Regulatory Avoidance and Spillover: The Effects of Environmental Regulation on Emissions at Coal-Fired Power Plants

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Abstract

This paper develops a conceptual framework that models the actions of plant managers who face environmental regulation and estimates the effects of the Clean Air Act's non-attainment designations on emissions at coal-fired power plants. Our empirical analysis uses panel data on emissions and other characteristics at coal-fired power plants from 1995-2016. This study adds to the literature on environmental regulation in three ways. First, we investigate avoidance of regulatory scrutiny by plants located in counties with non-attainment designation. We find that power plants not subjected to the technological requirements of New Source Review permits decreased NO_x emissions by 20% as a result of non-attainment designation. We also examine the mechanisms through which this abatement occurs, e.g., technology, use of cleaner inputs. Second, we identify spillover effects of environmental regulation for certain pollutants by examining the effects of disparate non-attainment designations from the emissions in question. We find a statistically significant decrease in NO_x and CO_2 emissions as the result of carbon monoxide and SO_2-affected non-attainment, respectively. We provide evidence that regulatory spillover in this case is the result of different emission control strategies. Finally, we are the first to examine the effects of non-attainment on emissions of several harmful air pollutants from one of the largest emitters - coal-fired power plants - at the boiler-level.

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1 Introduction

The Clean Air Act (CAA) authorizes EPA to create standards for pollutants that are considered harmful to public health and the environment. These standards, called the National Ambient Air Quality Standards (NAAQS), set allowable ambient air concentrations for six criteria pollutants: carbon monoxide (CO), lead (Pb), particulate matter (PM), ozone (O_3), nitrogen dioxide (NO_2), and sulfur dioxide (SO_2) (EPA, 2017c). These air pollution standards give EPA the means to improve air conditions and to address other challenges of air quality management.[1] The objective of the NAAQS is to reduce emissions within a geographic area to meet these standards. As part of the review process, EPA and state environmental agencies evaluate current environmental standard levels, identify whether standards are met, and make policy adjustments. Depending on ambient concentrations of each pollutant, a geographic area can: (1) meet the standard and be designated as in "attainment", (2) fail to meet the standard and be designated as a "non-attainment" area for any of the six criteria pollutants, or (3) be unclassified. The regulatory requirements that firms face are conditional on a facility's location status.

As part of New Source Review (NSR) permitting requirements, new sources of emissions and all existing sources located in attainment areas that undergo "major modification" are required to obtain Prevention of Significant Deterioration (PSD) permits (EPA, November 2016c) and are required to install Best Available Control Technology (BACT). New or modifying stationary sources located in non-attainment areas face even stricter regulations; these facilities must obtain non-attainment NSR permits, which require the installation of Lowest Achievable Emission Rate (LAER) technology (regardless of cost), acquisition of emission offsets, and to satisfy other requirements customized for that area (Walker, 2013). For existing sources, modifications that require permits are contingent on the expected increase in emissions. Stationary source modifications are considered major

[1]Each criteria air pollutant poses significant problems, health or otherwise. PM is a microscopic material small enough to be inhaled and can cause serious health problems, even with little exposure. Ground-level ozone, SO_2, and NO_x are reactive chemicals that can lead to respiratory problems. SO_2 and NO_x can create acid rain through interaction with other chemicals, which can cause groundwater and other problems. In large enough concentrations, PM, SO_2, and NO_x can also restrict visibility (for more on the environmental and health effects of each pollutant, see EPA (2017b)).

if emissions of SO_2 or NO_x are expected to increase by 40 tons per year (EPA, 1990).[2]

The purpose of the NAAQS and NSR permitting is to work in conjunction to allow incremental increases of emissions from new or modified sources while either: decreasing ambient criteria air pollutant concentrations (for non-attainment NSR permits) or meeting/maintaining ambient concentrations (for PSD permits). Regardless of permit type, ambient air quality is not allowed to exceed concentration levels set by the relevant NAAQS (EPA, 2016d). Baseline requirements for NSR/PSD programs are set by EPA, although states can heighten requirements.[3] The threat of regulatory intervention for failing to acquire proper NSR permits is severe. NSR consent decrees often contain millions of dollars in settlements, local outreach, fuel switching, and in certain cases, facility shutdown (Campbell and Levin, 2010).[4] This regulatory oversight provides a strong incentive for firm managers to maintain compliance, while also having a precautionary effect.[5]

Several studies have evaluated the effects of non-attainment status on a variety of economic outcomes. Greenstone (2004) empirically tests whether non-attainment status was responsible for the reduction in ambient SO_2 concentrations in the U.S. throughout the 1990s. Using county-level data, he finds that non-attainment status played a "minor" role in the reduction of SO_2 concentrations. Auffhammer et al. (2009) evaluate particulate matter emissions in the U.S. between 1990 and 2005 and find no significant effect on emissions using aggregated data. Using spatially disaggregated analysis, the authors find that environmental regulatory standards have a significant effect, which highlights the challenges of capturing effects of regulation using county-level data. Chay and Greenstone

[2]Thus, modifications consisting of capital improvements intended to reduce emissions, e.g., emission capture technology, do not require NSR permits. Importantly, an increase of 40 tons of SO_2 or NO_x represents less than a 1% change in emissions for the average facility.

[3]State Implementation Plans (SIP) provide a way to attain or maintain standards set by the NAAQS. SIPs are submitted to EPA and once approved are federally enforceable. If an area reaches non-attainment status for a given criteria air pollutant, then a SIP must be constructed to meet the NAAQS. The SIP process is extremely heterogeneous for stationary sources, as some are subjected to strict regulatory requirements and others very little. The EPA website further describes the non-attainment (https://www.epa.gov/green-book) and NSR permitting (https://www.epa.gov/nsr) processes.

[4]The EPA website lists all coal-fired power plant NSR settlements: https://www.epa.gov/enforcement/coal-fired-power-plant-enforcement.

[5]EPA's enforcement effort under the CAA has resulted in 32 coal-fired power plant lawsuits, which cover 97 individual facilities throughout the U.S. (EPA, September 2016a).

(2004) find that non-attainment designation increases housing values. At the facility-level, Lim (2016) finds that multiple deterrences can be used by regulators to decrease emissions, including financial penalties and additional inspections. Bi (2017) and Gibson (2018) use Toxics Release Inventory (TRI) data to examine how non-attainment status of air pollutants impacts pollution of other forms, i.e., environmental media, at coal-fired power plants. Both studies find a positive relationship between non-attainment status and solid or liquid toxic releases, but a negative relationship between non-attainment status and air emissions. Similar work by Nelson et al. (1993) studies the impacts of regulation on capital equipment at privately-owned electric utilities between 1969-1983. The authors show that regulation increases the age of capital used, but also that capital age is unrelated to firm emissions. Finally, Greenstone (2002) finds that non-attainment designations significantly affect employment in multiple manufacturing sectors. Importantly, none of these studies examine the joint nature of non-attainment designation and NSR permitting.

This study adds to the literature on environmental regulation in several ways. To our knowledge, no previous research has empirically tested whether non-attainment status impacts the scale of SO_2 and NO_x emissions at coal-fired power plants. Additionally, previous studies have examined the use of regulatory "threats" to curb emissions (Antweiler 2003; Brouhle et al. 2009), which sometimes require governments to impose new regulations Glazer and McMillan (1992). We approach this concept from a different angle and examine if firms intentionally avoid scrutiny from existing regulations, i.e., regulatory avoidance. Specifically, we do so in the context of NSR permitting. Finally, little attention has been paid to how emission standards can decrease emissions of disparate pollutants, thereby omitting secondary effects (benefits); we explicitly examine these secondary effects.

We first develop a conceptual model to identify how regulatory oversight and plant manager preferences can decrease emissions. The model illustrates how the presence of emission standards impacts facility decisions. Specifically, we model how regulation changes firm manager behavior and why these changes occur. Our analysis incorporates one of EPA's stated objectives of using a "multi-pollutant" method to research air pollution (EPA, 2017d). We show how a specific standard can have a multi-pollutant or "spillover" effect where regulatory surveillance of a specific pollutant can decrease emissions of other pollutants if certain (identified) conditions are met.

Using our conceptual framework as a guide, we exploit coal-fired power plant emissions data and county-level non-attainment status to empirically test the following: (1) the effect of regulatory oversight on facility-level emissions, (2) the effect of regulatory surveillance on facility-level emissions in the absence of direct enforcement (regulatory avoidance), and (3) the effect of regulatory surveillance of a specific pollutant on facility-level emissions of other pollutants (regulatory spillover). The mechanisms employed by facilities that result in emission decreases and regulatory spillover are then investigated. Since ambient air standards are updated periodically, we are able to evaluate how changes to regulatory standards have impacted emissions by utilizing data from 1995-2016. We examine how oversight affects emissions at coal-fired power plants by utilizing non-attainment status as an exogenous instrument of regulatory surveillance. Further, this is the first study to use NSR permit data to isolate the effects of non-attainment and to examine if the threat of future regulatory action alters firm behavior.

Our empirical analysis of coal-fired power plants supports the existence of regulatory avoidance, as non-attainment designation results in emission decreases of SO_2 and NO_x at large facilities regardless of whether the facility is subjected to NSR permit requirements. We are able to show that regulated plants choose to decrease emissions even without a direct technological threat. We find that the mechanisms through which increased abatement is achieved are both technological adoption (for NO_x emissions) and through the use of cleaner inputs (for SO_2 emissions). These results lend support to the idea that the desire to avoid future regulation may be more cost-effective than technological requirements. However, we find that the threat of punishment through the NSR program serves as a significant deterrent for regulated facilities and thus, the decrease in costs associated with avoidance may be accompanied by a decrease in abatement without this regulatory threat. In addition, our analysis of coal-fired power plants shows that surveillance of a specific pollutant decreases emissions of other pollutants. As one example, location of a coal-fired power plant in a county designated as non-attainment for CO results in a 16% decrease in NO_x emissions, even though emissions of the latter do not affect ambient air concentrations of the former. These results illustrate how a regulatory presence impacts both the scale and scope of emissions. The surveillance of pollutants encourages firm mangers to reduce emissions, while specific pollutant standards can encourage the reduction of other emissions.

This paper proceeds as follows. Section 2 provides background information on coal-fired power plant emissions and control technology used to abate these emissions. Section 3 develops the conceptual framework, which produces empirically testable hypotheses. Section 4 discusses the data used in our empirical analysis. Section 5 presents the empirical framework and Section 6 discusses empirical results. Section 7 offers a discussion of mechanisms through which facility managers decrease emissions. Section 8 provides policy implications of our findings. Section 9 concludes.

2 Background

2.1 Coal-Fired Power Plant Emissions

Regulatory requirements for stationary sources depend on the type, size, and location of facilities. The largest source of SO_2 and NO_x emissions includes coal-fired power-plants, as well as acid, glass, and cement plants. As part of the National Enforcement Initiative, EPA has focused enforcement efforts on these sectors (EPA, December 2016b). However, relative to acid, glass, and cement plants, coal-fired power plants represent the largest stationary source of SO_2 and NO_x emissions in the U.S. Emissions from coal-fired power plants constitute approximately two-thirds of SO_2 and one-third of NO_x stationary source emissions in the U.S. (EPA, 2017a). SO_2 and NO_x emissions constitute or directly add to ambient concentrations of four of the six criteria air pollutants designated by EPA.[6]

[6] SO_2 is a criteria air pollutant itself and NO_x combines with oxygen once emitted into the air to form NO_2, which is a second criteria air pollutant. Ambient PM - a third criteria air pollutant - concentrations are affected by both SO_2 and NO_x emissions. Ground-level ozone is the fourth criteria air pollutant affected by either SO_2 or NO_x emissions. This criteria air pollutant is affected only by NO_x emissions,

Various techniques and strategies exist to reduce emissions from the burning of coal (see below) and employment of clean technologies has decreased emissions of SO_2 and NO_x significantly in the U.S.[7] In 1999, emissions of SO_2 exceeded 11 million tons and emissions of NO_x were nearly 5 million tons (EPA, December 2016b). As of 2015, emissions of SO_2 had dropped to nearly 2 million tons, while emissions of NO_x decreased to slightly less than 2 million tons.

2.2 Emission Control Technology

A variety of emission control technologies exist for coal-fired power plants (Hu et al., 2000) and the quantity and variety of emitted pollutants also varies, e.g., for different coal types. The focus of our analysis is on the relevant subset of criteria pollutants whose ambient concentrations are affected by SO_2 and NO_x emissions (PM, SO_2, NO_x, and ground-level ozone) and intentionally excludes other pollutants.[8] Table 1 tabulates the six criteria air pollutants and identifies if ambient concentrations of each are affected by SO_2 and NO_x emissions.

Control technology for NO_x emissions includes: over-fire air, low-NO_x burners, re-burn, combustion optimization, selective catalytic reduction (SCR), and selective non-catalytic reduction (SNCR); the last two of which represent capital-intensive end-of-pipe capture technology. Control options for SO_2 emissions can include: pre-combustion cleaning, combustion optimization, wet flue gas de-sulfurization (FGD) [which represents capital-intensive end-of-pipe capture technology for sulfur], and dry sorbent injection. Multi-pollutant control methods also exist, e.g., activated coke, electro-catalytic oxidation, circulating fluidized-bed combustion.

as they combine with volatile organic compounds (VOCs) under sunlight to create ground-level ozone.

[7]Franco and Diaz (2009) provide details and reduction rates for a variety of control technologies.

[8]The combustion process of coal can also create emissions of lead, carbon monoxide, cobalt, mercury, manganese, and nickel.

3 Conceptual Framework

In this section we construct a representative facility (firm) and model its incentives created by ambient air quality standards, regulatory oversight, and regulatory programs, e.g., NAAQS, NSR, to identify the influence that regulators have on facility manager behavior.[9] Assume that a representative facility's (i) production creates emissions according to:

$$e_i = \left[(1 - \upsilon_i)\, e - \mu_i \right] q_i \tag{1}$$

where μ_i represents investment in clean technology, υ_i represents the cleanliness of fuel, e represents initial per unit emissions, and q_i represents facility output. Regulators can influence the use of cleaner fuel and technology. For example, the NSR/PSD program uses a technology standard, which requires each firm to invest in clean technology to meet the standard. However, firms can voluntary take actions to reduce emissions as well.

3.1 Firm Objective

Until the 1990s, most facilities operating under price regulation had prices set by a public utility commission (Fowlie, 2010), while facilities operating in recently restructured or deregulated markets faced competition. Therefore, we assume price is exogenous to the firm. For simplicity, we assume facility output is determined by market demand and that facilities minimize their input costs (for general costs unrelated to their emissions) at any given output level. Therefore, facility i's objective can be represented as:

$$\max_{s_i} \ \pi_i = \left[p - C\left(s_i \right) \right] q \tag{2}$$

where p represents price and $C\left(s_i\right)$ represents the cost of investing in clean strategies to reduce emissions. For now, we do not distinguish between clean strategies that the

[9] In our analysis, we define the manager of each plant as the facility manager. While an energy company may operate multiple facilities and each facility may have multiple boilers, a facility will have a unique manager. In this section, we examine how a facility (firm) manager's objective may deviate from profit maximization. In future sections we refer to the actual company that operates each facility as the operator.

firm could use except those required by law. Therefore, we assume that all facilities install abatement technology according to NSR permit requirements. Investment in clean strategies itself does not require an NSR permit, but managers can take additional actions outside of these regulatory requirements to reduce plant emissions. (Other objectives are explored in the following section.)

We expect managers to first select clean strategies (cleaner fuel or capture technology) with the lowest cost to decrease emissions. Borrowing from the literature, we represent the cost of investing in clean strategies as quadratic: $C(s_i) = \frac{s_i^2}{2}$. For simplicity, we assume that all other production costs are zero.[10] This gives the facility's profit, while in compliance, as:

$$\pi_i = \left(p - \frac{s_i^2}{2}\right) q \tag{3}$$

NSR permitting requirements differ (for both new and existing sources undergoing major modification) according to location of the facility. From the facility's perspective, location in a non-attainment area imposes additional restrictions. Therefore, facility i faces the following restrictions on its emissions (e_i):

$$\begin{bmatrix} e_i < e_R - \Sigma_{j \neq i} e_j & \text{if in an attainment area} \\ e_i \leq e_r & \text{if in a non-attainment area} \end{bmatrix}$$

where e_R represents the threshold for a non-attainment area and e_r represents additional emission restrictions due to facility location in a non-attainment area. An important aspect of non-attainment status is that failure to meet an ambient air concentration threshold for a particular criteria air pollutant is outside individual facility control.[11] For example, stationary sources accounted for less than 7% of PM_{10} emissions in 2000 (Auffhammer et al., 2011). Thus, individual facilities cannot affect non-attainment status

[10] Our focus is on clean strategies as it relates to the regulatory atmosphere that the facility faces, so the zero cost condition could be removed as long as profits are non-negative. Therefore, only relevance of input costs (unrelated to emissions) is on the facility's break-even point.

[11] Ambient air quality depends on emissions from a variety of sources within a county, thus making it a common pool resource management problem. States with counties that fail to meet the NAAQS are required to create SIPs to manage ambient air quality. A SIP requires EPA approval and must provide a path for a county's ambient air to meet (and maintain) the relevant NAAQS.

at the county-level by themselves.

The effect that non-attainment has on emissions is a key part of the NAAQS. As a result, facilities located within a non-attainment area have a stronger incentive to decrease emissions. Therefore, each facility satisfies the following condition $s_i^{NA,*} > s_i^{A,*}$, where superscript $_{NA}$ ($_{A}$) denotes facilities located in non-attainment (attainment) areas. Due to non-attainment designation, managers undertake clean strategies (thereby increasing υ_i, μ_i, or both in equation (1)). As a result, $e_i^{NA,*} < e_i^{A,*}$ or equivalently, our model predicts that:

Proposition 1 *Non-attainment status for specific pollutant(s) will decrease a local facility's emissions of that pollutant(s) (or precursor pollutants that directly affect ambient air concentrations).*

Previous work by Greenstone (2003, 2004), Auffhammer et al. (2009), Bi (2017), and Gibson (2018) has shown that non-attainment status has a negative effect on emissions or the ambient air concentration of criteria air pollutants. The additional regulatory requirements in non-attainment areas force facilities applying for NSR permits to adopt additional clean strategies, specifically technology. NSR permits ensure facilities install clean technology chosen by the regulator. Put another way, the regulator's objective is:

$$\min_{\mu_i} e_i = \left[\left(1 - \upsilon_i\right) e - \mu_i\right] q_i \quad s.t. \quad \pi_i = \left[p - C\left(\mu_i\right)\right] q > 0 \tag{4}$$

The technology requirement of NSR ensures that the facility's abatement efforts will increase. However, installed technology may not be cost-efficient, especially if cleaner inputs are available.

In sum, the dual nature of NSR and non-attainment designation allows firms to undertake (emission-increasing) capital improvements while allowing the regulator to increase firm abatement efforts. NSR-permitted facilities always abate through (NSR) technological requirements. Thus, facilities that obtain an NSR permit in a non-attainment area are expected to invest more heavily in clean strategies to meet regulatory standards (Walker, 2013). In the next section, we show that non-modifying facilities located in non-attainment areas are likely to have significant decreases in emissions as well.

3.2 Manager Preferences and Regulatory Avoidance

Until now, we have assumed that managers making decisions on behalf of the facility are concerned only with profit. However, the literature is rife with studies that discuss additional motives, including: appeasing regulators (Maxwell et al., 2000), environmental stewardship/CSR (Lyon and Maxwell, 2008), future regulatory repercussions (Raff and Earnhart, 2018), or even having a progressive operational outlook (Walter and Peterson, 2017). Additionally, managers are given thin emission margins (40 tons) before modifications necessitate NSR permits. These motives incentivize managers to invest additionally in clean strategies, which have the added benefit of appeasing regulators, thus allowing facilities to avoid or minimize regulatory oversight. For this reason, we refer to voluntary investment in clean strategies as regulatory avoidance.

We assume that facility managers gain utility from regulatory avoidance and that these preferences are heterogeneous. Therefore, managers avoid attention from the watchful "eye" of the environmental regulator, which is present in non-attainment areas (Walker, 2013). In addition, facilities will eventually be subjected to NSR requirements for any (future) emission-increasing modification, so appeasing the regulator now may benefit the facility manager later. Under our expanded framework, manager concerns are tied to his/her own preferences and facility profit. Borrowing from Doni and Ricchiuti (2013) and Sklivas (1987), we represent the facility manager's utility as multi-dimensional. Thus, managers face the following objective function:

$$\max_{s_i,\delta_i} \; U_i\left(\pi_i, V_i\right) = \underbrace{\left(1-\delta_i\right)\pi\left(s_i\right)}_{\text{profit maximization}} + \underbrace{\delta_i V\left(s_i\right)}_{\text{manager perferences}} \tag{5}$$

where $V(s_i)$ represents value from activities that lead to regulatory avoidance $\left(\frac{\partial V(s_i)}{\partial s_i} > 0\right)$ and δ_i represents a weighting of manager concern for facility profits and his/her own personal concerns.[12] Note that facilities that do not undergo major modifications, i.e.,

[12] We assume that all managers value activities that lead to regulatory avoidance, therefore $V(s_i) > 0$

those not requiring an NSR permit, are under no obligation to install BACT/LAER control technology. However, managers located in non-attainment areas will take steps to further avoid regulators by investing in additional clean strategies and satisfy $\delta_i V(s_i) > 0$, which implies that $\delta_i > 0$. Therefore, the presence of the regulator and its deterrence effects will incentivize managers to increase υ_i, μ_i, or both. This allows us to conclude that:

Proposition 2 *If facility managers value activities that lead to regulatory avoidance, then non-attainment status will incentivize managers to decrease facility emissions, regardless of whether or not they possess NSR permits.*

Regulator presence encourages a manager to increase the use of clean strategies, thereby increasing the manager's use of available mechanisms (cleaner fuel and clean technology). Additional investment in clean strategies due to regulatory avoidance illustrates a potential indirect benefit of non-attainment designation. Facility managers can always invest in clean strategies (regardless of non-attainment status). However, non-attainment designation provides a stimulus for managers to undertake additional improvements. Therefore, if non-attainment designation encourages managers to *voluntarily* undertake additional investment in clean strategies, then non-attainment designation provides an interesting policy instrument for regulators.

3.3 Jointness in Emission Production/Reduction

Facilities can use a variety of approaches to control emissions, which include cleaner inputs or capture technologies. We have evaluated how regulatory oversight can impact a manager's adoption of clean strategies. However, production creates emissions of a variety of pollutants. As managers decrease emissions of a specific pollutant, how does this impact emissions of other pollutants created during the same process? The expectation is that emissions of targeted pollutants will certainly be reduced, but it is unclear what impact this will have on emissions of other pollutants. More importantly, non-modifying plant

if $s_i > 0$.

managers can use several strategies to meet emission standards. Thus, what effect does environmental regulation have on emissions when production creates multiple pollutants simultaneously?

Clean strategies that focus on inputs lead to the creation of fewer byproducts if underutilized resources from production are the means of creating emissions. If clean strategies target a pollutant by using end-of-pipe capture techniques, non-targeted pollutants may be collected in the process. As a result, regulatory oversight that causes decreases in emissions of a specific pollutant may cause a decrease in emissions of disparate pollutants. In this section, we examine how regulation of specific pollutants can have spillover effects on interdependent pollutants.

We expand our previous framework to examine how regulation influences emissions when production creates multiple pollutants. Let $\overline{e} = (e_1, e_2, ..., e_N)$ represent initial emissions of N types of pollutants from the production of a marketable product. Production that exhibits this property, where $N > 1$, implies that production causes multi-pollutant emissions, which we refer to as "jointness in emission production". Electrical production from coal fired power-plants creates emissions of SO_2, NO_x, CO_2, lead, mercury, and other pollutants. This verifies that $N > 1$ for this industry.

Clean strategies that focus on inputs can have emission control effects that span more than one pollutant. For example, the use of different coal types can lead to reductions in phosphorus, CO, and SO_2 emissions. Therefore, if low-sulfur content coal is used to decrease SO_2 emissions at coal-fired power plants, the result is reduced emissions of both SO_2 and potentially other pollutants. Similarly, optimizing combustion and boiler operation decreases input requirements which reduces emissions of multiple pollutants. Due to jointness in emission production, these clean strategies have a multi-pollutant effect.

An alternative clean strategy for reducing emissions is installation of end-of-pipe or capture technology, which can also have a multi-pollutant effect. When a clean strategy exhibits this property we refer to it as "jointness in emission reduction". This occurs when a clean strategy aimed at reducing emissions of one pollutant decreases emissions of other pollutants. A simple example is a filter, which traps emissions from a variety of pollutants. A more complex example is FGD, which removes SO_2, NO_x, and other particulates.

To illustrate both jointness in emission production and jointness in emission reduction, let $\overline{\mu_i} = (w_1\mu_{i,1}; w_2\mu_{i,2}; ....w_N\mu_{i,N})$ represent a decrease in emissions due to jointness in emission reduction stemming from investment in capture technology by facility i and w_j represent a scalar signifying decreased emissions of pollutant j. Let $\overline{\upsilon_i} = (m_1\upsilon_{i,1}; m_2\upsilon_{i,2}; ....m_N\upsilon_{i,N})$ represent a decrease in emissions due to jointness in emission production stemming from investment in cleaner production by facility i and m_j represent a scalar signifying decreased emissions of pollutant j. Using equation (1), we represent a facility's emissions of multiple pollutants as:

$$\overline{e_i} = (\overline{\upsilon_i} \cdot \overline{e} - \overline{\mu_i})\, q_i = [(1 - \upsilon_1 m_1)\, e_1 - w_1\mu_{i,1};\;\; (1 - \upsilon_2 m_2)\, e_2 - w_2\mu_{i,2};\;\; .... \\ ....\, (1 - \upsilon_N m_N)\, e_N - w_N\mu_{i,N}]q_i \quad (6)$$

Next, we evaluate the effects that regulation of a specific pollutant has on emissions of other pollutants. Assume that regulatory restrictions exist for pollutants of type k, denoted $(e_{r,k})$, due to facility location in a non-attainment area. Therefore, facility i's emissions of pollutant k must satisfy $e_{r,k} \geq e_{i,k} = (1 - \upsilon_{k,i} m_k)\, e_k - w_k\mu_{k,i}$. The facility manager will invest a non-trivial amount in clean strategies targeted at pollutant e_k. Therefore, we can assume that investment in clean strategies is positive $(s_i > 0)$. As mentioned, the manager has two primary mechanisms by which to reduce emissions. If the facility's clean strategies focus on inputs and there exists jointness in the production of emissions then $1 - \upsilon_{j,i} m_j > 0$ for some j. Concurrently, if the facility's clean strategies focus on capture techniques which exhibit jointness in the reduction of emissions then $w_j\mu_{j,i} > 0$ for some j.

Our findings show that in the absence of direct emission regulations for pollutant(s) j (where $j \neq k$), facility i's emissions of pollutant j will satisfy $e_j > e_{i,j}$ if either of the previous (jointness) conditions are satisfied. This implies that the installation of clean strategies that exhibit jointness in the production/reduction of emissions creates spillovers and inadvertently decreases disparate emissions.

However, it is possible that coal-fired power plants, which demonstrate jointness in emission production and reduction, do not install clean strategies that utilize jointness conditions. This would result in facilities reducing emissions of only the targeted pollutant or, depending on the manager's approach, substituting emissions of the targeted pollutant for other disparate pollutants. Thus, emission reductions of one pollutant could potentially increase emissions of another pollutant. Simply put:

Proposition 3 *Emission restrictions for a target pollutant will lead to emission reductions of other pollutants if (1) the facility exhibits jointness in the production of emissions and efficiency increases, or (2) clean strategies are used that exhibit jointness in the reduction of emissions. Otherwise, emissions of other pollutants will remain constant or increase.*

This shows that emission reductions of one type of pollutant due to environmental regulation have the potential to create regulatory "spillover" that decreases emissions of other types of pollutants if jointness in emission production/reduction are present. Dissimilar to Greenstone (2003), who focuses on emissions of specific pollutants based solely on the non-attainment status of that pollutant, we believe, depending on strategies used by facilities to reduce emissions, that non-attainment for any pollutant may impact a facility's emissions of other pollutants. Two primary reasons exist why strategies that cut emissions of one type may affect other types of pollutants: (1) use of capture techniques that collect multiple pollutants and (2) use of cleaner inputs. However, pollutants may not always share these properties. Therefore, reductions for one type of pollutant may have no effect on other pollutants.

Given our assumptions about the form of a manager's utility and subsequent analysis, we produce several testable hypotheses:

Hypothesis H1*: Facility location in a non-attainment area will decrease facility emissions.*

Hypothesis H2: *Facility location in a non-attainment area will decrease facility emissions for facilities that are not subjected to the requirements of an NSR permit.*

Hypothesis H3: *Facility location in a non-attainment area for one criteria air pollutant can result in an increase, decrease, or have no effect on a facility's emissions of other (potentially) related pollutants.*

4 Data

4.1 Sources

This section discusses data sources used to perform our empirical analysis, which primarily examines the effects of non-attainment designation on emissions at coal-fired power plants. EPA's Air Markets Program Database (AMPD) provides emissions of SO_2 and NO_x, measured in tons, at the boiler-level. The AMPD contains data for all regulated facilities that were part of an emissions trading program from 1980-2016 (e.g., Acid Rain Program, NO_x Budget Program), which includes every coal-fired power plant. Most important, the data include boiler-level emissions for both SO_2 and NO_x. AMPD data also contain information on various facility- and boiler-level characteristics, e.g., operating capacity, status, facility location, installed pollution control technologies.

We culled observations from 1980-1990 to create our panel, as data are only available in five-year increments for this range. Using data available in contiguous years, we created a balanced panel of boiler-years from 1995-2016. To keep only coal-fired boilers at plants producing power, we first gathered all data available in the AMPD. The full set of data was then trimmed to include only those plants burning coal as the primary fuel and were categorized as the following: "Electric Utility", "Cogeneration", or "Small Power Producer".

To our knowledge, this is the first study to use these data to examine the effects of county-level non-attainment status on facility emissions. Previous studies (Greenstone 2003; Bi 2017; Gibson 2018) have used TRI data to examine the effects of non-attainment status on emissions. However, TRI data fail to capture emissions from all regulated facilities. The threshold for TRI reporting is substantial and thus, use of these data focuses solely on the largest emitters and only those that discharge pollutants necessary for TRI reporting. Other studies (Greenstone 2004; Auffhammer et al. 2009) examine the effects of non-attainment on the ambient air quality of an area using EPA's Air Quality System (AQS). By using the AMPD, we are able to gather data for all regulated plants that were part of an emissions trading program; specifically, those that burn coal for fuel and are classified as a power producer. Further, TRI emissions data are reported only at the facility-level and AQS data do not allow for facility-level analysis. The AMPD contains data at the boiler-level, which allows us to exploit greater variation in the data; boiler-level emissions can then be aggregated to the facility-level if necessary.

We obtained information on all NSR permits issued in the United States from 1970-2016 using the RACT/BACT/LAER Clearinghouse (RBLC). To ensure that permits are for coal boilers, we select only those permits that were for new plants or modifications at power producers and that burned some type of coal. We match permit data from the RBLC to our emissions data for coal-fired power plants, which allows us to distinguish between permitted and un-permitted facilities.

For non-attainment designation, we use the EPA Green Book (EPA, 2017c). The Green Book contains county-level non-attainment status for the United States from 1992-2016 for six criteria pollutants designated by the CAA. We utilize LCV yearly scorecards (1995-2016) to account for a state's level of environmental concern of its citizens. Finally, we gather information on coal-fired power plant NSR cases from EPA (2017a).

4.2 Statistical Summaries

Our complete panel contains 1,270 coal-fired power plant boilers located at 492 facilities over a period of 22 years, which results in 27,940 and 10,824 possible observations, respectively. Additionally, boilers at 59 coal-fired power plants were subjected to the requirements of an NSR permit over the sample period.

Table 2 provides summary statistics for the entire sample. The average facility emits slightly more SO_2 than NO_x and ground-level ozone is the most prevalent form of non-attainment designation. Table 2 also shows that PM non-attainment is prominent (14% of boiler-years). However, the remaining three non-attainment designations found in our sample occur in less than 5% of boiler-years. The average (mean) coal-fired power plant in our sample generates 2,001 GW-h of electricity, has a heat input of 1.8e7 MMbtu, a nameplate capacity of 343 MW, and is located in a state with an LCV score of almost 40.

Table 3 shows summary statistics broken up by treated and control facilities. For this definition, treatment represents non-attainment designations whose ambient concentrations are affected by the emissions in question, e.g., SO_2 and PM non-attainment for SO_2 emissions. Treated facilities emit slightly more SO_2 than control facilities for SO_2 treatment. Additionally, treated facilities contain boilers that generate more electricity and are larger than un-treated facilities. For NO_x emissions, treated facilities emit less NO_x than control facilities. Additionally, treated facilities contain boilers that generate less electricity and have smaller nameplate capacity than control facilities.

Finally, Table 4 provides summary statistics while distinguishing between facilities based on whether they were subjected to NSR permit requirements. For both types of emissions, facilities that received an NSR permit emit more than facilities without NSR requirements. Interestingly, facilities that are subjected to NSR permits contain boilers that are larger in terms of electricity generation and capacity than non-permitted facilities.[13]

5 Empirical Framework

We next discuss the framework used to empirically test hypotheses derived in section 3. In this section, we focus exclusively on the effects of various non-attainment designations on emissions at coal-fired power plants. This analysis represents an examination of several regulator stimuli used to prompt abatement, i.e., emission decreases, at regulated facilities. In the sections that follow, we explore deeper the mechanisms behind firm manager

[13] Our re-estimations that drop facilities subjected to NSR permits examine only these smaller facilities. As a result, the total amount of emission decreases from these facilities will be smaller, i.e., less economically meaningful than those decreases from the full sample.

decisions to alter emissions as a result of these stimuli.

In each year t, boiler i at facility f emits some level of SO_2 and NO_x, denoted Y_{it}. The level of emissions is affected by a number of factors. Most important, location - specifically whether the facility[14] is located in a NAAQS non-attainment county - may affect emissions at coal-fired power plants. Designation as a non-attainment county has proven to significantly decrease TRI air emissions (Bi 2017; Gibson 2018).

We rely on the exogeniety of non-attainment status to identify its effects on emissions (Greenstone 2002; Greenstone 2003; Bi 2017; Gibson 2018). Specifically, Auffhammer et al. (2011) state that non-attainment designation is exogenous given the relatively low contribution to ambient air quality by the average stationary source in each county.[15]

5.1 Effect of Non-attainment on Emissions

We first empirically test Hypothesis H1 by examining the effects of non-attainment status on SO_2 and NO_x emissions at coal-fired power plants. Here we consider as treated facilities located in counties that are designated as non-attainment for any of the criteria pollutants affected by SO_2 and NO_x emissions:

$$ln(Y_{it}) = \nu_t + \delta_i + \beta NA_{it-1} + \mu X_{it} + \epsilon_{it} \tag{7}$$

where Y_{it} is tons of SO_2 or NO_x emitted, ν_t are a set of year dummies, δ_i are boiler fixed effects, and ϵ_{it} is an exogenous error term. The primary regressor is the treatment dummy, NA_{it-1}, which is a one-year lagged binary variable indicating whether the county where the facility is located is designated as non-attainment for any of the three criteria pollutants affected by SO_2 or NO_x emissions, for a given year. Thus, NA_{it-1} represents if facilities are in non-attainment counties for SO_2, PM, and/or ground-level ozone, dependent upon which pollutant is the dependent variable; see Table 1 for details. Most important, β is the parameter of interest and represents the percent change of SO_2 and

[14]We refer throughout to the "facility"; however, each facility includes multiple boilers.

[15]The vast majority of criteria pollutants are emitted through non-stationary sources, i.e., vehicles (Auffhammer et al., 2011).

NO_x emissions as a result of non-attainment designation.[16][17] Finally, X_{it} represents a vector that captures the following facility- and boiler-level controls. First is a control for total electrical generation at each boiler, measured in gigawatts per hour (GW-h). It is expected that as more electricity is produced, the boiler will emit more SO_2 and NO_x. Next we include a control factor for heat input of each boiler. This factor captures inputs into the coal-burning process and is expected to be positive, as greater inputs into the generation process can produce more outputs, including emissions. Next, X_{it} contains a control variable for capacity of the boiler. The nameplate capacity of each boiler captures the size of each boiler and its ability to produce more output. We hypothesize this control to positively affect emissions, as larger boilers produce more output, including emissions. A fourth control factor is included as a proxy for environmental concern for the state in which the coal-fired power plant is located. We match League of Conservation Voters (LCV) pro-environment voting score, which is a measure from 0-100 for each state, where 100 indicates the most pro-environmental representatives for a state possible, to the state where each facility is located. This measure has been used in several studies to capture environmental concern of the voting public or to proxy for the regulatory stringency faced by facilities in each state (Shadbegian and Gray 2003; Grooms 2015). We expect this variable to be negatively associated with the level of emissions at the facilities in our analysis.

We next extend estimation of equation (7) to account for NSR permitting of regulated facilities, which tests our theoretical discussion of regulatory avoidance. One of the most important targets of non-attainment designation are those facilities that require NSR permits, i.e., new and modifying facilities. Pollution abatement requirements of NSR permits are much more stringent than non-attainment designation alone and include a

[16]Because all counties had reached attainment status for NO_2 by 1995 (the first year of our emissions data), there are no counties with NO_2 non-attainment designation in our panel. Thus, the specification in equation (7) does not show the effects of NO_2 non-attainment on NO_x emissions.

[17]We re-estimate equation (7) using a different sample as a robustness check. To assess whether or not power plants respond differently to non-attainment designation than other industrial facilities that burn coal as fuel (e.g., pulp and paper mills), we re-estimate equation (7) for all coal-burning facilities, regardless of sector. The results are statistically identical to those presented below, with only slightly different coefficient estimates.

technological component (LAER) for plants located in non-attainment counties. Because we expect facilities that receive an NSR permit to alter emissions differently than those that do not receive a permit, we remove from the analysis facilities that received an NSR permit during our sample period; the remaining facilities are those that were not subjected to the technological requirements of NSR. For these plants, non-attainment designation represents the only regulatory requirement, where efforts to control emissions must be "reasonable", rather than technologically mandated regardless of cost. Thus, we empirically examine avoidance behavior of managers not explicitly required to install technology. We first re-estimate equation (7). However, facilities that do not receive an NSR permit may not feel pressured to make significant emission reductions immediately upon entering non-attainment. Therefore, we also re-estimate equation (7) using multiple lags of non-attainment designation. This analysis reflects our initial empirical examination of Hypothesis H2. (Below, we account for the future "threat" of not complying with NSR requirements.)

5.2 Manager Heterogeneity and General Deterrence

To further test the effects of non-attainment on emissions and additional stimuli with which regulated facilities act upon, we re-estimate equation (7) with emissions of SO_2 and NO_x at the facility-level and include facility fixed effects. We also account for heterogeneity in managerial behavior toward environmental management by including operator dummies. The inclusion of these dummies controls for the operator of each facility, including potential "company-down" attitudes on environmental management and facility manager selection. Importantly, these dummies vary over time for facilities that experienced operator changes within our panel. Although not perfect (as some operators do not change throughout the panel and thus, dummies for those facilities are subsumed into the facility-specific fixed effects), these dummies can account for broad changes in facility manager behavior over time. We estimate the following specification:

$$ln(Y_{ft}) = \nu_t + \delta_f + \eta_{ft} + \beta NA_{ft-1} + \omega P_{it-1} + \mu X_{it} + \epsilon_{ft} \quad (8)$$

where subscript f represents factors at the facility-level. Thus, Y_{ft} is tons of SO_2 or NO_x emitted at the facility-level, η_{ft} are operator dummies, ν_t and δ_f are year dummies and facility fixed effects, respectively, X_{it} are controls from above, and ϵ_{ft} is an exogenous error term. We also include a measure of general deterrence (Earnhart 2004; Shimshack and Ward 2005; Raff and Earnhart 2018), denoted P_{it-1}, which represents the "threat" of future punishment based on experiences of similar facilities (Cohen, 2000). NSR cases against coal plants are rare and sizable (in terms of pecuniary punishment) and thus, carry with them considerable general deterrence effects (Campbell and Levin, 2010). This serves as an exogenous proxy for future regulatory costs, i.e., expected costs of non-compliance with NSR requirements. Inclusion of this measure also allows us to examine a second stimulus used by regulators to prompt abatement, specifically within the NSR program. The designation of non-attainment itself brings with it considerable regulatory attention (Walker, 2013). Further, the threat of sanctions for not complying with NSR, e.g., failing to secure a permit when undertaking major modifications, may also serve as an important stimulus urging managers to abate (if increased monitoring fails to motivate managers). To construct this measure, we gathered civil penalty data for all 32 coal-fired power plant NSR cases from EPA (2017a). We then aggregated these penalties for all plants in each year and subtracted each facility's own amount from the aggregated level (to ensure exogeneity of the measure). Finally, we divided each facility's "general" penalty amount by the number of coal-fired power plants operating during that year. Dis-similar to other studies (e.g., Raff and Earnhart 2018), we do not divide by the number of facilities at the regional level, as the cases in question are extremely rare and sizable, i.e., we expect all facilities in our sample to be aware of these cases. Finally, we lag these measures by one year to allow facilities time to react to penalties. This analysis reflects another empirical examination of Hypothesis H2, specifically a second stimulus to avoid the regulator - NSR civil penalties - and thus decrease emissions.[18]

[18]It is important to note that our measure of general deterrence is certainly a lower bound. NSR cases during our sample period contain much greater sanctions than civil penalties, including non-profit cooperation costs, fuel-switching, and shutdown.

5.3 Spillover

We next examine the effects of each individual criteria air pollutant's non-attainment designation on SO_2 and NO_x emissions at the boiler-level. Here we examine the effects of any non-attainment designation on SO_2 and NO_x emissions. Previously, we examined only non-attainment designations that affect the specific pollutant in question, e.g., PM and SO_2 non-attainment for SO_2 emissions, similar to all other non-attainment studies (e.g., Greenstone 2003). We examine disparate non-attainment designations, e.g., lead for SO_2 emissions, to determine if non-attainment decreases emissions for only a specific set of pollutants or if the policy results in other reductions, i.e., spillover. Potentially related pollutants may be jointly captured or reduced in the production process, e.g., the installation of pollution control technologies for lead may capture emissions of other pollutants, thus decreasing emissions of multiple pollutants. To determine if any non-attainment designation affects SO_2 and NO_x emissions at coal-fired power plants, we split treatment into five separate categories,[19] one for each criteria air pollutant. Thus, we estimate the following specification:

$$ln(Y_{it}) = \nu_t + \delta_i + \beta_1 O_{3,it-1} + \beta_2 PM_{it-1} + \beta_3 SO_{2,it-1} + \beta_4 CO_{it-1} + \beta_5 Pb_{it-1} + \epsilon_{it} \quad (9)$$

where Y_{it} is tons of SO_2 or NO_x emitted, ν_t are year dummies, δ_i are boiler fixed effects, and ϵ_{it} is the error term. Regressors of interest are the separate treatment indicators for each type of non-attainment designation found in our sample, which now include carbon monoxide (CO_{it-1}) and lead (Pb_{it-1}). Thus, our coefficients of interest are β_1 through β_5. We expect βs to be negative for non-attainment designations for criteria pollutants affected by either SO_2 or NO_x emissions. For non-attainment designations not affected by SO_2 or NO_x emissions (e.g., lead non-attainment for either pollutant), the hypothesized sign of the βs is either positive, negative, or zero. If a facility's abatement strategies jointly capture or reduce emissions, then non-attainment designations for all pollutants should result in a decrease in emissions of SO_2 and NO_x. If a facility's abatement strategies do not

[19] As mentioned, all counties had reached attainment status for NO_2 by 1995, which is the first year of our panel. Thus, we do not examine the effects of NO_2 non-attainment on emissions in this specification.

jointly capture or reduce emissions, the effect on SO_2 or NO_x emissions of alternative non-attainment designations is positive or zero. This approach provides an empirical testing of Hypothesis H3. Finally, equation (7) is re-estimated for facilities that did not receive an NSR permit during the sample period. As before, we examine multiple treatment lags.

6 Results

6.1 Effect of Non-attainment on Emissions

Results from the estimation of equation (7) without control variables are presented in the second and third columns of Table 5. Estimation results show that county-level non-attainment designation negatively affects both SO_2 and NO_x emissions at coal-fired power plants. For SO_2 emissions, location of a facility in a non-attainment county for either SO_2 or PM results in a 15% reduction in total tons of SO_2 emitted. For NO_x emissions, county-level non-attainment designation for either ground-level ozone or PM results in an 18% reduction in total tons of NO_x emitted. Results are robust when controls are added (sixth and seventh columns), with decreases of 19% and 14% of SO_2 and NO_x emissions, respectively, as a result of non-attainment. Therefore, non-attainment designation is effective at reducing emissions in a very important sector, which is consistent with Hypothesis H1.

Table 6 presents the changes in SO_2 and NO_x emissions as a result of treatment, but for facilities not subjected to the technological requirements of an NSR permit. These results show how regulated entities react to increased regulatory stringency solely via non-attainment designation. For SO_2 emissions, Table 6 shows three potential lags of facility entrance into treatment. Of the three, only the one-year lag measure does not significantly decrease SO_2 emissions. Although facilities are not explicitly subjected to greater regulation (technology) through NSR permits, non-attainment designation results in emission decreases, consistent with Hypothesis H2. For facilities that are not required to change their pollution abatement measures, it takes at least two years for SO_2 emissions decreases to occur. We hypothesize that this is because managers do not immediately feel the need to decrease emissions, as is oftentimes required for new or modifying plants. However, treatment still proves effective at reducing emissions through mechanisms other than the technological requirements of NSR permits.

For NO_x emissions, we see nearly similar results. However, there is now an immediate effect of treatment, with a 20% reduction in emissions after entrance into treatment, for the one-year lag measure. All three lags of non-attainment designation significantly decrease NO_x emissions; these results are again consistent with Hypothesis H2. Collectively, Table 6 results show that for certain emissions, the designation of a county as non-attainment is itself an effective tool for decreasing emissions; non-attainment designation provides greater regulatory stringency, even without the increased technological requirement of an NSR permit. Thus, results empirically identify regulatory avoidance behavior on the part of facility managers.

6.2 Manager Heterogeneity and General Deterrence

Results from the estimation of lagged non-attainment status on emissions at the facility-level (equation (8)) are presented in Table 7. We add operator dummies to this specification to better control for "top-down" heterogeneity of attitudes toward environmental management from the operator of each facility. Results from this specification are statistically identical to those from before, with only slightly differing coefficient estimates. We see that lagged non-attainment designation decreases emissions of SO_2 and NO_x by 14% and 13%, respectively, when including controls and operator dummies (columns four and five), at the facility-level. Importantly, we also include a measure of general deterrence (penalty amount) to this specification. This measure identifies expected future costs of facilities for not acquiring appropriate NSR permits when making major modifications (which is triggered by only a 1% increase in emissions for the average facility). The general deterrence measure indicates a potential stimulus in addition to non-attainment designation motivating managers to abate. We see a significant decrease in NO_x emissions as a result of similar facilities receiving NSR penalties in that calendar year (lagged one year). However, the measure is not statistically significant for SO_2 emissions (although the coefficient is negative). We see that as a result of levying significant penalties on similar regulated facilities, intervention on behalf of the regulator, in addition to increased presence as a result of non-attainment, motivates managers to decrease emissions. Collectively, desire to avoid the regulator in the future results in significant decreases of emissions, both through potential fines and potential technological requirements. These results further support Hypothesis H2 suggesting that managers take current actions to avoid interaction with the regulator in the future.

6.3 Spillover

The fourth and fifth columns of Table 5 present estimation results for our examination of regulatory spillover. Results represent the effect on emissions of multiple stimuli - non-attainment designation of multiple criteria air pollutants - regardless of the pollutant intended to regulate. For SO_2 emissions, PM non-attainment designation is the only significant treatment category; the other four treatment categories do not result in a statistically significant change in SO_2 emissions at the boiler-level. For NO_x emissions, estimation results show that PM non-attainment decreases emissions by 16% and ground-level ozone non-attainment designation results in a 12% decrease in emissions. One non-attainment designation for a criteria air pollutant not affected by the emissions in question negatively affects NO_x emissions at coal-fired power plants: CO, which results in a 16% decrease in emissions.

This set of results supports the following conclusions. For SO_2 emissions, only treatment for criteria air pollutants directly affected by SO_2 emissions results in emission decreases. Thus, perhaps pollution control technologies or input choices used to decrease emissions of other criteria air pollutants do not jointly capture or reduce the production of SO_2 (we explore this further in the next section). However, for NO_x emissions this is not the case. Although NO_x emissions do not affect the ambient concentration of CO, CO non-attainment designation significantly decreases NO_x emissions. Thus, in this case CO control technologies may jointly capture emissions of NO_x or inputs used to decrease the production of carbon monoxide also decrease the production of NO_x. These results are consistent with spillover presented in Hypothesis H3 for CO non-attainment but not SO_2 or lead.

Appendix Table A-1 presents results for the re-estimation of equation (9) for only those facilities that did not receive an NSR permit. Estimation results are similar to those presented for the definition of treatment presented in equation (7), as they are consistent with the narrative that certain non-attainment designations significantly decrease emissions at coal-fired power plants even though the facilities were not subjected to the technological requirements of NSR permits.

7 Mechanisms and Origins of Spillover

Results presented above indicate that non-attainment status and NSR penalties are strong stimuli that motivate emission reductions of SO_2 and NO_x at coal-fired power plants. This is the case even for facilities not subjected to the technological requirements of NSR and for designations other than those intended to regulate certain pollutants. This section examines the mechanisms through which managers choose to decrease emissions at regulated facilities. We then use these mechanisms to discuss the origins of spillover found in our analysis.

7.1 Capture Technology v. Cleaner Inputs

This sub-section examines *how* facility managers decrease emissions as a result of non-attainment designation. We examine as outcomes the use of certain strategies to reduce emissions for facilities that did not receive an NSR permit during our sample period as a function of non-attainment designation. We exclude NSR facilities from the analysis because they had specific technological requirements as part of the permit and thus, the mechanism for emission reductions for these facilities is always capital-intensive technological adoption. From this analysis, we can determine if managers choose to reduce emissions in other - potentially more cost-effective - ways than technological adoption. The first strategy that we explore is the installation of capital-intensive technology. We estimate the following equation for the sub-sample of facilities not subjected to NSR permitting requirements using a linear probability model (LPM):[20]

$$K_{it} = \nu_t + \delta_i + \eta_{it} + \beta NA_{it-1} + \mu X_{it} + \epsilon_{it} \tag{10}$$

where ν_t are year dummies, δ_i represent boiler fixed effects, η_{it} are operator dummies, X_{it} is the same vector of controls as above, and K_{it}, our outcome, is a dummy that indicates the presence of the most capital-intensive technologies that control emissions of SO_2 and NO_x, respectively, at each boiler. For SO_2 emissions, our outcome indicates the presence of FGD equipment. For NO_x emissions, the dummy indicates presence of SCR/SNCR equipment. For this specification, we are interested in the effect of lagged non-attainment designation, NA_{it-1}, on our outcome and we use the same definition of treatment as equation (7). Thus, our primary coefficient of interest is β and we expect this coefficient to be positive, negative, or zero. If non-attainment induces facilities to install emission reducing technologies, then β will be positive. If the effect of non-attainment designation on emissions is through other clean strategies, then β will be zero (or perhaps negative). Similar to equation (8), we include a series of operator dummies, which most likely control for the entity that decides to install such capital-intensive technology.[21]

Results for estimation of equation (10) are found in the second and third columns of Table 8. For SO_2 emission control technology, estimation results show that non-attainment designation does not significantly affect the probability that facilities install FGD. Alternatively, for NO_x emission control technology, we find that lagged non-attainment designation increases the probability that the facility installs SCR/SNCR by 6.5%.

We combine these results with those of the previous section to arrive at the following conclusions. Estimation results of this section suggest that facility managers choose to decrease emissions of SO_2 through methods other than capture technology when in non-attainment (and not subjected to NSR permit requirements). For SO_2 emissions then,

[20] Results are identical using both probit and logit models; we tabulate and discuss LPM estimation results for ease of interpretation.

[21] It is possible that facility managers on their own could decide to install these technologies. If so, these decisions are captured in the boiler fixed effects.

regulatory avoidance results in a different outcome (than an NSR permit) at each boiler in terms of technology. Estimation results from this section also show that facility managers choose to install emission reducing technology in the form of SCR/SNCR to control NO_x emissions when subjected to non-attainment designation, but not NSR requirements. NO_x emission reductions from non-NSR facilities come primarily through technology used to control emissions, even though facilities are not required by EPA to install SCR/SNCR. Therefore, the result of non-attainment is the same (technology installation) as if the facility were required to act based on technological requirements of NSR permits for NO_x emissions.

To identify the mechanism through which non-NSR permitted facilities decrease emissions of SO_2, we examine a different strategy: cleaner inputs. Reducing SO_2 emissions is possible through the burning of lower-sulfur coal; in fact, this strategy represents a low-cost option for emission reductions (Attanasi and Freeman, 2009). Thus, we determine if non-attainment designation prompts coal-type change by examining shipments of coal to facilities in our sample. We gather data on monthly coal shipments from EIA forms 423 and 923 and take the average quantity of each type (anthracite, bituminous, sub-bituminous, lignite) at the facility-level, measured in short tons.[22] To determine if non-attainment designation prompts managers to switch to fuel with lower sulfur content, we estimate the following equation:

$$Bit_{ft} = \nu_t + \delta_f + \eta_{ft} + \beta NA_{ft-1} + \mu X_{ft} + \epsilon_{ft} \tag{11}$$

which is nearly identical to equation (9) except for two components. First, the outcome, Bit_{ft}, is now a monthly average of the quantity of bituminous coal delivered to each facility in each year. Second, the analysis is performed at the facility-level and includes facility fixed effects due to the nature of the coal acquisition data. We again drop facilities subjected to the technological requirements of NSR permits for this specification. For our merged panel, only 13 facility-year observations contained a non-zero quantity of

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

anthracite coal[23] (0.1%). Thus, by dropping these rare observations and using the amount of bituminous coal as our outcome, we can determine whether facilities switch from coal with the highest sulfur content (bituminous) to those with lower sulfur contents (sub-bituminous and lignite). We are again interested in the effect of lagged non-attainment designation, NA_{ft-1}, on our outcome and we use the same definition of treatment as equation (7).

Results from the estimation of equation (11) are found in the fourth column of Table 8. The average monthly amount of bituminous coal shipments to facilities in our panel decreases by 4800 tons as a result of SO_2-affected non-attainment designation. Because we control for total electrical generation at each plant, this suggests that facility managers decrease SO_2 emissions as a result of non-attainment through the use of lower-sulfur coal. We see that facilities decrease their acquisition of bituminous coal and as a result switch to sub-bituminous or lignite coal to maintain electrical production. Ultimately, this switch results in less SO_2 emissions, as shown above.[24]

Collectively, our analysis of the mechanisms through which facility managers of plants not subjected to the technological requirements of NSR decrease emissions produces the following results. Non-attainment designation prompts the installation of capital-intensive technology for NO_x emission control. Thus, managers choose to abate in the same way as if they were subjected to NSR requirements without explicit EPA requirements to do so. We hypothesize this to be caused by the nature of NO_x emissions, where decreases through higher quality inputs are not as feasible as for other types of emissions. For SO_2 emissions, managers abate through the use of cleaner inputs rather than through the installation of capital-intensive technology. This strategy represents a low-cost option for emissions reductions (Attanasi and Freeman, 2009).

[23] Which represents the type of coal with the highest sulfur content.

[24] Coal-type acquisition changes occur after one year of entrance into non-attainment, but emission reductions of SO_2 (for non-NSR plants) do not occur until two years after treatment. We hypothesize that this is because we examine shipments of coal, not the type burned. Facilities may immediately change coal type acquisition, but existing stockpiles are burned first. Importantly, estimation using two- and three-year lagged measures of non-attainment generate results similar to those presented.

7.2 Origins of Spillover: Jointness in Emission Reduction or Production?

Our analysis has shown that facilities decrease emissions of different pollutants using different techniques, thus suggesting that production and reduction strategies are utilized to decrease emissions. As presented in section 3, environmental regulation may result in spillover effects, where regulation of some pollutants decreases emissions of other non-regulated pollutants. We seek to identify if emission reductions of disparate pollutants are the result of "jointness in emission production" or "jointness in emission reduction"; the former representing a change in inputs, the latter representing technological adoption. We first see evidence of spillover by finding that CO non-attainment decreases NO_x emissions. The lack of data on CO technology at each facility prevents us from testing if this is the result of jointness in emission reduction or production. Nonetheless, this result is indicative of regulatory spillover for CO non-attainment.

Next, empirical results show that facilities not subjected to NSR permitting install capital-intensive NO_x control equipment, although there is no EPA requirement to do so. Thus, emission reductions of NO_x at facilities stem from the installation of emission capture technology. Engineering literature finds reductions in mercury emissions as a result of SCR/SNCR installation (Senior and Johnson 2005; EPA 2017e), which highlights the spillover created by emission-reducing technology of NO_x. Thus, non-attainment designation of PM or ground-level ozone can potentially result in mercury emission decreases through technology installation aimed at reducing NO_x emissions. This decrease does not result from a change in inputs, but rather pollution control technology "capturing" related pollutants. Therefore, we identify this spillover effect as a result of jointness in emission reduction. This conclusion supports the first potential reason for spillover from environmental regulation found in our conceptual framework.

We also find that non-attainment designation for SO_2-affected pollutants does not induce the installation of FGD for facilities not subjected to NSR permitting. However, results show that facilities switch to coal with lower sulfur content, i.e., cleaner inputs, as a result of non-attainment designation. We are therefore unable to arrive at spillover conclusions similar to those for NO_x-affected non-attainment designations, i.e., jointness in emission reduction. To test for the presence of spillovers (and what type), we estimate the effect of SO_2-affected non-attainment designation on CO_2 emissions. We estimate the same specification as equation (7), but our outcome is now CO_2 emissions. If SO_2 and PM non-attainment significantly affect CO_2 emissions, we again see spillover from environmental regulation, but from a different source. Results of this estimation are found in the fifth column of Table 8. Empirical results show that for facilities not subjected to an NSR permit, non-attainment designation for SO_2-affected pollutants decreases emissions of CO_2 by nearly 8%. When combined with the previous result that SO_2 non-attainment induces input switching, we hypothesize that this spillover is the result of jointness in emission production; the decrease in emissions is not the result of technological improvements, but a result of the use of cleaner inputs. Indeed, ASTM (2005) ranks lignite and sub-bituminous coal lower in carbon content than bituminous coal.[25] This conclusion supports the second potential reason for spillover from environmental regulation found in our conceptual framework.

8 Policy Implications

Both theoretical and empirical results offer policy implications. The designation of counties as in non-attainment of air quality standards has, *ceteris paribus*, been successful at reducing harmful emissions at coal-fired power plants. Thus, absent costs, tightening the NAAQS could produce sizable benefits through reduced emissions at these facilities. Our analysis of regulatory avoidance also shows emission decreases for those facilities not subjected to the technological requirements of NSR permits as a result of non-attainment designation. Specifically, we find that non-attainment alone prompts managers to install abatement technology (for NO_x emissions) and use cleaner inputs (for SO_2 emissions). Initially, these mechanisms through which abatement occurs appear to indicate that tech-

[25]We believe that this is a reasonable assumption, as it would seem odd for a facility manager to install carbon control technology, e.g., carbon capture and sequestration, when responding to SO_2 non-attainment. We do not however, completely rule out this possibility.

nological requirements of NSR permits represent an unnecessary burden. (Prior research has shown that NSR creates problems of new source bias and cost-ineffectiveness (Gruenspecht and Stavins, 2002).) However, our analysis of the general deterrence effects of NSR shows that the threat of future regulatory involvement significantly decreases emissions at coal-fired power plants. Thus, NSR serves as an important regulatory "stick" when used jointly with non-attainment designation. In sum, our results suggest that a more cost-effective way to reduce emissions would be to simply designate counties as in non-attainment without additional technological demands. However, abatement for non-NSR plants could be less than the status quo without the threat of NSR.[26]

Our results also suggest that spillover benefits are possible from environmental regulation. Regulations for emissions of certain pollutants can decrease emissions of other related pollutants if there is jointness in emission production or reduction. Thus, benefits from environmental regulation, non-attainment designation in particular, are almost certainly understated. These results are important when setting environmental policy, as more pollutants than those regulated must be considered when calculating benefits. Our results also show that emission reductions from jointness in emission production may be more cost-effective than those represented by jointness in emission reduction. For SO_2 emissions in particular, we find that spillover occurs in the production of emissions, i.e., through inputs, rather than in reduction of emissions, i.e., through technology. Therefore, our results suggest that targeting reductions in emission production is the most cost-effective avenue for achieving emission decreases. Jointness in emission production found in the NAAQS also decreases CO_2 emissions, which are very imporatant in today's policy landscape. This spillover effect may have additional relevance in the crafting of greenhouse gas (GHG) policy. Regulation limiting emissions of SO_2 and NO_x from stationary sources impacts emissions of CO_2. Additionally, previously proposed rules by EPA have targeted CO_2 emissions from electric generators, thus requiring facilities to install

[26]From our analysis we are unable to determine if non-attainment designation is an effective way to bring counties into compliance with the NAAQS. We examine only one sector of stationary source emitters while ignoring the main source of pollutants responsible for poor ambient air quality: mobile sources, i.e., vehicles. Therefore, our policy implications deal only with "localized" emissions from certain regulated facilities and not with county-level ambient air quality as a whole.

millions of dollars worth of equipment (Shogren, 2013). While carbon emission standards will increase construction and compliance costs for coal-fired power plants, these emission standards are likely to impact other emissions, e.g., SO_2, NO_x. Finally, spillover results extend to regulatory targeting (Harrington 1988; Friesen 2003). Environmental regulation and enforcement budgets are limited each budget cycle and targeting specific areas on which to focus is important. Spillover possibilities may be considered by regulators when choosing policies to implement or areas to target, on the margin. For example, if a regulator were at the end of his/her enforcement budget and needed to inspect/fine one additional facility, spillover possibilities, e.g., location in an area with poor ambient CO concentration, may be the deciding factor of which facility to enforce upon.

9 Conclusion

The purpose of this study is to examine the effects of designating areas as in non-attainment of the NAAQS. Specifically, the study examines how these designations affect SO_2 and NO_x emissions at coal-fired power plants and if designations affect emissions without the additional technological requirements of NSR permits. Further, the study explores the potential spillover of the NAAQS by assessing the effects of disparate non-attainment designations on SO_2, NO_x, and CO_2 emissions, e.g., CO non-attainment on NO_x emissions. We find that designation of a county as non-attainment significantly decreases emissions of several important pollutants at coal-fired power plants. Additionally, results show that spillovers from disparate non-attainment designations exist, as SO_2-affected and CO non-attainment decrease boiler- and facility-level CO_2 and NO_xemissions, respectively. Finally, we show that non-attainment alone, without the technological requirements of an NSR permit, also decreases emissions. We identify the mechanisms through which abatement is achieved as technological installation to abate NO_x emissions and the use of cleaner inputs to abate SO_2 emissions.

These results highlight two significant contributions to the literature on environmental regulation and offer policy implications. As our first contribution, we show that managers of regulated facilities take actions to avoid future interaction with the regulator. The primary reason for this avoidance stems from managers wishing to avoid future costs as a result of non-compliance, i.e., fines. We examine avoidance behavior in connection with the additional technological requirements of NSR permits and empirically find that non-attainment alone is effective at decreasing harmful emissions from coal-fired power plants. However, our examination of general deterrence suggests that the threat of future NSR involvement serves as a strong "stick" which prompts abatement. Thus, we conclude that the joint nature of non-attainment designation and NSR permitting likely maximizes abatement, although likely not in a least-cost way. We also examine in what matter the avoidance takes place, i.e., through technology installation or the use of cleaner inputs. We find that both technology and cleaner inputs are used by regulated facilities to decrease emissions. Further, previous studies examine the threat of regulation rather than the avoidance of regulation (e.g., Antweiler 2003; Brouhle et al. 2009) and no previous study of non-attainment designation has taken into account the additional requirements of NSR permits (e.g., Greenstone 2003; Auffhammer et al. 2011; Bi 2017; Gibson 2018). Our second significant contribution is the examination of regulatory spillover associated with the NAAQS. We provide evidence that spillovers can come in one of two forms: (1) through jointness in emission production (e.g., use of cleaner inputs) and (2) through jointness in emission reduction (e.g., add-on technology). We are the first to provide evidence of spillover associated with non-attainment designation, as all previous studies simply study the effect on emissions or ambient air quality of non-attainment designations for specific pollutants in question (e.g., Greenstone 2002; Greenstone 2004). Thus, we conclude that benefit calculations of the NAAQS are most certainly understated. As a final and lesser yet nonetheless important contribution, we are the first to examine the effect of non-attainment designation on harmful emissions within a very important sector: coal-fired power plants.

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Table 1: Relationship of SO_2 and NO_x emissions to criteria air pollutants

Criteria air pollutant	Affected by SO_2 emissions	Affected by NO_x emissions
Sulfur dioxide	X	
Nitrogen dioxide		X
Particulate Matter	X	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 SO_2 or NO_x, respectively.

Table 2: Summary statistics for entire sample

Variable	Mean	Std. Dev.	Min	Max
Dependent variables				
Tons of SO_2 emitted (logged)	8.026	1.777	-6.908	12.06
Tons of NO_x emitted (logged)	7.254	1.483	-6.908	11.38
Non-attainment designations				
Ground-level ozone non-attainment	0.212	0.408	0	1
Particulate matter non-attainment	0.140	0.347	0	1
SO_2 non-attainment	0.040	0.197	0	1
Carbon monoxide non-attainment	0.013	0.115	0	1
Lead non-attainment	0.012	0.109	0	1
Other factors				
Total electrical generation (GW-h)	2001	1845	0	13,900
Heat input (MMbtu)	1.8e7	1.8e7	0	1.3e8
Maximum capacity (MW)	343.3	311.6	0.099	6283
House LCV score (0-100)	39.84	18.75	0	100
General deterrence - NSR penalty ($000)	52.69	112.0	0	490.9

Notes:
Non-attainment designations represent a county that is in non-attainment for that particular criteria air pollutant in a given year.

Table 3: Summary statistics by primary definition of treatment

	SO_2		NO_x	
	Treatment	Control	Treatment	Control
	n=4,776	n=23,164	n=8,034	n=19,906
Variables	Mean (Std. Dev.)	Mean (Std. Dev.)	Mean (Std. Dev.)	Mean (Std. Dev.)
Dependent variables				
Tons of SO_2 emitted (logged)	8.093	8.011		
	(1.834)	(1.763)		
Tons of NO_x emitted (logged)			7.140	7.301
			(1.400)	(1.513)
Control factors				
Total electrical generation (GW-h)	2084	1980	1915	2038
	(2025)	(1799)	(1895)	(1822)
Heat input (MMbtu)	1.9e7	1.8e7	1.7e7	1.8e7
	(1.8e7)	(1.7e7)	(1.7e7)	(1.8e7)
Maximum capacity of boiler (MW)	367.4	336.8	329.1	350.0
	(282.8)	(318.6)	(277.3)	(326.4)
House LCV score (0-100)	41.18	39.57	46.91	36.99
	(16.88)	(19.10)	(19.72)	(17.56)

Notes:
Treated facilities are those located in a non-attainment county for either PM or SO_2 for SO_2 emissions, and PM or ground-level ozone for NO_x emissions. The number of observations is represented by the number of boiler-years in the sample.

Table 4: Summary statistics by receipt of NSR permit

	Permit n=3,168		No permit n=24,772	
Variables	Mean	Std. Dev.	Mean	Std. Dev.
Dependent variables				
Tons of SO_2 emitted (logged)	8.310	1.364	7.987	1.823
Tons of NO_x emitted (logged)	7.867	1.120	7.171	1.499
Non-attainment designations				
Ground-level ozone non-attainment	0.141	0.349	0.220	0.415
Particulate matter non-attainment	0.091	0.287	0.147	0.354
SO_2 non-attainment	0.016	0.127	0.043	0.204
Carbon monoxide non-attainment	0.003	0.050	0.015	0.121
Lead non-attainment	0.009	0.094	0.013	0.111
Control factors				
Total electrical generation (GW-h)	2865	1823	1870	1813
Heat input (MMbtu)	2.8e7	1.9e7	1.7e7	1.7e7
Maximum capacity of boiler (MW)	501.5	346.7	321.0	299.7
House LCV score (0-100)	33.79	20.53	40.62	18.37

Notes:
Non-attainment designations represent a county that is in non-attainment for that particular criteria air pollutant in a given year. The number of observations is represented by the number of boiler-years in the sample.

Table 5: Fixed effects estimation results for additional regression specifications

	Dependent variable					
Variable	ln(SO_2)	ln(NO_x)	ln(SO_2)	ln(NO_x)	ln(SO_2)	ln(NO_x)
SO_2-affected county-level non-attainment (1-year lag)[a]	-0.149*				-0.188**	
	(0.079)				(0.080)	
NO_x-affected county-level non-attainment (1-year lag)[a]		-0.183***				-0.140***
		(0.064)				(0.049)
Ground-level ozone county-level non-attainment (1-year lag) [b]			0.124	-0.121**		
			(0.118)	(0.061)		
Particulate matter county-level non-attainment (1-year lag)[b]			-0.175**	-0.160***		
			(0.088)	(0.062)		
SO_2 county-level non-attainment (1-year lag)[b]			0.073	-0.047		
			(0.120)	(0.084)		
Carbon monoxide county-level non-attainment (1-year lag)[b]			-0.169	-0.158*		
			(0.126)	(0.085)		
Lead county-level non-attainment (1-year lag)[b]			0.221	0.004		
			(0.260)	(0.169)		
Total electrical generation (GW-h)					0.0005***	0.00001
					(0.0001)	(0.00006)
Heat input (MMbtu)					-9.15e-9	4.38e-8***
					(1.42e-8)	(7.02e-9)
Maximum capacity of boiler (MW)					0.00005	0.00006
					(0.0001)	(0.00006)
House LCV score (0-100)					0.002	0.002
					(0.003)	(0.002)
Constant	8.669***	7.927***	8.632***	7.926***	7.844***	7.070***
	(0.040)	(0.034)	(0.051)	(0.033)	(0.217)	(0.135)
Observations	21,639	22,511	21,639	22,511	14,060	14,174
Number of boilers	1,235	1,263	1,235	1,263	1,041	1,054
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
Boiler FE	Yes	Yes	Yes	Yes	Yes	Yes

Notes:
*** $p \leq 0.01$, ** $p \leq 0.05$, * $p \leq 0.1$. Standard errors clustered at the county level and located in parentheses.
[a] County-level non-attainment designation is only for those criteria air pollutants affected by emissions of the dependent variable: SO_2 and PM for SO_2 emissions, ground-level ozone and PM for NO_x emissions.
[b] County-level non-attainment designation for that specific criteria air pollutant, regardless of the effects of SO_2 or NO_x emissions on its ambient concentrations.

Table 6: Fixed effects estimation results for facilities without an NSR permit - primary definition of treatment

			Dependent variable			
Variable	ln(SO_2)	ln(NO_x)	ln(SO_2)	ln(NO_x)	ln(SO_2)	ln(NO_x)
County-level non-attainment	-0.103	-0.201***				
(1-year lag)	(0.083)	(0.067)				
County-level non-attainment			-0.213**	-0.205***		
(2-year lag)			(0.091)	(0.070)		
County-level non-attainment					-0.308***	-0.218***
(3-year lag)					(0.106)	(0.075)
Constant	8.640***	7.869***	8.714***	7.899***	8.732***	7.898***
	(0.042)	(0.036)	(0.043)	(0.036)	(0.047)	(0.039)
Observations	19,009	19,808	18,062	18,861	17,118	17,918
Number of boilers	1,092	1,119	1,092	1,119	1,092	1,119
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
Boiler FE	Yes	Yes	Yes	Yes	Yes	Yes

Notes:
*** $p \leq 0.01$, ** $p \leq 0.05$, * $p \leq 0.1$. Standard errors clustered at the county level and located in parentheses. County-level non-attainment designation is only for those criteria air pollutants affected by emissions of the dependent variable: SO_2 and PM for SO_2 emissions, ground-level ozone and PM for NO_x emissions. Estimation sample contains only those facilities not subjected to the requirements of an NSR permit.

Table 7: Fixed effects estimation results for primary definition of treatment at facility-level

	Dependent variable			
Variable	$\ln(SO_2)$	$\ln(NO_x)$	$\ln(SO_2)$	$\ln(NO_x)$
County-level non-attainment designation (1-year lag)	-0.165*	-0.224***	-0.144*	-0.131***
	(0.095)	(0.054)	(0.085)	(0.042)
Total electrical generation (GW-h)			0.0003***	0.000007
			(0.00006)	(0.00003)
Heat input (MMbtu)			-1.4e-8**	1.4e-8***
			(6.8e-9)	(3.9e-9)
Maximum capacity of boiler (MW)			0.00002	-0.000007
			(0.0001)	(0.00005)
House LCV score (0-100)			0.0009	0.00004
			(0.002)	(0.001)
General deterrence - NSR fine (000s) [1-year lag]			-0.001	-0.006**
			(0.005)	(0.003)
Constant	9.480***	8.774***	8.930***	7.837***
	(0.040)	(0.031)	(0.290)	(0.131)
Observations	8,339	8,720	5,384	5,461
Number of facilities	479	490	407	413
Facility FE	Yes	Yes	Yes	Yes
Operator dummies	No	No	Yes	Yes
Year FE	Yes	Yes	Yes	Yes

Notes:
*** $p \leq 0.01$, ** $p \leq 0.05$, * $p \leq 0.1$. County-level non-attainment designation is only for those criteria air pollutants affected by emissions of the dependent variable: SO_2 and PM for SO_2 emissions, ground-level ozone and PM for NO_x emissions.

Table 8: Fixed effects estimation results for technology, fuel type, and spillover

Variable	Dependent variable			
	FGD	SCR/SNCR	Bit. Coal Amount	$\ln(CO_2)$
County-level non-attainment designation (1-year lag)	0.044 (0.028)	0.065*** (0.024)	-4800** (2169)	-0.078* (0.045)
Constant	0.116** (0.057)	0.080 (0.084)	-26,308 (166,631)	13.06*** (0.137)
Observations	11,967	11,967	4,049	12,114
Number of boilers	917	917	—	908
Number of facilities	—	—	346	—
Controls	Yes	Yes	Yes	Yes
Boiler FE	Yes	Yes	No	Yes
Facility FE	No	No	Yes	No
Operator dummies	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes

Notes:
*** $p \leq 0.01$, ** $p \leq 0.05$, * $p \leq 0.1$. Standard errors clustered at the county level and located in parentheses. County-level non-attainment designation for estimations where technology is the outcome is for criteria air pollutants affected by emissions of what the technology is intended to control: SO_2 and PM for FGD, ground-level ozone and PM for SCR/SNCR. For specifications where coal type and CO_2 emissions are the outcome, county-level non-attainment designation represents those affected by SO_2 emissions: SO_2 and PM. Estimation sample contains only those facilities not subjected to the requirements of an NSR permit.

Table A-1: Fixed effects estimation results for facilities without an NSR permit - individual non-attainment

	Dependent variable					
Variable	$\ln(SO_2)$	$\ln(NO_x)$	$\ln(SO_2)$	$\ln(NO_x)$	$\ln(SO_2)$	$\ln(NO_x)$
Ground-level ozone county-level non-attainment (1-year lag)	0.060	-0.149**				
	(0.106)	(0.065)				
Particulate matter county-level non-attainment (1-year lag)	-0.126	-0.164**				
	(0.092)	(0.065)				
SO_2 county-level non-attainment (1-year lag)	0.093	-0.043				
	(0.123)	(0.086)				
Carbon monoxide county-level non-attainment (1-year lag)	-0.196	-0.180**				
	(0.129)	(0.088)				
Lead county-level non-attainment (1-year lag)	0.295	0.009				
	(0.310)	(0.185)				
Ground-level ozone county-level non-attainment (2-year lag)			0.0427	-0.146**		
			(0.109)	(0.064)		
Particulate matter county-level non-attainment (2-year lag)			-0.220**	-0.185**		
			(0.104)	(0.071)		
SO_2 county-level non-attainment (2-year lag)			-0.004	-0.067		
			(0.127)	(0.086)		
Carbon monoxide county-level non-attainment (2-year lag)			-0.170	-0.209**		
			(0.135)	(0.095)		
Lead county-level non-attainment (2-year lag)			0.236	-0.020		
			(0.349)	(0.200)		
Ground-level ozone county-level non-attainment (3-year lag)					0.058	-0.113*
					(0.110)	(0.068)
Particulate matter county-level non-attainment (3-year lag)					-0.310**	-0.216***
					(0.123)	(0.080)
SO_2 county-level non-attainment (3-year lag)					-0.096	-0.021
					(0.147)	(0.086)
Carbon monoxide county-level non-attainment (3-year lag)					-0.164	-0.232**
					(0.142)	(0.096)
Lead county-level non-attainment (3-year lag)					0.145	-0.064
					(0.378)	(0.209)
Observations	19,009	19,808	18,062	18,861	17,118	17,918
Number of boilers	1,092	1,119	1,092	1,119	1,092	1,119
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
Boiler FE	Yes	Yes	Yes	Yes	Yes	Yes

Notes:
*** $p \leq 0.01$, ** $p \leq 0.05$, * $p \leq 0.1$. Standard errors clustered at the county level and located in parentheses. Estimates contain an intercept term. County-level non-attainment designation for that specific criteria air pollutant, regardless of the effects of SO_2 or NO_x emissions on its ambient concentrations. Estimation sample contains only those facilities not subjected to the requirements of an NSR permit.