When the regulator goes home: The effectiveness of environmental oversight[*]

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Abstract

The Clean Air Act requires emission sources in areas with poor air quality to adopt abatement strategies to permanently reduce their emissions. These sources face greater regulatory oversight until air quality reaches acceptable levels. We examine how the reduction in regulatory attention after air quality has improved impacts the behavior of affected facilities. We find that the transitory nature of increased regulatory oversight results in emission increases at utility boilers which resulted in $1.2 billion in aggregate health damages during our sample period. These emission increases occur through the underuse of abatement inputs and the use of lower quality fuel.

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1 Introduction

The U.S. Environmental Protection Agency (EPA) administers the National Ambient Air Quality Standards (NAAQS) for six "criteria" air pollutants that are especially harmful to human health (see, e.g., Muller and Mendelsohn 2009) and the environment.[1] As part of the NAAQS, EPA designates geographic areas as "non-attainment" if ambient air concentrations of criteria pollutants exceed standard levels. Non-attainment areas as a whole are subjected to greater regulatory scrutiny and oversight than areas where air quality standards are met. Stationary emission sources located within non-attainment areas are also subjected to further regulatory requirements, including reasonable abatement technology adoption, emission inventories, and facility-specific emission limits (Walker 2013). These requirements are mandated as part of State Implementation Plans (SIPs) which are required by EPA. Non-attainment status is not a permanent designation; EPA's goal is to bring ambient concentrations of criteria pollutants below the appropriate NAAQS in non-attainment areas. Once ambient concentrations in the area drop below the standard level, these areas are re-designated as "maintenance". Importantly, oversight and administration of the SIP return to the state upon re-designation and EPA de-prioritizes oversight within that area.

The purpose of this paper is to examine how regulated firms respond when the increased regulatory scrutiny and oversight of non-attainment designation no longer applies. Specifically, how does re-designation out of non-attainment affect the operations at stationary emission sources located within these areas? The NAAQS mandate reasonable abatement technology adoption and other requirements, e.g., cleaner fuel, for stationary emission sources located in non-attainment areas. However, abatement technology and cleaner fuel usage without regulatory oversight does not ensure that these abatement strategies are operated in ways that will decrease emissions to acceptable levels. Many of the required abatement technologies have high variable costs (Xu et al. 2015) and inputs, e.g., technological reagents, are costly. Similarly, fuel contents vary by type, which results in differential emissions and heating values for each. Thus, the underuse of technological reagents or the use of lower quality fuel maximizes a stationary emission source's profit from production but increases emissions of dangerous pollutants. Using the substantial decrease in oversight after non-attainment exit, we witness how (or if) firm managers change their operations once certain strategies are no longer necessarily mandated by the regulator. Therefore, this paper examines whether the absence of direct regulatory oversight results in cost minimization of abatement at polluting facilities. Our research question is especially policy relevant because recent decreases in Clean Air Act enforcement may have contributed to decreases in ambient air quality, which produces sizable public health damages (Clay and Muller 2019).

There exist other reasons why polluting facilities no longer regulated under non-attainment re-

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[1] The criteria air pollutants are: particulate matter, lead, ozone, carbon monoxide, nitrogen dioxide, and sulfur dioxide.

quirements may change their operations. Non-attainment designation is exogenous to each stationary source's emissions because the average facility contributes little to ambient air concentrations of most criteria pollutants (Auffhammer et al. 2011; Gibson 2018).[2] As a result, firm managers may abate less upon exit from non-attainment because they feel that the "storm has passed", especially if managers perceive that agencies have fixed monitoring or oversight budgets (Raff and Earnhart 2018). Next, the primary purpose of SIPs is to bring the ambient concentrations of criteria air pollutants below standard levels. If areas do not make sufficient progress toward attaining standards, EPA can impose requirements in addition to those previously listed. As a greater incentive to reach attainment with the standards, states with areas that remain in non-attainment for excessive periods of time 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 areas in compliance with the NAAQS can be impacted. Holistically, our study examines whether regulated firms cost minimize by abating less when not subjected to the direct regulatory oversight of non-attainment designation, i.e., whether the emission changes at stationary sources made while in non-attainment are permanent (as mandated by EPA).

The literature is rife with studies that examine the effects of the NAAQS and non-attainment designation on different outcomes. Some studies examine the effect of non-attainment on emissions at stationary sources (Greenstone 2003; Raff and Walter 2017; Gibson 2018); these studies focus on county level entrance into non-attainment and the effects on emissions while in non-attainment. Other studies attribute aggregate 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 and

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[2] The exception is likely SO_2 non-attainment because few stationary sources produce a large amount of SO_2 emissions. We ignore SO_2 (and other) non-attainment in this paper for this reason.

the transitory nature of non-attainment.[3] The previous body of literature (specifically that dealing with emissions as the outcome) also does not examine the use of abatement technology or inputs 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 manager behavior of a substantial decrease in regulatory oversight. Previous studies examine oversight in the context of general deterrence (e.g., Shimshack and Ward 2005; Earnhart and Segerson 2012) 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 an exogenous instrument for a significant and certain decrease in regulatory oversight for firms. Second, we identify changes in manager behavior based on facility exit out of non-attainment rather than entrance into non-attainment. Previous studies do not consider the change in facility emissions once an area's ambient air quality reaches levels in attainment with the NAAQS, as emission changes are expected to be permanent. We examine the opposite scenario and study these ignored effects. 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, previous studies have examined firm behavior under differing market structures (Fabrizio et al. 2007). Ours is the first study to model and examine regulator and firm behavior within the context of regulatory oversight in these markets. 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. 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 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; this occurs only while the regulator is present under non-attainment designation. Once firms are no longer subjected to this scrutiny firms underuse clean strategies required previously by the regulator. In addition, emission reductions

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[3] Regardless, the literature does attribute sizable air quality benefits to the NAAQS.

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 air concentrations well below the NAAQS. This slack allows other sources to further increase emissions. As a result, the absence of direct oversight in the presence of static ambient emission standards can create a scenario which encourages stationary sources to cost minimize, which results in emission increases.

We then estimate the effect of facility exit from non-attainment on emissions. We use boiler level data on nitrogen oxide ($\mathrm{NO_x}$) 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. This analysis can determine if emissions changed for boilers previously regulated by non-attainment SIPs once the requirements are removed and regulatory oversight decreases substantially. Estimation results show that boiler level $\mathrm{NO_x}$ emissions and emission rate increased by 15.4% and 9%, respectively, once facilities were no longer regulated under non-attainment requirements. We also estimate a dynamic model to examine if these emission increases change over time. We find evidence of dynamic treatment effects where emission increases get larger as time progresses in the post-treatment period, suggesting that utility managers cost minimize in abatement even more once they have experience with decreased oversight. The monetary damages associated with these emission increases are substantial: over $1.2 billion in aggregate health damages during our sample period.

We also examine the mechanisms through which these emission increases occur. The NAAQS require the installation of Reasonably Available Control Technology (RACT) and the implementation of Reasonably Available Control Measures (RACM) for stationary emission sources in non-attainment areas. RACT and RACM designations depend on many factors, e.g., cost, technological availability, so there is considerable heterogeneity in these adopted abatement techniques throughout the United States. As a result, we examine how RACT and RACM are used upon non-attainment exit. We first examine if exiting non-attainment causes regulated utilities to simply turn off their installed $\mathrm{NO_x}$ abatement technology. Although we are unaware of instances where U.S. facilities turn off pollution abatement equipment, there is anecdotal evidence of this behavior in developing countries (Mufson 2013). We find that exiting non-attainment has zero effect on the amount of $\mathrm{NO_x}$ control technology usage hours at these plants. In fact, the use of control technology correlates almost perfectly to the operating time of each boiler. This behavior is unsurprising in the present context because it would likely result in considerable regulatory attention even after exiting non-attainment. Next, we use data on the type of $\mathrm{NO_x}$ abatement technology at each boiler and its installation date to examine what technology each facility had installed while in non-attainment. We re-estimate our primary regression specification for two sub-samples: (1) boilers with abatement technology that requires significant inputs and (2) boilers with abatement technology that requires zero inputs, i.e., “set it and forget it” technology. We use this analysis to test the assertion that facilities underuse (but do not turn off) abatement technology when additional regulatory oversight is removed; we show empirically that this is the case. The significant variable costs associated with abatement systems can be minimized by underusing technology inputs, e.g., chemical reagents, once direct regulatory oversight is removed. We find significant increases of $\mathrm{NO_x}$ emissions and emission rate at boilers with technology that requires costly inputs but no emission or emission rate increases at boilers with "set it and forget it" abatement technology.

In addition to RACT, RACM requires additional emission control measures that are feasible at each facility, e.g., operating procedures, use of raw materials. Therefore, we also 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. This coal is considerably cheaper than higher quality coal, yielding a lower price per unit of heat value ($/Btu). However, a larger quantity of coal is required to produce the same level of output and so emissions increase. Finally, we examine how regulated utilities acquire this lower quality fuel. Coal shipments are typically purchased through inflexible, long-term contracts (Kozhevnikova and Lange 2009). However, coal can also be acquired via the spot market, which allows utility managers more flexibility and the ability to change operations in the short-term. To examine whether managers change behavior via the manipulation of coal purchase contracts or the spot market, we estimate the effect of exiting non-attainment on coal prices and cost per heat content (Btu) of coal for purchases made in each setting. We find that prices paid in the spot market decreased and the cost per Btu of coal acquired in the spot market decreased after treatment, while there were no effects for contract purchases. Thus, we provide evidence that utility managers cost minimize in their inputs via the spot market rather than through the manipulation of coal contracts.

The remainder of this paper proceeds as follows. Section 2 provides background information on the NAAQS and non-attainment designations. Sections 3 and 4 provide theoretical analyses for firm behavior and regulator objectives, respectively. Section 5 provides the primary empirical analysis. Section 6 examines the mechanisms through which emission increases occur at coal-fired electric utilities located in areas that exit non-attainment designation. 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 abatement requirements for stationary sources located within non-attainment areas, highlighting the RACT requirements for stationary source emissions of $\mathrm{NO_x}$.

2.1 NAAQS and non-attainment designation

The CAA 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 and (2) secondary standards, which protect the environment and public welfare (EPA 2018a). Areas are in non-attainment with individual NAAQS if the ambient concentration 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 the steps that the state will take to bring that area into attainment with the relevant NAAQS. Development, execution, and oversight of SIPs depend on the air quality control region, which are overseen by EPA regional offices. 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.) All stationary sources in non-attainment areas are required to install RACT systems and employ various RACM. As part of a SIP, any required abatement strategies must demonstrate sufficient progress toward attainment while still being technologically and economically feasible. Therefore, fulfillment of a SIP can affect stationary sources in multiple ways. First, stationary sources must install appropriate emission abatement technology. Second, stationary sources classified as major emitters, i.e., those with the potential to emit 100 tons per year of any air pollutant (EPA 2018b), in non-attainment areas are subjected to plant-specific control measures 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 for failing to reach attainment status after a certain period of time.

States request that areas be re-designated out of non-attainment once ambient air concentrations of non-attainment pollutants fall below standard levels. This request occurs upon reaching the air quality threshold because of the negative consequences of having areas remain in non-attainment, e.g., industry avoidance, federal fund withholding. Thus, exit from non-attainment is similar to entrance into non-attainment because it is dependent upon reaching an air quality threshold. Once an area exits non-attainment, it is considered in maintenance for at least 10 years. As part of the exit process, states must submit to EPA a maintenance plan that outlines how the area's ambient air concentrations will remain in compliance with the relevant NAAQS. 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. In addition, maintenance plans contain provisions that allow the state to correct any violation after re-designation. However, the requirements of maintenance plans are not as strict as those of non-attainment SIPs. Federal regulatory oversight associated with non-attainment is also removed, meaning that the state regulatory agency is the sole party responsible for oversight and administration of maintenance plans. Importantly, the emission reduction requirements of maintenance plans are contingencies that are administered only if ambient air quality deteriorates to levels approaching the NAAQS (42 U.S.C. §7505a). Thus, stationary emission sources located in areas that exit non-attainment and enter into maintenance are subjected to an economically meaningful decrease in regulatory oversight.

2.2 Abatement strategies of the NAAQS

Major stationary emission sources in non-attainment areas are required to install RACT equipment for the control of criteria air pollutants. New or modifying 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.[4] We focus our discussion on RACT requirements because these are the primary requirements in 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 the control of NO_x emissions. The RACT requirements of SIPs are subjective and EPA provides only broad requirements. 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 as RACT.

EPA does not encourage a broad adoption of all cost-effective abatement technology. 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, the technology requirements of a non-attainment 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 non-attainment 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 practical 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 dif-

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[4] Stationary sources in maintenance or 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).

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.

ference in technology costs among similar sources with implemented emission reductions but takes into account whether the firm's technological installation costs are affordable. Simply put, technology requirements are based on the cost and effectiveness of installed technology on a similar source. This policy provides states considerable flexibility in reaching attainment, which requires the management of a variety of emission sources concurrently.

SIPs can also require the use of cleaner fuel as part of RACM. For coal-fired power plants, the quality and availability of fuel impacts the emissions created during electrical generation. Coal quality is representative of the impurities, heat content, and age of the coal. In general, coal is sub-divided into four categories (from lowest to highest quality): lignite, sub-bituminous, bituminous, and anthracite. Each category of coal corresponds to different percentages of carbon, sulfur, hydrogen, oxygen, and water. The contents of the coal also vary within each category, e.g., the carbon content of bituminous coal ranges from 45% to 86%, whereas sub-bituminous coal ranges from 35% to 45% (EIA 2018). Requiring the adoption of cleaner or higher quality fuels can further reduce a facility's emissions.

Emission reductions from higher quality coal occurs in two ways. First, coal with a lower carbon content increases the amount of residual "ash" left after combustion, which in turn increases waste and emissions. Second, higher quality coal contains greater heating potential. This additional heat content allows plants to burn less fuel to obtain the desired temperature necessary for boiler operation and electrical generation. Since higher quality coal contains more carbon, fewer impurities, and has greater heating potential, facilities generate fewer emissions per amount of energy produced. In the context of NO_x emissions, the heating value of coal is particularly important. Nitrogen impurities are fairly uniform across each coal type ranging from 0.5% to 2% of content (Meuleman et al. 2016). Holding production constant, using higher quality coal decreases the quantity of fuel consumption, which results in lower NO_x emissions.

3 Firm behavior under regulatory oversight

In this section we construct a representative firm and model the influence of regulators on operations and the use of clean strategies, i.e., methods to decrease emissions, at stationary emission sources. 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 emissions change as regulatory obligations are met. Our analysis focuses on power plants, but many of the abatement strategies examined are applicable to other stationary emission sources.

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.[5] In general, stationary emission sources face broad oversight from state and federal regulators creating some production restrictions ($\delta \in [0, 1]$). However, in the absence of direct regulatory oversight firms can voluntarily choose how to calibrate their operations to reduce emissions.[6]

Operations at most stationary sources can be altered depending on the firm's concern with emissions. The connection between calibration and emissions at electric utilities is well documented (Romero et al. 2006; Liu et al. 2007). 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 increases non-fuel input and operational costs thereby negatively impacting profits.

Unlike other stationary sources, the ability of electric utilities to influence revenue faces constraints. The price(s) that these plants receive for output is dependent on the regulatory structure of electricity markets. Before deregulation most power plant's prices were set by public utility commissions (Fowlie 2010). In addition, power plants in regulated areas must meet market demand to ensure effective grid management. For plants in deregulated areas, electricity provision includes other electrical producers (using other energy sources) representing a broad interdependence between competing providers. Due to the unique price and output requirements in electricity markets we focus on power plants for the remainder of our analysis. For these firms, price and output are exogenous regardless of the electricity market's regulatory structure. Profit maximization by the

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

[6] State and federal oversight create operational bounds in which a firm must operate to avoid additional scrutiny. In the absence of "reckless" or "imprudent" production, a firm maintains significant latitude in their operational decisions.

firm is limited to minimizing cost, which can be expressed by:

$$\max_{\delta_i} \ \pi_{i,k} = (p - (1 - \delta_i + \delta_i^2)c_k)q \qquad s.t. \ \delta \in [0, 1] \tag{1}$$

where p represents price and q represents output. The firm's production costs are denoted by c_k which depend on boiler age (k) for several reasons, most notably technology and design. For notational ease, let "o" denote old plants and "u" denote new or modified plants, where $c_o > c_u$. Equation (1) shows firms, left to their own devices, cost minimize where $\delta^* = \frac{1}{2}$, resulting in emissions of $e_i = (e_k - \frac{1}{2})q$. Simply put, firms calibrate equipment to make inputs as productive as possible without regard for their emissions.

3.2 Emission reductions

Multiple abatement options exist outside of production calibration. In this sub-section we incorporate additional emission-reducing techniques into our model. These techniques represent the various abatement strategies that regulators can require of firms located in non-attainment areas. Emission-reducing strategies influence firm i's emissions according to:[7]

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

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 of the technology depends on decisions related to its operation and maintenance.

Firms located in non-attainment areas are required to operate a RACT system. These abatement technologies have significant installation, maintenance, and operating costs.[8] For coal-fired power plants, RACM can require that firms adopt cleaner fuel inputs also at significantly higher cost.[9] While these are requirements of any SIP, firms can also voluntarily decrease emissions by employing the same clean strategies, e.g., cleaner inputs, abatement technology. Firm profit while employing

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[7] We intentionally ignore emission limits. In the absence of any additional abatement efforts, emission limits force facilities to reduce their production. This is identical to adjusting the facility's output, which is already assumed to be exogenous.

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

[9] 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 the heat and ash contents of the coal; we discuss this further in section 6.

these clean strategies is represented by:[10]

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

where $F\left(x_i, \delta_i\right)$ represents the additional cost of cleaner fuel and $T\left(s_i\right)$ represents the cost of the operation of installed abatement technology. Abatement efforts can also include updating or installing boiler equipment which alters production costs for 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, *ceteris paribus*.[11] Fuel prices increase quadratically according to quality such that $F\left(x_i\right) = \alpha x_i^2 - \delta_i x_i$, where α is a parameter representing the cost associated with location or transportation. We represent the associated emission reduction from cleaner coal as linear due to interest in $\mathrm{NO_x}$ emissions. Our representation of fuel cost is structured to incorporate the benefits of using higher quality 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 maintenance and inputs necessary for any installed technology to operate. For example, the use of reagents is necessary for certain abatement technology but also increases coal use and by extension coal ash byproducts (EPA 2017a) which increase operating costs. We represent the operating costs of an emission-capturing technology as $T\left(s_i\right) = \frac{\beta s_i^2}{2}$, where greater expenditures on inputs (s_i) yield larger emission reductions.[13]

Our interest is in technology where operational decisions can affect emissions. Abatement technology that lacks inputs still has fixed costs but likely has low operational costs. Equipment that requires routine maintenance still represents abatement technology that requires inputs, however, most post-combustion clean technology operates through chemical reaction or filtration, both of which require non-labor inputs. Equipment that adjusts combustion also changes the boiler's operations and affects emissions (e_k); this equipment would then influence boiler calibration (δ_i). For the remaining technology, operation has a minimum variable cost and thus, $\bar{s} > 0$.[14]

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

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[10] For the remainder of our exercise, we focus on coal-fired power plants which are impacted by fuel types, as opposed to natural gas which would limit our analysis to abatement technology.

[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 than lesser quality coal (subbituminous, lignite) [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 ammonia or urea as inputs of selective non-catalytic (or catalytic) reduction (SNCR or SCR) to reduce $\mathrm{NO_x}$ emissions.

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

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

$$\max_{x_i,\delta,s_i} \ \pi_{i,k} = \left[p - \alpha x_i^2 + \delta_i\left(x_i + c_k\right) - (1+\delta_i^2)c_k - \frac{\beta s_i^2}{2}\right] q \tag{4}$$

From the regulator's perspective, equation (4) illustrates three strategies to curb firm emissions: (1) production inputs, (2) emission capture technology, and (3) firm operations. We begin by examining (voluntary) firm emission-reducing efforts with additional access to clean strategies. Firms optimize equation (4) 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]

$$x_i^* = \frac{c_k}{4\alpha c_k - 1}; \qquad \delta_i^* = \frac{2\alpha c_k}{4\alpha c_k - 1}; \qquad s_i^* = \underline{s}; \qquad e_i^* = e_k - c_k\frac{2\alpha + 1}{4\alpha c_k - 1} - \underline{s} \tag{5}$$

Comparing emission reductions from old (c_o) and new/modified firms (c_u), equation (5) shows:[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 $\frac{c_u(2\alpha+1)}{4\alpha c_u - 1} > \frac{c_o(2\alpha+1)}{4\alpha c_o - 1}$. We conclude that $e_{i,o}^* > e_{i,u}^*$ since $c_u < c_o$. ■

4 Regulatory action

Any firm located in a non-attainment area is subjected to additional regulatory scrutiny and oversight (both state and federal). SIPs can require firms to use different fuels, purchase emission offsets, install RACT systems, or reduce emissions through facility-specific limits. Next, we examine mandatory emission reductions selected 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 qual-

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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] 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 $c_u \geq \frac{\alpha}{2}$.

[18] Firms may be concerned with future regulatory actions, public appearance, or future retribution.

ity 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 how and where emission abatement occurs. The socially optimal outcome requires weighing the benefits of production with damages from emissions. Identifying the optimal abatement requires aggregating local firm profits and environmental damages. Social welfare within an area with N firms can then be 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]

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

$$\max_{x_i,\delta_i,s_i} \ SW = \sum_{i=1}^{N} \left[\left(p - \alpha x_i^2 + \delta_i (x_i + c_k) - (1+\delta_i^2)c_k - \frac{\beta s_i^2}{2} \right) q - (e_k - s_i - \delta_i - x_i) q\gamma \right] \tag{6}$$

We identify the social welfare maximizing use of clean strategies (denoted by SW) using equation (6), which yields:

$$\begin{gathered} x_i^{SW} = \frac{\gamma + c_k(1+2\gamma)}{4\alpha c_k - 1}; \qquad \delta_i^{SW} = \frac{\gamma + 2\alpha(\gamma + c_k)}{4\alpha c_k - 1}; \qquad s_i^{SW} = \frac{\gamma}{\beta}; \\ e_i^{SW} = e_k - \frac{2\gamma(1+\alpha+c_k) + c_k(2\alpha+1)}{4\alpha c_k - 1} - \frac{\gamma}{\beta} \end{gathered} \tag{7}$$

Comparing (5) and (7) 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*

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[19] Similar to Fowlie and Muller (2019) we assume that the environmental damages from emissions are linear and additively separable by source.

[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.

to further decrease emissions.

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 estimates that the CAA produced $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' voluntary actions. Importantly, a social planner would remove the "reasonable" criteria for decisions about abatement technology adoption. Under the social planner, the firm's ability to afford the technology is ignored. In addition, currently operating firms could be forced to shutdown if their emissions yielded sizable damages. However, the regulator's method of emission reductions is much more constrained. In the next sub-section, we examine how the NAAQS influence the regulator's behavior.

4.2 Reaching attainment

Regulatory action is permitted as part of the NAAQS designation process until an area meets ambient air quality standards. 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 reduce emissions. 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. Regulators then have the following objective:

$$\begin{aligned} \max_{x_i,\delta_i,s_i} \quad \mathcal{L} = \sum_{i=1}^{n} \left[\left(p - \alpha x_i^2 + \delta_i \left(x_i + c_k \right) - (1 + \delta_i^2) c_k - \frac{\beta s_i^2}{2} \right) - \left(e_k - s_i - \delta_i - x_i \right) \gamma \right] q \\ - \lambda \left(\sum_{i=1}^{n} \left[\left(e_k - s_i - \delta_i - x_i \right) q \right] - e_R \right) \end{aligned} \tag{8}$$

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 (8) [we denote the regulator's decisions with "R"]. This yields:[22]

$$\begin{gathered}\delta_i^R = \frac{(2\alpha+\beta)\,c_o + (2\alpha+1)\,\beta\,(e_k - e_r)}{2\beta\,(1+\alpha+c_o)+4\alpha c_o - 1}; \qquad s_i^R = \frac{(4\alpha c_o - 1)\,(e_k - e_r) - (2\alpha+1)\,c_o}{2\beta\,(1+\alpha+c_o)+4\alpha c_o - 1}; \\ x_i^R = \frac{(1-\beta)\,c_o + \beta\,(2c_o+1)\,(e_k - e_r)}{2\beta\,(1+\alpha+c_o)+4\alpha c_o - 1}; \qquad e_i^R = e_r\end{gathered} \tag{9}$$

Comparing (5) and (9), 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 (7) and (9), 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, but have illustrated how regulators can move an area out of non-attainment. Therefore, 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).*

4.3 Technology requirements

In this sub-section we examine how the lack of abatement technology at regulated firms affects the regulator's decision. Requiring the 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). Regulators require firms in non-attainment areas to install at least RACT systems. All technological requirements are determined as part of the SIP, which can vary by area. Other factors, e.g., age of emission source, 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, which is set by the regulator. Constraints make the regulator's decision to require firm i to install abatement technology of type

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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.

v take the form:[24]

$$\text{if} \quad e_t < \frac{s_{iv}^{SW} q\gamma}{F_{iv} + \frac{\beta}{2}\left(s_{iv}^{SW}\right)^2} \quad \text{and} \quad \pi_i - F_{iv} > 0 \qquad \text{then install } v \tag{10}$$

where F_{iv} is the installation cost of technology v for firm i. Furthermore, if technology v is not affordable then firms must install some technology, W, where $F_{iv} > F_{iw}$. Importantly, abatement technologies can differ by the operating costs that they impose on firms. The more effective abatement technologies, e.g., SNCR, SCR, require inputs to capture emissions, whereas the less effective technologies, e.g., low NO_x burners (LNB), require no additional inputs. Importantly, the affordability requirement of RACT ensures heterogeneous technology requirements among firms, with some firms installing more affordable but less effective technology (which we denote by s_{iw}^{R-}, where $s_{iv}^{SW} > s_{iw}^{R-}$).

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 requirements such that:

$$\sum_{i}^{n_a} e_i q + \sum_{h(\neq i,j,g)}^{n_b} e_h q + \sum_{j(\neq h,i,g)}^{n_o} e_j q + \sum_{g(\neq h,i,j)}^{n_n} e_g q + \sum_{l=1}^{M} a_l = e_R + B \tag{11}$$

where n_a represents the minimum number of firms installing the most effective RACT (s_{iv}^{SW}), n_b represents the number of firms installing less effective (or more affordable) RACT (s_{iw}^{R-}), n_o represents the number of firms without new technology, n_n represents the number of firms with technology already installed ($n_a + n_b + n_o + n_n = N$), and B represents a buffer ensuring that the ambient standard is sufficiently satisfied, which we refer to as "standard slack". We denote all firms installing some form of RACT by n_t (where $n_t = n_a + n_b$). Figure 1 illustrates how ambient air quality changes in response to regulatory oversight.

Let n_t^* denote the minimum number of firms requiring (any) technology in order to satisfy equation (11) 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 the 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 (10) 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 the control technology

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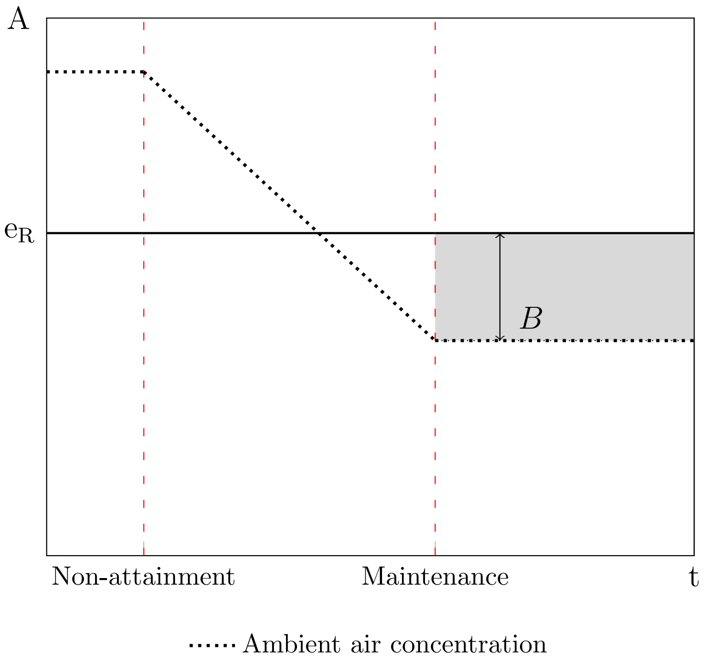
[24] We differentiate by technology because of their substitutability, i.e., certain technologies can not be used concurrently with other technologies. However, the regulator is unlikely to require a firm to install two different technologies for a specific non-attainment designation. We expand on this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

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 reductions) 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), the area is then re-designated as in attainment with the NAAQS (the area is first designated as maintenance for at least 10 years). B measures the “standard slack”, i.e., ambient air concentrations below the standard level.

(along with other SIP requirements) satisfies the ambient standard, or equivalently:

$$\min_{e_r} \; n_t \quad s.t. \; \sum_{i=1}^{n_t} e_i q + \sum_{j=1}^{n_o} e_j q + \sum_{h=1}^{n_n} e_h q + \sum_{l=1}^{M} a_l = e_R + B \quad \text{and} \quad B > 0 \tag{12}$$

Let $\overline{e}_t$ denote the RACT condition from (10) that satisfies (12) and let n_t^R represent the associated number of firms that the regulator requires to install RACT systems. This results in $n_t^R > n_t^*$ and $B > 0$ because of discrete changes in the number of firms subjected to RACT and RACM. 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 $n_t^{SW} > n_t^R > n_t^*$. In addition, the regulator may allow some firms to install less effective abatement technology. From this we conclude that:

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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.

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. However, the effectiveness and dispersion of abatement technology is less than 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.

4.4 Leaving non-attainment

We can identify the emission reductions that result from an area entering non-attainment using the regulator's decision to require abatement technology installation (equation (9)) and the associated investment in clean strategies ($n_t^{SW} > n_t^R > n_t^*$), as:[27]

$$\sum_{i=1}^{n_t^R} e_i^R q + \sum_{j=1}^{n_o} e_j^R q + \sum_{h=1}^{n_n} e_h^R q + \sum_{l=1}^{M} a_l = e_R + B \quad \text{where} \quad B > 0 \tag{13}$$

From equation (13) we observe the level and management of emissions when an area leaves non-attainment after complying with the relevant NAAQS. The regulator chooses the abatement efforts of firms (e_i^R) in non-attainment areas and constructs appropriate slack between the ambient air quality standard and local ambient air quality. The management of abatement efforts returns to the firm after an area complies with the standard and exits non-attainment.[28] In the absence of direct (federal) oversight firms decrease abatement efforts relative to the regulator (see Remark 3), which causes emissions to increase ($e_i^R < e_i^*$). For the remaining firms, emissions change according to:[29]

$$q\Delta e_i = q(e_i^R - e_i^*) \ll B \tag{14}$$

The switch in management from regulator to firm is caused by regulatory oversight after an area has complied with the ambient air quality 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. Regulatory oversight changes firms' aggregate emissions by influencing production. We examine

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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.

firm operations with and without direct regulatory oversight to identify emission changes. Once the federal regulator leaves, abatement efforts return to the firm and emissions increase.

Using the relationship between production and emissions in equation (2) highlights how the regulator's absence changes emissions:[30]

$$\Delta e_{it} = \Delta e_k - \Delta\delta_{it} - \Delta(x_{it} + s_{it}) \tag{15}$$

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

5 Empirical analysis

This section lays out the primary empirical foundation of our study, which estimates the effect of exit from non-attainment designation on $\mathrm{NO_x}$ emissions and emission rate at coal-fired power plants. First, we define treatment and provide the identification strategy. Second, we describe the data used. Third, we describe the estimating equation. Fourth, we present the empirical results. Finally, we estimate a dynamic model and discuss its implications.

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 sample 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

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

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

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 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 which depends on crossing an air quality threshold. Crossing the air quality threshold, i.e., ambient air concentrations decrease to a level in compliance with the standard, is exogenous to NO_x emissions and emission rate for the average stationary source (including coal-fired power plants) in each designated non-attainment area. First, emissions at each stationary source represent only a small contribution to ambient air concentrations of most criteria pollutants for such a large geographic area. Indeed, mobile source emissions are responsible for the majority of criteria air pollutant emissions, including PM and ground level ozone (Auffhammer et al. 2011). Further, 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 level emissions (Greenstone 2003; Bi 2017; Gibson 2018). Second, the non-attainment and SIP processes lend support to the exogeneity of our treatment. SIP requirements are intensive and cover all sources of emissions, including, e.g., outdoor wood-burning, in non-attainment areas.[32] Thus, all emission sources are required to abate while in non-attainment. The combined nature of the low relative contribution of coal-fired power plant emissions (most SIP areas contain only one coal-fired power plant) and the overarching requirements of SIPs lend support to the exogeneity of treatment because abatement at a single coal-fired boiler in a non-attainment area would not by itself cause an area to improve its air quality enough to exit non-attainment. Third, 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, e.g., SO_2 emissions and SO_2 non-attainment. Although SO_2 emissions are extremely important when examining coal-fired power plants, the ambient air concentration of SO_2 within an area is impacted far more by electric utility emissions than NO_x emissions affect our treatment (NEI data show that more than 50% of SO_2 emissions are from electric utilities). Abatement of SO_2 emissions at coal-fired power plants may then bring areas out of non-attainment independent of other abatement which would bias coefficient estimates. Thus, we carefully consider which pollutants and air quality standards

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[32] Individual SIPs often exceed 1500 pages and contain very specific emission reduction goals for entire non-attainment areas.

to examine to ensure the exogeneity of treatment.[33]

We test empirically for the exogeneity of treatment in two ways. First, we examine if coal-fired power plant emissions affect the probability of an area being designated as non-attainment. Our treatment may be 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 therefore estimate 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 described below) using OLS. The coefficient for lagged NO_x emissions is not statistically significant (p=0.890) 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. Second, we test whether lagged observables can predict entrance into treatment. This examination can lend further support to the exogeneity of treatment by testing whether exit from non-attainment is self-selected. Most important for this exercise is previous year NO_x emissions; a significant coefficient for this factor suggests that emissions (abatement) at coal-fired power plants can lead an area out of non-attainment which would bias our coefficient estimates. We use OLS to estimate NO_x-affected non-attainment exit as a function of lagged NO_x emissions and other controls described below. Lagged NO_x emissions do not predict treatment in our sample (p=0.992). Based on these results and the arguments listed above we are confident that we identify an exogenous exit from non-attainment and our empirical results are unbiased.

Finally, Stable Unit Treatment Value Assumption (SUTVA) concerns arise because of the structure of electricity markets and the inelastic demand faced by utilities. In the electricity market, production by each boiler must maintain generation levels necessary to service the electrical grid. If treated boilers change their operations, e.g., ramp down production, as a result of exiting non-attainment then there may be some treatment spillover to control units, e.g., they must maintain the grid by increasing production; this hypothetical would bias our coefficient estimates. To ensure that there are no treatment spillovers we estimate the primary regression specification of below with total electrical generation and operating time of each boiler as outcomes. If the $Exit_{ift-1}$ coefficient is statistically significant for either specification then this raises treatment spillover concerns because production (and thus emissions) is impacted at control units. The coefficients on $Exit_{ift-1}$ for each of these specifications are statistically insignificant: p=0.961 for total generation as the outcome and p=0.861 for operating time as the outcome. These results lend further credibility to our identification and also to the exogeneity of these measures with respect to non-attainment exit.

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[33] It is possible that lobbying for re-designation by firms may affect our estimates because the state must request to have the area re-designated once the air quality threshold necessary has been reached. We argue that this is unlikely for two reasons. First, states request re-designation as soon as the relevant NAAQS is attained because of the importance of exiting non-attainment, e.g., to avoid federal fund withholding, to avoid the deleterious economic effects of industries avoiding non-attainment areas. Second, there are many stationary sources in non-attainment areas, each with the incentive to exit non-attainment. It is unlikely that a single firm contributing little to overall ambient air quality would yield significant influence.

5.2 Data

We used 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 and that serve a generator greater than 25 megawatts (MW), from 1980-present. The AMPD includes individual boiler level emissions of NO_x and heat input; the latter is necessary for the calculation of NO_x emission rate.[34] The AMPD also contains information on the 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. We combined the AMPD data with non-attainment information from the EPA Green Book (EPA 2017b), League of Conservation Voter (LCV) scores (House of Representatives), and county level unemployment from the Bureau of Labor Statistics Local Area Unemployment Statistics program. Appendix A describes the data used in the empirical analysis in further detail.

5.3 Estimating equation

Let Y_{ift} represent tons of NO_x emissions[35] or emission rate (measured in lbs/MMBtu) of coal-fired power plant boiler i at facility f in year t. We use equation (15) as a guide and estimate the following specification using the definiton of treatment described in sub-section 5.1:

$$ln(Y_{ift}) = \psi_i + \mathbf{X'}_{ift}\Pi + \nu_{rt} + \beta Exit_{ift-1} + \mathbf{R'}_{ift}\Psi + \epsilon_{ift} \tag{16}$$

where ψ_i represents boiler fixed effects. X_{ift} is a vector containing a set of boiler level control variables which include total electrical generation, maximum capacity, operating time, House LCV score, and county level unemployment rate. These time-varying factors control for exogenous variation in boiler characteristics that impact NO_x emissions and emission rate.[36] The remaining variables represent time or regulatory constraints. ν_{rt} are EPA region by year fixed effects, which control for differential trends in NAAQS implementation across EPA regions and over time, e.g., variation driven by differences in regional office leadership. We control for variation across EPA region because the EPA regional office is the entity that approves each SIP and provides additional

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[34] 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.

[35] We transform rightward skewed outcome variables as n+1 to retain 0 observations (when the boiler is in operation) when log-transforming.

[36] Total electrical generation is not an endogenous choice variable for the plants in our sample because of the structure of electricity markets, where production must maintain generation levels necessary to service the electrical grid. Thus, generation is not chosen by the facility manager which is the primary reason why we include it as a control in our estimations, similar to Fabrizio et al. (2007). Importantly, removing total generation from our regression specifications does not disrupt any of our results.

oversight during non-attainment. For example, it is possible that the mandated requirements for a coal-fired power plant in a non-attainment area in EPA Region 10 are different than those for a similar plant in a non-attainment area in EPA Region 4.[37] $Exit_{ift-1}$ is the DD indicator which represents exit from PM or ozone non-attainment designation lagged one year.[38] We lag this measure to allow utility managers time to respond to the change in regulatory requirements after exiting non-attainment. (We examine varying lag lengths and dynamic treatment below.) 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 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. 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] ϵ_{ift} is the exogenous error term. Finally, standard errors are clustered at the county level which is the level of identifying variation.

5.4 Results

Results for the estimation of equation (16) are tabulated in Table 2. 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 EPA region by year fixed effects. 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 righthand 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. We find that boilers regulated under non-attainment SIPs increase NO_x emissions by 15.4% one year after exiting non-attainment and while regulated only by the state and under a maintenance contingency plan.[40] To put this value into greater context, this increase is 468 additional tons of NO_x emitted at the average boiler

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[37] Nevertheless, results are qualitatively and quantitatively similar when employing a standard two way fixed effects model, i.e., boiler and year fixed effects.

[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 qualitatively and quantitatively similar to those presented below.

[39] The Mercury and Air Toxics Standards (MATS) is not included in R_{ift} because coal-fired boilers over 25 MW were regulated under MATS requirements. Every boiler in our sample was regulated under the MATS because AMPD data contain information for all electric utility boilers that are greater than 25 MW. Thus, MATS regulation is subsumed into the EPA region by year fixed effects.

[40] For this value and all those that follow we calculate the percentage change in the logged dependent variable as a result of binary treatment as $\exp(\hat{\beta})$-1.

in our sample.

We also estimate the effect of exit from non-attainment on $\mathrm{NO_x}$ emission rates. Specifications where emission rate is the outcome allow us to examine emissions per amount of energy produced at each boiler. Although we control above for operating time and electrical generation, using $\mathrm{NO_x}$ 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., underuse abatement technology. Results presented in column seven of Table 2 show that this hypothetical is not the case: exit from non-attainment increases boiler level $\mathrm{NO_x}$ emission rates by 9%.

Table 2: Fixed effects estimation results for exit from non-attainment

			Dependent variable			
Variable	Emissions	Rate	Emissions	Rate	Emissions	Rate
$\mathrm{NO_x}$-affected non-attainment exit (one-year lag)	0.100* (0.059)	0.047 (0.042)	0.155*** (0.050)	0.091** (0.044)	0.143*** (0.049)	0.088** (0.045)
Observations	23,545	23,355	14,598	14,592	14,598	14,592
Number of boilers	1,339	1,326	1,095	1,096	1,095	1,096
Boiler FE	Yes	Yes	Yes	Yes	Yes	Yes
EPA region#year FE	Yes	Yes	Yes	Yes	Yes	Yes
Boiler level controls	No	No	Yes	Yes	Yes	Yes
Regulatory program controls	No	No	No	No	Yes	Yes

Notes: *** $p \leq 0.01$, ** $p \leq 0.05$, * $p \leq 0.1$. Standard errors are clustered at the county level and located in parentheses. There are 396 counties with coal-fired power plant boilers in the panel. Dependent variables are log-transformed. $\mathrm{NO_x}$-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.

These results support the following conclusions. Utility managers increase boiler level $\mathrm{NO_x}$ emissions in general when the area that each boiler is located within exits out of non-attainment. 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 the underuse of clean strategies present when in non-attainment. We examine this possibility further in section 6.

Economic impacts. We assess the economic importance of our empirical results by examining the health damages associated with increases in $\mathrm{NO_x}$ emissions from coal-fired power plants in our sample after exiting non-attainment. We estimate the health damages from these emission increases using Fann et al. (2012) who use the Air Pollution Emissions Experiments and Policy (APEEP) analysis model. Fann et al. (2012) estimate the value of a one-time, one-ton increase in NO_x emissions to be \$5,200 in health damages in 2016 (2010\$).[41] The average coal-fired utility boiler in our sample increased NO_x emissions by 468 tons when exiting non-attainment. We multiply this increase by the APEEP estimated damages for each ton of emissions and find that exiting non-attainment resulted in health damages of over \$2.43 million for the average coal-fired utility boiler. During our sample period, 484 individual utility boilers received treatment at some point. Thus, aggregate health damages as a direct result of a decrease in regulatory oversight at these plants exceeded \$1.2 billion during our sample period. Importantly, this value will increase into the future as long as these boilers continue to operate as coal-fired units in areas that attain the relevant NAAQS.[42]

5.5 Dynamic treatment effects

In this sub-section we estimate our DD model in an event study specification (Jacobson et al. 1993). This dynamic model is important for two reasons. First, an event study specification allows us to examine the pre-treatment trends in outcomes between the treatment and control groups. A key identifying assumption of our DD model is that the pre-treatment trends of the treated and control groups are similar, conditional on observable factors. An event study specification allows us to test this assumption empirically and again lend support to our identification and the causal nature of our estimates. Second, we can examine how treatment effects change over time by examining a dynamic model. DD estimates produce average treatment effects that occur in the post treatment period after a one-time shock. A dynamic model provides insight into how manager behavior changes in the post-treatment period. For example, it is possible that utility managers are at first hesitant to increase emissions but after some time gain knowledge of the level of regulatory oversight after non-attainment exit. A static model is unable to uncover this change in manager behavior.

We estimate the following specification to uncover dynamic treatment effects:

$$ln(Y_{ift}) = \psi_i + \mathbf{X}'_{ift}\Pi + \nu_{rt} + \mathbf{R}'_{ift}\Psi + \sum_{t=-10}^{-2} \eta_s T_c * 1(t - Y_c = s) + \sum_{t=0}^{10} \pi_s T_c * 1(t - Y_c = s) + \epsilon_{ift} \quad (17)$$

where Y_{ift} is boiler level NO_x emissions or emission rate, ψ_i are boiler fixed effects, X_{ift} are the control factors from above, ν_{rt} are EPA region by year dummies, R_{ift} are the programmatic dummies from above, and ϵ_{ift} is an exogenous error term. T_c is a dummy that indicates if the boiler was

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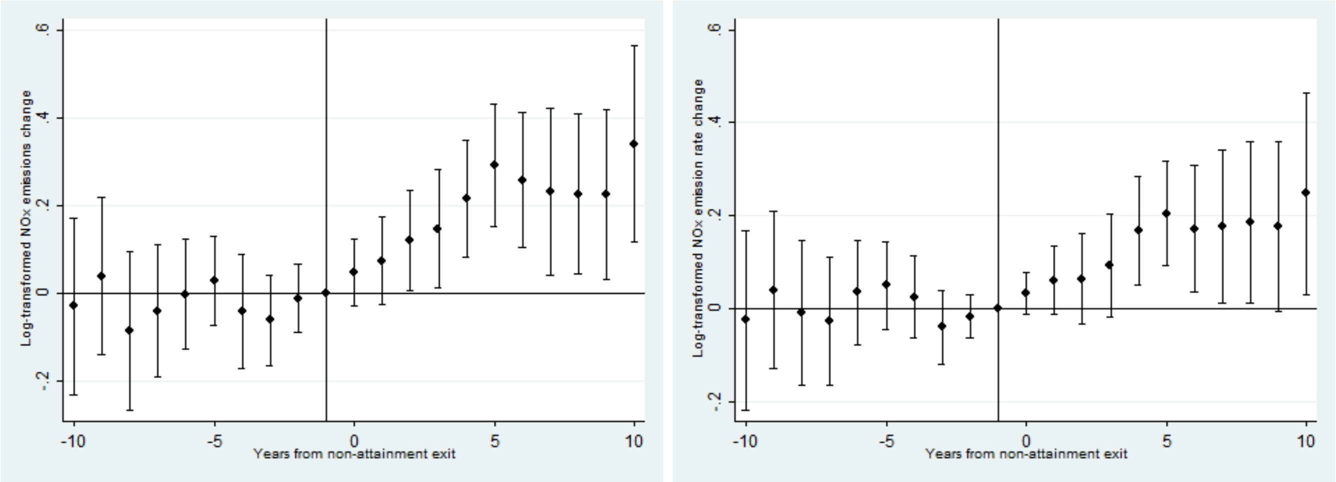
[41] The final 2015 Clean Power Plan (CPP), which uses photochemical grid modeling, has values consistent with those of Fann et al. (2012): a one-time, one-ton increase in NO_x emissions is valued between \$2,833 and \$6,500.

[42] Our results do not imply that the CAA and its amendments were unsuccessful. EPA estimated the benefits of the CAA to be roughly \$52 billion (EPA 2009). Our analysis identifies an area within the CAA where some level of damages has occurred.

subjected to treatment, i.e., is located in a county that has exited non-attainment. T_c is then interacted with the indicator function, $1(t - Y_c = s)$, which is 1 if the year of the observation, s, is between -22 and 22 years from non-attainment exit, Y_c. We combine years longer than 10 pre- and post-exit into a single dummy. The η_s coefficients represent pre-trends and the π_s coefficients represent the dynamic treatment effects. As shown in equation (17), the omitted category is the year preceding non-attainment exit. We choose this as the comparison year to allow us to see if the one-year lag of treatment defined above is appropriate. In this specification we are able to see NO_x emissions and emission rate in the year of non-attainment exit and all years following.

Figure 2: Event study analysis



Notes: Results provided are the point estimates from the estimation of equation (17). Standard errors are clustered at the county level and produce 95% confidence intervals which are included. Dependent variables are log-transformed. NO_x-affected non-attainment exit indicates years following exit from non-attainment for coal-fired boilers. Omitted category is the year prior to non-attainment exit.

Results from the estimation of equation (17) are presented in Figure 2. Both panels present evidence of causal and dynamic treatment effects. Importantly, NO_x emissions and emission rate trended similarly before non-attainment exit at both treated and control boilers. The pre-treatment differences between boilers that exited non-attainment and those that did not are close to zero and statistically insignificant. After non-attainment exit, there is a stark increase in outcomes at treated boilers. However, this increase does not occur until at least one year after exit; utility managers need at least some time before altering substantially their operations (we examine the change in operations below).[43] We also see that the effects of exiting non-attainment increase over time. Whereas there is a relatively small increase one and two years after exiting, the increases nearly double for both outcomes beginning in the third year after non-attainment exit. We interpret this as evidence of utility managers gaining experience with the lack of regulatory oversight and

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[43] Point estimates for NO_x emission rate are statistically significant at the 10% level two years after non-attainment exit.

adjusting their behavior accordingly (Maniloff 2019). Immediately after exiting non-attainment managers may feel that direct regulatory oversight is not changed substantially. However, after experiencing the new regulatory regime for some time, managers slowly increase emissions because they have learned it is possible to act this way. Finally, the DD specification ignores the change in status from maintenance to attainment. As mentioned, there is a considerable drop in regulatory oversight from non-attainment to maintenance designation. There may also be a drop in oversight from maintenance to attainment after 10 years. Our event study analysis shows that this change in designation also has significant effects on $\mathrm{NO_x}$ emissions and emissions rate, as both outcomes increase again at the ten year and after point.

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 level when in non-attainment. "Standard slack" created by the emission reductions of non-attainment allows firms the opportunity to minimize costs and thus increase emissions; Figure 3 illustrates this scenario.

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:

$$\sum_{i=1}^{n_t}\left(e_k - s_i - \delta_i - x_i\right)q + \sum_{j=1}^{n_o}\left(e_k - \delta_i - x_i\right)q + \sum_{h=1}^{n_n}\left(e_k - s_i - \delta_i - x_i\right)q + \sum_{l=1}^{M} a_l = e_R + B. \tag{18}$$

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 (18) reveals three ways that the typical firm can increase emissions: (1) abatement technology usage, (2) quality of inputs, or (3) re-calibration.[44] Comparing each firm's emissions in equation (18) to the firm's decision (without increased regulatory oversight) from equation (5), 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 decisions lead a profit maximizing firm to increase emissions after exiting non-attainment by minimizing abatement costs. Calibration depends on the inputs and technology available and so we focus on the primary effects of abatement technology and fuel type.

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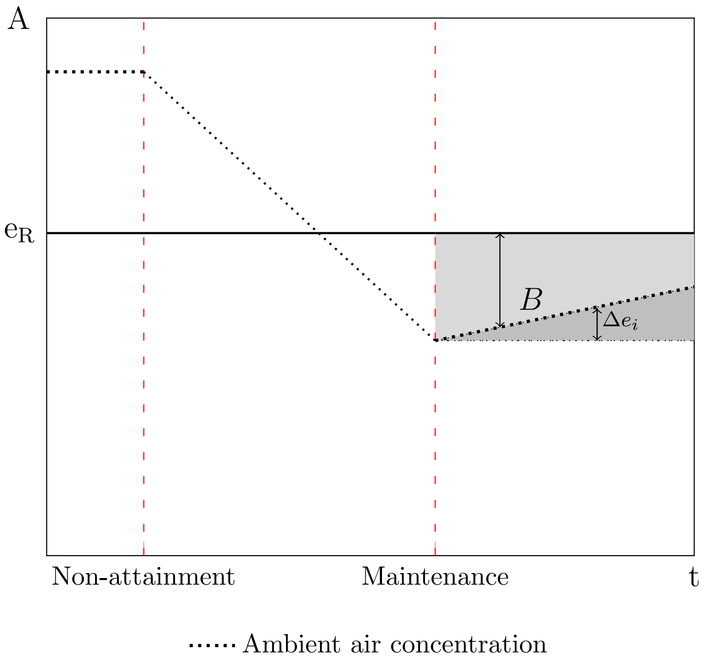
[44] These methods are possible for coal-fired power plants; other stationary sources may only be able to re-calibrate or change their use of abatement technology.

Figure 3: 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), the area is then re-designated as in attainment with the NAAQS (the area is first designated as maintenance for at least 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.

6.1 Abatement technology

We first examine how firms exiting non-attainment use the abatement technology required as part of non-attainment designation. We have shown that regulated firms minimize costs by underusing abatement methods when no longer subjected to the increased regulatory oversight of non-attainment designation; this in turn increases NO_x emissions.

Theoretical foundation. We examine the options available for firms to minimize their operational costs in the absence of direct regulatory oversight. Maintaining operations of clean technology requires a minimum variable cost ($\bar{s}$). Power plants capable of reducing input expenditures are limited to those with specific abatement technologies installed. The use of catalysts and reagents increases operating costs because of higher combustion (fuel) requirements and the cost of the inputs themselves. As a result, the quantity of inputs used by the firm will deviate from the optimal combination used by the regulator, i.e., $s_i^R > s_i^*$, increasing the firm's emissions ($q\Delta s_i > 0$). Stated formally:

Proposition 2 *In the absence of direct regulatory oversight, stationary emission sources decrease* *the use of abatement technology inputs after exiting non-attainment, which increases emissions.*

Emission increases are directly related to firm profit but the type of abatement technology installed at each boiler restricts the firm's options. In general, RACT requirements do not contain prescribed equipment or technologies that must be used. This lack of technological specification results in considerable heterogeneity across coal-fired boilers in non-attainment areas. For example, SCR/SNCR have higher installation and operation costs relative to 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 recurring operating costs while SCR/SNCR require the continuous purchase of reagents and catalysts, e.g., ammonia.[45]

NO_x emission reductions from SCR and SNCR are more effective than LNB and OFA (Xiong et al. 2016). However, the input requirements of SCR/SNCR relative to LNB/OFA are significant and include additional heat requirements and reagent 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 NO_x RACT. For firms with previously installed abatement technology, regulators can require firms to alter their abatement efforts. Input expenditures for abatement technology will differ considerably depending on the type of technology; this limits firm options and affects post-non-attainment emissions.

For example, if two abatement technologies exist, v and w, let v represent technology with input requirements and w represent technology without input requirements (or only unavoidable input requirements, e.g., maintenance). Then the type of technology installed at each boiler affects the regulator's ability to adjust firm expenditures. Specifically, $s_{iw}^R = \bar{s}_{iw}$ for technology without input requirements and $s_{iv}^R > \bar{s}_{iv}$ for technology with input requirements. The presence of the regulator forces the firm to increase expenditures on technology inputs which are above what the firm would choose independently. In the context of non-attainment this implies:

Proposition 3 *In the absence of direct regulatory oversight, a profit maximizing stationary emission source with abatement technology that requires costly inputs will decrease its use of (abatement technology) inputs and increase their emissions.*

This highlights that the type of abatement technology installed affects its management and post-non-attainment usage. The cost structure of abatement technology creates incentives that are rarely discussed. From the regulator's perspective, the firm is effectively managing its abatement technology if air quality standards are maintained. However, efficiency losses are possible even after the installation of abatement technology due to the firm's profit motive, which results in emission increases through the underuse of abatement technology inputs.

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[45] Reagent costs are considerable; purchases 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 coal-fired power plant with SCR technology and ammonia costs for this single-boiler plant were between \$3 and \$5 million per year.

Empirical examination. We test empirically if emission increases at boilers exiting non-attainment are the result of utility managers underusing abatement technology. Specifically, we show above that managers will minimize the costs associated with certain technologies in the absence of direct regulatory oversight. To test this assertion we restrict the sample to those boilers located in a county that was designated as non-attainment at some point during our sample period.[46] We restrict the sample to these boilers because this allows us to examine how regulatory oversight relative to a manager's discretion changes the operation of abatement technology.

First, we examine whether utility managers simply turn off their NO_x abatement technology after exiting non-attainment, which would decrease costs and increase boiler level emissions. We gathered data on the number of hours that each coal-fired boiler's NO_x control equipment was in service during each year from the Energy Information Administration (EIA) form 923; these data are available beginning in 2008.[47] We re-estimate equation (16) where the outcome is now the number of hours that each boiler's NO_x control equipment was in service during the year. A negative coefficient on our treatment dummy would indicate that utility managers shut off (or decrease the use of) NO_x control equipment when subjected to decreased regulatory oversight.

Table 3: Fixed effects estimation results for exit from non-attainment: NO_x abatement technology usage

	Dependent variable	
Variable	Usage hours	Usage hours
NO_x-affected non-attainment exit (one-year lag)	0.040	0.119
	(0.234)	(0.179)
Observations	2,608	2,317
Number of boilers	547	481
Facility FE	Yes	Yes
EPA region#year FE	Yes	Yes
Facility level controls	No	Yes
Regulatory program controls	No	Yes

Notes: *** $p \leq 0.01$, ** $p \leq 0.05$, * $p \leq 0.1$. Standard errors are clustered at the county level and located in parentheses. Dependent variables are (n+1) log-transformed yearly hours of NO_x control equipment usage at each boiler. NO_x-affected non-attainment exit indicates years following exit from non-attainment for coal-fired boilers. Unit of observation is the boiler-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 from 2008-2016.

Results from this re-estimation are presented in Table 3. These results provide evidence that is contrary to the anecdotes from developing countries where utility managers minimize abatement

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[46] SIPs often require the installation of abatement technology but firms may have abatement technology installed (previously) for other reasons, requirement from other regulations.

[47] Re-estimation of (16) for the sub-sample of 2008-2016 produces results nearly identical to those for the estimation of the entire sample. Thus, estimation of the sub-sample for which data are available for NO_x control usage are appropriate to examine this mechanism.

costs by turning off emission control equipment. The high p-value of the β coefficient indicates that we cannot reject the null hypothesis that there is no effect of exiting non-attainment on the number of hours that the NO_x abatement technology at each boiler is operated. This result is unsurprising given that turning off equipment seems extreme and is likely to result in attention from regulators or the public (it is also impossible to turn off some types of equipment). Indeed, a raw correlation of the number of hours that NO_x control equipment is operated and the amount of time that each boiler is operated is extremely high: 0.866 (p=0.00). These results collectively show that in the United States utility managers run a boiler's control equipment when the boiler is in operation regardless of the level of regulatory oversight.

Next, we use the heterogeneity of RACT requirements and data on the type and install date of abatement technology at each boiler to examine the differential effects of technology on exiting non-attainment on emissions. We now examine if cost minimization is achieved through the reduced usage of costly abatement technology inputs. We re-estimate equation (16) 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 NO_x emissions and emission rate for those boilers with technologies requiring reagents. This sub-sample includes boilers that had SCR, SNCR, or ammonia injection systems installed while in 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.

Results for the re-estimation of equation (16) for sub-samples based on technology type are tabulated in Table 4. 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 NO_x emissions by technology type are evident. Boilers with abatement technology that requires input costs are driving the significant increase in emissions after non-attainment exit. These boilers increase emissions by over 18% in the year following exit from non-attainment. Conversely, boilers with technology installed during non-attainment that do not require reagents see no change in emissions after treatment (point estimates are close to zero and statistically insignificant). Results for NO_x emission rate are similar. Emission rate increases after the exit from non-attainment are 12%. Like overall NO_x emissions, boilers with no necessary inputs in their abatement technology do not see any change in emission rates after non-attainment exit.

This set of results confirms empirically that a driving mechanism behind NO_x emissions and emission rate increases at boilers exiting non-attainment is the underuse of abatement technology. However, we find no evidence that utility managers simply turn off their abatement technology post-non-attainment exit. Our empirical results show that boilers with technology with considerable input costs increase emissions after non-attainment exit but those without input costs do not.

Table 4: Differential effects of non-attainment exit by abatement technology type

	Panel A: Reagent technology		Panel B: Non-reagent technology	
Variable	Emissions	Rate	Emissions	Rate
NO_x-affected non-attainment exit (one-year lag)	0.167**	0.114*	0.033	0.006
	(0.068)	(0.067)	(0.059)	(0.036)
Observations	2,971	2,970	4,393	4,390
Number of boilers	271	271	499	500
Boiler FE	Yes	Yes	Yes	Yes
EPA region#year FE	Yes	Yes	Yes	Yes
Boiler level controls	Yes	Yes	Yes	Yes
Regulatory program controls	Yes	Yes	Yes	Yes

Notes: *** $p \leq 0.01$, ** $p \leq 0.05$, * $p \leq 0.1$. Standard errors are 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 and contained 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.

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 underuse technologies and emissions remain unchanged.

6.2 Fuel

Because the level of regulatory oversight at plants 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.[48] A snapshot of EIA data show that bituminous coal costs roughly four times more per short ton than sub-bituminous and lignite coal.[49] 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 may 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 dis-

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[48] A fourth coal type, anthracite, is used at less than one percent of boilers and only in Pennsylvania.

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

posal, additional input requirements, and maintenance despite the decreased costs of acquiring this fuel type. However, the heating content and quantity of coal determine a boiler's heat output and electrical generation. From the firm's perspective, a lower price per heat content of coal (i.e., $/Btu) decreases the cost of electrical production. 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 content. Therefore, the quantity of fuel acquired and consumed varies considerably due to heat content even though the presence of certain byproducts are consistent across fuel types.

Presence in a non-attainment area encourages fuel optimization and the use of "better" coal because regulators often require firms to use better inputs as part of the emission reduction requirements of SIPs (RACM). 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. Coal-fired power plants have fairly lengthy contracts for the majority of their fuel purchases but plants can supplement these purchases using the spot market. Therefore, the spot market provides flexibility. We examine how operations differ once regulatory oversight is reduced.

Similar to abatement technology, the type of inputs required for operation 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 compliance 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 firm profit. Thus, exiting non-attainment incentivizes the firm to reduce the 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 and cheaper coal, i.e., lower heat content or higher ash content, once direct regulatory oversight is reduced substantially. We re-estimate equation (16) but examine coal shipments to regulated facilities as the outcome. We use coal acquisition data from the Federal Energy Regulatory Commission (FERC) 423, EIA 906, and EIA 923 forms for the entirety of our panel. The analysis is now at the facility-year level because coal acquisition data are only available at the facility (not boiler) level. Our analysis considers two dependent variables of interest: (1) type of coal acquired and (2) qualities of the coal acquired.[50]

First, we examine as our outcome the amount of bituminous coal delivered to each facility in each year. 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; these qualities make bituminous coal the most expensive coal type. We remove anthracite coal shipments from the analysis (which represent only 0.1% of yearly shipments). Thus, re-estimation of equation (16) with bituminous coal shipments as the outcome will show the relationship between the exit from non-attainment and the acquisition of the highest quality fuel for coal-fired power plants. Estimation results are presented in the second column of Table 5 and show that exit from non-attainment leads to a significant decrease in the amount of bituminous coal purchases. 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 large: non-attainment exit leads to a roughly 314,000 short ton decrease of bituminous coal acquired by treated facilities in the following year. This large negative relationship is due to the analysis being performed at the facility level and facilities that contain multiple boilers consume large amounts of coal. Thus, shipments are substantial.

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 - in addition to a different type - once regulatory oversight 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 in the upper 75th percentile for bituminous coal <u>and</u> heat content in the bottom 25th percentile for bituminous coal. The third column of Table 5 presents the results of this estimation. Similar to coal type, we see that once facilities exit non-attainment managers acquire lower quality fuel.

This pair of results identifies a second mechanism through which increases in $\mathrm{NO_x}$ emissions and emission rate occur once coal-fired power plants exit non-attainment. Fuel optimization and higher quality inputs are often part of the regulatory requirements of SIPs; these actions can decrease emissions. 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. The 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. However, the amount of extra coal that must be burned (two to three times) still provides cost savings because expensive coal is at least four times as expensive. This burning of additional coal results in emission increases.

These results pose the question of <u>how</u> regulated utilities acquire cheaper and lower quality coal.

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[50] 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.

Table 5: Fixed effects estimation results for exit from non-attainment: Fuel usage

	Dependent variable	
Variable	Bituminous coal amount	1(Poor coal)
NO_x-affected non-attainment exit (one-year lag)	-314.5***	0.008**
	(84.76)	(0.004)
Observations	5,405	5,405
Number of facilities	408	408
Facility FE	Yes	Yes
EPA region#year FE	Yes	Yes
Facility level controls	Yes	Yes
Regulatory program controls	Yes	Yes

Notes: *** $p \leq 0.01$, ** $p \leq 0.05$, * $p \leq 0.1$. Standard errors are 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 content. NO_x-affected non-attainment exit indicates years following exit from non-attainment for coal-fired boilers. Unit of observation is the facility-year.

Coal purchases are traditionally made through long-term contracts that are relatively inflexible (Kozhevnikova and Lange 2009). However, utilities can also purchase coal on the spot market; these purchases offer greater flexibility for managers to, e.g., increase production during periods of high demand. Through which of these avenues do utility managers acquire different types and qualities of fuel when exiting non-attainment? To answer this question we again use the coal acquisition data from above and now focus on how the purchases are made. A measure that identifies if the coal purchase was made through a contract or on the spot market is located within the FERC and EIA data on facility level coal shipments. We use this measure to re-estimate equation (16) with two new sets of outcomes at the facility-year level: (1) the average costs of spot and contract purchases and (2) the average price ($) per heat content (Btu) of spot and contract purchases ($/Btu). For (1), we can examine if the prices of coal acquisitions by plants change after exiting non-attainment. For example, in the absence of direct regulatory oversight managers may purchase cheaper coal through the spot market to minimize costs. If true, firms increase spot purchases of lower quality coal after treatment which decreases their average coal price. We re-estimate our primary regression specification with (2) to identify if lower quality coal is acquired via contracts or spot markets. This final outcome also includes the heat content of the fuel purchased, which highlights the quality of the coal. If the $/Btu of coal purchased decreases as a result of treatment then managers minimize costs by purchasing cheaper coal. Thus, managers maximize heat content and purchase more coal to produce the same level of output; this coal represents the best “bang for its buck” in terms of heat content.

Results for these estimations are presented in Table 6. Panel A contains estimation results

Table 6: Effects of non-attainment exit on coal purchase type prices

Variable	Panel A: Spot market		Panel B: Contracts	
	Price	\$/Btu	Price	\$/Btu
NO_x-affected non-attainment exit (one-year lag)	-20.80***	-0.856***	-2.057	0.002
	(6.869)	(0.274)	(4.738)	(0.003)
Observations	2,419	2,419	4,096	4,096
Number of facilities	291	291	325	325
Facility FE	Yes	Yes	Yes	Yes
EPA region#year FE	Yes	Yes	Yes	Yes
Facility level controls	Yes	Yes	Yes	Yes
Regulatory program controls	Yes	Yes	Yes	Yes

Notes: *** $p \leq 0.01$, ** $p \leq 0.05$, * $p \leq 0.1$. Standard errors are clustered at the county level and located in parentheses. Dependent variables are the price of spot and contract purchases and the price per Btu (\$/Btu) of spot and contract purchases. NO_x-affected non-attainment exit indicates years following exit from non-attainment for coal-fired boilers. Unit of observation is the facility-year.

for coal purchases made on the spot market while Panel B contains estimation results for coal purchases made as part of contracts. For prices, we see in the first column of panel A that exiting non-attainment decreases the average yearly price of spot purchases made by each facility. However, the first column of panel B shows that there is no effect on contract prices once a plant exits non-attainment. These results provide evidence that utility managers acquire cheaper and lower quality coal through the spot market and that they do not manipulate or enter into new contracts, at least not in the first year after exiting non-attainment. Estimation results for the price by heat content of coal present similar results. The second column of panel A shows that the \$/Btu of coal purchased on the spot market decreases after facilities exit non-attainment, meaning that facilities acquire coal that provides a better "bang for its buck", although more must be purchased. For contract purchases there is no significant change in the \$/Btu of coal acquired. The results for contract purchases are unsurprising because of the rigid nature of coal contracts, i.e., it is difficult to acquire new coal via contracts in only a single year. As a further extension we estimate the same specification using a five-year lag on treatment rather than a single year to see if managers change contracts once their current contracts expire. Results for this estimation are similar to those provided in Table 6: there is no significant effect of exiting non-attainment on coal contract purchase prices or price per heat content. Thus, we see that given a longer time with which to adjust, utility managers still choose to acquire different fuels through the spot market and not through contracts.

These results collectively yield the following results. Utility managers manipulate their coal purchases through the spot market upon exit from non-attainment. We have shown that lower quality and cheaper coal is used by cost minimizing firms once the increased regulatory oversight is removed. Because of the nature of coal contracts, it is difficult to acquire this coal through existing contracts. For example, entering a new contract to acquire cheaper coal does not cause other contracts (with better coal) to end; entering new contracts would only increase the amount of coal acquired and not minimize costs. Thus, spot markets are essentially the only option for changing a facility's fuel mix because managers can replace completely one type of coal purchased in the spot market previously for another (at least in the short-term). In our sample, 20% of each facility's coal acquisitions are via spot purchases; this 20% of purchases can be used to minimize costs and it is from here that we witness emission increases via the consumption of larger quantities of lower quality fuel. These extended results also show that utility managers consider the heat content of the coal purchased on the spot market, as the price per Btu decreases. Collectively, our results show that the nature of coal purchases presents an interesting policy lever for regulators to use when concerned with plants in areas exiting non-attainment.

Finally, of interest for fuel usage is the treatment effect heterogeneity by utility proximity to coal mines containing various types and qualities of coal. For example, our results may be driven by utilities in North Dakota switching from bituminous to sub-bituminous coal, which may be difficult for plants in, e.g., Michigan. However, we find no heterogeneous treatment effects in our sample, i.e., the effects are not driven by plants in any region. We attribute this lack of heterogeneity to the relative ease of access to various types of coal throughout the country, especially through the spot markets. For example, EIA data show that even plants in Michigan and Ohio - which are relatively far from sub-bituminous coal mines - purchase considerable amounts of sub-bituminous coal during our sample period. We leave a greater examination of coal transport and networks to future research.

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. We first add to the literature by focusing on the effects of firm exit from non-attainment designation on NO_x emissions and emission rate at coal-fired power plants; this represents a certain and significant change in regulatory oversight unlike previous studies on general deterrence. Our identification allows us to witness firm behavior when abatement decisions are made exclusively by the firm, rather than by the regulator. We find that NO_x emissions increase 15.4% and NO_x emission rates increase 9% once firms are no longer regulated under non-attainment SIPs. These emission increases accounted for aggregate health damages of over $1.2 billion during our sample period. We add to the literature a second contribution in our examination of the mechanisms behind these emission increases. Extended model results present evidence that emission increases are the result of the underuse of expensive emission reduction strategies by profit maximizing firms. First, regulators can impose additional restrictions or costs on stationary sources but in the absence of the regulator firms minimize costs by decreasing the use of inputs for high variable cost abatement technology. However, firms do not simply turn off the technology as has been the case in some developing countries. Second, firms cost minimize by switching to lower quality - and thus lower cost - fuel. These purchases are made through the spot market rather than via the manipulation of long-term coal purchase contracts. Collectively, our results show that the transitory nature of non-attainment designation results in cost minimization at regulated firms. This in turn results in significant health damages to local communities.

Our results present 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. Finally, our results show that firms reduce costs by purchasing cheaper fuel on the spot market. Thus, if regulators wish to maintain air quality standards then greater oversight of coal purchases - specifically those made via the spot market - are warranted.

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 the underuse of clean strategies. However, we cannot identify the exact costs of proper technological operation. Future research should examine specific input requirements and costs for abatement technology. We also examine one specific sector of regulated firms. Results from coal-fired electric utilities 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. Finally, there exists much research examining the effects of non-attainment on emissions. It may be interesting to compare the increases in emissions after exiting non-attainment found in this study to the decreases found when entering non-attainment.

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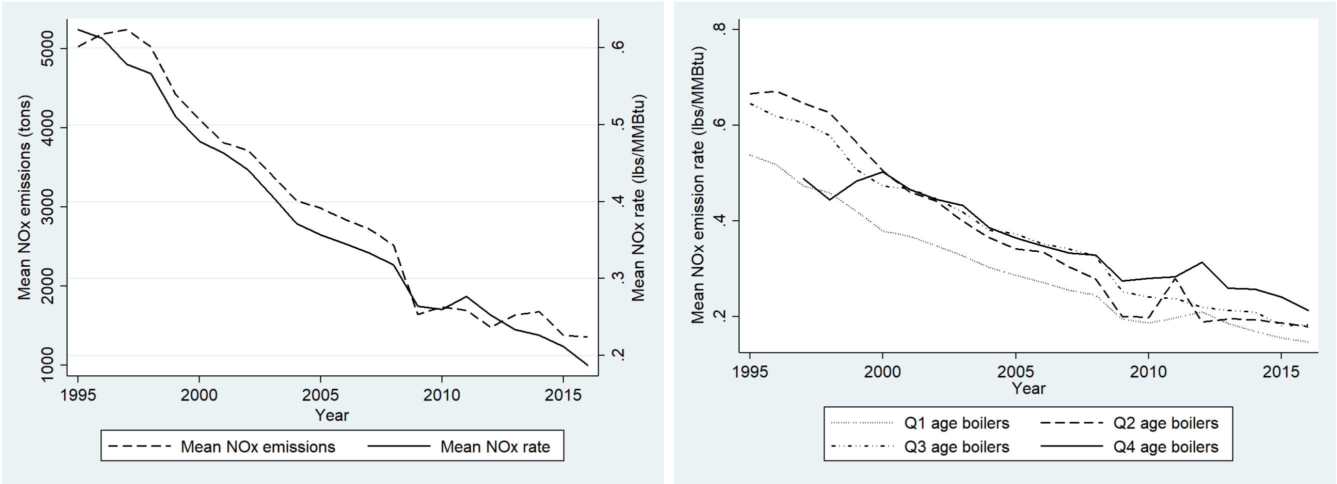
A Data appendix

This appendix describes in depth the data used in our empirical analysis. The first panel in Figure A1 shows mean boiler level trends of NO$_\mathrm{x}$ emissions and emission rate during 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. The second panel of Figure A1 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 in section 3, we expect emission rates to be higher for those boilers that are older; Figure A1 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. 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. 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 construction. Time series results for this exercise are nearly identical to those presented in Figure A1.

Figure A1: 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. Groups are determined by age quartiles, e.g., 0-25 percentile.

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”. We also estimate our primary regression specification for all facilities that burn coal as fuel, including those that do not generate electricity for the grid, e.g., pulp and paper mills. Empirical results are qualitatively and quantitatively similar to those presented below. Several boilers throughout our panel either shutdown, 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. To test if the unbalanced nature of our panel is problematic, 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 in the main text.

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 or (2) EPA tightens, i.e., lowers, the NAAQS to a level below the ambient air concentration of an area for that pollutant. (Nearly all occurrences within our sample are the result of (2).) As a specific example within our sample period, Floyd County (IN), which contains R. Gallagher Generating Station, is located in this county and was designated as non-attainment for ozone from 1995-2000. In 2001, the ambient air concentration of ozone in Floyd County reached attainment levels and the area was re-designated as maintenance, i.e., is treated in our specification. However, EPA promulgated new ozone standards in 2004 which decreased the ambient level of ozone necessary to be designated as non-attainment. As a result, Floyd 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 for a second time. There are no areas in our dataset that exit non-attainment three or more times. We correct for this potential measurement error by including twice in our panel, i.e., data for the entire period operating as a coal-fired boiler, 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.

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 regulated firm behavior changes when not subjected to regulatory oversight.

We used EPA's Green Book for information about non-attainment designation (EPA 2017b). The Green Book contains the 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 NO_x emissions.

We gathered data from the League of Conservation Voters (LCV) yearly scorecards (1995-2016) for the House of Representatives 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 (Nelson 2002). Each year, the LCV publishes a scorecard that ranks the level of pro-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. Finally, we gathered county level unemployment rates from the Bureau of Labor Statistics (BLS) Local Area Unemployment Statistics program to account for changes in electricity demand to due local macroeconomic conditions.

Table A1 provides statistical summaries for the measures used in the analysis. Most important, 17% of boiler-year observations receive the treatment described in the main text. Specifically, these boiler-years were at one point located in counties designated as non-attainment but then ambient air concentrations of PM or ozone improved and the county exited non-attainment. In our sample, coal-fired power plants are located in 396 counties, 162 of which were designated as NO_x-affected non-attainment at some point. 484 unique utility boilers within these non-attainment counties received treatment, i.e., these boilers represent the treated group. Table A1 shows considerable variation in most measures used in the analysis, including the outcomes and treatment measure; this temporal and cross-sectional variation strengthens our identification. We examine further variation in the dependent variables in two ways. First, we examine the variation that is unexplained by boiler and EPA region by year fixed effects. Across utility boilers, 35% of the variation in NO_x emissions

Table A1: Sample summary statistics

Variable	Mean	SD	Min	Max
Dependent variables				
NO_x emissions (tons)	3037	4119	0	87,823
NO_x emission rate (lbs/MMBtu)	0.383	0.280	0.001	22.16
Treatment				
NO_x-affected non-attainment exit (one-year lag)	0.173	0.378	0	1
Boiler level controls				
Total electrical generation (GW-h)	2004	1833	0	13,900
Maximum capacity (MW)	337.1	309.2	0.099	6283
Operating time (hours)	6696	1993	0.100	8784
House LCV score (0-100)	39.80	18.40	0	100
County level unemployment rate	6.204	2.465	1.100	19.80
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.

and 52% of the variation in NO_x emission rate is unexplained by boiler and EPA region by year fixed effects. Second, we explore the intra-boiler variation in the dependent variables. We calculate the standard deviation of each boiler's NO_x emissions and emission rate over the sample period. We then generate summary statistics for this measure. The boiler specific standard deviations have a mean and standard deviation of 1,444 and 2,181 for NO_x emissions and a mean and standard deviation of 0.136 and 0.174 NO_x emission rate. These values reveal coefficients of variation of 1.51 and 1.29, respectively. As a final note, minimum values of the dependent variables (and of some controls) highlight the importance of the identified control factors, especially the operating time of each boiler. In fact, some boiler-year observations show very little NO_x emitted, lending support to the idea that the boiler was operated only minimally as a coal-fired unit. Thus, controlling for such a measure appears imperative.

B Sensitivity analysis

This appendix assesses the robustness of the primary empirical 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. As a result, we re-estimate equation (16) with treatment now lagged by three and five years to examine manager behavior at these different time periods. Results for these alternative specifications are tabulated in Table A2. 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.

Table A2: 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)	0.173*** (0.050)	0.124*** (0.045)		
NO_x-affected non-attainment exit (five-year lag)			0.155** (0.063)	0.118* (0.061)
Observations	14,485	14,477	14,249	14,242
Number of boilers	1,095	1,096	1,095	1,096
Boiler FE	Yes	Yes	Yes	Yes
EPA region#year FE	Yes	Yes	Yes	Yes
Boiler level controls	Yes	Yes	Yes	Yes
Regulatory program controls	Yes	Yes	Yes	Yes

Notes: *** $p \leq 0.01$, ** $p \leq 0.05$, * $p \leq 0.1$. Standard errors are 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 yet 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, identification rests solely on the timing of treatment. Results from the estimation of equation (16) with this sub-sample are presented in Table A3. 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 A3: 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)	0.147***	0.115**
	(0.056)	(0.051)
Observations	7,364	7,360
Number of boilers	565	566
Boiler FE	Yes	Yes
EPA region#year FE	Yes	Yes
Boiler level controls	Yes	Yes
Regulatory program controls	Yes	Yes

Notes: *** $p \leq 0.01$, ** $p \leq 0.05$, * $p \leq 0.1$. Standard errors are 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.