When the regulator goes home: The effectiveness of environmental oversight

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Abstract

The U.S. EPA designates areas as in non-attainment with National Ambient Air Quality Standards (NAAQS) if ambient air concentrations of certain pollutants exceed standard levels. Stationary sources located in these areas are required to significantly reduce emissions through technological and other requirements; these sources are also subjected to greater regulatory oversight. However, non-attainment is not a permanent designation and regulatory oversight subsides once an area moves out of non-attainment. In this paper we examine whether the additional regulatory oversight of non-attainment designation is successful (and necessary) at reducing emissions from stationary sources. We estimate the effects of an area moving out of non-attainment on emissions at coal-fired power plants located in these areas. We first model the actions of utility managers subjected to emission reduction requirements. The model suggests that firms under additional scrutiny via non-attainment designation intentionally lower emissions. However, when areas exit non-attainment, i.e., direct regulatory oversight subsides, firms under-utilize clean strategies - including technology - which results in emission increases. Empirical analysis results show that boilers with abatement technology installed as a result of non-attainment increase NO_x emissions and emission rate by 16% and 9%, respectively, when exiting non-attainment. Extended model results present evidence that regulated firms are less likely to use fully emission control methods in the absence of direct regulatory oversight. Specifically, the emission increases of exiting non-attainment are driven by the under-utilization of abatement technology inputs and the switch to lower quality fuel.

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1 Introduction

The Clean Air Act (CAA) created air quality standards to control ambient concentrations of six "criteria" air pollutants that are especially harmful to human health (see, e.g., Muller and Mendelsohn 2009) and the environment. These National Ambient Air Quality Standards (NAAQS) control ambient concentrations of the following pollutants: particulate matter (PM)[1], ozone, lead, carbon monoxide, nitrogen dioxide, and sulfur dioxide (SO_2). The U.S. Environmental Protection Agency (EPA) is responsible for designing ambient air quality standards for these pollutants, which are administered nationally but enforced at the county level. EPA examines pollution concentrations within geographic areas and designates each as in "attainment" with individual NAAQS or, if pollutant concentrations exceed standard levels, as "non-attainment".

Non-attainment areas as a whole are subjected to greater regulatory scrutiny and oversight than attainment areas. Stationary emission sources in non-attainment areas are subjected to several regulatory requirements as part of State Implementation Plans (SIPs) required by EPA, including technological requirements, facility-specific emission limits, and greater and more frequent oversight and monitoring (Walker 2013). Importantly, non-attainment status is not a permanent designation. The goal of EPA is to bring ambient concentrations of criteria pollutants below the appropriate NAAQS in non-attainment areas; states can then request for these areas to be re-designated as in attainment with the NAAQS.[2] Once the area is no longer designated as non-attainment, the watchful "eye" of the regulator is no longer drawn to the area. This de-prioritization and reduced oversight results in less monitoring, which affects emissions and benefits provided to local communities (Gray and Shadbegian 2004; Lim 2016).

The purpose of this paper is to examine how regulated firms respond when the increased oversight of NAAQS non-attainment designation no longer applies. Rather than look at the overall emission effects of non-attainment designation, we focus exclusively on

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[1] Total Suspended Particulates prior to 1987 and PM after 1987.

[2] Areas that leave non-attainment are designated as "maintenance" for at least ten years. For ease of exposition, we refer to these areas as in "attainment" with the standards because ambient air concentrations are below standard levels.

the effect of areas changing out of non-attainment on stationary source emissions. Several studies examine the effect of non-attainment designation on emissions at stationary sources (e.g., Raff and Walter 2017; Gibson 2018). However, these studies focus on county level entrance into non-attainment and the effects on emissions while in non-attainment, while we identify the effects based on county level entrance out of non-attainment. The regulatory requirements of non-attainment designation are lessened when areas meet the appropriate NAAQS; regulatory monitoring and oversight decreases and facility-specific emission limits are not enforced as strictly, if at all. Additionally, required abatement technologies have high variable costs (Xu et al. 2015) and inputs are priced differentially. Abatement technology presence and differential input usage without monitoring and oversight does not ensure that emission reducing strategies are operated in ways that will decrease emissions to acceptable levels. Non-attainment designation is also exogenous to each stationary source's emissions because the average facility contributes little to ambient air concentrations of criteria pollutants (Auffhammer et al. 2011; Gibson 2018). As a result, firm managers may abate less because they feel the "storm has passed", especially if managers perceive that agencies have fixed monitoring budgets (Raff and Earnhart 2018). Finally, the primary purpose of SIPs are to bring the ambient air concentrations of criteria pollutants below standard levels. If areas do not make sufficient progress toward attaining the standard, EPA can impose further requirements. As a greater incentive to reach attainment, states with areas that remain in non-attainment can have highway or other federal funds withheld. Incentives such as these do not exist for areas that meet the standards and thus, the urgency with which states control emissions in non-attainment areas can be impacted. Holistically then, our study examines whether emission changes at stationary sources made while in non-attainment are permanent and continue into the future (as mandated in each SIP) even without direct regulatory oversight.

There exist many economic studies that examine the effects of the NAAQS and non-attainment status on different outcomes. Several studies attribute emission decreases of the past several decades at least partially to the NAAQS (Henderson 1996; Chay and Greenstone 2003; Walker 2013). More specifically, non-attainment designation played a "minor" role in the decrease of ambient SO_2 concentrations in the United States during the 1990s (Greenstone 2004) and significantly decreased PM emissions in the United States during the same time frame Auffhammer et al. (2009). Bi (2017) and Gibson (2018) use Toxics Release Inventory (TRI) data to examine how non-attainment status of air pollutants impacts emissions to other environmental media, e.g., water, land. Both studies find a negative relationship between non-attainment status and air emissions. Aside from emissions and ambient air quality, non-attainment designation increases the age of capital used at privately-owned electric utilities Nelson et al. (1993). Non-attainment status also positively affects housing values (Chay and Greenstone 2004) but negatively affects employment (Greenstone 2002; Walker 2011; Sheriff et al. 2019). Previous work identifies the effects of non-attainment primarily on the entrance of an area into non-attainment, rather than identification based solely on an area's exit from non-attainment. This focus assumes a lasting impact on emissions and ambient air quality (or other outcomes) from non-attainment designation and ignores the importance of regulatory oversight. The previous body of literature (specifically that dealing with emissions as the outcome) also does not examine the use of abatement technology at stationary sources. These studies focus on the effects of non-attainment in aggregate without exploring the mechanisms through which emission decreases occur or how firm manager behavior changes in different regulatory scenarios.

This study adds to the literature in several important ways. First, we identify the effects on emissions of a substantial decrease in regulatory oversight. Previous studies examine oversight in the context of general deterrence (e.g., Earnhart 2004; Shimshack and Ward 2005) by examining stochastic regulatory involvement at firms. However, general deterrence measures vary only slightly and at best these studies identify small decreases (and increases) in oversight. Our study uses non-attainment exit as a significant and certain decrease in regulatory oversight. Second, we identify changes in emissions based on facility exit out of non-attainment rather than entrance into non-attainment. Gibson (2018) for example, does not consider the change in facility emissions once an area moves back into attainment with the NAAQS, as emission changes are expected to be permanent. The author uses a generalized difference-in-differences estimator and considers as treated all facility-year observations after initial entrance into non-attainment. We examine the opposite scenario using data on all coal-fired power plants, not only those that are required to report TRI emissions. Thus, we are the first study to examine the behavior of firms once the direct regulatory oversight of non-attainment designation subsides, i.e., we study the effectiveness of increased regulatory oversight of non-attainment designation. Third, ours is the first study to model theoretically both regulator and firm behavior under an important government regulation. Finally, we examine the mechanisms through which firm managers make emission decisions when not subjected to direct regulatory oversight. There exist strong incentives for states to bring non-attainment areas back into attainment with the NAAQS. As a result, stationary sources are monitored closely and emission reductions occur (Raff and Walter 2017). However, once this incentive structure is removed, behavior may change; no study has examined the ways in which firm managers change behavior once the regulator is no longer as present.

To develop our contributions, we first model theoretically firm manager and regulator behavior as a result of non-attainment designation. We identify how regulators can target firms to reduce emissions and thus, attain ambient air quality standards. Standards can be met by requiring targeted firms to employ clean strategies, e.g., use of higher-quality inputs, installation of abatement technology. We show that clean strategies imposed by regulators will be operated fully by firms if the regulator is present, i.e., additional regulatory oversight exists. This incentivizes firms to employ fully clean strategies selected by the regulator to avoid additional scrutiny, which minimizes costs (Becker 1968); this occurs only while the regulator is present under non-attainment designation. Once firms are no longer subjected to this scrutiny, i.e., the area exits non-attainment, firms under-utilize clean strategies required previously by the regulator. In addition, permanent emission reductions from sources required by the regulator may provide "standard slack", i.e., emission decreases (and other activities beneficial to ambient air quality) that result in ambient concentrations well below the NAAQS. This slack allows other sources to further increase emissions. As a result, the absence of monitoring in the presence of static ambient emission standards can create a scenario which encourages stationary sources to increase emissions.

We then estimate several regression specifications that examine the effect of facility exit from non-attainment. We use boiler level data on NO_x emissions and emission rate at coal-fired power plants in the United States from 1995-2016 for this analysis. We consider as treated those boilers (facilities) that exit non-attainment, rather than those entering non-attainment. This analysis can determine if emissions changed for boilers previously regulated by SIPs once the requirements are removed, i.e., regulatory oversight normalizes to pre-non-attainment levels. Estimation results show that boiler level NO_x emissions and emission rate increase by 16% and 9%, respectively, once facilities are no longer regulated under non-attainment requirements.

Finally, we examine the mechanisms through which these emission increases occur. The NAAQS require installation of Reasonably Available Control Technology (RACT) for stationary emission sources in non-attainment areas. However, RACT designation depends on many factors, e.g., costs, facility age, technological availability, so there is considerable heterogeneity in this technology throughout the United States. Thus, we use data on the type of technology at each boiler and its installation date to examine what technology each facility implemented when in non-attainment. We use this analysis to test the theoretical assertion that facilities under-utilize abatement technology when additional regulatory oversight is removed, which we show empirically to be the case; the significant variable costs associated with abatement systems can be minimized by under-utilizing technology once direct regulatory oversight is removed. Specifically, we find significant increases of NO_x emissions and emission rate at boilers with technology that requires substantial variable costs, but no emission or emission rate increases at boilers with "set it and forget it" abatement technology. We also examine if other clean strategies used to decrease emissions are abandoned once a facility is no longer subjected to the SIP requirements of a non-attainment area. We estimate the effect that exiting non-attainment has on the use of inputs, namely coal type and quality. We find that exiting non-attainment induces regulated facilities to switch to coal with lower heat content and higher ash content, which is considerably cheaper than higher quality coal but more is required to produce the same level of output; thus, emissions increase. Importantly, we control for output and examine emission rate so our results do not indicate that managers simply run plants less when in non-attainment.

The remainder of this paper proceeds as follows. Section 2 provides background information on the NAAQS and non-attainment designations, including technological requirements. Sections 3 and 4 provide theoretical analyses for firm behavior and regulator obectives, respectively. Section 5 provides the primary empirical analysis, including a discussion of the data used. Section 6 examines mechanisms through which emission increases occur. Finally, section 7 concludes and issues policy recommendations.

2 Regulatory setting

This section describes the regulatory setting of our study. We first describe the specifics of the NAAQS, including its designations of areas as non-attainment. We then discuss the technological requirements for stationary sources located within non-attainment areas, highlighting RACT requirements for stationary source emissions of $\mathrm{NO_x}$.

2.1 NAAQS and non-attainment designation

The CAA of 1970 established the NAAQS to protect human health and the environment from especially harmful air pollutants. There exist two types of ambient air quality standards: (1) primary standards, which are tighter, i.e., lower, and provide public health protection (focusing on vulnerable populations, e.g., asthmatics) and (2) secondary standards, which protect the environment and public welfare (EPA 2018a). Areas are considered in “non-attainment” with individual NAAQS if ambient concentrations of that criteria air pollutant exceeds standard levels.

Once an area is designated as non-attainment, the state must submit to EPA a SIP outlining steps that the state will take to bring that area into attainment with the relevant NAAQS. Stationary emission sources in non-attainment areas are subjected to increased regulatory stringency and oversight as a result of non-attainment designation and individual SIPs. (Mobile emission sources, e.g., motor vehicles, and other sources of emissions, e.g., outdoor wood-burning, are also the subject of SIP requirements.) First, stationary sources must install appropriate emission abatement technology; in this sense, the NAAQS serve as technological standards. All stationary sources in non-attainment areas are required to install RACT systems, which are emission control technologies that are reasonably available and technologically and economically feasible. New or modified stationary sources located in non-attainment areas face even stricter technological requirements; facilities must obtain New Source Review (NSR) permits, which require the installation of Lowest Achievable Emission Rate (LAER) technology, regardless of cost.[3] Second, stationary sources classified as major emitters, e.g., coal-fired power plants, in non-attainment areas are subjected to plant-specific regulations, i.e., emission limits, and as a result are subjected to greater and more frequent oversight and monitoring (Walker 2013). Finally, EPA can impose further requirements (in addition to those in SIPs) for areas that fail to reach attainment with the standards, e.g., fuel requirements, emission offsets. States can also lose federal funds, e.g., highway funds, for failing to reach attainment status after a certain period of time.

States can petition for areas to be re-designated as attainment once ambient air concentrations of non-attainment pollutants fall below standard levels. Before being labeled as in attainment with the NAAQS, areas are first considered maintenance areas for 10 years following achievement of the relevant standard. As part of the petition process, states must submit to EPA a maintenance plan that outlines how the area will remain in attainment. The maintenance plan must show that the ambient air quality changes and emission decreases that occurred during non-attainment are the result of permanent actions, e.g., technology installation, and how the area will maintain ambient air quality for at least 10 years. Importantly, the requirements of maintenance plans are not as strict as those of SIPs, i.e., additional regulatory scrutiny and oversight associated with

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[3] Stationary sources in attainment counties are not required by the NAAQS to install any emission control technology. New or modifying plants however, are required to install Best Available Control Technology (BACT).

non-attainment is reduced because ambient air quality has reached acceptable levels (as determined by EPA).

2.2 Technological requirements of the NAAQS

Major stationary emission sources[4] in non-attainment areas are required to install RACT equipment for the control of criteria air pollutants, including those affected by NO_x emissions: PM and ground-level ozone.[5] New or modifying facilities are required to install BACT/LAER technology, which are more substantial than RACT and costs are considered immaterial. We focus our discussion on RACT requirements because these are the primary requirements of non-attainment areas. Table 1 presents a list of criteria air pollutants and those whose ambient air concentrations are affected by NO_x emissions. Non-attainment designation for pollutants whose ambient air concentrations are affected by NO_x emissions requires at least RACT installation for control of NO_x emissions. RACT requirements of non-attainment and SIPs are subjective and EPA provides only broad requirements.[6] EPA's NO_x RACT summary suggests that states consider total cost, total emission reductions, and cost effectiveness of controls needed to achieve emission limits or equipment standards when determining RACT EPA (2018b). Finally, EPA's "Menu of Control Measures for NAAQS Implementation" contains over 250 emission reduction measures, many of which can be considered RACT.

EPA does not encourage a broad adoption of all cost effective abatement technology. In general, EPA "believes it would be unreasonable to require that a plan which demonstrates attainment include all technologically and economically available control measures even though such measures would expedite attainment." SIPs are expected to map out and make reasonable progress toward attainment with linear emission reductions. The method is largely determined by the state (but must be approved by EPA). However,

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[4] Emission sources with the potential to emit "100 tons per year of any air pollutant" EPA (2018b).

[5] Ambient concentrations of nitrogen dioxide (a criteria air pollutant) are also affected by NO_x emissions. However, all counties in our sample had reached attainment with nitrogen dioxide standards by 1995. Thus, we focus on the two applicable standards.

[6] However, for certain emission sources, e.g., electric utilities, EPA establishes set emission limits (EPA 2018b).

Table 1: Relationship of NO_x emissions to criteria air pollutants

Criteria air pollutant	Affected by NO_x emissions
Sulfur dioxide	
Nitrogen dioxide	X
Particulate Matter	X
Ground-level ozone	X
Carbon monoxide	
Lead	

Notes: An X represents that the particular criteria air pollutant's ambient concentrations are directly affected by emissions of NO_x. An X also represents that stationary emission sources in areas designated as non-attainment for those pollutants are required to install at least RACT systems for NO_x emissions. All areas in our sample had reached attainment for nitrogen dioxide by 1995, so our analysis focuses on PM and ground-level ozone non-attainment.

the technology requirements of a SIP are to identify, plan, and demonstrate how an area will obtain attainment and not to install all cost effective abatement technology available. As a specific example for lead non-attainment, EPA states explicitly that RACT requirements of a SIP will be approved even without appropriate technology if it can be proven that attainment will be reached (EPA 1990).

EPA states that the philosophy behind RACT identification is that it is reasonable for similar sources to bear similar emission reduction costs (EPA 1990). However, an important secondary requirement of economic feasibility exists: reasonability. RACT determination considers the difference in technology costs among similar sources with implemented emission reductions, but takes into account whether the firm's installation costs of technology are affordable. Simply put, technology requirements are based on cost and effectiveness of the installed technology on a similar source. This policy provides states considerable flexibility in reaching attainment, which can require management of a variety of emission sources concurrently.

3 Firm behavior under regulatory oversight

In this section we create a representative firm and model the influence of regulators on firm operations and the use of clean strategies, i.e., methods to decrease emissions. Our goal is to identify how regulators influence firm operations to improve ambient air quality after an area fails to meet the NAAQS and is designated as non-attainment. Regulators, as part of a SIP, can require firms to undertake a variety of actions to reduce emissions. We examine how firm level emissions change as regulatory obligations are met in the context of ambient air quality standards.

3.1 Firm operation and profit

We begin with a simple representative firm unconcerned with emissions. Firm i creates emissions as a typical part of operation according to $e_i = (e_k - \delta_i)q$, where e represents initial per unit emissions scaled according to the age of initial production equipment k (e_k increases with age), q represents firm output, and δ_i represents calibration of production inputs to decrease emissions ($\delta \in [0, 1]$).[7] In the absence of direct regulatory oversight, a firm can voluntarily choose its level of calibration to reduce emissions.

Operations at a traditional coal-fired power plant can be altered depending on the firm's concern with emissions. For example, equipment maintenance, boiler adjustment, reaction temperature, and shutdown cycles all impact a plant's input costs. As examples, Liu et al. (2007) examine the effect of coal combustion parameters on PM emissions and Romero et al. (2006) discuss the impact of boiler operating conditions on mercury emissions at coal-fired utility boilers. In general, calibration can decrease firm emissions and fuel usage, resulting in efficiency gains (through cost savings) and emission reductions. However, at a certain point calibration to further reduce emissions can increase non-fuel input and operational costs.

Operational decisions have a significant impact on firm profit. The price(s) firms

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[7] The calibration of inputs includes operating decisions that decrease emissions, which may decrease fuel requirements but increase production costs, e.g., equipment maintenance, boiler calibration, shutdown optimization.

receive for output is dependent on the regulatory structure of electric utilities. Before electricity market restructuring, i.e., deregulation, most firm's prices were set by public utility commissions (Fowlie 2010). In addition, firms in regulated areas must meet market demand to ensure effective grid management. For firms in deregulated areas, electricity provision includes other electrical producers (using other energy sources) representing a broad interdependence between competing providers. We assume price and output requirements for a firm are exogenous regardless of the electricity market's regulatory structure and thus, a firm's profit maximization requires boiler optimization:

$$\max_{\delta_i} \quad \pi_{i,k} = (p - (1 - \delta_i + \delta_i^2)c_k)q \tag{1}$$

where p represents price and q represents output. A plant's age is relevant for several reasons, most notably technology and design. Therefore, a firm's production costs, c_k, depend on boiler age (k). For ease, we let "o" denote old plants and "u" denote new or modified plants where $c_o > c_u$.

Profit maximizing firms optimize production processes to minimize cost given some level of exogenous output. Equation (1) shows that firms, left to their own devices, will cost minimize where $\delta^* = \frac{1}{2}$, resulting in emissions of $e_i = (e_k - \frac{1}{2})q$. Simply put, firms will calibrate equipment to make inputs as productive as possible without regard for emissions.

3.2 Emission reductions

Multiple options outside of production calibration exist to reduce emissions. In this sub-section, we incorporate additional emission-reducing techniques into our model because regulators can require emission reductions for firms located in non-attainment areas. For instance, non-attainment designation requires SIPs which identify strategies to reduce emissions. SIPs can subject stationary sources to emission inventories, installation of RACT/LAER systems, clean fuel programs, and enhanced monitoring, among other things (EPA 2018c).[8] These (emission-reducing) strategies influence firm i's emissions

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[8] Required elements depend on the timeline to attainment and can include major source statements (for sources with over 100 tons of emissions), attainment demonstration, NSR offset ratios, and other

according to:

$$e_i = (e_k - \delta_i - s_i - x_i)q \tag{2}$$

where x_i represents the use of cleaner fuels in the production process (where $x_i \in [0, \overline{x}]$) and s_i represents the use of emission capture, i.e., abatement, technology. The employment of abatement technology causes some reduction in emissions (therefore $s_i \in [\underline{s}, \overline{s}]$), however, the relative effectiveness depends on decisions related to the operation and maintenance of the technology.

Firms located in non-attainment areas are required to install at least RACT systems. These abatement technologies have significant installation, maintenance, and operating costs.[9] In addition, SIPs can require that firms adopt cleaner fuel inputs.[10] At the same time, firms can voluntarily decrease emissions by employing clean strategies, e.g., cleaner inputs, abatement technology. Profit for firms employing these clean strategies is represented by:

$$\pi_{i,k} = \left[p - F\left(x_i, \delta_i\right) - (1 - \delta_i + \delta_i^2)c_k - T\left(s_i\right)\right] q$$

where $F\left(x_i, \delta_i\right)$ represents the additional costs of cleaner fuel and $T\left(s_i\right)$ represents the cost of operating installed abatement technology. Any changes due to updating or installing boiler equipment alters the production costs of firms with older equipment (from c_o to c_u).

A firm's production method also changes due to the cleaner production strategies employed. To incorporate the cost of cleaner fuel, we assume fuel prices reflect the quality and associated emission reductions,[11] *ceteris paribus*. Fuel prices increase quadratically

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vehicle requirements.

[9] We are not concerned with the adoption/installation of abatement technology, but its use. Therefore, we omit fixed costs.

[10] Our focus on "cleaner fuel" does not consider the sulfur content of different coal types, because we do not examine SO_2 emission regulations. Our focus is exclusively on heat and ash contents of the coal; we discuss this further in section 6.

[11] Coal prices incorporate heat content and ash (non-combustible) content of coal. Indeed, coal with higher heat content and lower ash content (bituminous) costs considerably more per short ton (roughly four times) than lesser quality coal (sub-bituminous, lignite)

according to quality such that $F(x_i) = \alpha x_i^2 - \delta_i x_i$, where α is a parameter representing cost associated with location or transportation. However, the associated emission reduction from cleaner coal is linear. Our representation of fuel cost is structured to incorporate the benefits of using higher quality (and cleaner) fuel from an operational and emissions standpoint since higher quality fuel can reduce plant maintenance costs and improve worker conditions.[12]

The installation of abatement technology is a significant fixed cost for any firm. However, our interest is in the operation and maintenance of technology which requires substantial inputs for proper operation. The use of reagents necessary for abatement technology increases coal use and by extension coal ash byproducts (EPA 2017a), further increasing operating costs. We represent operating costs of an emission-capturing technology as $T(s_i) = \frac{\beta s_i^2}{2}$, where greater expenditures on inputs (s_i) yields larger emission reductions.[13]

Our interest is in technology where management of the technology can affect emissions. Abatement technology that lacks inputs still has fixed costs but likely has low operational costs. Equipment that requires routine maintenance to operate efficiently would still represent abatement technology that requires inputs, however, most post-combustion clean technology operates through chemical reaction or filtration, both of which also require non-labor inputs. Equipment that adjusts combustion changes the boiler's operations which affects e_k; this equipment would then be influenced by δ_i. (This is also equivalent to updating components of the boiler.) For the remaining technology, there exists a minimum variable cost that a firm will spend to maintain operation of the abatement technology and thus, $\bar{s} > 0$.[14]

Substituting fuel and technology costs into the firm's profit function gives the following

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[https://www.eia.gov/coal/annual/pdf/table31.pdf].

[12] Build up of coal ash increases the frequency of equipment cleaning and byproduct disposal.

[13] This mirrors the use of a slurry or limestone in flue-gas desulfurization (FGD) to reduce SO_2 emissions or the use of ammonia or urea in the case of selective non-catalytic (or catalytic) reduction (SNCR or SCR) to reduce NO_x emissions.

[14] Different technologies have different input requirements. We examine the implications of using different technologies in later sections.

objective for firms voluntarily considering these emission control measures:[15]

$$\max_{x_i,\delta,s_i} \ \pi_{i,k} = \left[p - \alpha x_i^2 + \delta_i \left(x_i + c_k\right) - (1+\delta_i^2)c_k - \frac{\beta s_i^2}{2}\right] q \tag{3}$$

From the regulator's perspective, equation (3) illustrates three potential approaches to encourage or require firms to curb emissions: production inputs, emission capture technology, and firm operations. We begin by examining (voluntary) firm emission-reducing efforts with additional access to clean strategies. Firms optimize equation (3) by selecting the cost-minimizing input combination. For brevity, we assume that the representative firm has all three clean strategies available, i.e., abatement technology is already installed and alternative fuel choices are available. This yields the following emission results (we denote the firm's optimal decisions with "*"):[16]

$$x_i^* = \frac{c_k}{4\alpha c_k - 1}; \qquad \delta_i^* = \frac{2\alpha c_k}{4\alpha c_k - 1}; \qquad s_i^* = \underline{s}; \qquad e_i^* = e_k - c_k \frac{2\alpha + 1}{4\alpha c_k - 1} - \underline{s} \tag{4}$$

If we compare emission reductions from old (c_o) and new/modified firms (c_u), equation (4) shows that:[17]

Remark 1 *Older facilities will have higher emission rates, relative to new or recently modified facilities, ceteris paribus.*

Proof. As discussed, $c_o > c_u$ and $e_u < e_o$. In addition, the prices of abatement technology inputs are independent of firm age and therefore consistent across firms. If we compare emission reductions from fuel quality and calibration, we see that $c_u \frac{2\alpha+1}{4\alpha c_u - 1} > c_o \frac{2\alpha+1}{4\alpha c_o - 1}$. We conclude that $e_{i,o}^* > e_{i,u}^*$ since $c_u < c_o$. ■

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[15] Setting $s_i = 0$ represents firms without control technology installed. Similarly, setting $x_i = 0$ represents firms lacking or refusing to use cleaner fuels.

[16] Note: second order conditions are satisfied: $\frac{\partial^2 \pi_i}{\partial x_i^2} = -2q\alpha$; $\frac{\partial^2 \pi_i}{\partial s_i^2} = -q\beta$; $\frac{\partial^2 \pi_i}{\partial \delta_i^2} = -2qc_k$. For the remainder of our analysis we assume that input costs are sufficiently large such that $c_o > \frac{1}{4\alpha}$.

[17] To ensure that δ is bounded, we assume that $c_u \geq \frac{\alpha}{2}$.

4 Regulatory action

Any firm located in a non-attainment area is subjected to additional regulatory scrutiny and oversight. SIPs can require firms to use different fuels, purchase emission offsets, install RACT systems, or reduce emissions through facility-specific limits. Therefore, we now turn our attention to mandatory emission reductions imposed by regulators.

Regulatory oversight or presence produces stationary source emission reductions (Raff and Walter 2017). From a firm's perspective, voluntary emission reductions can be profit maximizing if a firm is concerned that regulators may take action against them.[18] Based on the cost of higher quality fuels and abatement technology installation and operation, firms may also voluntarily decrease emissions to avoid costly interaction with the regulator. However, a firm will only undertake voluntary emission-reducing efforts to the point of mirroring regulator expectations (while the regulator is present). Therefore, we start by identifying the socially optimal composition of clean strategies. We then identify the regulator's composition of these strategies based on options available and outlined by the NAAQS.

4.1 Abatement efforts

While air pollution control is mandated by the CAA, the regulator must choose where emission abatement occurs. However, the socially optimal outcome requires weighing the benefits of production with damages from emissions. Therefore, we begin by aggregating local firm profits and environmental damages, so social welfare within an area with N firms is represented as:

$$SW = \sum_{i=1}^{N} (\pi_i - D_i)$$

where D_i represents environmental damages stemming from firm i's production and each unit of emissions from firm i is assumed to produce γ damages.[19]

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[18] Firms may be concerned with future regulatory actions, public appearance, or future retribution, e.g., being unable to secure an NSR permit from EPA to undertake modifications (Raff and Walter 2017).

[19] Similar to Fowlie and Muller (2019), we assume the environmental damages from emissions are linear

Welfare maximization requires selecting a firm's fuel quality, abatement technology inputs, and operational calibration from emission sources. More explicitly, a planner optimizes:[20]

$$\max_{x_i,\delta_i,s_i} \; SW = \sum_{i=1}^{N}\left[\left(p - \alpha x_i^2 + \delta_i\left(x_i + c_k\right) - (1+\delta_i^2)c_k - \frac{\beta s_i^2}{2}\right)q - \left(e_k - s_i - \delta_i - x_i\right)q\gamma\right] \tag{5}$$

We identify the social welfare-maximizing use of clean strategies (SW) using equation (5):

$$\begin{gathered} x_i^{SW} = \frac{\gamma + c_k\left(1+2\gamma\right)}{4\alpha c_k - 1}; \qquad \delta_i^{SW} = \frac{\gamma + 2\alpha\left(\gamma + c_k\right)}{4\alpha c_k - 1}; \qquad s_i^{SW} = \frac{\gamma}{\beta}; \\ e_i^{SW} = e_k - \frac{2\gamma\left(1+\alpha+c_k\right) + c_k\left(2\alpha+1\right)}{4\alpha c_k - 1} - \frac{\gamma}{\beta} \end{gathered} \tag{6}$$

Comparing (4) and (6) we find that:

Remark 2 *In general, the welfare-maximizing outcome requires greater expenditures on clean strategies, relative to a firm's (voluntary) decision. As a result, the socially optimal outcome requires firms to further decrease emissions.*

This result is fairly obvious. The social planner would increase social welfare ideally by increasing expenditures on clean strategies to decrease emissions ($x_i^{SW} > x_i^*$; $\delta_i^{SW} > \delta_i^*$; $s_i^{SW} > s_i^*$). While this omits the cost of oversight, greater expenditures on clean strategies would increase social welfare nonetheless. Evaluation of the CAA provides evidence of this result (if we assume that the first abatement efforts taken are the more cost-effective). EPA's benefit-to-cost ratio from the CAA is estimated to be 4:1 or $52 billion in net benefits from emission reductions (EPA 2009). While this result does not mirror the regulator's ideal outcome, it highlights the benefits of emission regulation over firms'

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and additively separable by source for expositional ease.

[20] Not all stationary emission sources have abatement technology installed or access to cleaner fuel, although the regulator can require the installation of RACT. Regardless, our interests at this point are in the discrepancy between how regulators require a firm to operate and the firm's own operating decisions.

voluntary actions. However, the regulator's method of emission reductions is much more constrained. In the next sub-section, we examine how restrictions of the NAAQS influence regulator behavior.

4.2 Reaching attainment

Regulatory action is permitted as part of the NAAQS designation process only until an area meets ambient air quality standards, i.e., is designated as attainment (or maintenance). Any location's designation is determined by the following conditions:

$$\begin{bmatrix} e_i q + \sum_{j \neq i}^{N-1} e_j q + \sum_{l=1}^{M} a_l \leq e_R & \text{if in an attainment area} \\ e_i q + \sum_{j \neq i}^{N-1} e_j q + \sum_{l=1}^{M} a_l > e_R & \text{if in a non-attainment area} \end{bmatrix}$$

where a_l represents non-stationary source emissions from M sources and e_R represents the ambient air quality standard level of each NAAQS.

Non-attainment designation allows regulators to take action to restrict emissions. While the majority of emissions come from non-stationary sources (Auffhammer et al. 2011), coal-fired power plants and other major stationary sources are often the first targets of SIPs (EPA 2018c; Raff and Walter 2018). We assume that regulators focus their attention on reducing emissions from stationary sources using the methods discussed above. Although there exists a limit to what emission reduction methods regulators can require, we begin by examining regulator actions toward local stationary emission sources to help reach attainment with the NAAQS. Regulators then have the following objective:

$$\begin{aligned} \max_{x_i, \delta_i, s_i} \mathcal{L} = \sum_{i=1}^{n} \left[\left(p - \alpha x_i^2 + \delta_i \left(x_i + c_k \right) - (1 + \delta_i^2) c_k - \frac{\beta s_i^2}{2} \right) - \left(e_k - s_i - \delta_i - x_i \right) \gamma \right] q \\ - \lambda \left(\sum_{i=1}^{n} \left[\left(e_k - s_i - \delta_i - x_i \right) q \right] - e_R \right) \end{aligned} \tag{7}$$

For analytical ease, we assume that the regulator's requirement of clean strategies is proportional to a stationary source's production, i.e., $e_R = e_r q$, where e_r represents firm emission reductions.[21] We can identify the regulator's use of clean strategies under NAAQS restrictions using equation 7 (we denote the regulator's decisions with "R"). This yields:[22]

$$\begin{gathered}
\delta_i^R = \frac{(2\alpha+\beta)\,c_o + (2\alpha+1)\,\beta\,(e_k - e_r)}{2\beta\,(1+\alpha+c_o) + 4\alpha c_o - 1}; \qquad s_i^R = \frac{(4\alpha c_o - 1)\,(e_k - e_r) - (2\alpha+1)\,c_o}{2\beta\,(1+\alpha+c_o) + 4\alpha c_o - 1}; \\
x_i^R = \frac{(1-\beta)\,c_o + \beta\,(2c_o+1)\,(e_k - e_r)}{2\beta\,(1+\alpha+c_o) + 4\alpha c_o - 1}; \qquad e_i^R = e_r
\end{gathered} \tag{8}$$

Comparing (4) and (8), we find that the regulator increases expenditures on clean strategies to decrease emissions ($x_i^R > x_i^*$; $\delta_i^R > \delta_i^*$; $s_i^R > s_i^*$). This implies that the regulator will require firms to further reduce emissions beyond voluntary efforts. Comparing (6) and (8), we find that the emission reduction is smaller than socially optimal ($x_i^{SW} > x_i^R$; $\delta_i^{SW} > \delta_i^R$; $s_i^{SW} > s_i^R$).[23] We assume that every firm has abatement technology installed although we illustrate how regulators will move an area out of non-attainment. Regardless, we conclude:

Remark 3 *If stationary emission sources are required to use all clean strategies that are cost effective, the regulatory requirements stemming from non-attainment would not be socially optimal (but still exceed a firm's voluntary efforts).*

In the following sub-section, we examine how the lack of abatement technology at regulated firms affects the regulator's decision.

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[21] Note that e_r is the cheapest abatement strategy from those available.

[22] $\lambda^R = \left(\frac{\gamma(1-\beta)-(2\alpha+1)\beta(\gamma+c_o)+\beta(4\alpha c_o-1)(e_k-e_r)-(\beta+2\alpha)2\gamma c_o}{2(1+\alpha+c_o)\beta+4\alpha c_o-1}\right) q$

[23] We assume that $\frac{\beta(e_k-c_o)+(2\beta-1)\gamma+2\beta(\alpha\gamma+\alpha c_o+\gamma c_o)+4\alpha c_o(\gamma-e_k\beta)}{\beta(1-4\alpha c_o)} \geq e_r$ because the regulator will not require technology that is not cost effective. In the context of the NAAQS, additional scrutiny of non-stationary sources is examined, e.g., outdoor wood-burning bans.

4.3 Technology requirements

Requiring installation of abatement technology imposes a substantial financial burden on the firm. Cost estimates for an SNCR exceed \$10 million for equipment and site requirements necessary for installation (EPA 2017a) (this figure does not include operating costs). Regulators require firms in non-attainment areas to install at least RACT systems (LAER for those making significant modifications). All technological requirements are determined as part of the SIP, which can vary by area. Other factors, e.g., age of emission source, type of modification, cost of technology, are considered as part of technological requirement decisions.

The regulator must decide what abatement technology is required at each boiler given the absence of abatement technology. The social welfare-maximizing approach requires that technology with the greatest net benefits be installed. However, the regulator can only require RACT which commands that the mandated technology be economically feasible.

Let e_t represent the “reasonableness” of abatement technology (based on cost and effectiveness), which is set by the regulator. Constraints make the regulator’s decision to require firm i to install abatement technology, of type v, take the form:[24]

$$\text{if} \quad e_t < \frac{s_{iv}^{SW} q\gamma}{F_{iv} + \frac{\beta}{2}\left(s_{iv}^{SW}\right)^2} \quad \text{and} \quad \pi_i - F_{iv} > 0 \qquad \text{then install } v \tag{9}$$

where F_{iv} is the installation cost of technology v for firm i.

An additional requirement of any SIP is the demonstration that attainment with the NAAQS is possible given the prescribed regulatory actions. Therefore, the regulator must choose the level of emission reductions through abatement technology, fuel, and calibration

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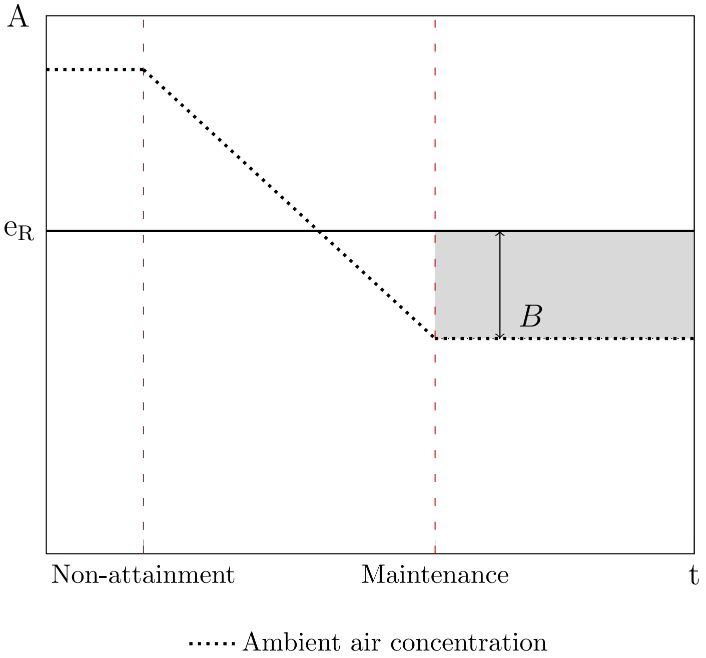
[24] We differentiate by technology because of their substitutability, i.e., certain technologies can not be used concurrently with other technologies. However, the regulator is unlikely to require a firm to install two different technologies for a specific non-attainment designation. We expand on this distinction in a later section.

requirements such that:

$$\sum_{i}^{n_t} e_i q + \sum_{j(\neq i,k)}^{n_o} e_j q + \sum_{h(\neq j,i)}^{n_n} e_h q + \sum_{l=1}^{M} a_l = e_R + B \tag{10}$$

where n_t represents the minimum number of firms installing RACT, n_o represents the number of firms without new technology, n_n represents the number of firms with technology already installed ($n_t + n_o + n_n = N$), and B represents a buffer ensuring that the ambient standard is sufficiently satisfied, which we refer to as "standard slack". Figure 1 illustrates how ambient air quality changes in response to regulatory oversight.

Figure 1: Ambient air quality and "standard slack"



Notes: The horizontal (and diagonal) dotted line represents the ambient air concentration of criteria air pollutants for the relevant NAAQS over time. The path shows the resulting air quality improvements (through aggregate emission decreases) from the execution of a SIP when an area is designated as non-attainment. Once ambient concentrations of criteria pollutants are below the appropriate NAAQS (e$_R$), states can then request for the area to be re-designated as in attainment with the NAAQS (if approved, an area obtains a "maintenance" designation which is used for 10 years). B measures the "standard slack", i.e., ambient air concentrations below the standard level.

Let n_t^* denote the minimum number of firms requiring technology in order to satisfy (10) when $B = 0$. The number of firms that install RACT as part of a SIP will exceed

n_t^* for several reasons. First, the regulator would prefer to have additional slack ($B > 0$) to account for variation of other emission sources. Second, the regulator is likely to use conservative estimates regarding expected emission decreases from installed technology. Third, the number of firms required to install RACT jumps discretely according to equation (9) as the "reasonableness" constraint for installing RACT (e_t) is lowered to satisfy the ambient standard. As a result, the regulator must determine "reasonableness" such that the number of firms required to install RACT (along with other SIP requirements) satisfies the ambient standard, or equivalently:

$$\min_{e_r} \; n_t \qquad s.t. \; \sum_{i=1}^{n_t} e_i q + \sum_{j=1}^{n_o} e_j q + \sum_{h=1}^{n_n} e_h q + \sum_{l=1}^{M} a_l < e_R + B \tag{11}$$

Let $\overline{e}_t$ denote the RACT condition that satisfies (11) and let n_t^R represent the associated number of firms installing RACT systems. $n_t^R > n_t^*$ and $B > 0$ because of discrete changes in the number of firms due to RACT conditions. In contrast, the socially optimal number of firms that should install abatement technology[25] is determined solely on the net benefits of available abatement technology.[26] Since the socially optimal condition to install abatement technology is stricter than the regulator's (as crafted by the CAA), we see that $n_t^{SW} > n_t^R > n_t^*$. From this we conclude that:

Remark 4 *The regulator will require installation of more abatement technology than is required to meet the ambient air quality standard in non-attainment areas, but less than is socially optimal.*

We next examine how this process evolves in relation to exiting non-attainment, given our clearer understanding of how regulators administer the installation and usage of abatement technology.

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[25] RACT is predicated on some technology satisfying the feasibility conditions outlined by the CAA. We intentionally avoid using "RACT" in this context because this is stricter than the socially optimal condition.

[26] A planner would require firms to install technology if $F_{iv} + \frac{\beta}{2}\left(s_{iv}^{SW}\right)^2 < s_{iv}^{SW} q\gamma$; some firms could be forced to shutdown due to the cost of the required technology.

4.4 Leaving non-attainment

We can identify emission reductions that result from an area entering non-attainment using the regulator's decision to require abatement technology installation and the associated investment in clean strategies. We can identify the decrease in emissions from entering non-attainment using equation (8) and technology installation ($n_t^{SW} > n_t^R > n_t^*$), as:[27]

$$\sum_{i=1}^{n_t^R} e_i^R q + \sum_{j=1}^{n_o} e_j^R q + \sum_{h=1}^{n_n} e_h^R q + \sum_{l=1}^{M} a_l < e_R + B \tag{12}$$

An important observation of (12) is the level and management of emissions when an area leaves non-attainment after attaining the relevant NAAQS. The regulator chooses abatement efforts of firms (e_i^R) in non-attainment and constructs appropriate slack between the ambient air quality standard and local ambient air quality. Management of abatement efforts returns to the firm after an area attains the standard and exits non-attainment.[28] Firms will decrease abatement efforts relative to the regulator (see Remark 3), which causes emissions to increase ($e_i^R < e_i^*$). A firm that increases emissions contributes to degradation of ambient air quality, which can lead to re-designation as non-attainment. Recall that in general, stationary sources account for a small minority of criteria air pollutant emissions in non-attainment areas. Additional slack has also been created through inefficient diffusion of technology. Therefore, a firm's emissions will change according to:[29]

$$q\Delta e_i = q(e_i^R - e_i^*) \ll B \tag{13}$$

The switch in management from regulator to firm is caused by the regulator leaving, i.e., regulatory oversight reducing, after an area has attained the ambient air quality

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[27] $s_i^R = 0$ for firms without abatement technology installed.

[28] Note that our analysis has focused on clean strategies where management can affect emissions.

[29] Our analysis focuses on how individual firms respond, however, we would expect the same increase with multiple firms. Firms strategically increase emissions, so multiple sources can concurrently increase emissions too.

standard. Thus, Δe_i represents the effect of exiting non-attainment on firm emissions. As shown, $q\Delta e_i > 0$. This allows us to state the following:

Proposition 1 *A stationary emission source located in a non-attainment area that has sufficiently met ambient air quality standards (i.e., exiting non-attainment with some level of "standard slack"), will increase its emissions, ceteris paribus.*

This is an extension of Remark 3 applied to areas that have met ambient air quality standards. We expect that as the regulator transfers abatement efforts to the firm emissions will increase.

Regulatory oversight changes firms' aggregate emissions by influencing production. We examine firm operations with and without direct regulatory oversight to identify emission changes. Using the relationship between production and emissions in (2) highlights how the regulator's absence changes emissions, yielding:[30]

$$\Delta e_{it} = \Delta e_t - \Delta\delta_{it} - \Delta(x_{it} + s_{it}) \tag{14}$$

The parameters influencing firm emissions are: properties of the plant (e_k), changes in plant operations ($\Delta\delta_{it}$), and (environmental) regulatory constraints ($\Delta(x_{it} + s_{it})$). We next move to testing empirically how firm emissions change in the absence of regulatory oversight using these parameters.

5 Empirical analysis

This section lays out the primary empirical foundation of our study, which estimates the effect of coal-fired power plant exit from non-attainment designation on $\mathrm{NO_x}$ emissions and emission rate at coal-fired power plants. First, we provide the identification strategy and define our treatment. Second, we describe the data used and present sample summary statistics. Third, we describe the estimating equation. Finally, we present results and robustness checks.

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[30] $\Delta e_i = e_i^* - e_i^R = (e_k - \delta_i^* - s_i^* - x_i^*)q - (e_k - \delta_i^R - s_i^R - x_i^R)q = (\Delta e_k - \Delta\delta_i - \Delta x_i - \Delta s_i)q$

5.1 Treatment definition and identification

Previous studies identify the effects of non-attainment designation on stationary source emissions or ambient air quality based on facility or area entrance into non-attainment. Most studies consider as "treated" all facilities after they enter into non-attainment for the remainder of the sample period - even if the facilities exit non-attainment eventually - because SIP-mandated emission reductions are expected to be permanent (EPA 2018c). Rather than examine how emissions and emission rate change when facilities enter non-attainment, we are interested in the opposite effect: the effect on emissions and emission rate of exit from non-attainment, i.e, the effect on emissions of a significant and certain decrease in regulatory oversight. Thus, we wish to examine if emission reductions made by stationary sources while in non-attainment are indeed permanent, as required by EPA.

We define our generalized difference-in-differences (DD) estimator in the following way. Boilers located in areas designated as non-attainment - for those designations that are affected by $\mathrm{NO_x}$ emissions (PM and ozone)[31] - at any point during our panel represent the treatment group. The "post" period represents the time after the area that was previously designated as non-attainment improves its ambient air quality to a level below the relevant NAAQS and is re-designated as no longer being in non-attainment, i.e., maintenance or attainment (this can happen at different times in our panel); this represents when an area received treatment. If areas remain in non-attainment for the entirety of our panel, then boilers in these areas never receive treatment. We thus leverage a one-time within-boiler change out of non-attainment to estimate its effects on coal-fired power plant $\mathrm{NO_x}$ emissions and emission rate. We denote our treatment indicator *Exit* in the empirical model specification.

Identification of these effects relies on an exogenous change in affected non-attainment status. The change of status out of non-attainment is plausibly exogenous to $\mathrm{NO_x}$ emissions and emission rate for the average stationary source in each designated non-attainment area because each stationary source's emissions represent a small contribution to ambient air concentrations of criteria pollutants for such a large geographic area. In-

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[31] There were no non-attainment areas for nitrogen dioxide at any point in our sample.

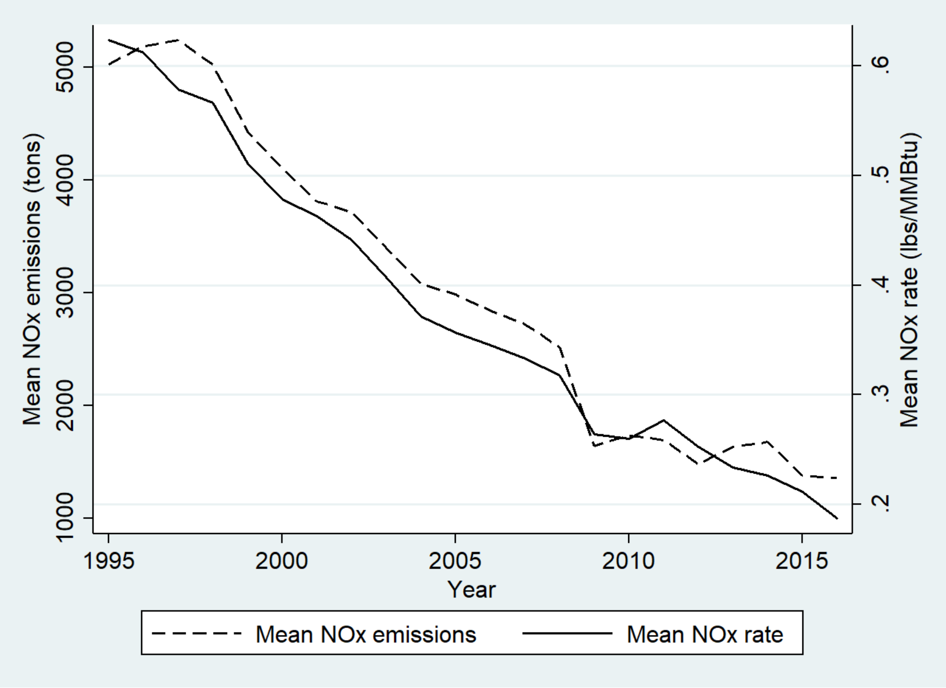
deed, mobile source emissions are responsible for the majority of criteria air pollutant emissions (Auffhammer et al. 2011). Further, EPA National Emissions Inventory (NEI) data show that in 2011 only 4% of NO_x emissions in New England were from electric utilities. Previous studies have also treated non-attainment designation as exogenous to facility emissions (Greenstone 2003; Bi 2017; Gibson 2018). Further, we lag our treatment indicator by one year to allow utility managers time to respond to changes in NAAQS designation. Thus, boiler exit from non-attainment is exogenous given the separation in time between lagged treatment and current boiler level emissions. Finally, we focus exclusively on NO_x emissions and emission rate due to the potential endogeneity concerns of other pollutants found in our data, e.g., SO_2 emissions and SO_2 non-attainment designation. For SO_2 in particular, the ambient air concentration of an area is more significantly impacted by electric utility emissions (NEI data show that more than 50% of SO_2 emissions are from electric utilities). Thus, our identification carefully considers which pollutants and air quality standards to examine to ensure the exogeneity of treatment.

We test further that non-attainment designation is exogenous and thus, that we have identified correctly the effects of exit from non-attainment on NO_x emissions and emission rate by examining if coal-fired power plant emissions affect the probability of non-attainment designation. Our treatment is endogenous if past period coal-fired power plant NO_x emissions can predict when an area is designated as non-attainment for PM or ozone. We test this by estimating an equation where NO_x-affected non-attainment designation is the dependent variable and the regressors are one-year lagged NO_x emissions (and other lagged controls, as described below) using OLS. The coefficient for lagged NO_x emissions is not statistically significant ($p=0.784$), which means that previous year coal-fired power plant NO_x emissions do not affect the probability that an area is designated as non-attainment for either PM or ozone. Collectively, we are confident that our treatment is exogenous and that its effects are identified correctly.

5.2 Data

We use EPA's Air Markets Program Database (AMPD) as our primary data source. The AMPD contains information on several measures for regulated facilities that burn fossil fuels, e.g., coal, and that serve a generator greater than 25 MW, from 1980-present; this includes nearly every coal-fired electric utility in the United States. The AMPD includes individual boiler level emissions of NO_x (measured in tons) and heat input (measured in MMBtu), which is necessary for the calculation of NO_x emission rate.[32] The AMPD also contains information on installed pollution control technologies at each boiler, including the year of installation. Finally, the AMPD includes data on other facility and boiler level characteristics such as operating capacity, total electrical generation, and federal programs under which each boiler is regulated.

Figure 2: NO_x emission trends



Notes: Trends are mean boiler level NO_x emissions and emission rate by year. Emissions are measured in tons and rates are measured in pounds per MMBtu.

Figure 2 shows mean boiler level trends of NO_x emissions and emission rate during

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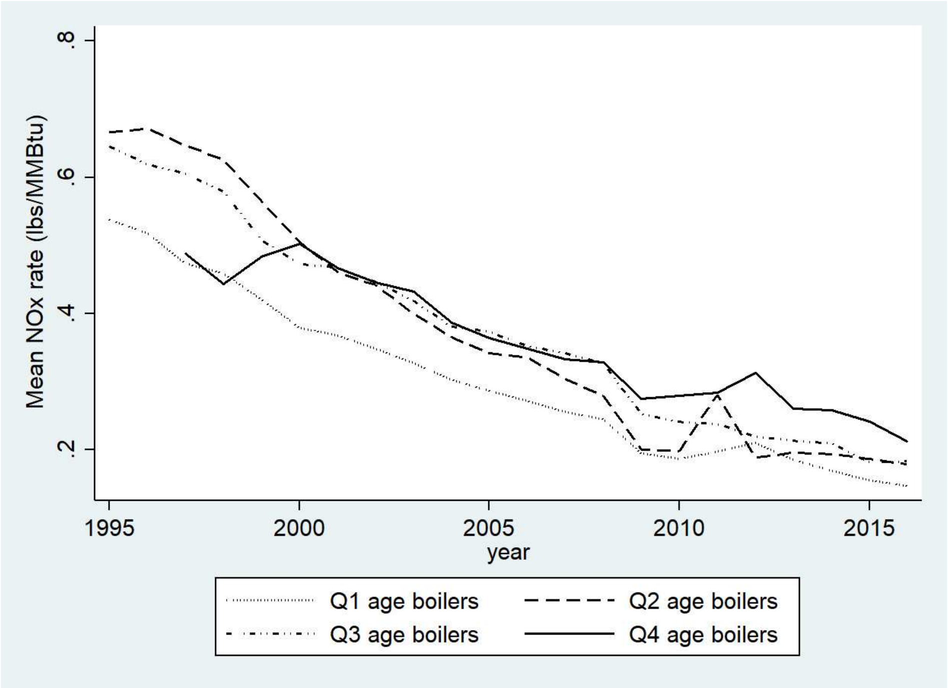
[32] NO_x emission rate is the amount of NO_x emitted per unit of energy produced. We calculate this as pounds of NO_x emissions/heat input.

our sample period. It is evident from this time series that the two measures trend very closely. Additionally, there is a steady downward emission trend in this sector during the past two decades. This highlights the importance of controlling for time trends and other regulatory programs that have potentially contributed to this decline in our analysis.

Figure 3: NO_x emission trends by boiler age



Notes: Trends are mean boiler level NO_x emission rates by boiler age, measured in pounds per MMBtu. Groups are determined by age quartiles, e.g., 0-25 percentile.

Figure 3 presents a time trend of mean boiler level emission rates by boiler age, with boilers grouped into four categories based on age quartiles. As represented above, we expect emission rates to be higher for those boilers that are older; Figure 3 confirms this assertion. We see that for boilers in the fourth age quartile, i.e., 75-100 percentile, emission rates are consistently higher than those for boilers in the other three age quartiles.[33] We perform this same exercise but condition emissions on installation date of NO_x abatement technology, i.e., “birth” of the boiler is at time of technology installation rather than initial

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[33] We have relatively few observations for fourth quartile boilers for years prior to 2000 (0 in 1995 and 1996). The oldest boiler in our sample is 46 years old in 1995 and the fourth age quartile is 48 years old and above.

construction. Time series results for this exercise are nearly identical to those presented in Figure 3.

We built our panel by collecting all boiler level data available in the AMPD through 2016. We then eliminated observations from 1980-1990 because data are only available in five-year increments until 1995. Next, we retained only those boilers that burn coal as the primary fuel and were categorized as "Electric Utility", "Cogeneration", or "Small Power Producer".[34] Several boilers throughout our panel either shut down, came online, or switched fuel (most to natural gas); we do not include in our analysis boiler-year observations where the boiler burns fuel other than coal or is not operating. The final analysis dataset is an unbalanced panel of coal-fired power plant boiler-years from 1995-2016. The unbalanced nature of our panel is not problematic because attrition is low and not endogenously determined. Indeed, we estimate a specification with only those boilers that operated during the entirety of our panel as coal-fired units, i.e., our panel is perfectly balanced. Empirical results are qualitatively and quantitatively similar to those presented below.

It is possible during our sample period for areas to exit non-attainment designation and then re-enter several years later. This can happen in one of two ways: (1) ambient air concentrations of criteria air pollutants in the area rise above the relevant NAAQS after re-designation (perhaps due to rising emissions as a result of decreased regulatory oversight) or (2) EPA tightens, i.e., lowers, the NAAQS to a level below the ambient air concentration of an area for that pollutant. As a specific example within our sample period, Floyd County (IN)[35] was designated as non-attainment for ozone from 1995-2000. In 2001, the ambient air concentration of ozone in the county reached attainment levels and the area was re-designated as maintenance, i.e., is treated in our specification. However, in 2004 EPA promulgated new ozone standards which decreased the ambient level of ozone necessary to be designated as non-attainment. As a result, Floyd County

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[34] We also estimate our primary regression specification for all facilities that burn coal as fuel, including those that do not generate electricity, e.g., pulp and paper mills. Empirical results are qualitatively and quantitatively similar to those presented below.

[35] R. Gallagher Generating Station, a 150 MW coal-fired power plant, is located in this county.

was re-designated as non-attainment under the new standards. Because our identification relies on a one-time exogenous shock out of non-attainment, we would miss (for boilers such as this) the second "shock" that occurred when areas go from non-attainment to maintenance and back into non-attainment.[36] We correct for this potential measurement error by including twice in our panel, i.e., data for the full 22 years, those boilers that exited non-attainment twice. Thus, we are able to witness the change in emissions and emission rate as a result of each of the two treatments for these boilers.[37]

Our use of the AMPD is preferred to other data sources used to estimate the effects of non-attainment on emissions or ambient air quality. First, previous studies have used EPA's Toxics Release Inventory (TRI) to estimate these effects (Greenstone 2002; Bi 2017; Gibson 2018). However, TRI data capture emissions from only regulated facilities that emit a certain amount of toxic pollutants necessary for TRI reporting. Of the criteria air pollutants regulated by the NAAQS, only lead and ozone are TRI chemicals. Second, other studies examine the effects of non-attainment on the ambient air quality of an area using EPA's Air Quality System (AQS), not emissions (Greenstone 2004; Auffhammer et al. 2009). AQS data do not allow for facility (boiler) level analysis and so use of these data does not allow an examination of how stationary source emissions change when not subjected to regulatory oversight.

We use EPA's Green Book for information about non-attainment designation (EPA 2017b). The Green Book contains non-attainment status of six criteria pollutants regulated by the NAAQS at the county level for the United States between 1992 and 2016. Table 1 depicts if ambient air concentrations of the six criteria air pollutants are affected by $\mathrm{NO_x}$ emissions.

Finally, we use the League of Conservation Voters (LCV) yearly scorecards (1995-2016) to account for a state's level of environmental concern of its citizens. This variable serves as a proxy for the level of regulatory stringency placed on regulated facilities in individual states. Each year, the LCV publishes a scorecard that ranks the level of pro-

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[36] There are no areas in our dataset that exit non-attainment three or more times.

[37] Estimation results are qualitatively and quantitatvely similar if we only estimate the effects based on the first exit from non-attainment.

environmentalism of each state's congressional delegation. The measure is calculated using each state's representatives' voting records on key pieces of environmentally related legislation. Table 2 provides statistical summaries for measures used in the analysis.

Table 2: Sample summary statistics

Variable	Mean	Std. Dev.	Min	Max
Dependent variables				
NO_x emissions (logged tons)	7.256	1.459	-6.908	11.38
NO_x emission rate (logged lbs/MMBtu)	-1.158	0.670	-6.725	3.098
Treatment				
NO_x-affected non-attainment exit (one-year lag)	0.173	0.378	0	1
Boiler level controls				
Total electrical generation (GW-h)	2003	1833	0	13,900
Maximum capacity (MW)	337.1	309.2	0.099	6283
Operating time (hours)	6564	2181	0	8784
House LCV score (0-100)	39.80	18.40	0	100
Regulatory program controls				
CAA Title IV Acid Rain Program	0.938	0.242	0	1
Clean Air Interstate Rule (NO_x)	0.263	0.440	0	1
SIP NO_x Program	0.005	0.070	0	1
Cross-State Air Pollution NO_x Program	0.058	0.233	0	1
NO_x Budget Program	0.189	0.392	0	1

Notes: Summary statistics are at the boiler-year level. NO_x-affected non-attainment exit indicates years following exit from non-attainment for coal-fired boilers. Regulatory program dummies indicate that a boiler is regulated under that program in a given year.

Most important, 17% of boiler-year observations receive the treatment described in the previous sub-section. Specifically, these boiler-years were previously located in counties designated as non-attainment but then ambient air concentrations of PM or ozone improved and the county exited non-attainment. Table 2 shows considerable variation in most measures, including our treatment indicator. Finally, minimum values of the dependent variables (and of some controls) highlight the importance of the identified control factors, especially operating time of each boiler. Some boiler-year observations emitted less than one ton of $\mathrm{NO_x}$ (as identified by log-transformed values less than zero). Thus, controlling for the amount of time that these boilers operated appears imperative.

5.3 Estimating equation

Let Y_{ift} represent $\mathrm{NO_x}$ emissions (measured in tons) or emission rate (measured in lbs/MMBtu) of coal-fired power plant boiler i at facility f in year t. Using equation (14) as a guide, we estimate the following generalized DD specification using the definiton of treatment described in the previous sub-section:

$$ln(Y_{ift}) = \psi_i + \mathbf{X'}_{ift}\Pi + \nu_{rt} + \beta Exit_{ift-1} + \mathbf{R'}_{ift}\Psi + \epsilon_{ift} \tag{15}$$

where ψ_i represents boiler fixed effects, which control for boiler specific features that do not change over time. X_{ift} is a vector containing a set of boiler level operation and control variables, which include total electrical generation, maximum capacity, operating time, and House LCV score. These time-varying factors control for variation in boiler level characteristics that impact $\mathrm{NO_x}$ emissions and emission rate. The remaining variables represent time or regulatory constraints. ν_{rt} are EPA region by year fixed effects, which control for year-specific variation in NAAQS implementation across EPA regions, e.g., variation driven by differences in regional office leadership. $Exit_{ift-1}$ is the DD indicator which represents exit from PM or ozone non-attainment designation, lagged one year.[38] We lag this measure to allow firm managers time to respond to the change in regulatory requirements after exiting non-attainment. (We examine varying lag lengths below.) Finally, R_{ift} is a vector that consists of a series of dummies that indicate whether boiler i at facility f in year t is subjected to the requirements of regulatory programs other than the NAAQS. These dummies help us better isolate the effects of exiting non-attainment on $\mathrm{NO_x}$ emissions and emission rate at coal-fired power plants because the programs are intended to decrease emissions and improve ambient air quality, similar to the NAAQS.

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[38] We also consider a specification where counties in the 13 state Ozone Transport Region (OTR) are considered in non-attainment for the entirety of our panel (Sheriff et al. 2019) and thus, OTR counties do not ever exit non-attainment. Results from this specification are nearly identical to those presented below.

Thus, exclusion of these programmatic dummies would result in the analysis attributing emission decreases/increases at coal-fired power plant boilers from other programs to the NAAQS. R_{ift} contains dummies for the CAA Title IV Acid Rain Program (ARP), Clean Air Interstate Rule, SIP NO_x Program, Cross-State Air Pollution NO_x Program, and the NO_x Budget Program.[39] Finally, ϵ_{ift} is the exogenous error term. Standard errors are clustered at the county level which is the level of identifying variation.[40]

5.4 Results

Results for the estimation of equation (15) are tabulated in Table 3. We include results for three model specifications to assess the robustness of our results based on control variables included in the analysis. Columns two and three present results from the estimation of the parsimonious model, which includes only the treatment regressor and boiler and year by region fixed effects. Without any boiler level or programmatic controls, we still see an increase of nearly 12% in coal-fired power plant boiler emissions when the direct regulatory oversight on non-attainment is eliminated. The lack of statistical significance for NO_x emission rate in this model specification perhaps highlights the importance of adding operating time and production variables as controls. Columns four and five add boiler level controls and columns six and seven add regulatory program controls. We focus our discussion of the results on those from the full model, which includes all possible controls on the right-hand side (columns six and seven); results from this specification are very similar to those when we include only boiler level controls. Column six presents results for the estimation where logged NO_x emissions is the dependent variable. The effects of exiting NO_x-affected non-attainment designation are presented as semi-elasticities because the outcome is log-transformed. We find that boilers regulated under non-attainment SIPs

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[39] An important regulatory program that was implemented during our sample period that is not included in R_{ift} is the Mercury and Air Toxics Standards (MATS) [2011 announcement and 2015 implementation]. Coal-fired boilers over 25 MW were regulated under MATS requirements. Because AMPD data contain information for all electric utility boilers that are greater than 25 MW, every boiler in our sample was regulated under the MATS. Thus, MATS regulation is subsumed into the EPA region by year fixed effects.

[40] Clustering standard errors at the boiler level produces results that are identical to those presented below.

increase NO_x emissions by 16% one year after exiting non-attainment and while regulated under a maintenance plan. To put this value into greater context, this increase is over 486 additional tons of NO_x emitted at the average boiler in our sample.

Table 3: Fixed effects estimation results for exit from non-attainment

			Dependent variable			
Variable	Emissions	Rate	Emissions	Rate	Emissions	Rate
Treatment						
NO_x-affected non-attainment exit (one-year lag)	0.117* (0.060)	0.047 (0.042)	0.173*** (0.050)	0.091** (0.045)	0.161*** (0.050)	0.088** (0.045)
Boiler-level controls						
Total electrical generation (TW-h)			-0.046 (0.040)	0.039* (0.020)	-0.047 (0.039)	0.038* (0.020)
Maximum capacity of boiler (GW)			0.033 (0.089)	-0.008 (0.110)	0.034 (0.090)	-0.009 (0.109)
Operating time (days)			0.069*** (0.0003)	-0.0007*** (0.0002)	0.069*** (0.0003)	-0.0008*** (0.0002)
House LCV score (0-100)			0.002* (0.001)	0.002* (0.001)	0.002* (0.001)	0.002* (0.001)
Regulatory program controls						
CAA Title IV Acid Rain Program					0.020 (0.108)	-0.033 (0.084)
Clean Air Interstate Rule (NO_x)					0.017 (0.059)	0.070 (0.047)
SIP NO_x Program					-0.437*** (0.125)	-0.291 (0.178)
Cross-State Air Pollution NO_x Program					0.097 (0.080)	0.054 (0.080)
NO_x Budget Program					-0.101* (0.057)	-0.023 (0.060)
Observations	23,524	23,355	14,596	14,592	14,596	14,592
Number of boilers	1,334	1,326	1,095	1,096	1,095	1,096
Boiler FE	Yes	Yes	Yes	Yes	Yes	Yes
Year#EPA Region FE	Yes	Yes	Yes	Yes	Yes	Yes

Notes: *** p≤0.01, ** p≤0.05, * p≤0.1. Standard errors clustered at the county level, which is the level of identifying variation, and located in parentheses. There are 396 counties (clusters) with coal-fired power plant boilers in the panel. Dependent variables are log-transformed. NO_x-affected non-attainment exit indicates years following exit from non-attainment for coal-fired boilers. Regulatory program dummies indicate that a boiler is regulated under that program in a given year.

We also estimate the effect of exit from non-attainment on NO_x emission rates. This rate is measured in pounds per million British Thermal Units (lbs/MMBtu) and allows us to examine emissions per amount of energy produced at each boiler. Although we control above for operating time and electrical generation, using NO_x emission rate as our outcome allows us to examine further how utilities respond when exiting non-attainment. For example, if boiler level emissions increase once counties exit non-attainment (as shown above), this may be the result of managers ramping up each boiler and producing more electricity rather than managers making a conscious decision to, e.g., under-utilize abatement technology due to decreased regulatory presence. Results presented in column seven of Table 3 show that this hypothetical is not the case: exit from non-attainment increases boiler level NO_x emission rates by 9%.

These results support the following conclusions. Utility managers increase boiler level NO_x emissions in general when the area that each boiler is located within exogenously exits out of non-attainment designation. Our examination of emission rate as the outcome provides evidence that this is not simply the result of managers running boilers harder and producing more electrical output, which would certainly increase emissions. We find that emissions per unit of output also increase when the additional regulatory stringency and oversight of non-attainment is reduced. These results provide initial evidence that emission decreases mandated within SIPs are not permanent. Further, results suggest that emission increases may be the result of under-utilization of clean strategies present when in non-attainment. We examine this possibility further in section 6.

5.5 Sensitivity analysis

In this sub-section we assess the robustness of our results to changes in regression specification and analysis sample. We first examine varying lag length of treatment. We lag treatment by one year in our primary regression specification to allow utility managers time to respond to the decrease in regulatory oversight associated with exit from non-attainment. However, it is possible that the response may not be immediate. Managers could take time to change their operations, as learning about the new regulatory environment occurs in a period longer than one year (Maniloff 2019). As a result, we re-estimate equation (15) with treatment now lagged by three and five years to examine manager behavior. Results for these alternative specifications are tabulated in Table 4. Columns two and three present results for a three-year treatment lag and columns four and five present results for a five-year treatment lag. Empirical results are similar for both alternative specifications to those presented in the full model of Table 3. Both NO_x emissions and emission rate increase significantly after exit from non-attainment, even with longer lag periods. These results indicate that changes in emissions and emission rate happen almost immediately after regulatory oversight is decreased and these increases remain into the future. Utility managers are aware of the change in oversight after only one year and increase emissions accordingly.

Table 4: Fixed effects estimation results for exit from non-attainment: Varying lag length

	Dependent variable			
Variable	Emissions	Rate	Emissions	Rate
NO_x-affected non-attainment exit (three-year lag)	0.178*** (0.050)	0.125*** (0.045)		
NO_x-affected non-attainment exit (five-year lag)			0.157** (0.063)	0.119** (0.060)
Observations	14,483	14,477	14,247	14,242
Number of boilers	1,095	1,096	1,095	1,096
Boiler-level controls	Yes	Yes	Yes	Yes
Regulatory program controls	Yes	Yes	Yes	Yes
Boiler FE	Yes	Yes	Yes	Yes
Year#EPA Region FE	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. Dependent variables are log-transformed. NO_x-affected non-attainment exit indicates years following exit from non-attainment for coal-fired boilers.

We also examine the robustness of the primary estimation results to changes in analysis sample. To do so, we exclude from the analysis those boilers that never experienced the increased regulatory oversight of non-attainment designation. Thus, our control group is now non-attainment boilers that have not exited non-attainment. This control group may be more appropriate because boilers that have never been in non-attainment may be a poor counterfactual for boilers that are subjected to significantly higher regulatory oversight. For this analysis then, identification rests solely on the timing of treatment. Results from the estimation of equation (15) with this sub-sample are presented in Table 5. Results are nearly identical to those presented in Table 3. We see that no matter the control group, exogenous exit from non-attainment significantly increases NO_x emissions and emission rate.

Table 5: Fixed effects estimation results for exit from non-attainment: Alternative sample

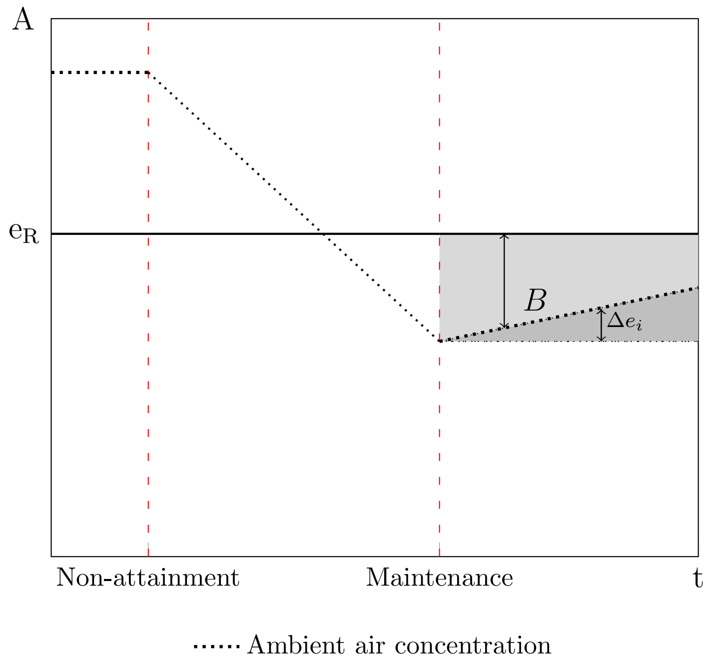
	Dependent variable	
Variable	Emissions	Rate
NO_x-affected non-attainment exit (one-year lag)	0.161*** (0.056)	0.115** (0.051)
Observations	7,363	7,360
Number of boilers	565	566
Boiler-level controls	Yes	Yes
Regulatory program controls	Yes	Yes
Boiler FE	Yes	Yes
Year#EPA Region FE	Yes	Yes

Notes: *** p≤0.01, ** p≤0.05, * p≤0.1. Standard errors clustered at the county level and located in parentheses. Dependent variables are log-transformed. NO_x-affected non-attainment exit indicates years following exit from non-attainment for coal-fired boilers. Analysis sample is boilers located in counties that were at one point designated as non-attainment. Control group is boilers that never exit non-attainment during our sample period, i.e., non-attainment boilers that never receive treatment.

6 Mechanisms

We discuss in this section the mechanisms through which coal-fired power plants increase post non-attainment emissions. As shown, the absence of direct regulatory oversight incentivizes utility managers to increase emissions above the non-attainment level. “Standard slack” created by the emission reductions of non-attainment allows firms the opportunity to minimize costs and thus increase emissions; Figure 4 illustrates this scenario.

Figure 4: Emission changes in the presence of “standard slack”



Notes: The horizontal (and diagonal) dotted line represents the ambient air concentration of criteria air pollutants for the relevant NAAQS over time. The path shows the resulting air quality improvements (through aggregate emission decreases) from the execution of a SIP when an area is designated as non-attainment. Once ambient concentrations of criteria pollutants are below the appropriate NAAQS (e_R), states can then request for the area to be re-designated as in attainment with the NAAQS (if approved, an area obtains a “maintenance” designation which is used for 10 years). B measures the “standard slack”, i.e., ambient air concentrations below the standard level. Δe_i represents the increase in emissions at stationary sources that occur once an area is no longer designated as non-attainment, i.e., direct regulatory oversight is absent.

We first examine local emission reductions created by the regulator through additional oversight and the requirements of SIPs. Recall that local emissions in an area that has met ambient air quality standards are:

$$\sum_{i=1}^{n_t} (e_k - s_i - \delta_i - x_i)\, q + \sum_{j=1}^{n_o} (e_k - \delta_i - x_i)\, q + \sum_{h=1}^{n_n} (e_k - s_i - \delta_i - x_i)\, q + \sum_{l=1}^{M} a_l < e_R + B \tag{16}$$

Ambient air quality “standard slack” allows local emission sources to increase emissions if it reduces their costs. All else equal, firms will attempt to find cost savings if $q\Delta e_i \ll B$. However, the methods by which emission increases occur may differ. Equation (16) reveals three ways that the typical firm can increase emissions: abatement technology usage, quality of inputs, or re-calibration. Comparing each firm's emissions in (16) to the firm's decision (without increased regulatory oversight) from (4), the firm's cost-minimizing and emission increasing options can be identified. Explicitly, we obtain $q\Delta e_i = (e_k - \Delta\delta_i - \Delta s_i - \Delta x_i)q$. The following sub-sections examine how operational changes lead a profit maximizing firm to increase emissions after exiting non-attainment. Fuel type and clean technology affect the calibration of other equipment, therefore we focus on the primary effects of fuel and technology.

6.1 Abatement technology

We first examine how firms leaving non-attainment use the abatement technology required as part of non-attainment designation.

Theoretical foundation. Many forms of abatement technology require significant input costs to operate effectively. The use of reagents and catalysts, e.g., ammonia, increases operating costs because of higher combustion (fuel) requirements and the cost of the inputs themselves. A profit maximizing firm will reduce expenditures in abatement technology; see Remark (3). As a result, the quantity of reagent used by the firm will deviate from the socially optimal amount required by the regulator, i.e., $s_i^R > s_i^*$, and by extension, $q(s_i^R - s_i^*) > 0$. In the context of non-attainment, this gives $q\Delta s_i > 0$. To state formally:

Proposition 2 *A profit-maximizing stationary emission source will decrease the use of abatement technology inputs when exiting non-attainment, which will increase emissions.*

Emission increases are directly related to firm profit. However, the type of abatement technology installed at each boiler also impacts the firm's options. In general, RACT requirements do not contain prescribed equipment or technologies that must be used. This lack of specification results in considerable heterogeneity in the installed abatement technology across coal-fired boilers in non-attainment areas. For example, SCR/SNCR have higher installation and operation costs relative to low $\mathrm{NO_x}$ burners (LNB) or over-fire air systems (OFA). Of interest is the firm's ability to adjust installed technology effectiveness. For example, LNB/OFA do not have reoccurring operating costs, while SCR/SNCR require continuous purchase of reagents and catalysts, e.g., ammonia (and also additional heat requirements).[41]

$\mathrm{NO_x}$ emission reductions from SCR (75-85%) or SNCR (40-60%) are more effective than LNB (35-55%) or OFA (20-30%) (Xiong et al. 2016). However, input requirements of SCR/SNCR relative to LNB/OFA are significant and include additional heat requirements and catalytic material (Van Caneghem et al. 2016). This highlights benefit and cost differences in RACT systems. As a result, regulators may require different abatement technologies when deciding $\mathrm{NO_x}$ RACT as part of SIPs. Input expenditures for abatement technology will differ considerably depending on the type; this limits firm options and affects post non-attainment emissions.

As a specific example, let two abatement technologies exist, v and w, where v represents technology with input requirements and w represents technology without input requirements (or only unavoidable input requirements, e.g., maintenance). The type of technology installed at each boiler affects the regulator's ability to adjust firm expenditures. Specifically, $s^R_{iw} = \bar{s}_{iw}$, for technology without input requirements, and $s^R_{iv} > \bar{s}_{iv}$ for technology with input requirements, as the regulator will require additional expenditure above the minimum. Formally:

Proposition 3 *A profit maximizing stationary emission source with abatement technology that requires costly inputs will decrease its use of these inputs (abatement technology) and increase emissions, relative to firms without abatement technology input requirements, in the absence of direct regulatory oversight.*

This finding highlights the fact that the type of abatement technology installed at

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[41] Reagent costs are considerable; purchase of ammonia to use with SCR/SNCR can cost millions of dollars per year for a single boiler. As anecdotal evidence, we discussed operations with the operator of a regulated coal-fired power plant in the midwest with SCR technology and ammonia costs for this boiler were between $3 and $5 million per year.

each boiler affects its management and post non-attainment usage. Importantly, the cost structure of abatement technology creates incentives rarely (if ever) discussed. From the regulator's perspective, as long as air quality standards are maintained the firm is effectively managing its abatement technology. Efficiency losses are possible after the costly installation of abatement technology due to the firm's profit motive, which results in emission increases because of the reduction in usage of abatement technology inputs.

Empirical examination. We test empirically if emission increases at boilers exiting non-attainment are the result of utility managers under-utilizing abatement technology. Specifically, we show above that managers will minimize input costs associated with certain technologies, e.g., SCR/SNCR, in the absence of direct regulatory oversight; this results in increased emissions. To test this assertion, we first restrict the sample to those boilers located in a county that was designated as non-attainment at some point during our sample period. We restrict the sample to these boilers because this allows us to examine abatement technology installed as a result of the technological requirements of SIPs, rather than manager decisions. We use data on the type and install date of abatement technology at each boiler to examine the differential effects. We re-estimate equation (15) for two sub-samples depending on the type of abatement technology installed at each boiler. First, we estimate the effects of exiting non-attainment on $\mathrm{NO_x}$ emissions and emission rate for those boilers with technologies requiring reagents, which represent a substantial input cost to technological operation. This sub-sample includes boilers that installed SCR, SNCR, or ammonia injection systems as a result of non-attainment designation. This sub-sample represents boilers with the potential to have varying success at decreasing emissions depending on input usage and thus, we expect emission increases at these boilers after exiting non-attainment. Second, we estimate the same effects for boilers with technology that does not require reagents, i.e., input costs. These boilers have fuel re-burning, LNB, or OFA systems installed when in non-attainment. This sub-sample represents boilers with technologies that are essentially "set it and forget it"; installation of these technologies is the primary cost and thus, we expect emissions to remain unchanged at these boilers when direct regulatory oversight is absent.

Results for the re-estimation of equation (15) for sub-samples based on technology type are tabulated in Table 6. Panel A presents results for technologies that require input costs and Panel B presents results for technologies that do not require input costs. The differential effects of non-attainment exit on $\mathrm{NO_x}$ emissions by technology type are evident. Boilers with abatement technology that requires substantial input costs are driving the significant increase in emissions after exiting non-attainment. These boilers increase emissions by 17% in the year following county exit from non-attainment. Conversely, boilers with technology installed during non-attainment that do not require reagents see no change in emissions after treatment. Results for $\mathrm{NO_x}$ emission rate are similar. Emission rate increases after the exit from non-attainment are 11.5%. Like overall $\mathrm{NO_x}$ emissions, boilers with no necessary inputs in their abatement technology do not see any change in emission rates after non-attainment exit.

Table 6: Differential effects of non-attainment exit by abatement technology type

	Panel A: Reagent technology		Panel B: Non-reagent technology	
Variable	Emissions	Rate	Emissions	Rate
$\mathrm{NO_x}$-affected non-attainment exit (one-year lag)	0.170** (0.067)	0.115* (0.066)	0.067 (0.056)	0.007 (0.036)
Observations	2,971	2,970	4,392	4,390
Number of boilers	271	271	499	500
Boiler-level controls	Yes	Yes	Yes	Yes
Regulatory program controls	Yes	Yes	Yes	Yes
Boiler FE	Yes	Yes	Yes	Yes
Year#EPA Region FE	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. Dependent variables are log-transformed. $\mathrm{NO_x}$-affected non-attainment exit indicates years following exit from non-attainment for coal-fired boilers. Analysis sample is boilers located in counties that were at one point designated as non-attainment and installed capture technology as part of RACT requirements. Panel A presents estimation results for the sub-sample of boilers with capture technology that requires substantial variable costs in the form of reagents. The technologies are SCR, SNCR, and ammonia injection. Panel B presents results for those boilers with technologies that do not require reagents. These technologies are fuel re-burning, LNB, and OFA.

This set of results confirms empirically that a driving mechanism behind $\mathrm{NO_x}$ emissions and emission rate increases at boilers exiting non-attainment is the under-utilization of abatement technology. We find that boilers with technology with considerable input costs increase emissions after non-attainment exit but those without input costs do not. Thus, profit maximizing utility managers choose to minimize input costs in the production process by purchasing (and using) less reagents. This in turn increases NO_x emissions and emission rate at these boilers. Alternatively, managers of boilers with no technological input costs do not have the option to cut costs in the operation of these technologies. Decreased regulatory oversight is no different than heightened oversight during non-attainment for these boilers. Thus, managers do not have the option to under-utilize technologies and emissions remain unchanged.

6.2 Fuel

Because increased regulatory oversight has important implications for the quality of fuel used, we next examine input decisions made by utility managers.

Theoretical foundation. The three primary types of coal used at electrical boilers in the United States are bituminous, sub-bituminous, and lignite.[42] Energy Information Administration (EIA) data show that bituminous coal costs roughly four times more per short ton than sub-bituminous and lignite coal.[43] This price differential is because bituminous coal is of higher quality; this fuel has generally a higher heat content and a lower ash content than sub-bituminous and lignite coal, meaning that it burns hotter and there is less residual after burning. Firms might not explicitly seek lower quality inputs, but cost minimization decisions can come into play.

The higher ash content of lower quality coal increases operating costs through byproduct disposal, additional input requirements, and maintenance, despite decreased costs of acquiring this fuel type. While contents of byproducts like nitrogen may be fairly consistent between coal types, the quantity of coal required for the same level of production can vary considerably due to heat value. Therefore, the quantity of fuel acquired and consumed will vary considerably due to its heat content, even though the presence of certain byproducts are consistent across fuel types.

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[42] A fourth coal type, anthracite, is used at less than one percent of boilers.

[43] https://www.eia.gov/coal/annual/pdf/table31.pdf

Utility boiler presence in a non-attainment area will encourage fuel optimization and the use of "better" coal because regulators often require firms to use better inputs (when available and feasible) as part of emission reduction requirements of SIPs. The acquisition and use of these higher quality inputs (either in terms of better heat content or lower ash content) increases operating costs for regulated firms. We examine how operations differ once regulatory oversight is reduced.

Similar to abatement technology, the type of inputs required for operation (e.g., fuel, technological reagent) affect the firm's operating expenditures considerably. We expect that $x_i^R > 0$ for fuel with higher combustion properties or lower ash content. As before, the regulator will require additional expenditures above the minimum (or the cost-minimizing level) for cleaner inputs (in this case fuel) to contribute to emission reductions necessary to achieve attainment with the NAAQS. The firm acting with its own discretion, i.e., without direct regulatory oversight, would avoid additional input expenses ($x_i^R > x_i^* = 0$) to maximize profits; see Remark (3). Thus, $q\Delta x_i > 0$ in the context of non-attainment. To state formally:

Proposition 4 *A profit maximizing stationary emission source that uses costly (and "cleaner") fuels while in non-attainment will decrease its use of these fuels in the absence of direct regulatory oversight, which increases emissions.*

As before, the use of cleaner fuels decreases the firm's profit. Thus, exiting non-attainment incentivizes the firm to reduce usage of cleaner fuels which will increase its profit, but also its emissions.

Empirical examination. We test empirically the assertion that utility managers switch to lower quality coal, i.e., lower heat content or higher ash content, once direct regulatory oversight is substantially reduced. We re-estimate equation (15) but examine coal shipments to regulated facilities rather than NO_x emissions or emission rate as our outcome. We use coal acquisition data from the EIA 906 and 923 forms for the duration of our panel.[44] The analysis is now at the facility-year level because EIA coal acquisition data

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[44] We graciously thank Ian Lange for help in securing these data.

are only available at the facility (not boiler) level. Our analysis considers two dependent variables of interest: (1) type of coal acquired[45] and (2) qualities of the coal acquired. We examine each in turn.

First, we examine as our outcome the amount of bituminous coal delivered to each facility in each year. As mentioned, bituminous coal is the highest quality coal type and typically has the highest heat content and lowest ash content of the three primary coal types. We remove anthracite coal shipments from the analysis (which represent only 0.1% of yearly shipments). Thus, re-estimation of equation (15) with bituminous coal shipments as the outcome will show the relationship between exit from non-attainment and acquisition of the highest quality input for coal-fired power plants. We again focus on facilities that were at one point in non-attainment during our sample period. Estimation results are presented in the second column of Table 7 and show that exit from non-attainment leads to a significant decrease in bituminous coal acquisition. We interpret a negative coefficient on the treatment indicator as evidence of utility managers switching to lower quality fuel one year after the increased regulatory oversight of non-attainment designation is reduced. The size of the effect is substantial: non-attainment exit leads to a roughly 313,000 ton decrease of bituminous coal acquired by treated facilities in the following year. We interpret this large negative relationship in two ways. First, the analysis is at the facility level. Facilities that contain multiple boilers consume large amounts of coal so shipments are substantial. Second, the coefficient value is roughly 55% of the mean facility-year shipment. Most facilities acquire fuel from a relatively small number of mines due to the nature of coal purchase contracts. Thus, any change in fuel acquisition is likely to be a large one, with facilities purchasing coal from entirely different mines or regions of the country.

Second, we estimate as a dependent variable an indicator for "poor coal" in a manner identical to that above using OLS. This analysis examines if firms acquire cheaper coal (and thus of lower quality) - in addition to a different type - once regulatory oversight

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[45] We consider coal shipments a reasonable proxy for fuel usage or utility manager input choice. Again anecdotally, our conversations with coal plant operators confirmed that coal acquisitions are typically burned first, i.e., coal is taken straight from trains to the boiler.

subsides. We define our indicator of poor coal using the heat content and ash content of coal acquisitions by regulated facilities. Our measure indicates if the average yearly shipment of coal to facilities has ash content above the median value for lignite and sub-bituminous coal and heat content below the median value for lignite and sub-bituminous coal. The third column of Table 7 presents results of this estimation. Similar to coal type, we see that once facilities exit non-attainment managers acquire lower quality fuel. The effect of exiting non-attainment on poor coal acquisition is statistically significant but practically small with an effect size of only 0.9 percentage points.

Table 7: Fixed effects estimation results for exit from non-attainment: Input usage

	Dependent variable	
Variable	Bituminous coal amount	1(Poor coal)
NO_x-affected non-attainment exit (one-year lag)	-313.6***	0.009*
	(83.88)	(0.005)
Observations	5,405	5,405
Number of facilities	408	408
Facility level controls	Yes	Yes
Regulatory program controls	Yes	Yes
Facility FE	Yes	Yes
Year#EPA Region FE	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. Dependent variables are thousands of tons of bituminous coal shipments (at the facility level) and an indicator for poor coal. Bituminous coal is the most expensive of the commonly used coal coal types and has the highest heat content and lowest ash content. The poor coal indicator represents coal that is high in ash content and low in heat value. NO_x-affected non-attainment exit indicates years following exit from non-attainment for coal-fired boilers. Unit of observation is the facility-year. Analysis sample is facilities located in counties that were at one point designated as non-attainment and installed capture technology as part of RACT requirements.

This pair of results identifies a second mechanism through which increases in NO_x emissions and emission rate occur once boilers exit non-attainment. Fuel optimization and higher quality inputs are often part of regulatory requirements of SIPs; these actions can decrease emissions and help areas reach attainment designation. However, these clean strategies are costly. Estimation results show that once input requirements are removed profit maximizing firm managers acquire lower quality fuel at a much lower cost. Lower heat content of these inputs requires firms to burn more coal to achieve the same level of electrical production as with hotter burning coal. This results in emission increases.

7 Conclusion and policy implications

The purpose of this study is to examine how firms respond once regulatory stringency and oversight substantially decreases. We examine this research question in the context of CAA non-attainment designations that are affected by NO_x emissions. Specifically, we add to the literature by focusing explicitly on the effects of firm exit from non-attainment designation on NO_x emissions and emission rate at coal-fired power plants. We find that emissions increase 16% and emission rates increase 9% once the increased regulatory stringency and oversight of non-attainment designation is removed. We provide a second important contribution in our examination of the mechanisms behind these emission increases. Extended model results present evidence that emission increases are the result of under-utilization of expensive emission reduction strategies by profit maximizing firms: high variable cost abatement technology and the use of higher quality inputs.

Our results present important policy implications. We have shown that emission initiatives lose their effectiveness in the absence of direct regulatory oversight. Thus, regulator attention is imperative for the proper implementation of environmental control policy. Our results also suggest that abatement technologies with low (or zero) variable costs may be preferred to those with high operating costs if regulatory oversight is not continual. We also highlight the inefficiencies of technology standards. The cost of emission control technology (both installation and operation) and oversight is substantial, but in the absence of continual oversight, inefficient. The high costs of technology standards remove incentives for innovative or cheaper emission reduction strategies and create an incentive to shirk costs when the regulator is not present.

We acknowledge that the need for future research remains. We have shown that emission increases due to a reduction in regulatory oversight are caused primarily by under-utilization of clean strategies. However, we cannot identify exact costs of proper technological operation. Future research should examine specific input requirements and costs for abatement technology, e.g., reagents. We also examine one specific sector of regulated firms. Results from coal-fired boilers may not apply broadly due to the specific nature of sector-specific technology and inputs. Future research should examine more sectors and emissions to different environmental media.

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