Electricity Rate Structure and SO_2 Emissions at U.S. Coal Power Plants

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Abstract

We examine how economic regulation interacts with environmental policy to affect the intensive and extensive margins of sulfur dioxide (SO_2) pollution control at coal power generators in the United States. We relate preexisting, within-state variation in the regulated status of generators to a uniquely granular dataset of generator characteristics, observed hourly SO_2 emissions, and the timing of court rulings that required control implementation. We find that regulated plants exhibited no difference in the adoption of pollution controls relative to nonregulated plants. This stands in contrast to prior findings for nitrogen oxides. However, regulated units were 15% more likely to operate controls in any given hour and achieved a 5% greater SO_2 removal rate on average. Federal consent decrees targeting nonregulated units for New Source Review violations appear to close the gap in SO_2 control use compared to regulated units. The consent decrees required plants to install and operate emissions control equipment to meet emissions performance requirements. This paper considers the effect of economic regulation on firms' responses to this type of environmental regulation, thereby testing whether electricity market restructuring changed the type of environmental regulation necessary to incentivize plants to control pollution.

1 Introduction

How societies elect to provide critical services such as power, water, and energy fuels for space heating have far-reaching consequences for development and social welfare both because these services are necessities and because of the large-scale, capital-intensive nature of their provision. Prior to the 1990s, electricity in the United States (U.S.) was provided by vertically integrated monopolies. Electricity restructuring in the U.S. aimed to increase operational efficiency and reduce system costs (Borenstein & Bushnell, 2015) in part by making fundamental changes to the compensation structure of power plants. Historically, firms operated as regulated monopolies, recovering fixed and variable costs through electricity rates stipulated by public utility commissions (PUCs). In deregulated markets, generators' compensation is determined in auctions that allocate generation to the lowest bidder (Lazar, 2016).

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In addition to economic, or rate-based, regulation, power plants in the U.S. are subject to environmental regulation. The objectives of cost control, or operational efficiency, and environmental control are not necessarily aligned. Therefore, an important question is how the efficiency-motivated changes to compensation structure embodied in deregulation interact with firm behavior under environmental regulation. Prior research provides evidence that economic regulation influences how firms comply with environmental regulation (Fowlie, 2010). The present paper adds to and builds on this literature in three ways. First, we estimate generator responses at the extensive margin (installation of equipment) and the intensive margin (operation of equipment) of pollution control decisions using hourly emissions data, decomposing emissions into a function of multiple operator decisions. Second, we study the interaction among economic regulation, environmental policy enforcement and litigation, and firms' environmental compliance decisions in the context of the New Source Performance Standards. Third, we concentrate on sulfur dioxide (SO_2) while the literature focused on nitrogen oxides, or NO_x (Fowlie, 2010).

Changes in economic regulation and firms' compensation structure should affect both the extensive and intensive margins of pollution control. On the extensive margin, firms subject to economic, or rate-of-return, regulation are often permitted to recover a portion of capital investments through electricity rates. This reduces the financial risk relative to firms operating in deregulated markets in which cost recovery occurs through market-determined prices (Borenstein & Bushnell, 2000; Delmas & Tokat, 2003; Di Maria, Lange, & Lazarova, 2018). All else equal, the reduction in financial risk associated with economic regulation provides an incentive to invest in pollution control technology (Fowlie, 2010). On the intensive margin, plants that operate pollution control equipment are likely to incur increased marginal costs from material inputs like sorbent, additional power to run the control technology, and additional maintenance costs. Plants subject to economic regulation can recover these costs by including operation of pollution control equipment among the allowable costs in their rate base (Lazar, 2016). In contrast, to recover higher costs from operating pollution control equipment, firms in restructured markets must pass along these costs in the form of higher bids in power auctions. Higher bids may in turn decrease their chances of dispatch, which would decrease economic viability. A dual focus on both the intensive and extensive margins of pollution control is essential to obtain a full picture of the impacts of electricity market deregulation on firm behavior as it pertains to environmental performance.

This study also focuses on how economic regulation interacts with enforcement of environmental policy and subsequent compliance behavior by firms. We examine how firms in regulated markets differ from firms in restructured markets in terms of their response to policy promulgation *ex ante* and litigation *ex post*. Specifically, we estimate the effect of whether firms are subject to rate-of-return regulation on the installation and operation of pollution control technology following the implementation of New Source Performance Standards (NSPS), and after the settlement of litigation over New Source Review (NSR) reporting requirements (Environmental Protection Agency, 1979). The empirical analysis of the response to litigation is made possible by a newly assembled dataset of the legal documentation pertaining to NSR litigation. These settlements essentially operated by fiat: ultimately, they required plants to install emissions control equipment and to operate it to meet emissions performance requirements in perpetuity. As a result, plants subject to these consent decrees had relatively little flexibility to choose how to achieve emissions rate reductions compared to other units due to the technology-forcing nature of the NSPS (Ackerman & Hassler, 1981). By considering the effect of economic regulation on responses to this type of environmental regulation, we can test whether electricity market restructuring changed the type of environmental regulation necessary to incentivize plants to control pollution.

Finally, Fowlie (2010) found that, in response to market-based NO_x controls, facilities in reg-

ulated markets were more likely to install NO_x control equipment and that installed technology was more expensive and of higher quality. In contrast, we focus on SO_2. Like NO_x, SO_2 is a criteria air pollutant, with local and regional impacts on public health and welfare. However, the emission control strategies targeting SO_2 are different than those used to control NO_x. These include burning low sulfur coal and the installation of flue gas desulfurization (FGD) units. For NO_x, control strategies include low-NO_x burners and selective catalytic reduction (SCR). We note that sulfur content of coal varies systematically across space according to the composition of coal seams. This presents plants with differential opportunities to exploit low sulfur coal depending on the location of the plant. In turn, this affects plants' adoption of FGD in a manner that differs from SCR. Our particular focus is on FGD, which embody different cost structures and pollution removal rates than SCR. Thus, we view our study of SO_2 as a substantive addition to the prior research focusing on NO_x.

Among the three contributions to existing work noted above, we contend that the study of how uncertainty in cost recovery interacts with uncertainty about the requirements of environmental policy is especially novel. As Fowlie (2010) demonstrated, firms' ability to recover costs of pollution control suggests differential adoption and/or use of pollution control equipment based on whether they operate in regulated markets. Upon this foundation, we add an analysis of the role played by state action that implied particularly inflexible SO_2 emissions reduction requirements. Specifically, we obtain variation in environmental policy requirements from the time-varying civil enforcement of the NSR. We then estimate the effect of consent decrees litigated under NSR that mandate FGD installation with specific rates of SO_2 removal and examine how this effect varies between regulated and nonregulated units.

We report four main results. First, in contrast to the findings of Fowlie (2010), we find no empirical difference in FGD adoption by a plant's regulatory status. This null result is robust to several econometric specifications. Second, regulated units achieve a 9% to 11% higher hourly SO_2 removal rate than nonregulated units. We then decompose the effect of economic regulation on the SO_2 removal rate into two components: differential scrubber use and differences in removal rates conditional on use. We find that regulated plants are about 15% more likely to operate their FGD units than nonregulated facilities. And, regulated plants exhibit 5% greater SO_2 removal rates, conditional on the FGD being in operation. We posit that this enhanced performance of the FGD units may reflect regulated firms' willingness to rely on higher quality FGDs and variable inputs (e.g., sorbents) because of their ability to recover costs. These results support our intuition regarding firm environmental performance at the intensive margin. We note that such behaviors would be overlooked if the focus of this paper had been strictly on FGD adoption. Third, we find that economic regulation has a significant effect on how units respond to environmental regulation in the context of performance-based standards. Rate-of-return regulated units that were also regulated under federal consent decrees for NSR violations achieve statistically similar SO_2 removal rates to those that did not operate under consent decrees. However, nonregulated units under NSR consent decrees removed 13% more SO_2 than other nonregulated units, achieving similar performance to regulated units (whether under consent decree or not). This result suggests that any gap in emissions control technology performance induced by competitive generation markets may have been closed through the application of technology-based standards of control technology operation. Fourth, the differential performance of FGD units operated by firms in regulated and competitive markets has appreciable impacts on public health. In 2011 alone, suboptimal FGD performance at nonregulated plants was associated with 1,100 excess deaths from exposure to subsequently formed fine particulate matter.

The remainder of the paper is structured as follows. Section 2 provides a review of the policy

background, SO_2 abatement options, and the mechanisms linking electricity market regulation and environmental performance. Section 3 explores our data, empirical methods, and hypothesis tests. Section 4 reports our empirical results and section 5 concludes.

2 Background

2.1 Electricity market restructuring and incentives for environmental compliance

This paper exploits heterogeneity in unit-level electricity market regulation within states to compare SO_2 emissions control by two categories of plants: regulated and nonregulated. We define regulated plants as those owned by a utility that can recover costs through a state's revenue requirement (Lazar, 2016). Nonregulated plants are not owned by a regulated utility and thus must recover capital costs through either a wholesale power market or through long-term contracts with customers in a competitive market.

Present heterogeneity in generator ownership is driven by the differential rates of wholesale and retail market restructuring. Prior to 1990, the electricity industry was dominated by vertically-integrated utilities who owned generation, distribution and transmission assets (Warwick, 2002). From 1996 to 2000, several states "restructured" or "deregulated" the retail side of generation, forcing utility companies to divest their generating assets so that nonregulated generators could compete directly for end customers. This retail market restructuring substantially increased the proportion of nonregulated generators. However, restructuring plans often allowed the existing regulated utilities to retain a portion of generating capacity to serve as a provider of last resort and sometimes allowed municipalities to keep local regulated utilities, enabling comparisons between regulated and non-regulated plants located in the same state. Furthermore, federal efforts to promote wholesale electricity market deregulation through the Public Utility Regulatory Policies Act in 1978, the 1992 National Energy Policy Act, and FERC Order 888 in 1996 mean that even states without restructured retail electricity markets often have a mix of utility-owned and merchant plants (Federal Law, 2013; Stuntz, 1995). Over the period 1995 to 2020, we find that 35 states had both regulated and nonregulated coal-fired plants operating simultaneously for at least one year.

Research quantifying the effects of restructuring on state electricity markets after the fact largely focuses on economic outcomes. Many papers use plant- or unit-level data to assess the effect of deregulation on fuel consumption (Cicala, 2015; Knittel, Metaxoglou, & Trindade, 2019), generator productivity (Fabrizio, Rose, & Wolfram, 2007; Linn & McCormack, 2019), and electricity cost (Borenstein & Bushnell, 2015; Fabra & Reguant, 2014).

Research that estimates the environmental impacts of restructuring mainly focuses on the effects of changes in regional electricity mix (Palmer & Burtraw, 2005; Swisher & McAlpin, 2006) or only as a byproduct of improved operational efficiency resulting from market competition Chan, Fell, Lange, and Li (2017). Other papers also look at how market structure affected emissions, but look only at differences in CO_2 emissions indirectly through differences in fuel efficiency and fuel price sensitivity (Knittel et al., 2019; Sharabaroff, Boyd, & Chimeli, 2009). Acworth, de Oca, Boute, Piantieri, and Matthes (2020) compares the outcomes of emissions trading regulations under different electricity market regulatory schemes, finding that trade can occur even in non-competitive markets. However, the study also only estimates the effect of electricity markets on environmental outcomes as a function of estimated efficiency gains relative to rate-of-return

regulation. Indeed, the relative sparsity of power plants with operating carbon capture systems and ambiguous regulation of CO_2 emissions means that it is difficult to infer whether differences in market structure affect emissions through differentiated incentives to adopt emissions mitigation strategies in the context of CO_2.

Research that projected possible outcomes of restructuring on SO_2 emissions offers evidence that utilities' capital cost recovery rules might impact the effectiveness of SO_2 allowance trading as part of the 1990 Acid Rain Program (Bohi & Burtraw, 1992; Coggins & Smith, 1993; Fullerton, McDermott, & Caulkins, 1997). These studies used market simulations to show that including environmental costs into a utility's rate base could result in substantially different outcomes across the market. In particular, Coggins and Smith (1993) shows that when subject to plant-level emissions caps, superior environmental outcomes were achieved when plants were allowed to receive a rate of return on the capital costs of abatement. While this research focused on the effects of policies applied to regulated utilities, it suggested that the cost recovery component of the regulated utility structure may create an incentive to invest in reducing emissions. Other prospective analyses directly addressed the potential environmental impacts of increased competition among generators as a function of the degree of deregulation (Burtraw, Palmer, & Paul, 1998), and projected lower prices and increased NOx emissions associated with increasing degrees of deregulation.

Fowlie (2010) provides a focused treatment of the effect of electricity market regulation on firms' environmental compliance behaviors using data on NO_x control installation and costs post-restructuring. The study empirically estimates a model of the effect of the capital and operating cost of NO_x controls on plant compliance decisions for regulated and nonregulated plants and finds that nonregulated units were significantly less likely to install NO_x controls with high capital cost, and that nonregulated units may have been more sensitive to operating costs than regulated units (Fowlie, 2010). Furthermore, the study finds that operating costs had a somewhat greater negative effect on nonregulated units' likelihood of adopting a particular technology (Fowlie, 2010).

Our study focuses on SO_2 control along both the extensive and intensive margins, disentangling both the decision to operate the scrubber and the resulting SO_2 removal rate. We build upon the analysis of Fowlie (2010) in several ways. First, we consider the results in the context of SO_2 regulation, which requires entirely different control strategies. Namely, while plants can adopt a variety of NO_x control strategies to mitigate NO_x emissions including altering combustion characteristics of the boiler, SO_2 emissions can only be mitigated by either purchasing coal with less sulfur or by installing end-of-pipe control technologies. This limits the flexibility of plants to vary their decision-making at the installation margin. Second, rather than characterizing units' operational decisions by comparing operating costs, we estimate emissions outcomes directly by comparing the estimated rate of SO_2 generation with measured hourly emissions. This provides a more direct measure of the effect of market regulation on emissions performance. Third, we consider the effect of regulation on U.S. power plants over the decades since deregulation by choosing a different environmental policy target with national scope: the New Source Performance Standards.

2.2 Market-based and command-and-control SO_2 regulation

Over the past three decades, the landscape of SO_2 regulation changed dramatically. The passage of the 1990 Clean Air Act introduced market-based regulation of SO_2 emissions through the Acid Rain Program (ARP) (EPA, 1993). In the decades since, the ARP has been celebrated for achieving aggregate SO_2 emissions reductions in the electricity sector while distributing the burden

of reduction to units with the lowest cost of compliance (Burtraw, Krupnick, Mansur, Austin, & Farrell, 1998; Chan, Chupp, Cropper, & Muller, 2018). Compared with previous command-and-control policies, the ARP employed a market-based approach to regulating emissions. The ARP first set a system-wide cap on SO_2 emissions and distributed this limited pool of emissions allowances to existing units. Units with emissions greater than their allowances could then choose to comply with the ARP by buying excess allowances from firms that emitted less than initially allotted.

As the EPA developed and broadened its market-based regulatory efforts in the 1990s, it simultaneously ramped up its enforcement of command-and-control policies, specifically the New Source Performance Standards (NSPS) (Environmental Protection Agency, 1979). Compared with other federal pollution regulations, the NSPS provide plants little flexibility in selecting a compliance strategy. Despite the relative unpopularity of NSPS, starting in 1999, the EPA began pursuing legal action against utilities that did not undergo the New Source Review (NSR) process to receive NSPS permits for modified plants (EPA, 2024). These cases often ended in consent decrees, negotiated settlements which imposed strict emissions limits on electricity generating units and required the installation of FGDs and other expensive control technologies.

Fowlie (2010) used compliance cost elasticities estimated from data to simulate how electricity restructuring may affect health outcomes from the NO_x Budget Program (NBP), a similar market-based instrument to the ARP that instead targeted NO_x emissions. Those results indicated that restructuring likely resulted in negative public health outcomes due to the redistribution of NO_x control adoption from plants in low- to high-impact regions relative to the counterfactual where all plants were subject to identical economic regulation.

Our study takes a different approach by estimating the effect of economic regulation on units' responses to environmental regulation rather than on the distribution of emissions across units. We are motivated in part by interest in how economic regulation changes the incentives to install and operate control technologies. Since we directly observe hourly emissions and fuel consumption at plants, we can estimate hourly SO_2 removal rates of FGD units and can estimate the effect of rate-of-return regulation on not only input cost but on the achieved SO_2 removal rate. Furthermore, our environmental policy of interest—whether a unit is subject to "binding" regulation under an NSR consent decree—acts heterogeneously in space and time and between and within utility owners. We use this heterogeneity to both identify the effect of regulation under an NSR consent decree and to identify the difference in the effect between regulated and nonregulated units.

2.3 Interactions between environmental regulation and economic regulation

Coal power plants are subject to heterogeneous market regulation which produces different economic incentives for environmental compliance strategies. Meanwhile, environmental regulation impacts how much flexibility a plant has in the choice of technology for mitigating emissions. This section outlines how economic regulation could mediate the effects of environmental regulation at the installation and operation margin of SO_2 emissions control.

2.3.1 Installation margin

When responding to environmental policy, regulated utilities might have more incentive to install capital-intensive FGDs than nonregulated utilities because regulated rates are structured to allow a rate of return on capital investments. For nonregulated units, the high capital cost of pollution

controls must be recovered through competitive markets. Without a revenue requirement, FGDs are less likely to be the least-cost option for environmental compliance and thus less likely to be installed by profit-maximizing utilities. Furthermore, the revenue requirement mitigates some of the risk assumed by regulated units when making capital expenditures, and may make an FGD cheaper to finance.

If the likelihood of having an FGD installed is different between regulated and nonregulated units, we might expect that difference to be greater in the absence of technology-forcing policy. If the prevailing environmental policy is flexible about how a firm decides to control its emissions, a cost-minimizing utility will only install an FGD if it is the least cost option to achieve compliance. However, when SO_2 regulations are very stringent, FGD installation may be the only SO_2 mitigation strategy available to achieve the necessary reductions. Furthermore, firms regulated under technology-forcing policies like the NSPS may be mandated to install control technologies and achieve ongoing emissions limits, severely restricting the set of potential compliance strategies (unless a firm chooses not to comply).

2.3.2 Operation margin

Regulated units may not only have more incentive to install FGDs, but they may be incentivized to operate them to achieve higher rates of SO_2 removal. Unlike nonregulated units, regulated units may be able to recover some of their FGD operating costs through their rate base (Lazar, 2016). In addition, if a regulated utility claims FGD operating costs as part of the rate-based cost of operations, that utility may face additional governmental pressure to run their scrubbers to remain compliant with the rate agreement. Meanwhile, nonregulated utilities must recover marginal costs through electricity markets, and risk not being dispatched if their costs are too high. Thus nonregulated utilities may have greater incentive to minimize marginal costs of operating emissions control equipment by reducing expenditures on sorbent and system maintenance and incur the corresponding penalties to SO_2 removal rate. Nonregulated units may also reduce marginal costs by choosing not to operate their FGDs at certain times to avoid parasitic load or generator downtime during FGD, particularly if such non-operation would not place the unit in jeopardy of environmental noncompliance. Nonregulated units' FGDs may also already have a lower baseline removal rate, since regulated units benefit from the revenue requirement and may be more likely to invest in higher quality scrubber systems (Fowlie, 2010).

If FGDs at nonregulated units remove less SO_2 because of uncertainty in cost recovery, while regulated units are able to write FGD operation costs into the rate base, then we might expect the relative difference in removal rate to narrow under more stringent environmental regulation. For units subject to relatively lax environmental regulation, an installed FGD might be capable of achieving substantially greater abatement than necessary to achieve compliance. In these situations, cost-minimizing firms may be able to reduce their operating expenses by employing lower quality sorbent, or if the prevailing regulation only limits total annual emissions, they may be able to operate their FGD intermittently to avoid downtime if doing so would not exceed the annual limit. Meanwhile, units under stricter regulations like NSPS would be more likely to operate their FGDs to achieve higher average rates of SO_2 removal. If nonregulated units are more likely to employ marginal cost-minimizing strategies that result in lower SO_2 removal rates, we would expect that the relative increase in removal rate to meet more stringent environmental regulation would be greater than for regulated units.

3 Data and Methods

3.1 Unit Characteristics

Data used in the study was obtained from several forms submitted to the Energy Information Administration (EIA) (EIA, 2021a) and the EPA through the Clean Air Markets Division (CAMD) (EPA, 2023). Observations for each variable are either at the unit level or at the unit and annual level. Unit operational characteristics and emissions control information was drawn from the EPA's CAMD dataset and from Form EIA-860, a survey submitted by plant owners containing data at the level of plant, generator, boiler and control technology; Form EIA-767, which contains information about environmental controls and monthly fuel use from 1995-2005; Form EIA-861, which provides characteristics of electric utilities; and Form EIA-923, which provides monthly fuel use and generation data for 2008 onwards.

A unit's regulatory status is determined through the status of its operator as a utility or non-utility entity in Form EIA-861. While form EIA-860 provides plant-level regulatory status starting in 2006 and gives service areas for non-utilities from 2001 onwards, no plant-level data on regulated status is available pre-2001. This study determines the plant operator's regulatory status based on EIA Form EIA-861, as the EIA only requires regulated utilities to complete and submit this form. The EIA defines regulated plants as "investor-owned electric utilities that are subject to rate regulation, municipal utilities, federal and state power authorities, and rural electric cooperatives" (EIA, 2021b). Nonregulated plants are defined as "qualifying cogenerators, qualifying small power producers, and other generators that are not subject to rate regulation, such as independent power producers" (EIA, 2021b). As a robustness check, this measure was compared against utility- or plant-level regulatory classifications available from 2001-2021 and over 97% were exact matches.

Unit-level variables include fuel type, nameplate capacity, and retirement date. Unit fuel type for each year was determined from the list of primary fuels listed in the EPA's CAMD dataset. Separate dummy variables for coal, natural gas, oil and "other" indicate whether a unit can run using that fuel during a given year. Nameplate capacity is also taken from the EPA data. For each unit, the nameplate capacity is the sum of the capacities of the unit's generators.

Table 1 provides information about the regulatory history of coal units over the period 1995-2021, focusing on all plants that did not have an FGD installed in 1995. Units are grouped based on whether they were always observed as regulated, always observed as non-regulated, were observed to change status from regulated to non-regulated, or were observed to change from non-regulated to regulated from 1995-2021. The table also summarizes the year of initial operations for units of each type. Table 1 suggests that across all coal-fired units, nameplate capacity varied substantially even among units with similar regulatory history. Units that were always non-regulated had substantially smaller nameplate capacities on average, about 142 MW, while all other unit types together had an average nameplate capacity of 284 MW.

The distributions of start-up years for units that were either always regulated or changed status from regulated to non-regulated were roughly similar, with most units built from 1940-1980. By comparison, most units that were always observed as non-regulated began operations in 1980-2000. This is consistent with the gradual opening of utility generation markets to non-regulated utilities starting with the passage of the Public Utilities Regulatory Policies Act in 1978. However, the non-negligible percentage of units that were always observed as nonregulated but built from 1940-1980 suggests that at least some of these non-regulated units may have been originally owned by regulated utilities, but sold to non-regulated utilities before 1995.

Table 1 suggests that out of units that did not have an FGD installed by 1995, 33% of units

that changed from regulated to nonregulated status installed an FGD by 2021, compared with 38% of always regulated units and 31% of always non-regulated units. Units that changed status from regulated to nonregulated were much more likely to stop reporting data in EPA's Clean Air Markets Program Data (CAMPD), with a 78% attrition rate relative to only a 53% attrition rate for always regulated units and 47% for always nonregulated units.

	Regulatory history (1995-2021)				
	Always RE	RE to NR	Always NR	NR to RE	Total
# unit-years	14,449	5,526	2,101	760	22,836
# units	663	255	132	31	1,081
# plants	252	98	61	14	425
# states	38	24	22	6	
# unit retirements	348	175	62	16	601
# units installing an FGD	255	84	41	8	388
# units under NSR consent decree	240	75	3	5	323
Mean unit namplate (MW)	283.7	278.7	142.3	331.4	266.6
	(255.7)	(244.9)	(226.8)	(282.8)	(254.7)
Start-up year					
1920-1939	0.5%	0.0%	1.6%	0.0%	0.5%
1940-1959	43.6%	50.6%	16.1%	35.5%	41.8%
1960-1979	39.7%	44.3%	18.5%	58.1%	38.9%
1980-1999	10.6%	4.7%	49.2%	6.5%	13.5%
2000-2019	5.7%	0.4%	14.5%	0.0%	5.3%

Table 1: Summary statistics for full sample of CAMPD coal-fired units. Includes all units that do not already have an FGD installed in 1995.

FGD-level variables include control start/end dates and expected SO_2 removal rates. The installation and retirement dates of FGDs were inferred from both EIA and EPA data as described in Appendix A. The rated SO_2 removal rate of an FGD was defined as the expected removal rate reported each year to the EIA, since this rate would necessarily correspond with the FGD system installed during the given year.

The monthly unit SO_2 emissions rate in pounds of SO_2 per mmBtu are estimated using Form EIA-923 data on coal heat content and sulfur content. First pounds of sulfur per mmBtu coal is calculated as percent sulfur per unit weight of fuel divided by heat content per unit weight of fuel. This value is then multiplied by two to estimate the SO_2 emissions rate per mmBtu assuming that all sulfur is converted to SO_2 by reacting with oxygen in the atmosphere.

Finally, data on whether units were regulated under federal NSR consent decree was drawn from the settlement agreements published by the EPA (EPA, 2024). The consent decrees list all units regulated under the settlement and provide detailed information about the updated permit requirements and emissions standards that those units must meet. Table 1 shows that in the full set of coal units, a greater proportion of always regulated units were under consent decree relative to those that changed from regulated to nonregulated.

3.2 Hourly Operational Data

After cleaning, the annual data on boiler and FGD characteristics from EIA forms were merged with hourly observations from the EPA's CAMPD to estimate the hourly SO_2 removal rate and

operating status of the FGD. This data included a separate set of annual characteristics at the unit level reported to the EPA as well as hourly CEMS data that included generation, heat input, and the mass of various pollutants including SO_2.

Table 2 provides information about 1995-2020 coal units that had an FGD installed, reported hourly emissions to the EPA Clean Air Markets Program, and submitted monthly fuel use data to the EIA. As in Table 1, mean values are calculated over units' aggregated measures from 1995-2020. Unit nameplate capacity varied widely both within and across historic patterns of utility ownership. On average, units that were always regulated from 1995-2020 were larger than units that were always non-regulated from 1995-2020, and units that changed status from regulated to non-regulated were larger than all other categories.

The average rated SO_2 removal rates of scrubbers were similar for all groups—about 90%—except units for that changed status from non-regulated to regulated, with scrubbers only rated to remove about 74% of SO_2 on average. Though the rated SO_2 removal rates of scrubbers were similar, units that changed regulatory type had scrubbers that were installed earlier on average than units that remained under the same type of owner throughout the time period. Finally, the total SO_2 emissions rate was highest for units sold from regulated to nonregulated utilities at 0.21 lbs of SO_2/mmBtu relative to only 0.17 lbs of SO_2/mmBtu for regulated units and 0.31 lbs of SO_2/mmBtu for nonregulated units.

Since a goal of this study is to infer FGD operating behavior, it was necessary to estimate the effective SO_2 removal rate of the scrubber each hour and then infer whether the scrubber was operating. While most coal plants have to report hourly emissions data to the EPA, they do not need to directly report the operating status of control equipment. Therefore, this study develops a methodology to characterize the performance of FGDs relative to their rated removal rates.

To estimate the hourly SO_2 removal rate $AR_{i,t}$ of the FGD at unit i in hour t, the estimated SO_2 emissions generated per mmBtu of coal combusted in month m ($C_{i,m}$) was treated as the expected emissions rate if no FGD was run on the unit. The proportion of SO_2 removed from the flue gases was then calculated from the measured hourly SO_2 emissions $E_{i,t}$ as

$$AR_{i,t} = \frac{C_{i,m} - E_{i,t}}{C_{i,m}} \tag{1}$$

FGD operating status was calculated for each hour by comparing the estimated proportion of SO_2 removed to the rated SO_2 removal rate of the scrubber reported annually to the EIA. Given the estimated SO_2 emissions rate from coal combustion $C_{i,m}$, an FGD with a rated SO_2 removal rate of RR_i and a measured hourly emissions rate of $E_{i,t}$ for unit i during hour t, FGD operating status $O_{i,t}$ was defined as

$$O_{i,t} = \begin{cases} 0 & E_{i,t} > 3 \times C_{i,m} \times \min(RR_i, 0.95) \\ 1 & \text{otherwise} \end{cases} \tag{2}$$

Based on the distributions of hourly emissions rates, it was rare for a unit to exceed this level of emissions after FGD installation except in cases where the data exhibited a bimodal distribution.

3.3 Empirical Setup

Equation 3 estimates the effect of regulatory status on likelihood of having an FGD installed in a given year for units that were and were not subject to a federal consent decree over NSR violations.

$$FGD_{iy} = \alpha + \beta_{NR} NR_{iy} + \beta_{CD} CD_{iy} + \beta_i NR_{iy} \times ActiveCD_{iy} + \gamma N_{iy} + u_{it} \tag{3}$$

Table 2: Summary statistics for coal units that had FGD units installed from 1995-2020. Statistics represent number of units by category, or the mean value across units

	Regulatory history (1995-2021)				
	Always RE	RE to NR	Always NR	NR to RE	Total
# units-years	250	5	94	3	352
# units	250	5	94	3	352
# plants	113	3	42	1	159
# states	22	2	12	1	37
# units that stop reporting	72	0	49	3	124
Mean unit nameplate (MW)	461.5	464.9	425.3	173.8	449.4
	(282.9)	(266.4)	(287.7)	(0.9)	(283.6)
Mean FGD installation year	2009	2009	2009	2006	2009
	(4.7)	(2.0)	(3.2)	(0.0)	(4.3)
Mean rated SO_2 removal rate	0.927	0.970	0.875	0.950	0.914
	(0.117)	(0.006)	(0.155)	(0.000)	(0.129)
Mean SO_2 production from fuel (lbs/mmBtu)	2.290	4.261	2.776	4.886	2.470
	(1.740)	(1.143)	(1.975)	(0.004)	(1.828)
Mean SO_2 stack emissions rate (lbs/mmBtu)	0.172	0.212	0.312	0.188	0.210
	(0.260)	(0.067)	(0.263)	(0.004)	(0.265)
Mean estimated SO_2 capture rate	0.914	0.955	0.843	0.966	0.896
	(0.157)	(0.006)	(0.216)	(0.001)	(0.176)
FGD type					
Wet scrubber	158	5	39	3	205
Dry scrubber	51	0	30	0	81
Injection-based scrubber	21	0	6	0	27
Other FGD type	7	0	4	0	11
New Source Performance Standard					
Not covered under NSPS.	151	3	60	3	217
1971 boiler standards	61	1	7	0	69
1978 boiler standards	24	1	10	0	35
1984 boiler standards	11	0	17	0	28

The dependent variable of the regression is the indicator of FGD installation FGD_{iy}, which was equal to 1 when an FGD was present at unit i in year y and 0 otherwise. The independent variables include unit regulatory status NR_{iy}, which is equal to 1 when unit i was nonregulated in year y and 0 otherwise, and CD_{it}, which is equal to 1 on the first day d that a unit was listed in a settlement agreement and for all days afterwards. Nameplate capacity in TW (N_i) of unit i is included as an additional regressor. The regression includes year fixed effects (δ_y) and state fixed effects (ζ_s) to control for time-invariant state policy and economic factors as well as annual changes in national average commodity prices and electricity demand. All standard errors are clustered at the power plant level. Appendix C.1 provides results for different levels of clustering.

Coefficient β_{NR} estimates the average difference between nonregulated units and regulated units absent a consent decree, while β_{CD} estimates the average difference between regulated units under consent decree compared with regulated units not under consent decree. Coefficient β_i represents the difference between the effect of a consent decree on nonregulated FGD installation relative to the effect on regulated units.

Equation 4 estimates the effects of regulatory status on overall SO_2 removal rate achieved by FGDs for units that were and were not regulated under NSR consent decree.

$$RR_{it} = \alpha + \beta_{NR}NR_i + \beta_{CD}CD_{id} + \beta_I NR_{iy} \times CD_{id} + \gamma N_{iy} + \delta_y + \zeta_s + \epsilon_d + \epsilon_h + \epsilon_m + \eta_a + u_{it} \tag{4}$$

Dependent variable RR_{it} represents the proportion of SO_2 removed from flue gases by the FGD at unit i in hour t, which is estimated in equation 1. NR_{iy} is still an annual variable indicating nonregulated status in year y, while CD_{id} indicates consent decree status at the daily level. Further, ζ_s represents state fixed effects, δ_y represents annual fixed effects, ϵ_d represents day-of-week fixed effects, ϵ_h represents time-of-day fixed effects (either 10 PM to 6 AM, 6 AM to 2 PM, or 2 PM to 10 PM), and ϵ_m represents season fixed effects. To control for scrubber age as a confounding variable, the regression includes fixed effects for the age of the FGD in years as η_a. Coefficient β represents the average difference in the proportion of SO_2 removed if a unit is nonregulated. β_{CD} estimates the effect of the consent decree on regulated units, and β_I represents the additional effect of a consent decree for nonregulated units.

Identification of the effect of economic regulation on FGD operation relies on within-state variation in regulatory status. This variation permits the inclusion of state-level fixed effects which account for state-level economic, regulatory, and political causes of FGD operation that are time-invariant. The appendix to this analysis includes additional robustness checks which run the FGD operation regressions on an expanded set of units (Appendix C.2) and include additional variables controlling for attainment status with the SO_2 National Ambient Air Quality Standards (Appendix C.3) and for the type of FGD installed (Appendix C.4).

To better understand the mechanism behind differences in FGD operation, we consider the differential effect of economic regulation and consent decree status on likelihood of FGD operation and SO_2 removal rate conditional on FGD operating status. To determine whether regulated units were more likely to operate their SO_2 controls than nonregulated units, equation 5 estimates a linear probability model regressing units' hourly FGD operating status on annual regulatory status.

$$O_{it} = \alpha + \beta_{NR}NR_{iy} + \beta_{CD}ActiveCD_{id} + \beta_I NR_{iy} \times ActiveCD_{id} + \gamma N_{iy} + u_{it} \tag{5}$$

The independent variables are defined as in equation 4, but the dependent variable O_{it} now represents the likelihood that the SO_2 emissions rate matches the expected removal rate of that

unit's FGD as defined in equation 2. Coefficient β_{NR} represents the effect of nonregulated status on the proportion of hours during which a scrubber was operational.

Equation 6 estimates the effect of nonregulated status on RRS_{it}, the SO_2 removal rate when the FGD is classified as operating by O_{it}:

$$RRS_{it} = \alpha + \beta_{NR} NR_{iy} + \beta_{CD} ActiveCD_{id} + \beta_I NR_{iy} \times ActiveCD_{id} + \gamma N_{iy} + u_{it} \tag{6}$$

Other than the change in dependent variable, this specification is the same as equation 5. Coefficient β_{NR} now represents the expected absolute change in the SO_2 removal rate if that unit was nonregulated.

3.4 Health Impacts

The health impacts of inconsistent operation of FGDs are estimated using the AP4 model (Dennin, 2023), an updated version of the Air Pollution Emission Experiments and Policy analysis model (APEEP) which estimates the effect of pollutant emissions on ambient PM2.5 concentrations and estimates the resulting health impacts (Muller & Mendelsohn, 2007). Baseline emissions data from point and area sources is taken from the National Emissions Inventory (NEI) produced by the EPA, which is then used to estimate baseline PM2.5 concentrations in U.S. counties. The concentrations and resulting health impacts of realized SO_2 emissions are compared against the counterfactual where units with FGDs installed emit the quantity of SO_2 expected based on the rated removal rate of the FGD. The difference in subsequent mortality represents the estimated effect of variable FGD operation on public health in the U.S. The effect is then estimated separately for regulated plants and for nonregulated plants to compare the relative impacts of emissions based on regulatory status. The health impacts of inconsistent FGD operation are estimated first for 2017 using the full NEI dataset, and then estimated for years 2008, 2011, and 2014 by updating the 2017 baseline with NEI estimates of electricity generating unit emissions specifically from each of these years.

4 Results

Results are reported here in four parts. First, we estimate the effect of rate-based regulation on FGD adoption employing annual unit-level data. Second, we examine the effect of regulated status on the overall SO_2 removal rate of FGDs using hourly unit-level emissions data. Third, we decompose the effect of regulated status on SO_2 removal rate into the effect on likelihood of FGD operation and on the average removal rate of the FGD conditional on operation, respectively. Fourth, we evaluate the health impacts of inconsistent FGD operation.

4.1 FGD Adoption

Table 3 reports results from the regression analyses examining whether or not plants subject to rate-of-return regulation were more or less likely to install FGD units. The overall conclusion from the six different specifications included in the table is that regulatory status does not influence firms' decisions regarding whether or not to install a scrubber. In all six models, the sign on the coefficient of interest is positive; but in all six the coefficient is insignificant. In column (1), the model includes only plants' regulatory status as an explanatory variable. The inclusion of nameplate capacity in column (2) does not change this result. Column (3) includes year fixed

effects and both state and year fixed effects are included in column (4). In all four columns the coefficient of interest is insignificant. The null result for the effect of nonregulated status on FGD installation runs counter to our intuition regarding how cost-of-service regulation would have distorted investment behavior pertaining to pollution control devices. These results also do not align with the central findings from Fowlie (2010), which is discussed further in the concluding remarks.

Columns (5) and (6) test whether FGD installation responded to NSR enforcement and how this response is mediated by economic regulation. Column (5) presents the same specification as column (4) but also includes an indicator equal to one in years after a unit was named under an NSR consent decree. While the coefficient on active consent decree is positive, which would suggest that units under a consent decree would be more likely to have an FGD installed, this coefficient is not significantly different from zero. Column (6) includes an additional interaction term that indicates whether a unit is both nonregulated and under an active consent decree in a given year. This coefficient is also positive but only weakly significant ($p < 0.1$). We therefore cannot conclude that regulated and nonregulated units have different rates of FGD installation after being subject to a consent decree.

Table 3: Likelihood of having an FGD installed in a given year by regulatory status.

	(1)	(2)	(3)	(4)	(5)	(6)
Nonregulated	0.0329	0.0505	−0.0154	−0.0214	−0.0168	−0.0410
	(0.0337)	(0.0315)	(0.0320)	(0.0361)	(0.0355)	(0.0351)
Nameplate (GW)		0.470***	0.370***	0.450***	0.443***	0.440***
		(0.0460)	(0.0442)	(0.0410)	(0.0414)	(0.0407)
Active Consent Decree					0.0774	0.0314
					(0.0426)	(0.0472)
Nonreg. x Active CD						0.178*
						(0.0834)
Average FE	0.194***	0.0508**	0.0968***	0.0746***	0.0660***	0.0733***
	(0.0161)	(0.0184)	(0.0188)	(0.0195)	(0.0198)	(0.0198)
Year FE			Y	Y	Y	Y
State FE				Y	Y	Y
Unit N	1081	1081	1081	1081	1081	1081
Obs.	22,836	22,836	22,836	22,836	22,836	22,836
Adjusted R^2	0.0012	0.0942	0.3192	0.4025	0.4055	0.4088

Notes: * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Regression results estimating the likelihood that a coal-fired generating unit has an FGD installed in a given year, given no FGD installed in 1995. Robust standard errors are given in parentheses, and are clustered at the power plant level.

4.2 Overall SO_2 Removal Rate

Table 4 reports the results from estimating equation 4 with hourly emissions data to test whether plant regulatory status affects the average SO_2 removal rate achieved by installed FGDs. While the models in columns (1) and (2) do not provide evidence of a relationship between the SO_2 removal rate and regulatory status, once state fixed effects are included in column (3), nonregulated status is negatively associated with the SO_2 removal rate. The coefficient in column (3) suggests that

FGD units installed at nonregulated plants remove an average of 11.1% less SO_2 than a comparable regulated plant in a given hour. The negative effect of nonregulated status on the SO_2 removal rate remains consistent (decreasing slightly to -11.2%) as year fixed effects are added in column (4) and as time-of-day, day-of-week, and season fixed effects are added in column (5). The specification in column (6) also controls for the age of the FGD to account for the possibility that scrubber use may vary systematically with the age of the FGD unit. For example, it may be the case that firms learn how to operate their FGD units more effectively over time. If this was the case, we would expect to see increased operation rates with age. In contrast, like other forms of physical capital, FGD units depreciate. This may induce lower rates of use as the units grow older. The results in column (6) suggests that nonregulated units with installed FGDs remove 9.94% less SO_2 in a given hour than regulated units. Thus, inclusion of FGD age fixed effects does not appreciably affect the coefficient of interest. The analysis in Appendix C.2 shows that this result is robust to the inclusion of plants with FGDs that were installed before 1995, and Appendix C.3 shows the result is robust to including 2010 SO_2 NAAQS attainment status. Appendix C.4 shows that this effect is primarily driven by differences in dry FGD performance between market types, though wet FGDs at nonregulated units also had lower removal rates on average. Table 4 supports the hypothesis that nonregulated units with FGDs installed achieve lower rates of SO_2 removal than regulated units.

This empirical difference in SO_2 removal contrasts with the much smaller difference of 5.2 percentage points between the rated SO_2 removal rate at regulated and nonregulated facilities. Appendix B shows that the difference is only 2.19 percentage points conditional on state, year and plant characteristics. The greater difference in actual removal rate must be attributable to either more frequent FGD underperformance or lower rates of operation at nonregulated units relative to regulated units. We explore this decomposition in Section 4.3.

Columns (7) and (8) of Table 4 consider the effect of regulatory status on the SO_2 removal rate, conditional on whether a unit was included in an NSR consent decree and therefore subject to more stringent environmental regulation. The coefficient on active consent decree in column (7) suggests that the units under NSR consent decree did not have significantly different removal rates from other units. Including the active consent decree indicator also has minimal effect on the magnitude or significance of the estimated effect of nonregulated status on SO_2 removal rate.

The results change substantially when we include an interaction term between the presence of an active consent decree and the plants' regulatory status in column (8). First, the estimated effect of nonregulated status becomes more negative, suggesting that the SO_2 removal rate achieved by nonregulated units not under consent decree is 13.9 percentage points lower than the rate achieved by regulated units not under consent decree. However, the presence of environmental regulation under NSPS considerably narrows the gap between regulated and nonregulated units. Specifically, the consent decree improves SO_2 removal rates achieved by a unit's FGD by 12.5 percentage points when that unit is nonregulated. In contrast, FGDs at regulated units perform similarly regardless of whether they are under consent decree.

Table 4: Effect of regulatory status on overall SO_2 removal rate.

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Nonregulated	−0.0405	−0.0395	−0.111***	−0.112***	−0.112***	−0.0994***	−0.0966***	−0.139***
	(0.0394)	(0.0310)	(0.0346)	(0.0346)	(0.0345)	(0.0327)	(0.0357)	(0.0350)
Nameplate (GW)		0.216***	0.177**	0.176**	0.176**	0.168***	0.171***	0.171***
		(0.0673)	(0.0701)	(0.0700)	(0.0700)	(0.0631)	(0.0630)	(0.0611)
Active Consent Decree							−0.0236	−0.0541
							(0.0329)	(0.0417)
Nonreg. x Active CD								0.125**
								(0.0605)
Average FE†	0.890***	0.783***	0.817***	0.818***	0.818***	0.819***	0.823***	0.832***
	(0.0191)	(0.0470)	(0.0409)	(0.0408)	(0.0408)	(0.0374)	(0.0355)	(0.0342)
State FE			Y	Y	Y	Y	Y	Y
Year FE				Y	Y	Y	Y	Y
Time FE‡					Y	Y	Y	Y
FGD Age FE						Y	Y	Y
Unit N	352	352	352	352	352	352		352
Obs.	16,416,209	16,416,209	16,416,209	16,416,209	16,416,209	16,416,209	16,416,209	16,416,209
Adjusted R^2	0.0064	0.0901	0.2695	0.2738	0.2741	0.3054	0.3068	0.3129

Notes: * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

† Average FE refers to the expected value of the sum of fixed effects for a given unit.

‡ Time FE is an index that includes fixed effects for time-of-day, day-of-week, and season.

Regression results estimating the proportion of SO2 emissions removed by the FGD in the given hour. Robust standard errors are given in parentheses, and are clustered at the power plant level.

These results support the hypothesis that stringent enforcement of environmental regulation has a strong positive effect on nonregulated units' SO_2 removal rates on average. We can gauge the effect of the consent decree by considering the expected SO_2 removal rate of a nonregulated unit with sample mean nameplate capacity (0.43 GW) relative to a regulated unit of the same size. While a regulated unit of this size without a consent decree would on average achieve an SO_2 removal rate of 89.0%, a nonregulated unit without a consent decree would only achieve an average SO_2 removal rate of 75.1%. However, nonregulated units of that size that *are* subject to a consent decree have an average SO_2 removal rate of 82.2%, which according to the Wald test is not significantly different from the average for a regulated unit without a consent decree. Thus, the consent decree effectively closes the gap in SO_2 removal between regulated and nonregulated plants.

4.3 Decomposing FGD Operation

This section decomposes the difference in removal rate between regulated and nonregulated units into the difference due to inconsistent FGD operation and difference due to removal rate, conditional on operating the FGDs. Panel A in Table 5 reports the results from the model in equation 5 that tests whether plants' regulatory status influences the frequency that installed FGDs are operated. Column (1), which includes only whether plants were subject to rate-of-return regulation as a control, indicates that, over 19 million plant-hour observations, we find no evidence of differential FGD use. Controlling for nameplate capacity in column (2) does not change this result. In column (3) we add state fixed effects. With this specification, nonregulated status is negatively associated with the operational frequency of the FGD unit. Specifically, in a given hour, a plant that is not subject to rate-of-return regulation is 16.0% ($p < 0.05$) less likely to run its scrubber than a regulated plant. Columns (4) and (5) add year fixed effects and then the full array of temporal fixed effects, respectively. In both specifications, nonregulated status exhibits a negative effect (16.1%) on whether the FGD unit is operational ($p < 0.05$). Column (6) indicates that inclusion of age fixed effects slightly diminishes the magnitude of the coefficient for nonregulated status (from 16.1% to 14.5%) but only slightly affects the statistical significance of the coefficient of interest. This result is robust when including units with FGDs installed pre-1995 as shown in Appendix C.2, and is also robust to the inclusion of 2010 SO_2 NAAQS attainment status as shown in Appendix C.3. Appendix C.4 shows that dry FGD performance drives the difference in likelihood of FGD operation between nonregulated and regulated units.

Employing the specification in column (6), the magnitude of the difference in FGD usage rates between regulated and nonregulated plants is large. For simplicity, if we assume a unit has average installed capacity (for plants in the sample the average is 0.43 GW), the specification in column (6) suggests that nonregulated plants operated their scrubbers 80 percent of the hours encompassed by the sample. An identically-sized plant in a regulated state would use their FGD unit 92 percent of its generating hours. More generally, a plant operating 365 days a year would operate its FGD unit an additional 46 days if it were owned by a regulated utility relative to if the plant were operating in a deregulated market.

Columns (7) and (8) in Panel A of Table 5 include the estimated effect of an active consent decree on likelihood of FGD operation in a given hour. Column (7) suggests that a consent decree alone does not have a statistically significant effect on the likelihood of FGD operation. Column (8) indicates that a consent decree significantly affects FGD operations at nonregulated plants. Such plants without a consent decree are 20% less likely to operate the FGD unit that a regulated plant not subject to a consent decree. In contrast, nonregulated plants that operate under a

consent decree operate the FGD units 15% more frequently in any given hour than a nonregulated plant without a consent decree. Returning to our earlier thought experiment, a 0.43 GW capacity regulated unit that was not under consent decree could be expected to operate 91.6% of hours on average, while on average a nonregulated unit not under consent decree would operate only 70.9% of the time. However, for regulated units under consent decree, the average rate of FGD operation would be 87.0%—no longer significantly different from the rate of FGD operation for regulated units. These results suggest that while NSR enforcement does not have a significant effect on likelihood of FGD operation for the average unit, there is a significant effect on FGD operation for nonregulated units specifically.

Panel B in Table 5 reports the results from the regression models characterized by equation 6 that test whether regulatory status systematically influences the SO_2 removal rate achieved by operational FGD units. Table 4 conducts this test for all hours during which the plant operates. Panel B only considers the difference in SO_2 removal rate achieved during hours when the FGD is operating.

Columns (1) and (2) of Table 5 suggest that there is no significant difference between the removal rates achieved by FGD units at regulated and nonregulated plants. However, once state fixed effects are included in the model in column (3), we find a significant relationship between regulatory status and the SO_2 removal rate. Nonregulated plants achieve a 6.2% lower removal rate ($p < 0.01$). This difference in removal rates is robust to the inclusion of year, temporal, and FGD unit age fixed effects. The difference is also present when expanding the vintage of FGD considered (see Appendix C.2) and including 2010 SO_2 NAAQS attainment status as a covariate (see Appendix C.3). The analysis in Appendix C.4 shows that the largest difference in FGD performance while the FGD is operating is between nonregulated and regulated dry FGDs, though the difference in wet FGD performance is still statistically significant. In columns (3) through (6) nameplate capacity is not significantly associated with the SO_2 removal rate. Using the fitted model in column (6) of panel B, a plant in a deregulated state would achieve an 87% SO_2 removal rate. In contrast, a plant subject to cost-of-service regulation would achieve an 92% removal rate.

The results in columns (7) and (8) suggest that after conditioning on FGD operating status, regulation under consent decree has a limited effect on SO_2 removal rate of the FGD. Column (7) shows that the average estimated effect of a consent decree on SO_2 removal rate while operating is negative, though it is marginally significant ($p < 0.10$). Including the consent decree indicator slightly decreases the magnitude of the estimated effect of nonregulated status on SO_2 removal rate when operating ($p < 0.05$). Column (8) allows for the effect of a consent decree to vary by economic regulation. Unlike Panel A and Table 4, an active consent decree does not appear to have a significantly different effect on the FGD removal rate at nonregulated units relative to regulated units. Further, for plants without a consent decree, the difference between nonregulated operating SO_2 removal rates relative to regulated units remains significant and negative.

Table 5: Effect of regulatory status on FGD operating status and SO_2 removal rate conditional on operating.

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Panel A: Scrubber Operating Status								
Nonregulated	−0.0663	−0.0654	−0.160**	−0.161**	−0.161**	−0.145**	−0.151**	−0.201***
	(0.0743)	(0.0652)	(0.0677)	(0.0666)	(0.0665)	(0.0641)	(0.0622)	(0.0685)
Nameplate (GW)		0.207**	0.221***	0.219***	0.219***	0.211***	0.204***	0.204***
		(0.102)	(0.0731)	(0.0726)	(0.0726)	(0.0655)	(0.0671)	(0.0657)
Active Consent Decree							0.0492	0.0133
							(0.0422)	(0.0500)
Nonreg. x Active CD								0.147**
								(0.0707)
Average FE†	0.931***	0.828***	0.842***	0.843***	0.843***	0.843***	0.836***	0.847***
	(0.0235)	(0.0655)	(0.0443)	(0.0442)	(0.0442)	(0.0407)	(0.0388)	(0.0361)
Obs.	16,416,209	16,416,209	16,416,209	16,416,209	16,416,209	16,416,209	16,416,209	16,416,209
Adjusted R^2	0.0096	0.0524	0.2687	0.2747	0.2749	0.2988	0.3023	0.3070
Panel B: Removal Rate, Only Scrubbed Hours								
Nonregulated	−0.0293	−0.0333	−0.0620***	−0.0597***	−0.0597***	−0.0572***	−0.0488**	−0.0662***
	(0.0220)	(0.0207)	(0.0190)	(0.0187)	(0.0187)	(0.0180)	(0.0206)	(0.0186)
Nameplate (GW)		0.107**	0.0490	0.0488	0.0487	0.0503	0.0541	0.0549
		(0.0446)	(0.0496)	(0.0494)	(0.0494)	(0.0485)	(0.0460)	(0.0451)
Active Consent Decree							−0.0373*	−0.0490*
							(0.0204)	(0.0271)
Nonreg. x Active CD								0.0485
								(0.0400)
Average FE†	0.930***	0.876***	0.911***	0.911***	0.911***	0.910***	0.915***	0.918***
	(0.00936)	(0.0273)	(0.0247)	(0.0245)	(0.0245)	(0.0241)	(0.0240)	(0.0243)
Obs.	15,056,744	15,056,744	15,056,744	15,056,744	15,056,744	15,056,744	15,056,744	15,056,744
Adjusted R^2	0.0084	0.0592	0.3843	0.3905	0.3910	0.3985	0.4077	0.4101
State FE			Y	Y	Y	Y	Y	Y
Year FE				Y	Y	Y	Y	Y
Time FE‡					Y	Y	Y	Y
FGD Age FE						Y	Y	Y
Unit N	350	350	350	350	350	350	350	350

Notes: * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

† Average FE refers to the expected value of the sum of fixed effects for a given unit.

‡ Time FE is an index that includes fixed effects for time-of-day, day-of-week, and season.

Regression results estimating the proportion of SO2 emissions removed by the FGD in the given hour. Robust standard errors are given in parentheses, and are clustered at the power plant level.

	2008	2011	2014	2017
Regulated				
Unit Count	46	85	104	104
Deaths	-185.6	252.5	572.8	-231.6
Damages (billion $)	-1.85	2.52	5.71	-2.31
Emissions (thousand tonnes)	-21.6	15.8	47.8	-10.0
Damage Rate (thousand $/tonne SO_2)	85.7	159	119	231
Nonregulated				
Unit Count	10	28	37	30
Deaths	178.6	1098.8	771.1	515.4
Damages (billion $)	1.78	11.0	7.69	5.14
Emissions (thousand tonnes)	12.4	76.1	56.4	38.1
Damage Rate (thousand $/tonne SO_2)	144	145	136	135

Table 6: Net damages associated with variable FGD operation from regulated and nonregulated units estimated using the AP4 model.

4.4 Health Impacts

We next turn to an analysis of the consequences that inconsistent FGD operation has on public health. Our focus lies on the formation of $PM_2.5$ due to emissions of SO_2 and the associated impact on premature mortality. Table 6 shows the estimated aggregate damages and associated health impacts of actual FGD operation relative to the counterfactual where FGDs operated at their rated removal rates. The modeling results indicate that inconsistent FGD performance at nonregulated units had a greater aggregate impact on public health than underperformance at regulated units.

This analysis centers on 2008, 2011, 2014, and 2017 because the USEPA publishes the NEI for these years which enables application of the AP4 model. In every year, excess SO_2 emissions, additional premature deaths and monetary damages are larger for nonregulated plants. In 2008 and 2017, FGDs at regulated plants exceeded their rated removal rates - hence damages are negative. For nonregulated plants, excess emissions induced between 200 and 1,100 premature deaths per year. Damages ranged between $200 million and $11 billion.

Table 6 indicates that the damage per tonne of SO_2 emissions associated with nonregulated units are greater in 2008 and 2014 and regulated units exhibited higher per-tonne damage in 2011 and 2017. Furthermore, there is more variability in the average damage per tonne across years at the regulated units. In fact, the per-tonne damages from nonregulated units are within a narrow range between $135 thousand and $145 thousand. This may reflect the fact that nonregulated units are more spatially concentrated than regulated units, and that the locations of regulated units with FGDs that perform differently from their rated removal rates are more variable over time.

Some of the differential public health impact of FGD underperformance reported in Table 6 may be due to the distribution of units across space. Figure 1 shows the effect of inconsistent FGD operation at regulated and nonregulated units across the U.S. on average annual PM2.5 concentrations. The results across all years suggest that inconsistent FGD operation at regulated units primarily impacted the midwest region of the U.S. while nonregulated unit underperformance impacted the mid-Atlantic region. The mid-Atlantic generally has greater exposed populations which may explain the difference in damages reported in Table 6.

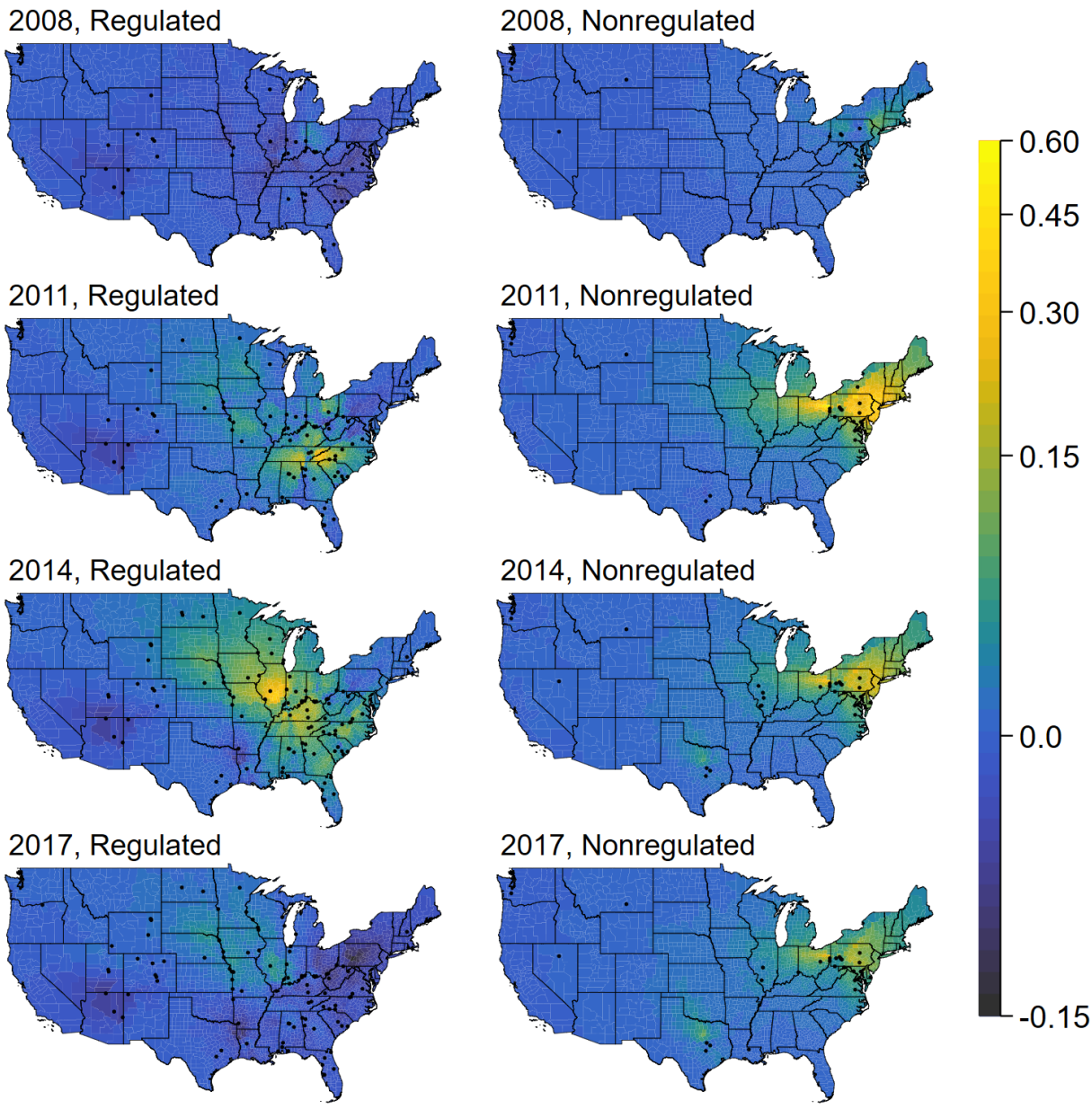


Figure 1: Effect of variable FGD operation on average annual PM2.5 concentrations ($\mu g/m^3$) for regulated and nonregulated units.

5 Conclusion

This analysis tests whether electricity market restructuring affected decisions to deploy and operate pollution control equipment in response to environmental policy. We consider the effects of regulatory status on both SO_2 control technology installation and operation. We use high frequency emissions data to analyze how environmental regulation impacts both the extensive and intensive margins of pollution control at fossil fuel-fired power plants. Based on both findings from prior research (Fowlie, 2010) and the incentives presented by rate-of-return regulation, we hypothesize that regulated plants would be more likely to install and use FGD units.

The empirical results only partially support this hypothesis. At the extensive margin, we find no difference in the likelihood of scrubber installation at plants owned and operated by regulated or deregulated firms. Despite the intuitive appeal of our initial hypothesis, and the results pertaining to NO_x control in Fowlie (2010), these results suggest that some combination of market forces and regulatory forces counteract any differential incentives for firms to invest in FGDs in regulated and deregulated settings.

While we do not find different patterns of investment in FGDs between regulated and nonregulated units, we do find significant differences in the operation of installed FGDs. We find that FGD units operated at regulated plants achieve an 8% to 10% greater SO_2 removal rate than plants in deregulated markets despite installed FGDs having similar rated removal rates on average.

When breaking down average SO_2 removal rate by whether a scrubber was operating consistently with its rated removal rate in a given hour, we found that regulated plants operate their scrubbers between 12% and 14% more frequently than plants in deregulated markets. For an average-sized plant in our sample, this amounts to a difference of over 40 days in a given year. Finally, regulated plants achieve a 5% higher removal rate, conditional on the scrubber being in use, than deregulated plants. These findings support the hypotheses that regulated units are more likely to operate their scrubbers consistently and effectively, since non-regulated units may be subject to greater pressure to reduce their marginal operating costs to generate financial returns in the wholesale electricity market.

We note here that the estimated cumulative social cost associated with the differential use and removal rates was substantial. Of 24.3 million tonnes of SO_2 emissions generated by coal plants with FGDs since 1995, 3.7 million—over 15%—were generated when the FGD was not operational. Plants not subject to cost-of-service regulation emitted 6.0 million tonnes of SO_2, of which 1.2 million tonnes (19%) were emitted when the FGD was not operating as anticipated by engineering estimates. Meanwhile, regulated plants emitted 18.3 million tonnes total, of which 2.6 million tonnes (14%) came from hours the FGD was not operating. Air quality modeling with AP4 estimates that the net impact of variable FGD operations on PM2.5 generation was associated with 1,350 deaths in 2011, with 1,100 of these deaths attributable to excessive emissions from nonregulated units.

We also consider how economic regulation interacts with the stringency of environmental regulation. When exploring the mechanism through which economic regulation acts on FGD operating behavior, we found that the SO_2 removal rate improved substantially for units owned by deregulated utilities when they were regulated under an NSR consent decree. Meanwhile, units owned by rate-of-return regulated utilities did not have substantially different SO_2 removal rates when a consent decree was in place despite the relatively stringent requirements of a consent decree. We further find that the difference in overall SO_2 removal rate by consent decree status may be better explained through the effect of NSR enforcement on the measure of FGD operating status. This may indicate that when nonregulated units with FGDs are regulated under relatively lax en-

vironmental regulations, they use the opportunity to reduce their marginal control costs through means which result in substantial short-term increases in hourly emissions rates beyond the level theoretically achievable by the installed controls.

Our results suggest that policies like electricity deregulation may have increased the importance of policies such as the New Source Performance Standards, which place strict limits on emissions and mandate control technology installation. Units in restructured markets may have installed SO_2 controls on the assumption that federal regulations would increase in stringency, making FGD installation a relatively attractive compliance option. However, as competition from natural gas increased and courts struck down an EPA proposal to lower the SO_2 markets emissions cap, units that did not benefit from cost recovery guarantees under a revenue requirement and did not face binding regulatory constraints may not have been able to justify the marginal costs required to achieve the maximum removal rate of installed FGDs. In this context, the relative inefficiency of environmental expenditures from rate-of-return utilities that continued achieving maximum removal rates even without binding environmental requirements may have compensated for inefficiencies in federal rule-making that delayed the measures necessary for firms to internalize the environmental externalities of SO_2 pollution.

We conclude by noting a policy relevant implication of this work that pertains directly to carbon capture and storage (CCS) technologies. CCS deployment, while currently incentivized by the Section 45Q tax credit, is not required at either coal or natural gas-fired plants. Hence, CCS use depends on a mix of market and policy forces and is, ultimately, left up to firms. If regulated firms are able to capitalize equipment and especially operating cost into their capital rate base, as is the case with FGD, one would anticipate significant differences in usage rates, relative to firms operating in deregulated markets. Therefore, if CCS is deployed by the fossil fuel-fired power generation fleet, insights from the present study may inform policymakers' *ex ante* analyses of deployment, use, and emission reductions from CCS, which are pertinent to the achievement of aggregate carbon dioxide (CO_2) reduction goals.

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Electricity Rate Structure and SO_2 Emissions at U.S. Coal Power Plants

March 20, 2025

Appendix A Data Description

A.1 Details on Processing Unit Characteristics

The EIA and EPA datasets were sometimes inconsistent regarding the retirement dates of coal-fired generators. The retirement date of the unit is not necessarily provided in the EPA data. However, the EIA-860 data do list the retirement dates of old generators and boilers. To infer unit retirement date, the EPA's unit-to-generator data was merged with the EIA-860's generator-to-boiler data, resulting in the list of boilers associated with each unit. The retirement date for a unit is then given as the retirement date of the last boiler still in operation within that unit, i.e. the date after which a unit has no boilers left in operation or standby.

A.2 Details on Processing FGD Characteristics

Information regarding control technologies was gathered from EPA's CAMD dataset as well as the EIA-767 and EIA-860. Forms included start and end dates either by FGD ID or, starting in 2013, by equipment type within each FGD ID.

To get an accurate account of the control technologies available at a plant, it was important to resolve ambiguity surrounding what technology was represented under the same FGD ID. While in some cases FGD equipment would be retired and replaced with a new FGD system with a new ID, other respondents used a single ID to describe both the old system and its replacement. To account for the latter possibility, each FGD was given up to two installation dates. The variable for control start date contained the latest installation date listed by the plant in any year. Then, for plants that had reported a much earlier start date in a previous form (¿5 years earlier), that earlier start date was stored as the "old" control start date to signify that the ID represented both a newer system and the older system it replaced.

Control retirement dates were treated similarly to start dates. For each observed FGD ID, the control retirement date corresponded to the latest listed retirement date where the FGD was never again listed as operating. In cases where the same FGD was either retired twice or was retired before returning to operating at a later date, the earlier retirement year would be stored in a second variable corresponding to the "old" control retirement year.

Appendix B Predicting Plant Features

B.1 Conditional Rated Removal Rate

Table B.1 below shows the results of estimating the rated SO_2 removal rate as a function of regulatory status and active consent decree. The results in columns (1), (2) and (3) correspond to the results from columns (6), (7) and (8) respectively in Table 4.

Nonregulated unit status is associated with a lower rated SO_2 removal rate across all specifications, but the magnitude of the difference is considerably smaller than that of operating SO_2 removal rate. There is also no significant difference in rated removal rate between units with and without a consent decree for either market type.

Table B.1: Effect of regulatory status on rated removal rate.

	(1)	(2)	(3)
Nonregulated	−0.0216**	−0.0192*	−0.0219**
	(0.0108)	(0.0116)	(0.0108)
Nameplate (GW)	0.0358	0.0385	0.0385
	(0.0388)	(0.0370)	(0.0369)
Active Consent Decree		−0.0201	−0.0220
		(0.0155)	(0.0217)
Nonregulated x Active Consent Decree			0.00781
			(0.0315)
Average FE†	0.911***	0.914***	0.915***
	(0.0183)	(0.0189)	(0.0202)
State FE	Y	Y	Y
Year FE	Y	Y	Y
Time FE‡	Y	Y	Y
FGD Age FE	Y	Y	Y
Unit N	352	352	352
Obs.	16,416,209	16,416,209	16,416,209
Adjusted R^2	0.4423	0.4479	0.4480

Notes: * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

† Average FE refers to the expected value of the sum of fixed effects for a given unit.

‡ Time FE is an index that includes fixed effects for time-of-day, day-of-week, and season.

Regression results estimating the rated removal rate of the FGD. Robust standard errors are given in parentheses, and are clustered at the power plant level.

Appendix C Regression Sensitivities

C.1 Alternate levels of clustering

The following regressions consider the effect of clustering on the results predicting FGD operation by both regulatory status and active NSR consent decree. Table C.1 shows the standard errors and associated significance of the estimates from column (6) in Table 4, which regressed actual SO_2 removal rate in a given hour on nonregulated status, showing that the estimate is significant at the $p = 0.01$ level using robust standard errors and clustering at either the unit, plant, or county level, but at the state level the estimate is no longer significant. Table C.2 replicates the results from column (6) in Table 5, showing that the difference between nonregulated and regulated units' likelihood of operating an FGD is significant at the $p = 0.05$ when clustering at levels up to the county level, but no longer significant with state level clustering. However, the difference in in-use SO_2 removal rate shown in panel B is significant even with state level clustering.

Tables C.3 and C.4 show alternate clustered standard errors for the regressions estimate FGD operation as a function of both regulatory status and consent decree status, and replicate results from columns (8) in Tables 4 and 5, respectively. Table C.3 shows that the effect of regulatory status on SO_2 removal rate remains significant at the $p < 0.01$ level when clustering at the unit, plant and county levels, and is still significant at the $p < 0.05$ level with state level clustering. Meanwhile, the effect of an active consent decree on regulated plants is only significant with robust standard errors ($p = 0.01$) and the unit level ($p = 0.05$), but not significant at higher levels of clustering. The effect of an active consent decree on nonregulated units however is significant at the $p < 0.05$ level for every level of clustering except the state level, where it is not significant.

In Table C.4, at the state level, the effect of nonregulated status on both FGD operating status and SO_2 removal rate while operating remains significant at the $p = 0.01$ level for clusters up to the county level, but at the state level the effect on in-use removal rate is significant instead at the $p = 0.05$ level and the effect on operating status is no longer significant. The effect of an active consent decree on scrubber operating status for regulated units only is significant using robust standard errors, while the effect on in-use removal rate is significant given both robust errors and unit-level clustering at the $p = 0.05$ level. Finally, the effect of an active consent decree on FGD operating status for nonregulated units is significant at the $p = 0.05$ level at all clustering levels except the state level, while the effect on in-use removal rate is only significant using robust standard errors.

Table C.1: Clustered standard errors regressing actual SO_2 removal rate on regulatory status and consent decree

	(1)	(2)	(3)	(4)	(5)
Clustering Level	None	Unit	Plant	County	State
Nonregulated	−0.0994***	−0.0994***	−0.0994***	−0.0994***	−0.0994*
	(0.000153)	(0.0207)	(0.0327)	(0.0358)	(0.0568)
Nameplate (GW)	0.168***	0.168***	0.168***	0.168***	0.168**
	(0.000256)	(0.0402)	(0.0631)	(0.0631)	(0.0642)
Average FE†	0.720***	0.720***	0.720***	0.720***	0.720***
	(0.000203)	(0.0297)	(0.0478)	(0.0497)	(0.0617)
FGD Age FE	Y	Y	Y	Y	Y
Time FE‡	Y	Y	Y	Y	Y
Year FE	Y	Y	Y	Y	Y
State FE	Y	Y	Y	Y	Y
Unit N	352	352	352	352	352
Obs.	16,416,209	16,416,209	16,416,209	16,416,209	16,416,209
Adjusted R^2	0.3054	0.3054	0.3054	0.3054	0.3054

Notes: * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

† Average FE refers to the expected value of the sum of fixed effects for a given unit.

‡ Time FE is an index that includes fixed effects for time-of-day, day-of-week, and season.

Regression results estimating the proportion of SO2 emissions removed by the FGD in the given hour. Robust standard errors are given in parentheses, and are clustered at the level indicated in the column name.

Table C.2: Regulatory status vs. in-practice SO_2 removal rate, clustering sensitivities

Clustering Level	(1) None	(2) Unit	(3) Plant	(4) County	(5) State
Panel A: Scrubber Operating Status					
Nonregulated	−0.145***	−0.145***	−0.145**	−0.145**	−0.145
	(0.000268)	(0.0424)	(0.0641)	(0.0676)	(0.119)
Nameplate (GW)	0.211***	0.211***	0.211***	0.211***	0.211**
	(0.000271)	(0.0404)	(0.0655)	(0.0656)	(0.0907)
Average FE†	0.699***	0.699***	0.699***	0.699***	0.699***
	(0.000303)	(0.0463)	(0.0745)	(0.0771)	(0.126)
Obs.	16,416,209	16,416,209	16,416,209	16,416,209	16,416,209
Adjusted R^2	0.2988	0.2988	0.2988	0.2988	0.2988
Panel B: Removal Rate, Only Scrubbed Hours					
Nonregulated	−0.0572***	−0.0572***	−0.0572***	−0.0572***	−0.0572**
	(0.0000919)	(0.0130)	(0.0180)	(0.0194)	(0.0262)
Nameplate (GW)	0.0503***	0.0503	0.0503	0.0503	0.0503
	(0.000208)	(0.0343)	(0.0485)	(0.0485)	(0.0464)
Average FE†	0.853***	0.853***	0.853***	0.853***	0.853***
	(0.000154)	(0.0239)	(0.0339)	(0.0345)	(0.0374)
Obs.	15,056,744	15,056,744	15,056,744	15,056,744	15,056,744
Adjusted R^2	0.3985	0.3985	0.3985	0.3985	0.3985
FGD Age FE	Y	Y	Y	Y	Y
Time FE‡	Y	Y	Y	Y	Y
Year FE	Y	Y	Y	Y	Y
State FE	Y	Y	Y	Y	Y
Unit N	350	350	350	350	350

Notes: * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

† Average FE refers to the expected value of the sum of fixed effects for a given unit.

‡ Time FE is an index that includes fixed effects for time-of-day, day-of-week, and season.

Regression results estimating the proportion of SO2 emissions removed by the FGD in the given hour. Robust standard errors are given in parentheses, and are clustered at the level indicated in the column name.

Table C.3: Clustered standard errors regressing actual SO_2 removal rate on regulatory status and consent decree

Clustering Level	(1) None	(2) Unit	(3) Plant	(4) County	(5) State
Nonregulated	−0.139***	−0.139***	−0.139***	−0.139***	−0.139**
	(0.000178)	(0.0239)	(0.0350)	(0.0356)	(0.0578)
Active Consent Decree	−0.0541***	−0.0541**	−0.0541	−0.0541	−0.0541
	(0.000192)	(0.0263)	(0.0417)	(0.0417)	(0.0527)
Nonregulated x Active Consent Decree	0.125***	0.125***	0.125**	0.125**	0.125
	(0.000317)	(0.0396)	(0.0605)	(0.0619)	(0.0775)
Nameplate (GW)	0.171***	0.171***	0.171***	0.171***	0.171***
	(0.000248)	(0.0382)	(0.0611)	(0.0612)	(0.0619)
Average FE†	0.832***	0.832***	0.832***	0.832***	0.832***
	(0.000142)	(0.0210)	(0.0342)	(0.0343)	(0.0275)
FGD Age FE	Y	Y	Y	Y	Y
Time FE‡	Y	Y	Y	Y	Y
Year FE	Y	Y	Y	Y	Y
State FE	Y	Y	Y	Y	Y
Unit N	352	352	352	352	352
Obs.	16,416,209	16,416,209	16,416,209	16,416,209	16,416,209
Adjusted R^2	0.3129	0.3129	0.3129	0.3129	0.3129

Notes: * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

† Average FE refers to the expected value of the sum of fixed effects for a given unit.

‡ Time FE is an index that includes fixed effects for time-of-day, day-of-week, and season.

Regression results estimating the proportion of SO2 emissions removed by the FGD in the given hour. Robust standard errors are given in parentheses, and are clustered at the level indicated in the column name.

Table C.4: Regulatory status vs. in-practice SO_2 removal rate, clustering sensitivities

Clustering Level	(1) None	(2) Unit	(3) Plant	(4) County	(5) State
Panel A: Scrubber Operating Status					
Nonregulated	−0.201***	−0.201***	−0.201***	−0.201***	−0.201
	(0.000322)	(0.0489)	(0.0685)	(0.0684)	(0.119)
Active Consent Decree	0.0133***	0.0133	0.0133	0.0133	0.0133
	(0.000215)	(0.0318)	(0.0500)	(0.0504)	(0.0700)
Nonregulated x Active Consent Decree	0.147***	0.147***	0.147**	0.147**	0.147
	(0.000404)	(0.0494)	(0.0707)	(0.0711)	(0.0969)
Nameplate (GW)	0.204***	0.204***	0.204***	0.204***	0.204**
	(0.000270)	(0.0394)	(0.0657)	(0.0660)	(0.0865)
Average FE†	0.847***	0.847***	0.847***	0.847***	0.847***
	(0.000152)	(0.0205)	(0.0361)	(0.0361)	(0.0300)
Obs.	16,416,209	16,416,209	16,416,209	16,416,209	16,416,209
Adjusted R^2	0.3070	0.3070	0.3070	0.3070	0.3070
Panel B: Removal Rate, Only Scrubbed Hours					
Nonregulated	−0.0662***	−0.0662***	−0.0662***	−0.0662***	−0.0662**
	(0.0000895)	(0.0121)	(0.0186)	(0.0192)	(0.0261)
Active Consent Decree	−0.0490***	−0.0490**	−0.0490*	−0.0490*	−0.0490
	(0.000135)	(0.0198)	(0.0271)	(0.0270)	(0.0380)
Nonregulated x Active Consent Decree	0.0485***	0.0485*	0.0485	0.0485	0.0485
	(0.000195)	(0.0287)	(0.0400)	(0.0416)	(0.0608)
Nameplate (GW)	0.0549***	0.0549*	0.0549	0.0549	0.0549
	(0.000197)	(0.0319)	(0.0451)	(0.0451)	(0.0424)
Average FE†	0.918***	0.918***	0.918***	0.918***	0.918***
	(0.000105)	(0.0172)	(0.0243)	(0.0244)	(0.0249)
Obs.	15,056,744	15,056,744	15,056,744	15,056,744	15,056,744
Adjusted R^2	0.4101	0.4101	0.4101	0.4101	0.4101
FGD Age FE	Y	Y	Y	Y	Y
Time FE‡	Y	Y	Y	Y	Y
Year FE	Y	Y	Y	Y	Y
State FE	Y	Y	Y	Y	Y
Unit N	350	350	350	350	350

Notes: * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

† Average FE refers to the expected value of the sum of fixed effects for a given unit.

‡ Time FE is an index that includes fixed effects for time-of-day, day-of-week, and season.

Regression results estimating the proportion of SO2 emissions removed by the FGD in the given hour. Robust standard errors are given in parentheses, and are clustered at the level indicated in the column name.

C.2 Operation regressions for all FGDs installed pre- and post-1995

This section assesses whether the patterns of FGD operation found in the main results are consistent for a wider universe of units installing FGDs before 1995 as well as after. The main results focus on the operating behavior of units with FGDs installed after 1995 since units installed pre-1990 a) may have different technological characteristics and b) were likely installed in response to a different set of policy requirements and the associated units may therefore exhibit different operating behaviors. Furthermore, nonregulated units with pre-1995 FGDs are much more likely to have changed regulatory status after the FGD was built, and these units may have different operational behaviors on average to units that both built and operated FGDs while nonregulated.

However, if the hypothesis that nonregulated units operate FGDs less consistently than regulated units holds due to differences in incentives, we might still expect to see differences between nonregulated and regulated FGD operation between units that built FGDs before 1995 as well as after. Firstly, we would still expect that nonregulated units remove less SO_2 on average than regulated units regardless of when the FGD was built. Secondly, we might expect that the likelihood of FGD operation in a given hour is still lower for nonregulated units than regulated units regardless of when the FGD was installed, since this behavior is less dependent on the characteristics of the installed FGD and more dependent on the relationship between economic incentives and prevailing environmental regulation in the hour of operation. Thirdly, we might expect that the difference in in-use SO_2 removal rate may be smaller in magnitude for units with pre-1995 FGDs, since these FGDs were likely installed while units were regulated regardless of subsequent regulatory status, and were likely installed under more stringent environmental standards such as NSPS that would have mandated these earlier installations. However, there may still be differences between operational SO_2 removal rate if nonregulated units with pre-1995 FGDs are more likely to operate their FGDs under nonstandard conditions.

The following regressions reproduce the results in columns (6) from Tables 4 and 5, represented by equation 1, with the entire universe of units that had FGDs installed and reported emissions to CAMPD.

$$[opvar]_{it} = \alpha + \beta_{NR} NR_i + \gamma N_{iy} + \delta_y + \zeta_s + \epsilon_d + \epsilon_h + \epsilon_m + \eta_a + u_{it} \tag{1}$$

For each variable describing FGD operation $[opvar]_{it}$, the regression above is run followed by additional specifications including an indicator equal to 1 when a unit's FGD was installed after 1995 both as a covariate and as an interaction with nonregulated status. The full set of units with FGDs has 583 units and 40,985,812 total observations.

Table C.5 below shows the regression results estimating overall SO_2 removal rate across all units. Column (1) shows the results estimating equation 1 on the set of all units with FGDs. The result indicates that nonregulated units still remove less SO_2 than regulated units in the full sample and that this difference is statistically significant at the $p = 0.05$ level. This difference is robust to including the indicator for FGD installation year in column (2). Column (3) breaks down the estimated difference in SO_2 removal rate between units with pre-1995 and post-1995 FGDs. The difference in SO_2 removal rate between regulated and nonregulated units with FGDs from before 1995 is about half of the magnitude of the difference for units with post-1995 FGDs, though these magnitudes are estimated with less precision (neither the coefficient for nonregulated status or nonregulated status $\times$ post-1995 FGD are statistically significantly different from 0).

Table C.6 shows the regression results estimating likelihood of FGD operation and in-use SO_2 removal rate as a function of regulatory status for all FGD units. Column (1) in Panel A indicates that nonregulated units have a lower likelihood of FGD operation and this difference

is both still significant at the $p = 0.05$ level and is similar in magnitude. This difference is robust to both including an indicator for post-1995 FGD installation as a covariate in column (2) and to interacting this indicator with regulatory status in column (3). The Panel A column (3) result in particular indicates that nonregulated units are 11.2 percentage points less likely to operate the installed FGD regardless of when that FGD was installed—the interaction term is both insignificant and small in magnitude relative to the coefficient on nonregulated status. This result is particularly interesting given that units that have pre-1995 FGDs had substantial time to identify discrepancies between the initial rated removal rate from manufacturer estimates and actual capabilities of the technology observed after installation.

For Panel B in Table C.6, column (1) shows that the result indicating nonregulated units with FGDs installed achieve higher SO_2 removal rates when expanding to the full sample of units with FGDs installed in any year. Column (2) shows both that this result is robust to including an indicator of FGD installation period as a covariate. Furthermore, the coefficient on the post-1995 FGD indicator in column (2) is not significantly different from zero ($p = 0.05$), meaning that in-use SO_2 removal rate of FGDs is not strongly correlated with the period in which the FGD was installed. Finally, column (3) shows that when interacting nonregulated status with the post-1995 FGD indicator, the coefficient on nonregulated status alone is both no longer statistically significant and is not meaningful in magnitude. Meanwhile the coefficient on nonregulated status for post-1995 FGD units only is both significant ($p = 0.01$) and similar in magnitude to the main result: column (3) indicates nonregulated units with FGDs built after 1995 have removal rates -5.42 percentage points lower than regulated units built after 1995 compared with the -5.72 percentage point difference from Table 5 column (6). This suggests that, while nonregulated units with pre-1995 FGDs have similar rates of FGD operation to those with post-1995 FGDs and that these rates are lower than regulated units with any vintage of FGD on average, the discrepancy in-use removal rate achieved by nonregulated and regulated units is only different for units with post-1995 FGDs. This is consistent with the fact that nonregulated units have slightly lower rated SO_2 removal rates on average (see Table B.1), and the rest of the difference may be explained by technological characteristics related to the technology at time of installation that either cause the baseline removal rate to deviate from that predicted by manufacturers or that impose different incentives or restrictions on operator behaviors that would effect the removal rate of the FGD while it operates.

Table C.5: Actual SO_2 removal rate by regulatory status, pre- and post-1995 FGDs

	(1)	(2)	(3)
Nonregulated	−0.0622**	−0.0659**	−0.0486
	(0.0247)	(0.0255)	(0.0298)
Nameplate (GW)	0.0876**	0.0860**	0.0889**
	(0.0345)	(0.0354)	(0.0355)
Post-1995 FGD		−0.0426	−0.0320
		(0.0359)	(0.0352)
Nonregulated × Post-1995 FGD			−0.0472
			(0.0461)
Average FE†	0.838***	0.856***	0.851***
	(0.0219)	(0.0324)	(0.0319)
State FE	Y	Y	Y
Year FE	Y	Y	Y
Time FE‡	Y	Y	Y
FGD Age FE	Y	Y	Y
Unit N	583	583	583
Obs.	40,985,812	40,985,812	40,985,812
Adjusted R^2	0.1491	0.1506	0.1520

Notes: * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

† Average FE refers to the expected value of the sum of fixed effects for a given unit.

‡ Time FE is an index that includes fixed effects for time-of-day, day-of-week, and season.

Regression results estimating the proportion of SO2 emissions removed by the FGD in the given hour. Robust standard errors are given in parentheses, and are clustered at the power plant level.

Table C.6: FGD operating status and in-practice SO_2 removal rate by regulatory status, pre- and post-1995 FGDs

	(1)	(2)	(3)
Panel A: Scrubber Operating Status			
Nonregulated	−0.106**	−0.109**	−0.112**
	(0.0414)	(0.0426)	(0.0492)
Nameplate (GW)	0.0756*	0.0744	0.0738
	(0.0447)	(0.0458)	(0.0461)
Post-1995 FGD		−0.0330	−0.0349
		(0.0500)	(0.0472)
Nonregulated × Post-1995 FGD			0.00848
			(0.0816)
Average FE†	0.918***	0.932***	0.933***
	(0.0275)	(0.0430)	(0.0418)
Obs.	40,985,812	40,985,812	40,985,812
Adjusted R^2	0.1523	0.1530	0.1530
Panel B: Removal Rate, Only Scrubbed Hours			
Nonregulated	−0.0210**	−0.0238**	0.000228
	(0.00919)	(0.00950)	(0.0110)
Nameplate (GW)	0.0287	0.0272	0.0317
	(0.0207)	(0.0209)	(0.0211)
Post-1995 FGD		−0.0263	−0.0126
		(0.0186)	(0.0175)
Nonregulated × Post-1995 FGD			−0.0668***
			(0.0236)
Average FE†	0.889***	0.901***	0.894***
	(0.0115)	(0.0147)	(0.0146)
Obs.	38,127,053	38,127,053	38,127,053
Adjusted R^2	0.3096	0.3116	0.3213
State FE	Y	Y	Y
Year FE	Y	Y	Y
Time FE‡	Y	Y	Y
FGD Age FE	Y	Y	Y
Unit N	581	581	581

Notes: * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

† Average FE refers to the expected value of the sum of fixed effects for a given unit.

‡ Time FE is an index that includes fixed effects for time-of-day, day-of-week, and season.

Regression results estimating the proportion of SO2 emissions removed by the FGD in the given hour. Robust standard errors are given in parentheses, and are clustered at the power plant level.

C.3 Regressions with NAAQS attainment status

This section considered the concern about whether the effect of regulated status on FGD operating status and on actual SO_2 removal rate might be biased by differential treatment under environmental regulations. For example, if regulated units were more likely to operate in states or counties that were targeted more strongly by ambient emissions standards, then they might be more greatly incentivized to utilize their scrubbers regardless of regulatory status. To test for this bias, the following sensitivity analysis includes both an indicator for county-level nonattainment status for each unit and an indicator equal to one when a unit's county or any neighboring county is in nonattainment with the 2010 SO_2 NAAQS. This regulatory change not only resulted in new non-attainment classifications for counties in violation of the air quality standard, but it is generally associated with stricter environmental regulation, part of which includes stricter regulation under the NSPS.

Table C.7 shows the results of the sensitivity analysis. Column (1) reproduces the regression results from column (6) in Table 4, while column (2) adds the indicator for location in a 2010 SO_2 NAAQS nonattainment county and column (3) adds an additional indicator for location in or neighboring a nonattainment county. The column (2) estimates indicate that county nonattainment status is associated with higher rates of SO_2 removal on average. Furthermore, including nonattainment status as a covariate does not affect the significance or sign of the coefficient for nonregulated status, and actually increases the magnitude of the effect.

Column (4) in Table C.7 recreates column (8) in Table 4, while column (5) adds the indicator for unit county 2010 SO_2 NAAQS nonattainment status and column (6) adds an additional indicator for unit location in or neighboring a nonattainment county. While the coefficient on 2010 SO_2 NAAQS nonattainment status is still positive, it is no longer significant, which may indicate that including consent decree status absorbs part of the NAAQS nonattainment effect. This explanation is consistent with the statutory relationship between NAAQS nonattainment and stricter standards for facilities regulated under NSPS. Furthermore, we find that the coefficient on nonregulated status is still negative, significant, and similar in magnitude across all specifications while the coefficient on nonregulated status interacted with the active consent decree indicator remains positive and significant.

Table C.8 shows the same set of regressions with scrubber operating status and in-use removal rate as the dependent variables. Column (1) reproduces the results from column (6) of Table 5 and column (4) reproduces the results from column (8) of Table 5. Once again, the magnitude, direction and significance of the main results are not affected by the inclusion of nonattainment status in any specification.

Table C.7: Actual SO_2 removal rate by regulatory status, consent decree status and 2010 SO_2 NAAQS attainment status

	(1)	(2)	(3)	(4)	(5)	(6)
Nonregulated	−0.0994***	−0.118***	−0.118***	−0.139***	−0.152***	−0.151***
	(0.0207)	(0.0233)	(0.0234)	(0.0239)	(0.0282)	(0.0284)
Nameplate (GW)	0.168***	0.175***	0.175***	0.171***	0.180***	0.180***
	(0.0402)	(0.0432)	(0.0433)	(0.0382)	(0.0408)	(0.0410)
2010 SO_2 NAAQS Nonattainment		0.0306**	0.0323		0.0245*	0.0322
		(0.0135)	(0.0227)		(0.0136)	(0.0229)
Adjacent to SO_2 Nonattainment			−0.00209			−0.00904
			(0.0259)			(0.0247)
Active Consent Decree				−0.0541**	−0.0643**	−0.0649**
				(0.0263)	(0.0288)	(0.0287)
Nonregulated x Active Consent Decree				0.125***	0.116***	0.116***
				(0.0396)	(0.0422)	(0.0422)
Average FE†	0.819***	0.818***	0.818***	0.832***	0.832***	0.833***
	(0.0212)	(0.0224)	(0.0222)	(0.0210)	(0.0223)	(0.0221)
State FE	Y	Y	Y	Y	Y	Y
Year FE	Y	Y	Y	Y	Y	Y
Time FE‡	Y	Y	Y	Y	Y	Y
FGD Age FE						
Unit N	352	352	352	352	352	352
Obs.	16,416,209	16,416,209	16,416,209	16,416,209	16,416,209	16,416,209
Adjusted R^2	0.3054	0.2750	0.2750	0.3129	0.2836	0.2837

Notes: * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

† Average FE refers to the expected value of the sum of fixed effects for a given unit.

‡ Time FE is an index that includes fixed effects for time-of-day, day-of-week, and season.

Regression results estimating the proportion of SO2 emissions removed by the FGD in the given hour. Robust standard errors are given in parentheses, and are clustered at the power plant level.

Table C.8: FGD operating status and in-practice SO_2 removal rate by regulatory status, consent decree status and 2010 SO_2 NAAQS attainment status

	(1)	(2)	(3)	(4)	(5)	(6)
Panel A: Scrubber Operating Status						
Nonregulated	−0.145***	−0.169***	−0.168***	−0.201***	−0.216***	−0.215***
	(0.0424)	(0.0477)	(0.0480)	(0.0489)	(0.0550)	(0.0556)
Nameplate (GW)	0.211***	0.218***	0.218***	0.204***	0.214***	0.214***
	(0.0404)	(0.0427)	(0.0428)	(0.0394)	(0.0422)	(0.0423)
2010 SO_2 NAAQS Nonattainment		0.0451**	0.0713**		0.0214	0.0441
		(0.0190)	(0.0356)		(0.0159)	(0.0358)
Adjacent to SO_2 Nonattainment			−0.0312			−0.0266
			(0.0364)			(0.0370)
Active Consent Decree				0.0133	0.00123	−0.000602
				(0.0318)	(0.0331)	(0.0331)
Nonregulated x Active Consent Decree				0.147***	0.136***	0.136***
				(0.0494)	(0.0507)	(0.0509)
Average FE†	0.843***	0.842***	0.844***	0.847***	0.848***	0.850***
	(0.0211)	(0.0219)	(0.0218)	(0.0205)	(0.0210)	(0.0207)
Obs.	16,416,209	16,416,209	16,416,209	16,416,209	16,416,209	16,416,209
Adjusted R^2	0.2988	0.2759	0.2765	0.3070	0.2814	0.2818
Panel B: Removal Rate, Only Scrubbed Hours						
Nonregulated	−0.0572***	−0.0646***	−0.0647***	−0.0662***	−0.0697***	−0.0696***
	(0.0130)	(0.0135)	(0.0136)	(0.0121)	(0.0127)	(0.0127)
Nameplate (GW)	0.0503	0.0483	0.0482	0.0549*	0.0532*	0.0532
	(0.0343)	(0.0349)	(0.0349)	(0.0319)	(0.0322)	(0.0324)
2010 SO_2 NAAQS Nonattainment		0.0240**	0.0201		0.0284***	0.0305
		(0.00944)	(0.0206)		(0.0103)	(0.0206)
Adjacent to SO_2 Nonattainment			0.00468			−0.00238
			(0.0238)			(0.0225)
Active Consent Decree				−0.0490**	−0.0512**	−0.0514**
				(0.0198)	(0.0205)	(0.0204)
Nonregulated x Active Consent Decree				0.0485*	0.0386	0.0386
				(0.0287)	(0.0277)	(0.0277)
Average FE†	0.910***	0.911***	0.911***	0.918***	0.919***	0.919***
	(0.0171)	(0.0173)	(0.0168)	(0.0172)	(0.0174)	(0.0170)
Obs.	15,056,744	15,056,744	15,056,744	15,056,744	15,056,744	15,056,744
Adjusted R^2	0.3985	0.3925	0.3926	0.4101	0.4058	0.4058
State FE	Y	Y	Y	Y	Y	Y
Year FE	Y	Y	Y	Y	Y	Y
Time FE‡	Y	Y	Y	Y	Y	Y
FGD Age FE						
Unit N	350	350	350	350	350	350

Notes: * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

† Average FE refers to the expected value of the sum of fixed effects for a given unit.

‡ Time FE is an index that includes fixed effects for time-of-day, day-of-week, and season.

Regression results estimating the proportion of SO2 emissions removed by the FGD in the given hour. Robust standard errors are given in parentheses, and are clustered at the power plant level.

C.4 Regressions controlling for FGD type

The following analysis estimates the effect of regulated status on unit FGD operating decisions with type of FGD as a covariate and considers the effect of regulated status by FGD type. One difficulty of this analysis is that of 89 nonregulated units spread across 45 nonregulated power plants, fewer than nonregulated 30 plants had FGDs installed of each type, which limits statistical inference under the assumption of correlated error at the plant level. However, given this caveat, this section attempts to provide a preliminary sense of how the operational differences observed in the main results are distributed across FGD types.

Table C.9 shows the results of regressing actual hourly SO_2 removal rate on regulatory status, with column (1) reproducing the result from column (6) in Table 4. Column (2) adds FGD type as a covariate, and we see that while nonregulated units still have a lower removal rate on average than regulated units, this difference is no longer significant. One explanation could be the fact that FGD type is correlated with regulatory status—Table 3 showed that a much higher proportion of nonregulated units had dry FGDs installed relative to regulated units. The coefficient on the dry FGD indicator is significant ($p = 0.01$) and negative, and may be absorbing some of the effect of regulatory type if the distribution of dry FGDs amongst nonregulated units is correlated with unit decisionmaking affecting operational removal rate. Column (3) shows that when decomposing the effect of regulatory status across types of FGD installed, the coefficient on nonregulated status indicates that nonregulated units with wet FGDs achieve lower removal rates by 5.08 percentage points on average, but the relationship between regulated status and wet FGD performance is weak (significant at the $p = 0.1$ level). Meanwhile, the estimated effect of regulated status on dry FGD performance suggests nonregulated units underperform regulated dry FGD removal rates by 12.6 percentage points, which is significantly with $p = 0.05$.

Tables C.10 and C.11 show the results when decomposing the effects seen in column (6) of Table 5 of regulatory status on likelihood of FGD operation (reproduced in column (1) of Table C.10) and SO_2 removal rate conditional on FGD operation (reproduced in column (1) of Table C.11) by type of FGD. In column (2) of both Table C.10 and Table C.11, we see that the effect of nonregulated status is no longer significant when including type of FGD as a covariate, and may again indicate that type of FGD installed is differently correlated with unit decisions around FGD operation between regulated and nonregulated units. When decomposing the effect of nonregulated status by FGD type on likelihood of FGD operation in column (3) of Table C.10, the coefficient on nonregulated status is still negative but is not significant, while the total effect of nonregulated status on dry FGD operation is -23.2 percentage points relative to regulated dry FGD units. Regarding SO_2 removal rate contingent on FGD operation, column (3) in Table C.11 shows that nonregulated units with wet FGDs and dry FGDs do remove significantly more SO_2 on average than regulated units with wet FGDs and dry FGDs, respectively.

Table C.9: Actual SO_2 removal rate by regulatory status and FGD type

	(1)	(2)	(3)
Nonregulated	−0.0994***	−0.0330	−0.0508*
	(0.0327)	(0.0310)	(0.0266)
Nameplate (GW)	0.168***	0.0946***	0.0810**
	(0.0631)	(0.0308)	(0.0333)
Dry FGD		−0.118***	−0.110***
		(0.0209)	(0.0272)
Injection FGD		−0.238***	−0.334***
		(0.0491)	(0.0780)
Other FGD		−0.324***	−0.416***
		(0.0799)	(0.127)
Nonregulated × Dry FGD			−0.0753
			(0.0556)
Nonregulated × Injection FGD			0.250***
			(0.0885)
Nonregulated × Other FGD			0.345**
			(0.141)
Average FE†	0.819***	0.903***	0.915***
	(0.0374)	(0.0170)	(0.0186)
State FE	Y	Y	Y
Year FE	Y	Y	Y
Time FE‡	Y	Y	Y
FGD Age FE	Y		Y
Unit N	352	352	352
Obs.	16,416,209	16,416,209	16,416,209
Adjusted R^2	0.3054	0.4212	0.4570

Notes: * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

† Average FE refers to the expected value of the sum of fixed effects for a given unit.

‡ Time FE is an index that includes fixed effects for time-of-day, day-of-week, and season.

Regression results estimating the proportion of SO2 emissions removed by the FGD in the given hour. Robust standard errors are given in parentheses, and are clustered at the power plant level.

Table C.10: FGD operating status by regulatory status and FGD type

	(1)	(2)	(3)
Nonregulated	−0.145**	−0.0820	−0.0645
	(0.0641)	(0.0601)	(0.0413)
Nameplate (GW)	0.211***	0.148***	0.132***
	(0.0655)	(0.0472)	(0.0435)
Dry FGD		−0.159***	−0.124***
		(0.0451)	(0.0438)
Injection FGD		−0.0591	−0.0931
		(0.0413)	(0.0565)
Other FGD		−0.253*	−0.337**
		(0.135)	(0.157)
Nonregulated × Dry FGD			−0.167
			(0.114)
Nonregulated × Injection FGD			0.103
			(0.0628)
Nonregulated × Other FGD			0.293*
			(0.169)
Average FE†	0.843***	0.919***	0.924***
	(0.0407)	(0.0249)	(0.0229)
State FE	Y	Y	Y
Year FE	Y	Y	Y
Time FE‡	Y	Y	Y
FGD Age FE	Y	Y	Y
Unit N	352	352	352
Obs.	16,416,209	16,416,209	16,416,209
Adjusted R^2	0.2988	0.3399	0.3568

Notes: * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

† Average FE refers to the expected value of the sum of fixed effects for a given unit.

‡ Time FE is an index that includes fixed effects for time-of-day, day-of-week, and season.

Regression results estimating the probability of a scrubber being turned on in a given hour. Robust standard errors are given in parentheses, and are clustered at the power plant level.

Table C.11: SO_2 removal rate (scrubbed hours only) by regulatory status and FGD type

	(1)	(2)	(3)
Nonregulated	−0.0572***	−0.0191	−0.0364**
	(0.0180)	(0.0153)	(0.0143)
Nameplate (GW)	0.0503	0.0204	0.0178
	(0.0485)	(0.0229)	(0.0232)
Dry FGD		−0.0531***	−0.0639**
		(0.0204)	(0.0262)
Injection FGD		−0.238***	−0.350***
		(0.0497)	(0.0790)
Other FGD		−0.129**	−0.174**
		(0.0526)	(0.0876)
Nonregulated × Dry FGD			−0.0135
			(0.0339)
Nonregulated × Injection FGD			0.270***
			(0.0907)
Nonregulated × Other FGD			0.130
			(0.0997)
Average FE†	0.910***	0.948***	0.955***
	(0.0241)	(0.0141)	(0.0151)
State FE	Y	Y	Y
Year FE	Y	Y	Y
Time FE‡	Y	Y	Y
FGD Age FE	Y		Y
Unit N	350	350	350
Obs.	15,056,744	15,056,744	15,056,744
Adjusted R^2	0.3985	0.5374	0.5845

Notes: * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

† Average FE refers to the expected value of the sum of fixed effects for a given unit.

‡ Time FE is an index that includes fixed effects for time-of-day, day-of-week, and season.

Regression results estimating the proportion of SO2 emissions removed by the FGD in the given hour. Robust standard errors are given in parentheses, and are clustered at the power plant level.