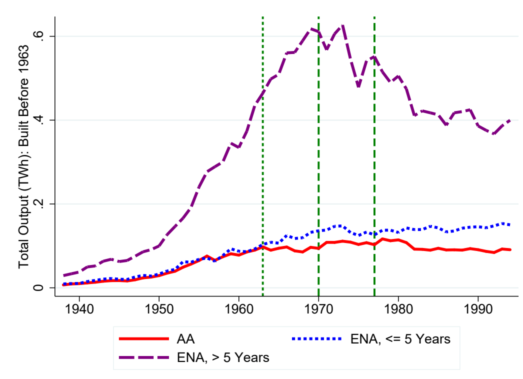


(a) Total Output

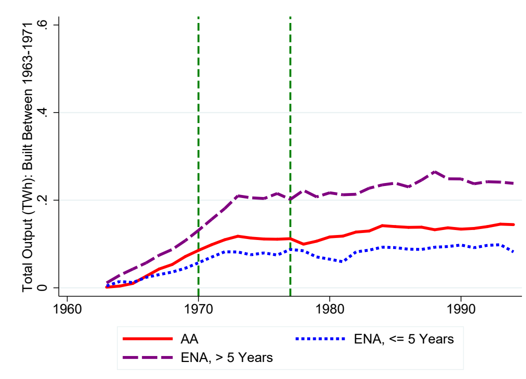
(b) Total Capacity

Notes: This figure documents the 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 between 1938-1994. We consider three plant vintage groups: plants built before 1963, plants built between 1963-1971, and plants built after 1972. The short-dashed green vertical line represents the passage of the Clean Air Act of 1963 and the dashed green vertical lines represent the passing of the Clean Air Act of 1970 and its amendments in 1977.

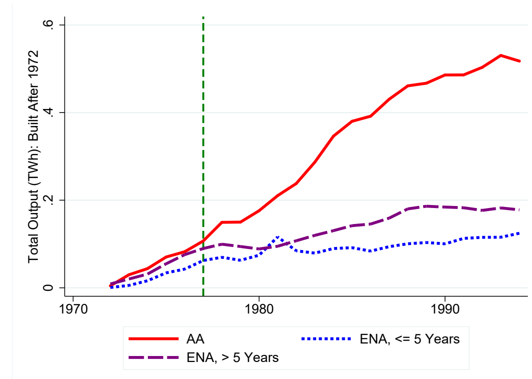
Figure C.6: Annual Total Electricity Generation and Capacity for Fossil-Fuel Power Plants by Vintage and Years in Nonattainment



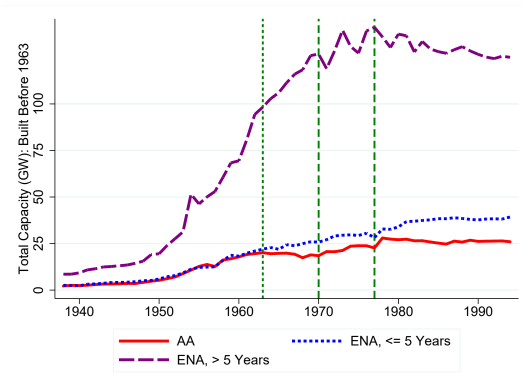
(a) Output – Built Before 1963



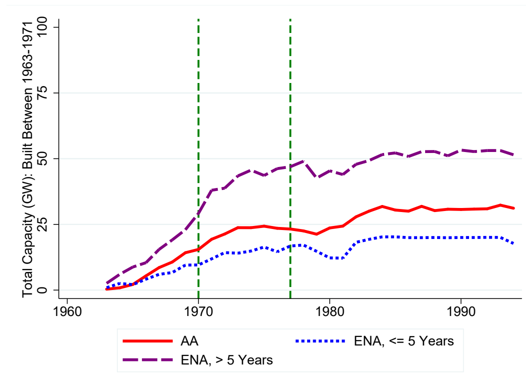
(b) Output – Built Between 1963-1971



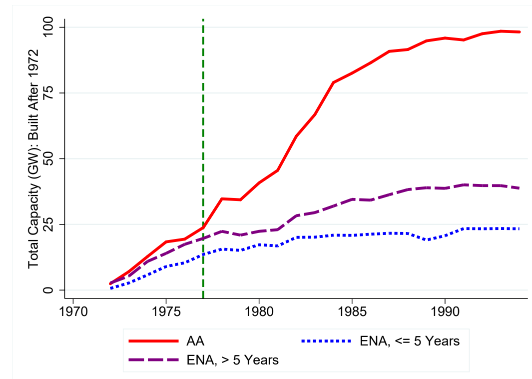
(c) Output – Built After 1972



(d) Capacity – Built Before 1963



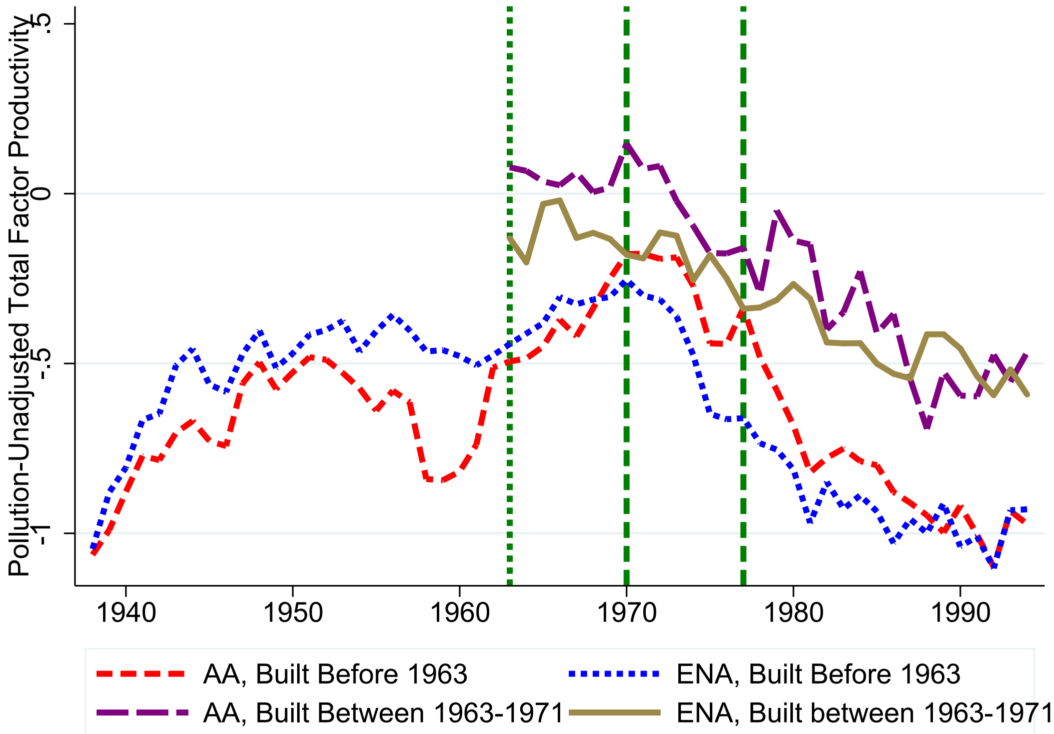
(e) Capacity – Built Between 1963-1971



(f) Capacity – Built After 1972

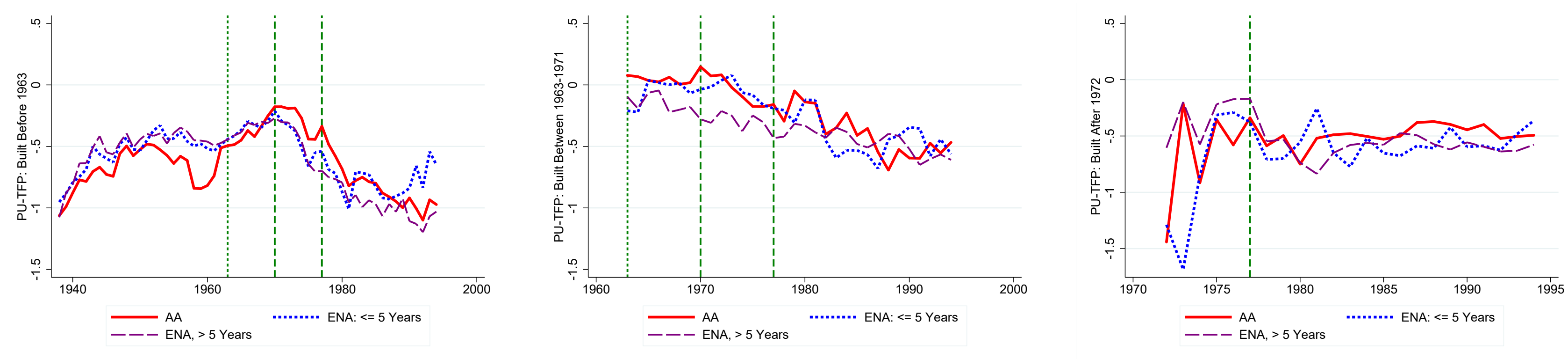
Notes: This figure documents annual total electricity generation and annual total electricity generating capacity for fossil-fuel-fired power plants in the United States. We consider three vintage categories based on whether the plant was built before 1963, between 1963-1971, or after 1972. We consider three regulatory status categories: always-attainment (AA) – counties that never went out of attainment with the NAAQS for any pollutant between 1938-1994; ever-nonattainment for less than five years (ENA, $\leq$5 Years) – counties that went out of attainment with the NAAQS for less than five years between 1938-1994; and ENA for more than five years (ENA, >5 Years) – counties that went out of attainment with the NAAQS 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.7: Annual Average Total Factor Productivity for Fossil-Fuel Power Plants by Vintage and Attainment Status



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

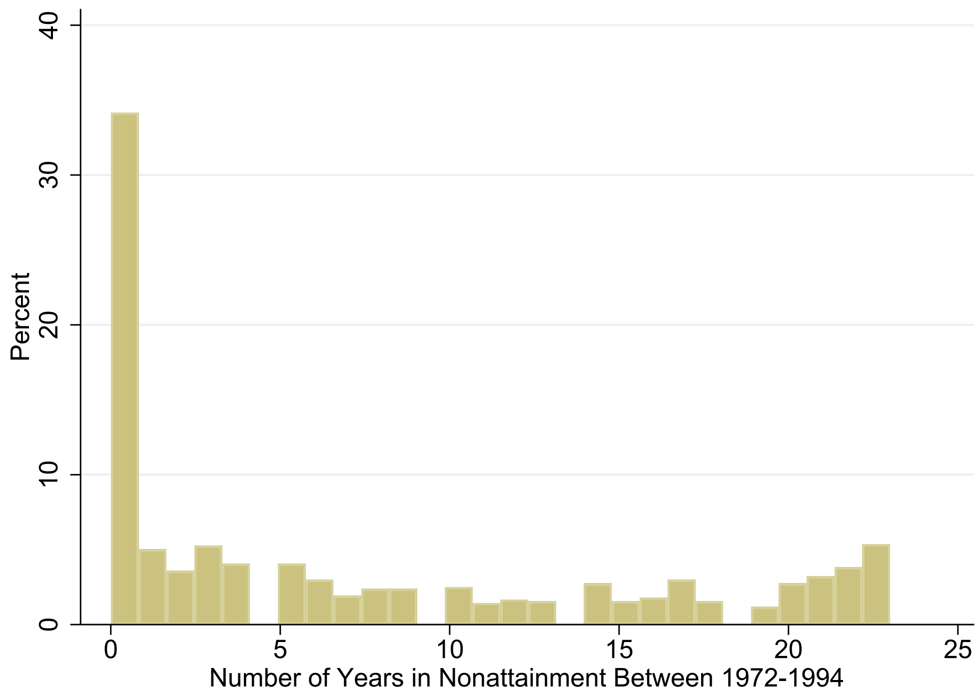
Figure C.8: Annual Average Total Factor Productivity for Fossil-Fuel Power Plants by Vintage and Years in Nonattainment



(a) PU-TFP – Built Before 1963 (b) PU-TFP – Built Between 1963-1971 (c) PU-TFP – Built After 1972

Notes: This figure documents annual average pollution-unadjusted total factor productivity (PU-TFP) for fossil-fuel-fired power plants in the United States. We consider three vintage categories based on whether the plant was built before 1963, between 1963-1971, or after 1972. We consider three regulatory status categories: "always-attainment" (AA) – counties that never went out of attainment with the NAAQS for any pollutant between 1938-1994; "ever-nonattainment" for less than five years (ENA, $\leq$5 Years) – counties that went out of attainment with the NAAQS for less than five years between 1938-1994; and ENA for more than five years – counties that went out of attainment with the NAAQS 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.9: County-Level Distribution of the Number of Years Facing 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, considering only counties that were home to at least one fossil-fuel power plant in our sample spanning 1938-1994.

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 1963-1971	Built After 1972
Always Attainment	197	46	147
Ever Nonattainment	372	81	97
Total	569	127	244
Panel B. Proportion By Vintage			
	Built Before 1963	Built Between 1963-1971	Built After 1972
Always Attainment	0.35	0.36	0.60
Ever Nonattainment	0.65	0.64	0.40

Notes: The top panel of this table lists the number of fossil-fuel-fired power plants in our sample in each cell defined by the intersection of attainment status and vintage. The bottom panel lists the proportion of plants in a given vintage group in each attainment status. The first row of each panel focuses on plants that never faced nonattainment between 1972-1994 while the second row focuses on plants that faced nonattainment at least once between 1972-1994. The first, second and third columns of each panel consider plants built before 1963, plants built between 1963-1971, and plants built after 1972 respectively.

Table C.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*	6,630	600
Nonattainment in Year *t-1*	335	5,398
Panel B. Conditional Probability		
	Attainment in Year t	Nonattainment in Year t
Attainment in Year *t-1*	0.92	0.08
Nonattainment in Year *t-1*	0.06	0.94

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

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

Panel A: Power Plant Operations, Sample Period 1938-1994			
Variable	**No. of Obs.**	**Mean**	**Std. Dev.**
Log Pollution-Unadjusted Total Factor Productivity	21,767	-0.56	0.76
Electricity Output (GWh)	21,767	1,858.67	2,403.47
Electricity Generating Capacity (MW)	21,767	435.09	502.63
Number of Employees	21,767	127.28	126.44
Fuel Burned (in Billion BTU)	21,767	19.32	30.03
Panel B: Indicator for NAAQS Noncompliance, Sample Period 1972-1994			
Variable	**No. of Obs.**	**Mean**	**Std. Dev.**
1[Out of Attainment with any NAAQS]	10,374	0.51	0.50
1[Out of Attainment with NAAQS: TSP or PM]	10,374	0.17	0.38
1[Out of Attainment with NAAQS: SO_2]	10,374	0.05	0.22
1[Out of Attainment with NAAQS: CO]	10,374	0.12	0.33
1[Out of Attainment with NAAQS: O_3 or NO_2]	10,374	0.41	0.49

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

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

Dep. Var.: Log Output	(1)	(2)	(3)	(4)
Panel A. Estimated Parameters				
Log Labor (l)	1.712***	2.137***	0.309***	0.313***
	(0.003)	(0.011)	(0.000)	(0.014)
Log Capacity (k)	0.193***	-0.335***	0.903***	0.961***
	(0.003)	(0.012)	(0.000)	(0.033)
l × l	-0.183***	-0.126***		
	(0.003)	(0.006)		
l × k	0.066***	-0.155***		
	(0.000)	(0.012)		
k × k	0.023**	-0.012		
	(0.009)	(0.012)		
Functional Form	Translog	Translog	Cobb-Douglas	Cobb-Douglas
Includes Nonfuel Cost?		Y		Y
Number of Obs.	24,749	24,384	24,749	24,384
Number of Plants	940	935	940	935
Panel B. Post-Estimation Elasticities				
Log Employees	0.42	0.28	0.31	0.31
Log Capacity	0.74	0.89	0.90	0.96
Log Nonfuel Expenses		0.07		0.03

Notes: This table reports the production function estimates that are used to construct pollution-unadjusted total factor productivity (PU-TFP). Panel A presents the estimated parameters of the production function with capital (electricity generating capacity), labor (average number of employees), and fuel (the heat input in mmBTU from the fuel burned) using the estimation procedure developed by Ackerberg, Caves and Frazer (2015). We use two functional forms – Translog and Cobb-Douglas and two specifications – with and without nonfuel cost, which refers to all operating expenses other than those associated with fuel. Our preferred specification, which is the basis for the PU-TFP measure used in the main analysis, is presented in column 1. Panel B reports implied elasticities for each input. The unit of observation for all of these analyses is plant-year. *** denotes statistical significance at the 1% level, ** at the 5% level, and * at the 10% level. Standard errors in parentheses are calculated by bootstrapping.

D Additional Results

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

Appendix Figure D.1 examines how the estimated impacts of nonattainment on power plant outcomes for plants of different vintages vary by the first year of data in the analysis. This figure highlights the importance of utilizing data from well before the Clean Air Act (CAA) of 1970 or even the 1963 CAA.

Appendix Table D.1 reports the estimated impacts of nonattainment on power plant outcomes for more granular vintage groups. For reference, the main analysis estimates separate effects only for plants built before 1963 versus plants built between 1963-1971. Appendix Table D.2 presents robustness checks of the estimated impacts of nonattainment on log output and log PU-TFP using alternative econometric specifications and sample restrictions. Appendix Table D.3 reports the results of the Goodman-Bacon decomposition. These results indicate that the bulk of the impacts of first-nonattainment on outcomes come from a comparison of plants that ever versus never faced nonattainment between 1972-1994. This highlights again the importance of estimating the effects of nonattainment including data from before the implementation of the CAA in 1972.

Appendix Table D.4 checks whether the estimated impact of nonattainment on pollution-unadjusted total factor productivity (PU-TFP) changes if we estimate PU-TFP including a measure of input materials or consider alternative production functions. Appendix Table D.5 examines the heterogeneity of the main results by the plant's primary fuel type. Appendix Table D.6 investigates the effects of nonattainment with the standards for specific pollutants rather than focusing on nonattainment with any pollutant standard.

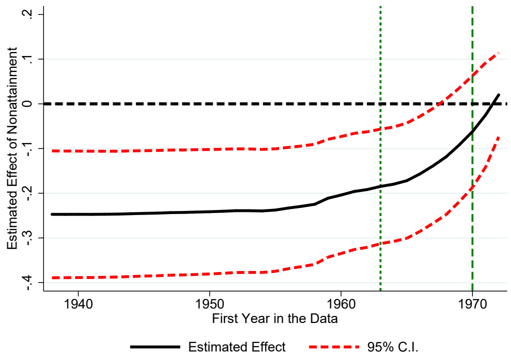
Appendix Table D.7 reports heterogeneous impacts of nonattainment by the first year that the county faces nonattainment, These results suggest again that the bulk of the impacts are driven by the initial county-level designations of attainment status in 1972. Appendix Table D.8 examines how annual statewide electricity generating capacity by source responds to the proportion of counties in nonattainment in the state in the year.

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

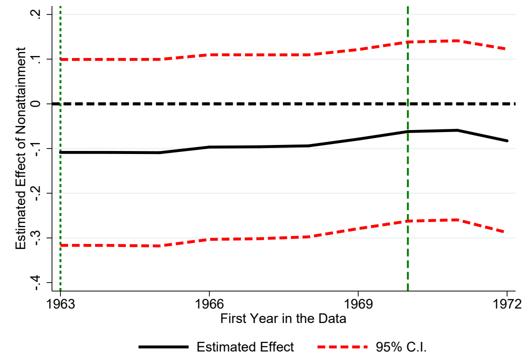
- Figure D.1. Impacts of Nonattainment on Power Plant Outcomes by Vintage and Initial Sample Year

- 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. Impacts of Nonattainment on PU-TFP Estimated Using 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 on Plant Outcomes By Pollutant Standard
- Table D.7. Impacts of Nonattainment on Power Plant Outcomes by First Year in Nonattainment
- Table D.8. Impact of Proportion of Counties in Nonattainment on State-Level Capacity

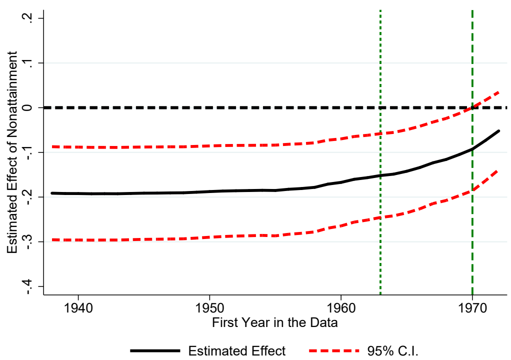
Figure D.1: Impacts of Nonattainment on Power Plant Outcomes by Vintage and Initial Sample Year



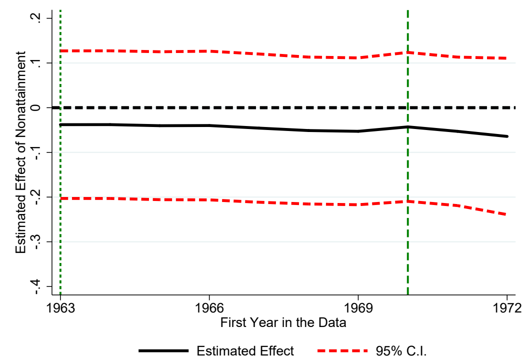
(a) Effects on Log Output – Built Before 1963



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



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



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

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. Namely, for initial year X on the x-axis, we artificially restrict the sample period used to estimate the relevant effect to X-1994 (ex: the effect for initial year 1950 is estimated using data from 1950-1994). We estimate these effects using only data from plants built before 1963 for the two left panels and plants built between 1963-1971 for the two right panels. 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, and fuel-type-by-year fixed effects. 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[Built Before 1955]	-0.226**	-0.174***	-0.155*	-0.040	-0.118**
	(0.085)	(0.062)	(0.078)	(0.039)	(0.051)
NA × 1[Built Between 1955-1962]	-0.289***	-0.213***	-0.112	0.013	-0.116*
	(0.089)	(0.068)	(0.090)	(0.055)	(0.069)
NA × 1[Built Between 1963-1966]	-0.078	0.095	-0.028	-0.125	-0.121
	(0.134)	(0.094)	(0.140)	(0.087)	(0.078)
NA × 1[Built Between 1967-1971]	-0.082	-0.083	-0.012	0.024	0.008
	(0.115)	(0.106)	(0.087)	(0.053)	(0.051)
R^2	0.822	0.608	0.752	0.870	0.915
Mean of Dep. Var.	6.730	-0.562	9.155	4.489	5.462
Number of Obs.	21,767	21,767	21,767	21,767	21,767
Number of Plants	687	687	687	687	687
Plant FE	Y	Y	Y	Y	Y
State By Year FE	Y	Y	Y	Y	Y
Fuel Type By Year FE	Y	Y	Y	Y	Y
Vintage Group By Year FE	Y	Y	Y	Y	Y

Number of Plants by Vintage Group: There are 399 plants built before 1955, 161 plants built between 1955 and 1962, 67 plants built between 1963 and 1967, and 60 plants built between 1967 and 1971.

Notes: This table reports the impacts of nonattainment on power plant operations 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. In contrast, the specifications in this table present separate estimates for vintage groups defined by whether the plant was built before 1955, between 1955-1962, between 1963-1966, or between 1967-1971. The unit of observation for the regressions in this table is plant-year, and the estimation considers all plants that were built before 1972. For all specifications, "nonattainment" (NA) 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. 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: Impacts of Nonattainment on Power Plant Outcomes from Alternative Specifications and Samples

	(1) Primary	(2) Larger	(3) Coal	(4) Utility-State By Year FE	(5) No State Standard
Panel A. Log Output					
NA × 1[Built Before 1963]	-0.247***	-0.246***	-0.277***	-0.110	-0.313***
	(0.071)	(0.079)	(0.093)	(0.066)	(0.085)
NA × 1[Built Between 1963-1971]	-0.060	-0.003	0.040	0.040	-0.009
	(0.091)	(0.081)	(0.084)	(0.086)	(0.109)
R^2	0.818	0.775	0.837	0.856	0.825
Mean of Dep. Var.	6.730	7.100	6.946	6.864	6.725
Panel B. Log PU-TFP					
NA × 1[Built Before 1963]	-0.187***	-0.154***	-0.192***	-0.091*	-0.205***
	(0.052)	(0.055)	(0.060)	(0.050)	(0.062)
NA × 1[Built Between 1963-1971]	0.020	0.079	0.096	0.061	0.003
	(0.074)	(0.062)	(0.058)	(0.067)	(0.085)
R^2	0.605	0.619	0.609	0.731	0.619
Mean of Dep. Var.	-0.562	-0.529	-0.538	-0.565	-0.584
Number of Obs.	21,767	17,327	13,942	21,664	16,275
Number of Plants	687	507	421	687	497
Plant FE	Y	Y	Y	Y	Y
Utility By State By Year FE				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: The top and bottom panels of this table present estimates of the impact of nonattainment on log output and the log of pollution-unadjusted total factor productivity (PU-TFP) respectively. The unit of observation for these regressions is plant-year, considering only plants built before 1972. We estimate separate effects for plants built before 1963 and plants built between 1963-1971. For all specifications, "nonattainment" (NA) is defined as the 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 and fuel-type-by-year fixed effects. The specification considered in Column 5 additionally includes utility-by-state-by-year fixed effects, noting that this eliminates the need to include state-by-year fixed effects. For Column 2, 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 3 focuses only on coal-fired plants. Column 5 drops plants located in the ten states that had state-level air quality standards by 1966 – California, Colorado, Delaware, Missouri, Montana, New York, Oregon, Pennsylvania, South Carolina, and Texas (Stern, 1982). Standard errors in parentheses are 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	-0.133	-0.035	0.062	-0.027	-0.101
DD Est.: T vs. Never Treated	-0.172	-0.052	0.099	-0.016	-0.128
DD Est.: Earlier T vs. Later C	-0.157	-0.010	0.041	-0.109	-0.135
DD Est.: Later T vs. Earlier C	0.061	-0.011	-0.049	0.066	0.056
Weights: T vs. Never Treated	0.597	0.597	0.597	0.597	0.597
Weights: Earlier T vs. Later C	0.251	0.251	0.251	0.251	0.251
Weights: Later T vs. Earlier C	0.153	0.153	0.153	0.153	0.153
Number of Obs.	3,948	3,948	3,948	3,948	3,948
Number of Plants	188	188	188	188	188

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. For all specifications, "first nonattainment" is an indicator variable that is equal to one for each year on or after the first year that the plant faced nonattainment with the NAAQS for any pollutant. The Goodman-Bacon method decomposes the overall difference-in-differences ("DD") effect of first nonattainment into three components: (i) counties that ever 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 before and after 1972. We also only consider observations in the 10 years before and after 1972. Plant-year observations must have data listed for output, electricity generating capacity, number of employees, and input energy for the whole 20 year span in order to be included.

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

Dep. Var.: Log PU-TFP	(1)	(2)	(3)	(4)
NA × 1[Built Before 1963]	-0.180***	-0.168***	-0.130***	-0.120***
	(0.050)	(0.047)	(0.045)	(0.044)
NA × 1[Built Between 1963-1971]	0.017	-0.007	0.024	0.004
	(0.074)	(0.074)	(0.075)	(0.076)
R^2	0.603	0.606	0.609	0.625
Mean of Dep. Var.	-0.562	-1.900	0.411	-0.147
Number of Obs.	21,767	21,535	21,767	21,535
Number of Plants	687	687	687	687
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 estimates of the impact of nonattainment on pollution-unadjusted total factor productivity (PU-TFP). The unit of observation for these regressions is plant-year, considering only plants built before 1972. We estimate separate effects for plants built before 1963 and plants built between 1963-1971. For all specifications, "nonattainment" (NA) is defined as the county being out of attainment with the NAAQS for any pollutant in the year. We estimate PU-TFP using the methodology developed by Ackerberg, Caves and Frazer (2015). The first two columns estimate PU-TFP assuming that the function relating capital and labor to output is translog while the next two columns are based on the assumption that this function is Cobb-Douglas (CD). Finally, the even columns include nonfuel expenditures as a measure of materials when estimating PU-TFP while the odd columns estimate PU-TFP without including any measure of materials. Standard errors in parentheses are 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]	-0.288***	-0.159***	-0.228***	-0.103**	-0.153***
	(0.083)	(0.054)	(0.077)	(0.040)	(0.051)
NA × 1[Oil Plant]	-0.069	-0.049	0.015	0.046	-0.122
	(0.192)	(0.092)	(0.198)	(0.125)	(0.148)
NA × 1[Gas Plant]	-0.102	-0.173*	0.071	0.116*	-0.010
	(0.115)	(0.094)	(0.112)	(0.059)	(0.068)
R^2	0.818	0.604	0.747	0.860	0.912
Mean of Dep. Var.	6.730	-0.562	9.155	4.489	5.462
Number of Obs.	21,767	21,767	21,767	21,767	21,767
Number of Plants	687	687	687	687	687
Plant FE	Y	Y	Y	Y	Y
State By Year FE	Y	Y	Y	Y	Y
Fuel Type By Year FE	Y	Y	Y	Y	Y
Vintage Group By Year FE	Y	Y	Y	Y	Y

Number of Plants by Primary Fuel Type: Focusing on plants built before 1972, there are 421 coal-fired plants, 70 oil-fired plants, and 196 gas-fired plants.

Notes: This table measures how annual plant-level outcomes change with nonattainment interacted with three bins associated with whether the primary fuel burned by the plant was coal, natural gas, or oil. The fuel type is specified as "primary" if the plant's aggregate total heat input in mmBTU from the fuel type divided by the plant's aggregate total heat input in mmBTU from all fuel types is greater than 1/3. 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 plant-year, considering only plants built before 1972. 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 on Plant Outcomes By Pollutant Standard

	(1)	(2)	(3)	(4)	(5)
Dep. Var. (in Logs)	Output	PU-TFP	Fuel Use	No. Employees	Capacity
NA: TSP or PM	-0.030	-0.051	-0.031	0.013	0.010
	(0.038)	(0.034)	(0.046)	(0.025)	(0.029)
NA: SO2	-0.045	-0.021	-0.008	-0.013	-0.032
	(0.084)	(0.055)	(0.079)	(0.039)	(0.048)
NA: CO	-0.165*	-0.031	-0.090	-0.121***	-0.141**
	(0.095)	(0.061)	(0.087)	(0.045)	(0.054)
NA: O_3 or NO_2	-0.155**	-0.137***	-0.081	0.003	-0.058
	(0.064)	(0.049)	(0.063)	(0.032)	(0.041)
R^2	0.818	0.604	0.746	0.860	0.912
Mean of Dep. Var.	6.730	-0.562	9.155	4.489	5.462
Number of Obs.	21,767	21,767	21,767	21,767	21,767
Number of Plants	687	687	687	687	687
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 the NAAQS associated with each of four sets of pollutants: total suspended particulates or particulate matter (TSP or PM), sulfur dioxide (SO_2), carbon monoxide (CO), and nitrogen dioxide or ozone (NO_2 or O_3). There are separate standards for O_3 and NO_2, but we group these two standards together because the vast majority of counties that were in nonattainment for NO_2 were also in nonattainment for O_3. PU-TFP stands for pollution-unadjusted total factor productivity, and NA for nonattainment. The unit of observation for these regressions is plant-year, considering only plants built before 1972. 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 Outcomes by First Year in Nonattainment

	(1)	(2)	(3)	(4)	(5)
Dep. Var. (in Logs)	Output	PU-TFP	Fuel Use	No. Employees	Capacity
NA × First NA in 1972-1977	-0.260***	-0.171***	-0.157**	-0.048	-0.139***
	(0.068)	(0.047)	(0.065)	(0.033)	(0.044)
NA × First NA in 1978-1983	0.101	-0.068	0.136	0.142*	0.128
	(0.140)	(0.115)	(0.123)	(0.076)	(0.098)
NA × First NA in 1984-1994	0.058	0.146	0.047	-0.015	0.068
	(0.253)	(0.186)	(0.253)	(0.251)	(0.115)
R^2	0.818	0.605	0.747	0.860	0.913
Mean of Dep. Var.	6.730	-0.562	9.155	4.489	5.462
Number of Obs.	21,767	21,767	21,767	21,767	21,767
Number of Plants	687	687	687	687	687
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 that the county the plant was located in went out of nonattainment was in 1972-1977, 1978-1983 or 1984-1994. 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 plant-year, considering only plants built before 1972. 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: Impact of Proportion of Counties in Nonattainment on State-Level Capacity

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

Notes: This table presents estimates of the impact of annual state-level proportion of counties in nonattainment on annual state-level electricity generating capacity. Specifically, the independent variable of interest is the population-weighted proportion of counties in the state in nonattainment with the NAAQS for any pollutant in each year. The unit of observation for these regressions is state-year, excluding Alaska and Hawaii. All specifications include state fixed effects and year fixed effects. The dependent variable considered in Columns 1, 2, 3 and 4 is the annual state-level electricity generating capacity aggregating over fossil-fuel-fired sources using either steam turbines or internal combustion, fossil-fuel-fired sources using either gas turbines or a combined-cycle technology, nuclear sources, and hydro sources respectively. 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.