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Evaluating the Efficacy of Ambient Air Quality Standards at Coal-Fired Power Plants

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This study evaluates the health benefits and abatement costs of the $PM_{2.5}$ National Ambient Air Quality Standards (NAAQS) at coal-fired power plants. We find that the emission reductions from the $PM_{2.5}$ NAAQS between 1995 and 2016 are sizable and that the health benefits from these reductions far exceed the abatement expenditures of affected plants. We then use this *ex post* analysis to simulate future health benefits and abatement costs in this sector from more stringent $PM_{2.5}$ standards. Our policy simulation shows that tightening these standards to levels recommended by the World Health Organization also passes a benefit-cost test.

Key words: health benefits, National Ambient Air Quality Standards, Particulate Matter, policy simulation

Introduction

As part of the Clean Air Act (CAA), the U.S. Environmental Protection Agency (EPA) created the National Ambient Air Quality Standards (NAAQS), which set allowable ambient air concentrations of six criteria pollutants.[1] Areas with ambient air concentrations of these pollutants that exceed standard levels are designated as "nonattainment" and are required to reduce emissions to "attain" the standards. One specific criteria air pollutant, particulate matter (PM), is of noteworthy concern. PM is distinct from other criteria pollutants because particles can be suspended in the air for long periods of time (Idaho Department of Environmental Quality, 2018). The adverse health effects of PM exposure are also serious and can occur from both short- and long-term exposure (Atkinson et al., 2014). Emissions of sulfur dioxide (SO_2) and nitrogen oxide (NO_x) are the primary precursors of ambient PM concentrations due to their reaction with other chemicals. While SO_2 and NO_x emissions come from a variety of sources, coal-fired power plants are one of the largest contributors (U.S. Environmental Protection Agency, 2018b). Thus, the NAAQS mandate SO_2 and NO_x abatement requirements for plants located in areas that do not meet the PM standards. These requirements are designed to reduce emissions and subsequently ambient PM concentrations.

In this study, we examine the health benefits and abatement costs of the $PM_{2.5}$ NAAQS within the coal-fired electric utility sector from a retrospective and prospective outlook.[2] We first perform an *ex post* analysis by identifying a causal effect of the $PM_{2.5}$ standards on SO_2 and NO_x emissions at coal-fired power plants. We then use these emission reductions to identify the benefits to human health as a direct result of the standards. We compare these benefits to the costs of abatement

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[1] Carbon monoxide (CO), lead (Pb), ground level ozone (O_3), nitrogen dioxide (NO_2), sulfur dioxide, and particulate matter.

[2] $PM_{2.5}$ are particulates with a diameter of 2.5 microns or less.

technology required at plants located in areas designated as nonattainment. This retrospective analysis is similar to previous studies examining the benefits and costs of environmental regulations after their promulgation (Kopits et al., 2014; Wolverton, Ferris, and Simon, 2019). We then use the recommendations of the World Health Organization (WHO) and EPA data to propose a tightening of the current $PM_{2.5}$ NAAQS. We simulate from this proposal a scenario where the NAAQS for $PM_{2.5}$ are adjusted and determine the health benefits and abatement costs from this policy shift.

Identifying the health benefits from emission reductions is challenging, but recently estimated benefits are considerable (e.g., Janke, Propper, and Henderson, 2009). Fann, Baker, and Fulcher (2012) estimate the average lifetime health benefit of a one-time, 1-ton reduction of electricity generating unit (EGU) emissions in 2016 to be $35,000 for SO_2 and $5,200 for NO_x (in 2010$).[3] Importantly, EGU emission controls have generated the greatest reductions in total emissions throughout the United States (U.S. Environmental Protection Agency, 2011b). EPA's *ex ante* analysis finds that the Mercury and Air Toxics Standards (MATS) for emissions at coal- and oil-fired electric utilities would result in net benefits of between $27 billion and $80 billion in the United States (U.S. Environmental Protection Agency, 2011a). For the CAA, expenditures on emission controls are substantial, but research shows an overall net benefit since the 1990 CAA Amendments.[4] The overall value of emission reductions (including EGUs and other sources) as estimated by U.S. Environmental Protection Agency (2011b) "vastly exceeds the cost of efforts to comply with the requirements of the 1990 Clean Air Act Amendments."

This study adds to the literature a policy relevant, *ex post* and *ex ante* examination of the health benefits and abatement costs of the $PM_{2.5}$ NAAQS at coal-fired electric utilities. First, we find that the $PM_{2.5}$ NAAQS have produced over $32 billion in public health benefits via emission decreases over the past 2 decades while costing utilities only $14 billion in abatement. Previous studies focus on ambient air quality changes at the aggregated (Greenstone, 2004) and disaggregated (Chay and Greenstone, 2003; Auffhammer, Bento, and Lowe, 2009) level, while we focus on emissions at the micro level and incorporate a discussion of abatement costs. Second, we use WHO air quality recommendations and current air quality conditions in the United States to propose two new sets of $PM_{2.5}$ standards. We then examine which areas with coal-fired power plants located within them would enter into nonattainment with our proposed standards and simulate SO_2 and NO_x emission reductions that we expect to occur at these plants as a result. We find that lowering the threshold for nonattainment designation to 10 $\mu g/m^3$ (annual mean) and 25 $\mu g/m^3$ (24-hour) would produce estimated health benefits of $655.3 million and lowering the threshold to 8 $\mu g/m^3$ (annual mean) and 25 $\mu g/m^3$ (24-hour) would produce estimated health benefits exceeding $1.9 billion. Overall, we find that the public health benefits of the proposed changes far outweigh the private abatement costs, both in the short and the long term.

Background

This section outlines the necessary background information for our study. We first describe the NAAQS and provide a preliminary examination of emissions at coal-fired power plants and then review the relationship between PM and human health.

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[3] Similar work by Fann, Fulcher, and Hubbell (2009) analyzing EGUs shows that a 1-ton reduction of SO_2 emissions yields $82,000 in benefits, while a 1-ton reduction of NO_x emissions yields, on average, a $15,000 benefit. The National Academy of Sciences estimates the average benefit from EGU emission reductions to be $13,000 for SO_2 and $2,200 for NO_x (National Academy of Science, 2009). EPA's Clean Power Plan estimates the average benefit (at EGUs) of a 1-ton reduction of SO_2 to be between $31,481 and $70,370 and a 1-ton reduction of NO_x to be between $2,833 and $6,500 U.S. Environmental Protection Agency (2015).

[4] U.S. Environmental Protection Agency (2011b) estimates the benefit-to-cost ratio from the CAA to be 4:1, which corresponds to roughly $52 billion in net benefits from emission reductions. These estimates are for all CAA programs, not only those for stationary sources.

Table 1. Historical $PM_{2.5}$ NAAQS

Year	Average time	Level	Form
1997, 2005	24-hour	65 μg/m^3	98th percentile, averaged over 3 years
1997, 2005	Annual	15 μg/m^3	Annual arithmetic mean, averaged over 3 years
2006, 2009	24-hour	35 μg/m^3	98th percentile, averaged over 3 years
2012, 2015	Annual	12 μg/m^3	Annual arithmetic mean, averaged over 3 years

Notes: The first year listed is the year in which the updated Final Rule was published in the *Federal Register*. The second year listed is the year in which areas were first designated as nonattainment under the new standards.

The NAAQS and Emission Trends

As part of the NAAQS, locations unable to achieve ambient air concentrations outlined by the standards are designated as nonattainment areas. Once a location is designated as nonattainment, additional regulatory actions are undertaken (e.g., increased monitoring, abatement technology installation). State Implementation Plans (SIP) are required for areas designated as nonattainment, which can include additional requirements (e.g., plant-specific emission limits for local emission sources, Walker, 2013). Several studies evaluate the effects of nonattainment status on emissions and ambient air quality and show that ambient air standards reduce emissions (Greenstone, 2004; Bi, 2017; Gibson, 2019; Raff and Walter, 2020).

The process to update the NAAQS is lengthy, but the CAA requires that the NAAQS for each criteria pollutant protect public health and the environment (U.S. Environmental Protection Agency, 2018c). The standards for PM have evolved since their creation by changing allowable ambient concentration levels and the form of PM measured. The initial NAAQS for PM required that total suspended particulates (TSP) not exceed 260 μg/m^3 on average over a 24-hour period, more than once per year. EPA has since shifted its focus on TSP to a more hazardous pollutant: $PM_{2.5}$.[5] Table 1 describes the history of the $PM_{2.5}$ standards.

The most recent update of the $PM_{2.5}$ standards occurred in 2012; as of 2016 only 20 coal-fired power plants remained in nonattainment areas. U.S. Environmental Protection Agency (2011b) projects that overall $PM_{2.5}$ emissions are expected to remain flat between 2010 and 2020, although estimates for the rate of emission reductions of SO_2, NO_x, and $PM_{2.5}$ between 2010 and 2020 are lower than those for the previous decade. U.S. Environmental Protection Agency (2011b) does not expect further "substantial" emission reductions of $PM_{2.5}$ from EGU compliance stemming from the 1990 CAA amendments. In the absence of $PM_{2.5}$ health-related damages, acceptance of the status quo or current emission levels is appropriate. However, if further emission reductions and health benefits are possible, examination of the current NAAQS is warranted.

We examine the trends of SO_2 and NO_x emissions at coal-fired power plants in Figure 1. The figure also provides vertical lines where the $PM_{2.5}$ NAAQS policy changes were implemented (identified in Table 1). The figure provides preliminary evidence that the emission decreases in this sector over the past 20 years can be attributed at least partially to the tightening of the $PM_{2.5}$ standards. As one example, both emission trends were stagnating or increasing during the 5 years leading up to the first $PM_{2.5}$ standard, which went into effect in 2005. After areas were initially listed as nonattainment for $PM_{2.5}$ and the regulatory requirements of this listing went into effect, emissions decreased and continued to do so for at least the next 10 years. The following sections test these relationships more formally.

[5] For a description of the different forms of particulate pollutants and a history of all particulate standards, see https://www.epa.gov/pm-pollution.

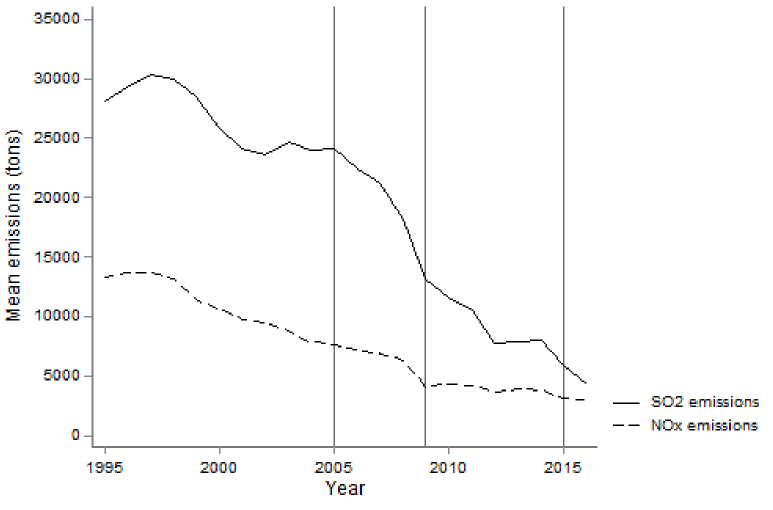

Figure 1. SO_2 and NO_x Emission Trends, 1995–2016

Notes: Trends are mean facility level emissions of SO_2 and NO_x at coal-fired power plants. Vertical lines represent the years in which counties were first designated as nonattainment for the three $PM_{2.5}$ standards identified in Table 1.

Health Effects of PM and Its Precursors

The relationship between PM, its precursors, and human health is well studied. Gaseous pollutants like SO_2 and NO_x can cause cardiopulmonary diseases (Cao et al., 2011), respiratory and hematological problems, and cancer (Kampa and Castanas, 2008). The photochemical reaction of converting SO_2 and NO_x gases into aerosol sulfate and nitrate is an important process for secondary $PM_{2.5}$ formation (Lee, Chang, and Kim, 2018). Since ambient PM is often produced by reactions that include SO_2 and NO_x, EPA uses SO_2 and NO_x emission reductions as part of its National $PM_{2.5}$ Control Strategy (National Research Council, 2005). Ambient PM's negative health effects (e.g., respiratory and heart problems, natural-cause mortality, Seaton et al., 1995), are pervasive, impacting healthy young adults and the elderly (Shaughnessy, Venigalla, and Trump, 2015). The health impacts of PM inhalation depend critically on particle size, which is a primary determinant for deposition in the respiratory tract, with inhalability decreasing as the diameter of a particle increases above 1 micron (U.S. Environmental Protection Agency, 2018b).

Epidemiological studies of $PM_{2.5}$ have shown adverse health effects from even short-term exposure (Rückerl et al., 2011; Atkinson et al., 2014) and the WHO's health assessments of ambient air pollutants provide the scientific basis for formulating policy actions to improve air quality (Héroux et al., 2015). Further, EPA's benefit–cost analysis of the CAA estimates that decreased $PM_{2.5}$ emissions reduced 2010 adult mortalities by 160,000 cases (U.S. Environmental Protection Agency, 2011b). Decreases in ambient $PM_{2.5}$ are also associated with a reduction in bronchitic symptoms in children (Berhane et al., 2016). Overall, the integrated science assessment (ISA) for PM observes a consistent relationship between decreasing $PM_{2.5}$ concentrations and improved respiratory health (U.S. Environmental Protection Agency, 2018b). Using an integrated planning model (IPM) to analyze the final MATS, U.S. Environmental Protection Agency (2011a) finds that environmental programs for $PM_{2.5}$- related emissions at coal- and oil-fired electric utilities could result in welfare gains of \$36–\$89 billion. Finally, Muller and Mendelsohn (2009) use a reduced-form dispersion model and find that efficient environmental programs for SO_2 ($PM_{2.5}$) could result in welfare gains of \$5–\$20 billion (\$50–\$200 billion) annually.[6]

Empirics

This section includes the empirical analysis used to perform an *ex post* examination of the health benefits and abatement costs of the $PM_{2.5}$ NAAQS at coal-fired power plants over the past 2 decades. We first estimate the effect of $PM_{2.5}$ nonattainment on SO_2 and NO_x emissions at coal-fired power plants. We then use these estimates to identify the health benefits created by the standards within this sector. Finally, we compare these benefits to the abatement costs borne by affected plants.

Data

For our analysis, we primarily use the Air Markets Program Database (AMPD), an EPA data source that contains boiler-level characteristics of all facilities that serve a generator that is greater than 25 megawatts (MW). The AMPD includes boiler-level emissions of SO_2 and NO_x, measured in tons, and information on each plant's location, generating capacity, relevant programs under which the boiler is regulated, and other characteristics. Because we examine total output of SO_2 and NO_x emissions, we collect data at the facility level.

From the AMPD, we create a panel of facility-years for 1995–2016. We are interested in the largest emitters of SO_2 and NO_x: coal-fired power plants. To focus on these emitters, we trim the panel to include only those facilities classified as "electric utility," "cogeneration," or "small power producer."

For nonattainment designations, we use the EPA Green Book, which contains county-level nonattainment status for six criteria air pollutants designated by the CAA from 1992 to 2016. Nonattainment status, specifically for $PM_{2.5}$, represents our treatment category (we also use two other forms of nonattainment as controls). Ambient air concentration levels necessary for nonattainment designation have changed several times since the implementation of the NAAQS. Additionally, counties can enter and exit nonattainment yearly based on ambient concentrations of $PM_{2.5}$. Thus, our identification rests on the variation in ambient air quality over time as well as variation in the standards over time.

We use the League of Conservation Voters (LCV) yearly scorecards to proxy for the regulatory stringency placed on facilities in each state (Bi, 2017). Each year, the LCV publishes a ranking of the level of pro-environmentalism of each state's congressional delegation. The measure ranges from 0 to 100, with 0 (100) representing the least (most) environmentally conscious electorate.

Table 2 reports sample summary statistics for the measures used in our analysis. Just over 10% of facility-years are located in a $PM_{2.5}$ nonattainment area during the sample period.[7] However, in 2016, less than 5% of facilities were located in a $PM_{2.5}$ nonattainment area.

Finally, we use EPA's Air Quality System (AQS) for ambient air pollutant concentrations. AQS contains air quality monitoring data for locations throughout the United States for several pollutants. We gather ambient $PM_{2.5}$ concentrations for the United States and use these values to determine which counties are in nonattainment with adjusted NAAQS for $PM_{2.5}$. Similar to how EPA establishes standards, we take the arithmetic mean and 24-hour 98th percentile readings from AQS and average these values over the 3 most recent years (2015–2017), at the county level.

[6] Rückerl et al. (2011) provide an extensive review of the epidemiological literature and quantify the number of short- and long-term studies showing the health outcomes associated with $PM_{2.5}$ exposure.

[7] The sample contains data for 492 coal-fired power plants that operated for at least 1 year during the period of 1995–2016. These plants are located in 392 counties, 92 of which experienced a change in $PM_{2.5}$ nonattainment designation at some point over the sample period.

Table 2. Sample Summary Statistics

Variable	Mean	Std. Dev.	Min	Max
Dependent variables				
Tons of SO_2 emitted (logged)	8.880	1.828	−6.215	12.56
Tons of NO_x emitted (logged)	8.129	1.540	−6.215	12.07
Treatment				
$PM_{2.5}$ nonattainment	0.102	0.303	0	1
Control factors				
SO_2 nonattainment	0.037	0.188	0	1
O_3 nonattainment	0.211	0.408	0	1
CAA Title IV Acid Rain Program	0.988	0.109	0	1
Cross-State Air Pollution SO_2 Program (Group 1)	0.044	0.204	0	1
Cross-State Air Pollution SO_2 Program (Group 2)	0.014	0.118	0	1
Cross-State Air Pollution NO_x Program	0.058	0.233	0	1
SIP NO_x Program	0.005	0.068	0	1
NO_x Budget Program	0.166	0.372	0	1
Maximum capacity (MW)	548.2	782.9	0	7636
Total electrical generation (GW-h)	3.4*e*6	4.6*e*6	0	2.7*e*7
House LCV score (0-100)	40.01	19.66	0	100
Senate LCV score (0-100)	43.64	32.46	0	100

Notes: Nonattainment designations represent a county that is in nonattainment for a given criteria air pollutant in a given year. Regulatory programs indicate that a facility is a part of that program in a given year.

Estimating the Effect of $PM_{2.5}$ Nonattainment on Emissions at Coal-Fired Power Plants

We next estimate the effect of $PM_{2.5}$ nonattainment status on SO_2 and NO_x emissions at facilities in our sample. Our econometric analysis uses facility and year fixed effects and control variables to estimate the effect of lagged $PM_{2.5}$ nonattainment on emissions of SO_2 and NO_x at coal-fired power plants.[8] Identification relies on variation over time of nonattainment status, which can change for one of two reasons: (i) the air quality standard changes or (ii) the ambient concentration of $PM_{2.5}$ in an area falls below the nonattainment level (i.e., exit treatment) or rises above the nonattainment level (i.e., enter treatment). Similar to other studies, we rely on the exogeneity of treatment (Greenstone, 2003; Auffhammer, Bento, and Lowe, 2011; Bi, 2017; Gibson, 2019; Raff and Walter, 2020) to correctly identify the effects of nonattainment status on emissions. PM nonattainment status is exogenous for the average stationary source in each county given the low contribution to ambient PM levels from these sources (Auffhammer, Bento, and Lowe, 2011).[9] We further examine the possibility of endogenous treatment in a subsequent sub-section.

For this analysis, we estimate the following equation, where facility i operates in year t:

$$ln(Y_{it}) = \nu_t + \delta_i + \beta PM_{it-1} + \lambda O_{3,it-1} + \pi SO_{2,it-1} + \sigma \boldsymbol{R}_{it} + \rho \boldsymbol{X}_{it} + \varepsilon_{it}, \tag{1}$$

[8] Retired and converted (i.e., different fuel type) observations are dropped from the panel when the event occurs. Analysis of only those plants that remain in our sample for its entirety (i.e., a perfectly balanced panel) produces results qualitatively and quantitatively similar to those below.

[9] Three-quarters of all PM pollution is caused by mobile sources (i.e., vehicles) (Auffhammer, Bento, and Lowe, 2011).

where Y_{it} is tons of SO_2 or NO_x emitted, ν_t are a set of year dummies,[10] δ_i are facility fixed effects, and ε_{it} is an exogenous error term.[11] $O_{3,it-1}$ and $SO_{2,it-1}$ are 1-year lagged county-level nonattainment designation of SO_2 (for SO_2 emissions) and ground-level ozone (for NO_x emissions).[12,13] For ground-level ozone nonattainment designation, we also consider counties in the 13 state Ozone Transport Region (OTR) as in nonattainment for the entirety of our panel (Sheriff, Ferris, and Shadbegian, 2019). These counties can be identified as attainment in the EPA Green Book (because ambient concentrations are below the standard), but requirements of the OTR are similar to those of ozone nonattainment counties. $\boldsymbol{R}_{it}$ represents a series of dummies indicating whether facility i in year t is subjected to the regulatory requirements of some program other than the NAAQS. Inclusion of these programmatic dummies makes the β estimate more precise and mitigate bias because these programs are implemented with the goal of decreasing emissions and improving ambient air quality. For estimations where SO_2 emissions is the dependent variable, we include dummies for the Cross-State Air Pollution SO_2 Program Groups 1 and 2 (separate dummies for each).[14] For estimations where NO_x emissions is the dependent variable, we include dummies for the CAA Title IV ARP, Cross-State Air Pollution NO_x Program, the NO_x Budget Program, and the SIP NO_x Program.[15] $\boldsymbol{X}_{it}$ is a vector containing a set of exogenous, time-varying facility-level controls to add further precision to our estimation of β and to mitigate bias. The vector includes total maximum capacity of all boilers at each plant, total electrical generation for each plant, and House and Senate LCV scores.[16] Our primary regressor, PM_{it-1}, is an indicator that represents nonattainment designation for $PM_{2.5}$, with a 1-year lag (Table S2 in the Online Supplement assesses varying lag lengths). Standard errors are clustered at the county level.

Identification

In this subsection, we provide evidence that our effects are identified correctly in three ways. First, we perform a falsification test. For this test, we re-estimate our primary regression specification with nonattainment status as a 1-year lead indicator rather than a 1-year lag indicator. If our identification is correct, the lead factor should not significantly affect contemporaneous emissions. Estimation results from this specification show that the lead factor is not statistically significant ($p = 0.680$).

Second, we test whether lagged observables can predict entrance into treatment. This test can lend further support to the exogeneity of treatment by testing whether nonattainment is self-selected (i.e., factors determining treatment are correlated with the error term) (see, e.g., Depew, Eren, and Mocan, 2017; Lu and Slusky, 2019). We are especially concerned with prior-year SO_2 and NO_x emissions because a significant coefficient for these factors presents evidence of self-selection into

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[10] Our analysis takes place during the fracking boom, so natural gas prices may impact the outcomes. However, natural gas prices are invariant across facilities in our sample because prices are represented by the Henry Hub spot price. Thus, natural gas prices are captured in the year-specific fixed effects.

[11] Alternatively, we estimate a specification where the dependent variables are SO_2 or NO_x emission rates to determine whether plants simply produce less as a result of nonattainment designation. Estimation results are statistically identical to those presented below. As a result, we focus on estimations with emission totals as outcomes for ease of the calculation of benefits.

[12] We include these factors in our primary regression specification only as controls. We do not simulate an adjustment of these designations as empirical results are not statistically significant (SO_2) or economically meaningful (NO_x). Estimation results for these factors and other controls are provided in Online Supplement (www.jareonline.org).

[13] We do not include a control for NO_2 nonattainment (for NO_x emissions) because all areas had reached attainment status for this pollutant by 1995, which is the beginning of our panel.

[14] We do not include a dummy for the CAA Title IV Acid Rain Program (ARP) in this specification because all facilities in our sample are regulated under the program for the entirety of our panel (i.e., the effects of the program on SO_2 emissions are subsumed into the facility specific fixed effects).

[15] All facilities in our sample are regulated under the MATS program upon its implementation because the AMPD gathers data for only those boilers larger than 25 MW and the MATS regulates only boilers larger than 25 MW. Thus, MATS regulation is subsumed into the year-specific fixed effects.

[16] Electrical markets are either competitive or regulated. Regardless, grid balancing (i.e., matching supply with demand) is essential. Therefore output (and price) are exogenous for each individual plant.

Table 3. Effects of $PM_{2.5}$ Nonattainment on Facility Emissions

	Dependent variable			
Variables	**ln(SO_2)**	**ln(NO_x)**	**ln(SO_2)**	**ln(NO_x)**
$PM_{2.5}$ nonattainment	-0.193^{*}	-0.118^{*}	$\mathbf{-0.207}^{**}$	$\mathbf{-0.112}^{**}$
(1-year lag)	(0.099)	(0.055)	(0.104)	(0.057)
No. of obs.	8,339	8,720	8,339	8,720
No. of facilities	479	490	479	490
Year FE	Yes	Yes	Yes	Yes
Facility FE	Yes	Yes	Yes	Yes
Facility-level controls	No	No	Yes	Yes

Notes: Single, double, and triple asterisks (*, **, ***) indicate significance at the 10%, 5%, and 1% level. Numbers in parentheses are standard errors clustered at the county level. Bold text identifies changes in emissions used for benefit calculations. Facility-level controls include total maximum capacity of all boilers, total electrical generation, and Senate and House LCV scores.

treatment (i.e., $PM_{2.5}$ nonattainment designation is triggered by SO_2 and NO_x emissions from coal-fired power plants). For this estimation, we use a fixed effects logit estimator to estimate $PM_{2.5}$ nonattainment as a function of lagged county-level SO_2 and NO_x emissions from coal-fired power plants, total generation at coal plants, total capacity at coal plants, and LCV scores.[17] Most important, lagged SO_2 and NO_x emissions do not affect $PM_{2.5}$ nonattainment designation ($p = 0.642$ and $p = 0.870$, respectively). These tests lend support to our identification strategy and to the exogeneity of treatment.

Finally, Stable Unit Treatment Value Assumption (SUTVA) concerns may arise because of the composition of coal-fired power plants and the structure of electricity markets. Coal-fired power plants can easily alter production depending on various conditions (e.g., demand). However, electricity providers must maintain generation levels necessary to service the electrical grid. If treated plants change their operations as a result of treatment, there may be spillovers from treated facilities to control facilities if the operators switch production to plants outside of the treated area. To account for this potential spillover, we consider a specification where we match control facilities to other control facilities located in a separate electrical grid (Fowlie, Holland, and Mansur, 2012). Results for this estimation are presented in Table S4 in the Online Supplement and present conclusions that are similar to those of the primary analysis. This matching exercise lends support to the fact that our treatment does not spill over to control units and thus our estimates are identified correctly.

Estimation Results

Table 3 presents results from the estimation of equation (1). We estimate two model specifications to assess the robustness of our results. Because results are similar for each model, we discuss only those from the full model, which are found in columns 4 and 5 of Table 3. For this specification, we include regulatory program and facility-level control variables to better account for omitted factors that may affect emissions at plants in our sample. Estimation results show that as a result of $PM_{2.5}$ nonattainment designation, SO_2 emissions at coal-fired power plants decrease 18.7% and NO_x emissions decrease 10.6%.[18]

We see from the primary estimation results that $PM_{2.5}$ nonattainment results in sizable decreases of SO_2 and NO_x emissions at coal-fired power plants. The mechanism through which these emission reductions occur is important for policy analysis. We eliminate from our sample all observations where plants have shut down or switched fuel and control for total electrical generation in our analysis. Thus, we can eliminate these events as reasons for the emissions decreases. Given the

[17] Our estimation is at the county level because some counties in our sample contain more than one coal-fired power plant.

[18] Percentage decreases in our dependent variables are calculated as $e^{\hat{\beta}-1}$.

technological requirements of $PM_{2.5}$ nonattainment,[19] we conclude that the emission reductions present within our sample are the result of abatement technology installation.[20]

Ex Post Benefits and Costs of the $PM_{2.5}$ NAAQS

We next quantify the health benefits and abatement costs of the $PM_{2.5}$ NAAQS at coal-fired power plants over the past 2 decades. We acknowledge that there exist benefits and costs in addition to health and abatement (e.g., labor market effects). However, we focus on health benefits and abatement costs because these represent the first-order benefits and costs of the NAAQS. Further, the benefits that we calculate are public, while the costs are borne by private entities producing a negative externality. Thus, we argue that this is an important examination of the appropriate benefits and costs for the design of policy. We leave a further examination of the full general equilibrium effects of the NAAQS to future research.

We see in Table 3 that from 1995–2016, nonattainment with the $PM_{2.5}$ NAAQS had a direct, causal effect on PM precursor emissions at coal-fired power plants. Specifically, nonattainment resulted in an 18.7% decrease in SO_2 emissions and a 10.6% decrease in NO_x emissions at these plants. Using these values as guides, we calculate the average emission decreases at plants subjected to the regulatory requirements of PM nonattainment designation. In our sample, the mean treated facility emitted 34,114 tons of SO_2 and 10,451 tons of NO_x per year. Thus, average emission decreases as a direct result of $PM_{2.5}$ nonattainment for these plants were 6,379 tons of SO_2 and 1,108 tons of NO_x.

Like previous studies, we use a linear approximation to estimate the health benefits of a 1-ton decrease of SO_2 and NO_x emissions (Kerl et al., 2015). Several approaches and estimates exist for the calculation of health benefits from emission abatement.[21] First, (Fann, Baker, and Fulcher, 2012, p. 143) analyze 17 different emission sectors in a way to "ensure that the benefit per ton estimates would be useful to the formulation of EPA air quality management policy." Using the Air Pollution Emissions Experiments and Policy (APEEP) analysis model, the authors estimate that the lifetime health benefits of a one-time, 1-ton reduction of SO_2 emissions are valued at \$35,000 and the lifetime health benefits of a one-time, 1-ton reduction of NO_x emissions are \$5,200. Second, the final 2015 Clean Power Plan (CPP) uses photochemical grid modeling to account for physical processes in the atmosphere to predict PM concentrations. The CPP estimates that a 1-ton reduction of SO_2 emissions is valued at between \$31,481 and \$70,370 and a 1-ton reduction of NO_x emissions is valued at between \$2,833 and \$6,500 (U.S. Environmental Protection Agency, 2015). We estimate the monetary benefits from emission reductions using EPA's sector-based $PM_{2.5}$ benefits, which fall within the bounds of the CPP and updates (Fann, Baker, and Fulcher, 2012) to reflect more current demographic, health, and economic input parameters (U.S. Environmental Protection Agency, 2018d). Importantly, these are the values used by EPA when determining the health benefits of environmental policies.[22] EPA estimates that the lifetime health benefits of a one-time, 1-ton reduction of SO_2 emissions (for EGUs) are valued at \$40,000 and the lifetime health benefits of a one-time, 1-ton reduction of NO_x emissions are \$6,000 (2015\$).

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[19] $PM_{2.5}$ nonattainment requires the installation of RACT for the control of PM and all PM precursor emissions, which includes SO_2 and NO_x emissions.

[20] Raff and Walter (2020) also present evidence that emissions reductions can be the result of a switch to lower-sulfur coal for SO_2 emissions. We do not rule out this possibility as contributing to the reductions that we find.

[21] Estimating the monetary benefits of emission reductions creates several challenges; the most significant is identifying the location of the reduction of harmful emissions and the range of damages. Several modeling techniques exist to address these challenges. For example, the monetary estimates from (Fann, Baker, and Fulcher, 2012, p. 143) simulate emissions and "particle-phase pollutants in the atmosphere" while using the Benefits Mapping and Analysis Program (BenMAP) "to calculate the health impact function." We address this further below using spatial modeling.

[22] See, for example, estimates of the health benefits from emission reductions of coal-fired power plant lawsuits: https://www.epa.gov/enforcement/coal-fired-power-plant-enforcement.

Table 4. Aggregate Health Benefits and Abatement Costs of the $PM_{2.5}$ NAAQS, 1995–2016

Aggregate Health Benefits ($billions)	Aggregate Abatement Costs ($billions)
32.5	13.9
(6.1–54.8)	(2.6–23.6)

Notes: The estimated total benefits are calculated by multiplying the average emission reductions of each pollutant by values of U.S. Environmental Protection Agency (2018d) and multiplying the average value at each plant by the number of plants entering nonattainment. The estimated total abatement costs are calculated using EPA's upper threshold of $15,000/ton of PM precursor abatement. Values in parentheses represent the 90% confidence interval. Standard errors are calculated using the delta method. Values are in 2015$.

We calculate the recognized health benefits from the $PM_{2.5}$ NAAQS within this industry from 1995 to 2016 by multiplying the emission decreases caused by the standards by the estimated health benefits from U.S. Environmental Protection Agency (2018d). For SO_2 emissions, the $PM_{2.5}$ NAAQS were responsible for $255.2 million worth of health benefits at the average facility while in nonattainment. Multiplying this value by the number of facilities that were ever treated during our sample period (124) gives aggregate health benefits from these standards of $31.6 billion. For NO_x emissions, health benefits totaled $6.7 million for the average facility, or $824.2 million in aggregate.

Next, we consider abatement costs as a measure of the most direct costs of NAAQS nonattainment. Because of the heterogeneity of approaches available to reduce emissions at EGUs when in nonattainment (even for facilities implementing identical emission control technology), we use maximum emission control costs determined by EPA. Benefit–cost analysis from U.S. Environmental Protection Agency (2011b) uses the costs of abatement technologies that do not exceed $15,000/ton for SO_2 and NO_x emissions. U.S. Environmental Protection Agency (2011b) justifies the use of $15,000/ton in its analysis because "few identified controls have a cost per ton higher than the $15,000 threshold used in the analysis." These costs are typically representative of abatement systems required by the NAAQS.[23] Table 4 presents total aggregate health benefits and abatement costs (and 90% confidence intervals). (Table S5 in the Online Supplement provides these values disaggregated by state to give a better representation of where the benefits and costs are realized.)

We find that with the upper cost threshold, the health benefits of the $PM_{2.5}$ NAAQS greatly outweigh the abatement costs borne by utilities over the past 2 decades. Additionally, actual costs per facility may differ due to the heterogeneity of abatement approaches available; lower-cost approaches (e.g., changing coal type) may be used first.

Tightening the $PM_{2.5}$ NAAQS

We next use the previous sections as a guide and propose tighter $PM_{2.5}$ NAAQS. From these tighter standards, we perform an *ex ante* examination of the health benefits and abatement costs of the proposed $PM_{2.5}$ NAAQS at coal-fired power plants.

As mentioned, the $PM_{2.5}$ NAAQS have not been changed in nearly a decade, there are few coal-fired power plants located in $PM_{2.5}$ nonattainment areas, emission reductions of PM precursors are expected to flatten in the coming years (U.S. Environmental Protection Agency, 2011b), and the WHO has recommended standards that are tighter than those used in the United States. Thus, we propose new standards. The current NAAQS for $PM_{2.5}$ come in two forms: (i) annual mean and (ii) 24-hour 98th percentile. To provide options for policy change, we propose two potential decreases of the primary annual mean standard and one potential decrease for the 24-hour standard. First, the WHO air quality guidelines recommend a $10\,\mu g/m^3$ annual mean and $25\,\mu g/m^3$ 24-hour mean standard (World Health Organization, 2018). We therefore propose a decrease of the primary annual mean standard from $12\,\mu g/m^3$ to the WHO-suggested level of $10\,\mu g/m^3$. Second, we use current $PM_{2.5}$ concentrations in the United States to propose a more strict standard. EPA data show that the

[23] EPA calculates these costs as the average total costs of emission decreases, which includes capital and operating costs.

national average $PM_{2.5}$ concentration is 8 μg/m^3.[24] Thus, we concurrently propose an annual mean standard of 8 μg/m^3, which would ensure that all areas in attainment with the standard would have $PM_{2.5}$ concentrations below the national average. For the 24-hour standard, we propose a change from 35 μg/m^3 to 25 μg/m^3, as recommended by the WHO.

Using AQS data for 2015–2017, we take 3-year averages of the annual mean and of the 24-hour 98th percentile value for all $PM_{2.5}$ monitoring locations in the United States and determine which areas are in nonattainment with the new, proposed standards (this calculation is identical to that of previous standards). Next, proposed nonattainment counties are matched to the county in which each coal-fired power plant in our sample is located. This allows us to determine which facilities are located in nonattainment areas for the proposed standards but were in attainment areas for the old (current) standards. Using our estimation results, we simulate counterfactual emission reductions and, in turn, health benefits, as a result of entrance into nonattainment for these additional plants. We expect future emission reductions to be similar to past emission reductions for several reasons.[25] First, as part of nonattainment designation, stationary sources are required to install at least Reasonably Available Control Technology (RACT). In our sample, over 85% of boilers at plants entering nonattainment for the proposed standards do not have the most effective abatement technology installed, which identifies a potential avenue for emission decreases (we discuss this further below). Second, plants classified as major emitters (e.g., coal-fired power plants) in nonattainment areas face greater regulatory scrutiny than those in attainment areas. Specifically, SIPs require states to implement plant-specific regulations (i.e., emission limits) (Walker, 2013). Third, EPA can impose requirements in addition to those in SIPs for areas that fail to attain the standards.[26]

For the proposed $PM_{2.5}$ standards of 10 μg/m^3 and 25 μg/m^3, an additional 12 active coal-fired power plants will enter $PM_{2.5}$ nonattainment. The number of active plants entering nonattainment for the 8 μg/m^3 and 25 μg/m^3 standards is 61. To determine emission reductions as a result of treatment, we find mean SO_2 and NO_x emissions at these facilities and simulate reductions using the coefficient estimates of the full model found in Table 3. Mean SO_2 and NO_x emissions of the 12 plants entering nonattainment for the less stringent standards are 7,025 and 3,238 tons, respectively. Therefore, the average plant will decrease SO_2 emissions by 1,314 tons and NO_x emissions by 343 tons while treated. For the 61 plants entering nonattainment for the more stringent standards, mean SO_2 and NO_x emissions are 3,973 and 2,666 tons, respectively, which would entail average emission decreases of 743 tons of SO_2 and 283 tons of NO_x while treated.[27] These values are substantially lower than those of plants entering nonattainment between 1995 and 2016. This is unsurprising and likely a result of the overall downward trend in PM precursor emissions over the past several decades.

As previously mentioned, at least 85% of boilers at the plants entering nonattainment with the proposed standards do not have the most effective abatement technology installed for SO_2 (flue

[24] https://www.epa.gov/air-trends/particulate-matter-pm25-trends

[25] Several studies attribute decreases in emissions at least partially to the NAAQS (Henderson, 1996; Chay and Greenstone, 2003; Walker, 2013). Most similar to our study, Auffhammer, Bento, and Lowe (2009) highlights the benefits of using disaggregated data (i.e., data at the monitor rather than the county level) and finds significant beneficial effects of the NAAQS. We examine emission reductions at an even more disaggregated level, the facility level, and find consistent emission decreases. However, we are unaware of a comparable study that examines emissions at the facility level, so we are unable to contrast directly our point estimates with those of previous studies.

[26] Previous points notwithstanding, we acknowledge that there is no way to *ensure* that these out-of-sample emission decreases occur in a way similar to previous changes. However, below we compare our results to those from EPA air quality models and find consistent results.

[27] Our identification assumes an equal increase in emissions when facilities exit treatment. To test whether increases in emissions upon exiting treatment are similar to the decreases in emissions upon entering treatment, we estimate the effect of only entrance into treatment. Coefficients for this estimation are quantitatively and qualitatively similar to those presented in Table 3. The possibility of increasing emissions after technological installation is discussed extensively in Walter and Raff (2019). Specifically, the authors find that facilities can increase emissions by reducing abatement inputs for certain equipment (e.g., the use of urea as a technological reagent for SCR/SNCR equipment) and by purchasing lower-quality coal. Thus, emissions can increase even after technological installation.

Table 5. Policy Simulation of Proposed 2019 NAAQS Changes, All Plants

Proposed Standard	Plants Entering Nonattainment	Estimated Aggregate Health Benefits ($millions)	Estimated Aggregate Abatement Costs ($millions)
10 $\mu g/m^3$ annual mean,	12	655.3	298.2
25 $\mu g/m^3$ 24-hour[a,b]		(122.0–1,105.5)	(54.2–506.7)
8 $\mu g/m^3$ annual mean,	53	1,664.9	815.3
25 $\mu g/m^3$ 24-hour[a]		(309.2–2,810.9)	(146.6–1,389.2)
8 $\mu g/m^3$ annual mean,	61	1,916.2	938.4
25 $\mu g/m^3$ 24-hour[b]		(355.9–3,235.1)	(168.7–1,598.8)

Notes: [a] Facilities entering nonattainment without the most effective abatement technology installed at all boilers.
[b] All facilities entering nonattainment regardless of installed abatement technology. The estimated total benefits are calculated by multiplying the average emission reductions of each pollutant by values of U.S. Environmental Protection Agency (2018d) and multiplying the average value at each plant by the number of plants entering nonattainment. The estimated total abatement costs are calculated using EPA's upper threshold of $15,000/ton of PM precursor abatement. Values in parentheses represent the 90% confidence interval. Standard errors are calculated using the delta method. Values are in 2015$.

gas desulfurization [FGD]) and NO_x (selective catalytic reduction/selective noncatalytic reduction [SCR/SNCR]) emissions. Clean technologies are required as part of RACT for coal-fired power plants in nonattainment areas. Emission reductions for boilers already with FGD or SCR/SNCR must come from alternative sources, which may not be as effective as FGD and SCR/SNCR. Thus, as a second health benefit estimation, we eliminate those plants entering proposed nonattainment with FGD and SCR/SNCR installed at all boilers.

We estimate health benefits from changing the $PM_{2.5}$ NAAQS to 10 $\mu g/m^3$ and 25 $\mu g/m^3$ using our simulated reductions to be $54.6 million for the average facility. In aggregate, this results in $655.3 million worth of health benefits throughout the United States. For a tightening of the NAAQS to 8 $\mu g/m^3$ and 25 $\mu g/m^3$, these values are $31.4 million and $1.9 billion, respectively.

For benefit estimation where we focus only on those plants with room for technological improvement, total benefits for the less stringent standards are the same as above because none of the 12 facilities entering nonattainment have the most effective NO_x and SO_2 abatement technology installed at all boilers. For the more stringent standards, the total health benefits are nearly $1.7 billion. Table 5 summarizes the policy simulation and health benefit estimation for each set of standards (and includes 90% confidence intervals). Health benefit estimates provided are conservative, as the values given are only for the year immediately following implementation of the altered NAAQS. Some coal-fired power plants would certainly operate into the future, thus accruing health benefits each year while operating in a nonattainment area. We do not calculate the health benefits accrued into the future due to the uncertainty with which regulated plants will continue to operate as coal-fired units.

Importantly, geography and population density also affect the health benefits of emission decreases. Thus, the location of affected plants may influence any estimate. As an additional check, we conduct a spatial analysis using EPA's Co-Benefit Risk Assessment (COBRA) Screening Model (U.S. Environmental Protection Agency, 2018a), which estimates the overall health benefits from simultaneous emission reductions as opposed to previous methods which identify a single per ton health benefit. For a tightening of the NAAQS to 10 $\mu g/m^3$ and 25 $\mu g/m^3$, our econometric approach calculates health benefits within the low and high estimates provided by COBRA ($437 million and $988 million). For a tightening of the NAAQS to 8 $\mu g/m^3$ and 25 $\mu g/m^3$, our econometric approach calculates health benefits nearly identical to the low estimate provided by COBRA ($1.9 billion and $4.4 billion). Figure 2 shows spatially where the health benefits are realized.

Finally, we consider abatement costs. We again use EPA's upper threshold for control costs per ton of PM precursor and find that the abatement costs of the proposed NAAQS are $24.9 million for the average facility, which when aggregated represent $298.2 million in total abatement costs

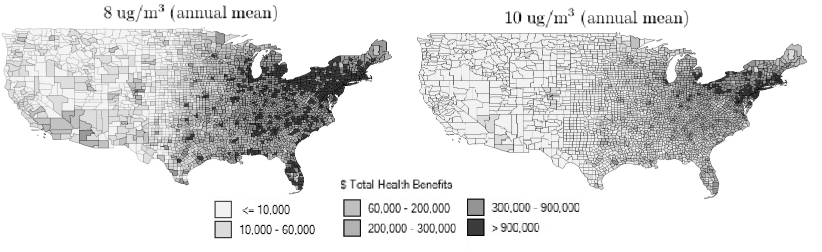

Figure 2. COBRA Spatial Health Benefit Estimates

Notes: Shade illustrates the concentration of health benefits resulting from the estimated emission reductions from a tightening of the $PM_{2.5}$ standards. Estimated health benefits are provided for 8 $\mu g/m^3$ annual mean and 25 $\mu g/m^3$ 24-hour mean standard (left) and 10 $\mu g/m^3$ annual mean and 25 $\mu g/m^3$ 24-hour mean standard (right). Facility emission reductions are calculated as a percentage decrease of current emissions (18.7% decrease for SO_2 emissions and 10.6% decrease for NO_x emissions).

for the less stringent standard. For the more stringent standard, abatement costs are $15.4 million for the average facility and $938.4 million in aggregate. These values are presented in the far right column of Table 5. With this cost threshold, our proposed policies have direct health benefits that far exceed the abatement costs necessary for the emission decreases. Again, abatement costs represent upper bounds, as the cost of control technology at individual facilities can be much less than those presented.[28]

Discussion and Policy Implications

The impact of the proposed policy changes on electricity production and pricing is worthy of consideration. Nonattainment designation could elicit three potential responses from plant managers: (i) invest in strategies to cut emissions, (ii) convert to alternative fuel, or (iii) retire. The availability of the most effective clean technologies, which are absent at many plants,[29] is an important factor in a firm's decision. In addition, the regulatory presence in the market also factors into a firm's response. In our sample, over 60% of plants entering nonattainment (for both sets of proposed standards) are located in deregulated electricity markets. We can infer that firms that choose to reduce emissions have sufficiently low costs such that the plant remains profitable (in either regulated or deregulated energy markets) causing relatively minor price or production changes. Unprofitable plants in regulated electrical markets that reduce emissions would likely seek electrical rate increases from regulators.

For plants that choose to convert fuel, current nonattainment designation (and modifications necessary to convert fuel) will require the plant to install more stringent pollution control technology, which would further lower emissions (Walker, 2013). The underlying conversion and technology cost may still yield savings and would likely yield similar market effects (on price) relative to firms that choose only to reduce emissions. The final alternative is that plants could retire, which would likely cause the most disruption to electricity markets. Plant retirement could lead to higher output from other plants or higher electrical prices.[30] We expect the retirement of plants to be more disruptive in states with regulated markets. However, these plants would be more likely to see regulators raise electrical prices, thereby facilitating the required investment in abatement technology.

[28] Several studies examine the employment effects of the CAA and its amendments and find that losses to workers and firms are only a small fraction of the health benefits provided by the CAA (Walker, 2013). Thus, these costs are omitted from our estimates.

[29] With a standard of 8 $\mu g/m^3$, less than 10% of plants have the most effective control technologies installed for both SO_2 (FGD) and NO_x (SCR/SCNR) on all boilers. According to Xiong, Jiang, and Gao (2016), wet FGD and SCR/SNCRs have a removal efficiency of 92.5% and 75%, respectively. Thus, installation of either technology would significantly contribute to the attainment of the proposed standards.

[30] Running other EGUs (outside of a nonattainment zone) harder or longer could increase emissions if the plants are coal-fired.

Our results show that the NAAQS have proven effective at reducing harmful pollutants and that public health benefits exceed private abatement costs. Updating the NAAQS incentivizes firms located in relatively high emission locations to decrease emissions. Environmental policy has temporal effects on technology adoption and abatement efforts (Walter, 2018). If the use of ambient emission standards is to continue, increasing the frequency of revisions and updating emission standards may lead to efficiency gains through firms' voluntary abatement actions or the execution of SIPs.

Conclusion

This study offers a retrospective and prospective examination of the health benefits and abatement costs of the $PM_{2.5}$ NAAQS at coal-fired power plants. We find that the emission decreases caused by the $PM_{2.5}$ NAAQS produced over $32 billion in health benefits over the previous 2 decades. We further find that the abatement costs borne by affected plants are much less than these health benefits. The study then simulates a tightening of the NAAQS and shows that this tightening would result in significant emission reductions and, in turn, increased public health benefits. We again find that these health benefits far exceed the abatement costs required for emission reductions to occur.

Of course, this study is only the first step in examining the efficacy of the NAAQS. Our analysis focuses on one specific criteria air pollutant and emission reductions in only one sector, so potential health benefits exceed those presented in this study. Additionally, we present in our prospective analysis only health benefits from decreases in emissions for 1 year following the policy change due to the uncertainty of future operating decisions of those plants moving into nonattainment (e.g., plants may retire 5 or 10 years after moving into nonattainment, which would considerably alter our health benefit estimations). Several plants will certainly continue to operate into the future, meaning that the health benefits presented here are conservative. We also examine only abatement costs. Monitoring and enforcement of the program is substantial and, thus, these costs should also be factored into any analysis. There may exist other costs (e.g., labor market effects) as well. Finally, we are unable to determine whether the proposed standards are attainable in all counties using the econometric analysis presented in this study. However, we show that tightening air quality standards does have the potential to reduce emissions from stationary sources, which contribute to ambient concentrations of criteria pollutants. We believe that an examination of the attainability of the proposed standards using air quality modeling is a topic worthy of future study.

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Online Supplement: Evaluating the Efficacy of Ambient Air Quality Standards at Coal-Fired Power Plants

Zach Raff and Jason M. Walter

Data and Preliminary Evidence of Treatment Effects

This supplement examines the data in greater depth and provides preliminary evidence of treatment effects. First, Table S1 examines mean emissions before and during nonattainment for those facilities that constitute the treatment group, i.e., those that are ever listed as $PM_{2.5}$ nonattainment. Table S1 shows that for these plants, mean emissions of both SO_2 and NO_x are considerably lower once they are designated as non-attainment.

Table S1. Emission Summaries by $PM_{2.5}$ Nonattainment Status for Treated Facilities

	Attainment		Nonattainment	
Variable	***N***	**Mean**	***N***	**Mean**
SO_2 emissions (tons)	1,367	38,799	914	27,108
NO_x emissions (tons)	1,415	12,960	952	6,722

Notes: Summaries are for those facilities that operated within a nonattainment area during at least one period of the sample. Summary statistics are at the facility-year level.

Figure S1 provides a time series of the proportion of facilities in our sample designated as PM2.5 nonattainment. The figure includes vertical lines that indicate the year where areas are first designated as nonattainment for each new standard. As mentioned in the main text, very few facilities in our sample are designated as nonattainment in 2016. This decrease in treated facilities is evident from the time series.

Treatment Lag Length

This supplement provides a sensitivity analysis of the primary regression specification by altering the lag length of our treatment indicator. In many instances, the process for SIP development and approval can take more than one year. In addition, once SIPs become federally enforceable, the plans to achieve the SIPs, e.g., abatement technology installation at stationary sources, may take additional time. For these reasons, we re-estimate the primary regression specification of equation (1) with two-, three-, four-, and five-year lags on $PM_{2.5}$ nonattainment rather than with a one-year lag to determine when the emission reductions occur. Results for these regression specifications are presented in Table S2.

Estimation results for the sensitivity analysis offer conclusions consistent with those presented in the main text. We wish to highlight three main points regarding these results. First, the size of the reductions of SO_2 emissions are significantly larger when accounting for a longer lag period. As mentioned, many requirements of SIPs may take longer than one year to implement. Results from our sensitivity analysis show that over longer periods of time, decreases in emissions are larger as a result. This indicates that for SO_2 emissions, a sizable amount of the reductions takes some

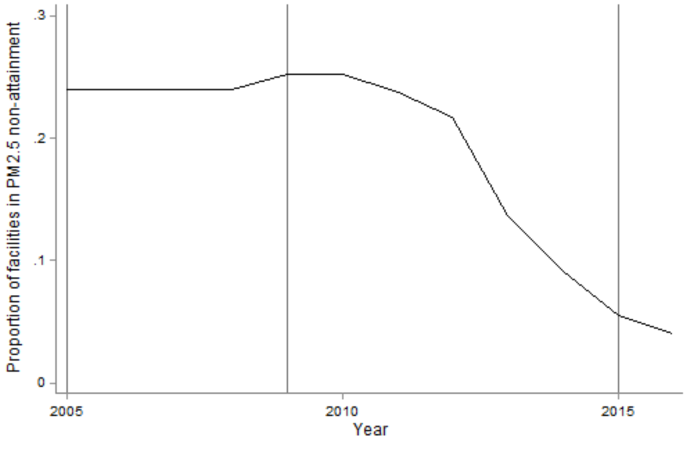

Figure S1. Time Series of the Proportion of Facilities in $PM_{2.5}$ Nonattainment, 2005-2016

Notes: Trend represents the proportion of coal-fired power plants in our sample that are classified as nonattainment for $PM_{2.5}$ for each year. Vertical lines represent the years where counties are first designated as nonattainment for the three $PM_{2.5}$ standards identified in Table 1.

Table S2. Effects of $PM_{2.5}$ Nonattainment on Facility Emissions: Varying Lag Structures

	Dependent Variable							
Variables	**ln(SO_2)**	**ln(NO_x)**	**ln(SO_2)**	**ln(NO_x)**	**ln(SO_2)**	**ln(NO_x)**	**ln(SO_2)**	**ln(NO_x)**
$PM_{2.5}$ nonattainment	-0.250**	-0.095*						
(2-year lag)	(0.110)	(0.057)						
$PM_{2.5}$ nonattainment			-0.334***	-0.119*				
(3-year lag)			(0.129)	(0.067)				
$PM_{2.5}$ nonattainment					-0.365**	-0.134*		
(4-year lag)					(0.145)	(0.075)		
$PM_{2.5}$ nonattainment							-0.395**	-0.104
(5-year lag)							(0.154)	(0.076)
Observations	7,931	8,312	7,527	7,908	7,120	7,501	6,711	7,070
Number of facilities	477	488	477	488	477	488	474	485
Year FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Facility FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Control factors	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes

Notes: *** $p \leq 0.01$, ** $p \leq 0.05$, * $p \leq 0.1$. Standard errors clustered at the county level and located in parentheses.

time to occur, perhaps as a result of the timely process of technological installation. Second, the effect of $PM_{2.5}$ nonattainment on NO_x emissions are significantly negative for two-, three-, and four-year lags. For these estimations, the percentage decrease in NO_x emissions is consistent for all lag lengths. These results show that decreases in emissions for NO_x occur relatively quickly after facility entrance into non-attainment. Finally, average treatment effects eventually move to zero after these lags. Thus, policy changes are necessary to continue emission decreases in the sector.

Table S3. Effects of $PM_{2.5}$ Nonattainment on Facility Emissions: Control Factors

	Dependent Variable	
Variables	**ln(SO_2)**	**ln(NO_x)**
SO_2 nonattainment (one-year lag)	0.074	
	(0.142)	
O_3 nonattainment (one-year lag)		-0.194^{***}
		(0.059)
Title IV ARP		-0.076^{*}
		(0.041)
Cross-State Air Pollution SO_2 Program (Group 1)	-0.739^{***}	
	(0.191)	
Cross-State Air Pollution SO_2 Program (Group 2)	-0.237	
	(0.209)	
Cross-state Air Pollution NO_x Program		-0.354^{***}
		(0.086)
SIP NO_x Program		-0.179
		(0.367)
NO_x Budget Program		-0.036
		(0.044)
Maximum capacity (GW)	-0.004	0.077^{***}
	(0.047)	(0.029)
Total electrical generation (GW-h)	0.00007^{***}	0.00007^{***}
	(0.00002)	(0.00001)
House LCV score (0-100)	-0.003	-0.001
	(0.002)	(0.001)
Senate LCV score (0-100)	0.002^{*}	0.002^{***}
	(0.002)	(0.0007)
Observations	8,339	8,720
Number of facilities	479	490
Year FE	Yes	Yes
Facility FE	Yes	Yes
Treatment indicator	Yes	Yes

Notes: *** p≤0.01, ** p≤0.05, * p≤0.1. Standard errors clustered at the county level and located in parentheses.

Control Factors

In this supplement we provide estimation results for the control factors of the primary empirical specification. We include these controls to estimate more precisely the primary regressor coefficients and mitigate omitted variable bias. Given these purposes, we are not claiming that the control factor coefficients represent causal effects on our outcomes. Nevertheless, we assess the estimation results for the control factors. First, SO_2 nonattainment designation does not have a statistically significant effect on SO_2 emissions at coal-fired power plants. We hypothesize that this is the case because SO_2 nonattainment is likely to be endogenously determined with respect to SO_2 emissions from coal-fired power plants because a large proportion of SO_2 emissions come from this sector. Importantly, estimation results are nearly identical to those presented when omitting SO_2 non-attainment from the set of controls. Second, ground-level ozone nonattainment significantly decreases NO_x emissions, as expected. Third, we see that several regulatory programs significantly decrease emissions at coal-fired power plants, e.g., Cross-State Air Pollution SO_2 Program. Finally, Senate LCV score is positively associated with emissions. We hypothesize that this unexpected result is because senator voting records lag behind citizen concern for the environment, as senators are elected only once every six years.

Additional Tables

Table S4. Effects of $PM_{2.5}$ Nonattainment on Facility Emissions: Matching

	Dependent Variable	
Variables	**ln(SO_2)**	**ln(NO_x)**
$PM_{2.5}$ nonattainment	-0.289^{**}	-0.246^{***}
(one-year lag)	(0.129)	(0.076)
Observations	6,640	6,491
Number of facilities	393	395
Year FE	Yes	Yes
Facility FE	Yes	Yes
Facility level controls	Yes	Yes
Control facility matching	Yes	Yes

Notes: *** p≤0.01, ** p≤0.05, * p≤0.1. Standard errors clustered at the county level and located in parentheses. Results are calculated using a matching technique similar to Fowlie, Holland, and Mansur (2012) where control plants are matched to other control plants in a separate electrical grid. We use nearest neighbor propensity score matching based on facility characteristics and environmental regulations. Facility level controls include total maximum capacity of all boilers, total electircal generation, and Senate and House LCV scores.

Table S5. Heterogeneity of Emission Reduction Benefits and Abatement Costs by State, 1995-2016

State	Total Benefits from Emission Reductions (billion $)	Total Abatement Costs (billion $)
AL	1.744	0.757
CT	0.033	0.015
DE	0.040	0.017
GA	3.085	1.303
IL	1.311	0.573
IN	3.681	1.615
KY	0.742	0.331
MD	1.401	0.597
MI	1.975	0.857
MO	0.999	0.419
NC	0.407	0.178
NJ	0.315	0.137
NY	0.222	0.097
OH	7.132	3.062
PA	6.168	2.564
TN	0.640	0.273
VA	0.154	0.068
WI	0.366	0.159
WV	2.052	0.905

Notes: The second and third columns represent the total benefits from emission reductions and the abatement costs expended to achieve these reductions from our sample between 1995 and 2016 by state. We calculate estimates by disaggregating the values of Table 4. Benefit estimates are only for emission reductions within that state and do not consider spillovers like Figure 2.

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