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# Adoption of SO<sub>2</sub> Emission Control Technologies - An Application of Survival Analysis

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## **Abstract**

Using data on coal-fired electric power plants, this article investigates the contributing factors affecting the investment decisions on flue-gas desulfurization (FGD), a capital-intensive emission control technology. The paper makes two contributions to the literature. First, our results show that the public regulatory status of electric power plants has a strong influence on whether FGD investment is made. Compared to deregulated power plants, those that are still under rate-of-return regulations by Public Utility Commissions are more likely to install FGD. Second, a higher rate of inspections of polluting facilities (not just electric utility power plants) in a state in the previous year is associated with a higher probability of power plants adopting FGD this year. In addition, sulfur content of coal and plant size are both positively associated with the likelihood of FGD installation. The service length of boilers is negatively associated with the likelihood.

key words: Flue-gas desulfurization, Coal-fired electric power plants, Survival analysis, Environmental regulations

# 1 Introduction

A large share of air pollution in the US is generated in the energy sector, especially by fossil-fired electric power plants. According to a 2012 report by the Environmental Protection Agency (EPA), about two thirds of all  $\text{SO}_2$  and one quarter of all  $\text{NO}_x$  come from coal-fired electric power plants. The most important piece of environmental regulation on  $\text{SO}_2$  emissions has been the Acid Rain Program, established by Title IV of the 1990 Clean Air Act Amendments to address the issue of acid rain caused by emissions. The primary goal of the Acid Rain Program is to reduce annual  $\text{SO}_2$  emissions to 10 million tons below 1980 levels, mainly via emission monitoring and compliance enforcement. To monitor emissions, all plants regulated by the Acid Rain Program installed Continuous Emission Monitoring systems and report emissions to the EPA every quarter. Enforcement, on the other hand, is performed by the delegated state and local environmental agencies, which report to Environmental Protection Agency's Air Facility System.

Power plants have a number of ways to reach compliance: installing flue-gas desulfurization (FGD, also called scrubbers), switching to low-sulfur coal or natural gas, or adopting renewable energy. For an established electric power plant, it's not always easy to switch from coal to natural gas. For new power plants, the options of using renewable energy are predetermined by location and the availability of renewable energy sources such as solar and wind. For all these reasons, FGD stands as a relatively practical option to reduce emission.

In the 1990s and 2000s, emissions of sulfur dioxide and nitrogen oxides declined continuously<sup>1</sup>. The achievement was most noticeable in the electric power sector,

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<sup>1</sup>On the contrary, greenhouse gas emissions from electricity have increased by about 11% since

where total SO<sub>2</sub> emissions decreased from close to 16 million short tons in 1990, to 11 million short tons in 2000, to under 4 million short tons in 2012. The US Energy Information Administration (EIA) attributes such attainment to the increasing number of coal-fired units retrofitted with FGD, among a few other reasons.

FGD is a type of control device that removes SO<sub>2</sub> emissions from large electric coal-fired utility boilers<sup>2</sup>. Traditional FGD systems use an alkaline reagent to produce a solid compound to enhance the absorption of acid gases (EPA-APTI, 2014). Though effective – the reduction efficiency is between 50% and 98% – FGD involves substantial capital cost and the operation and maintenance costs. According to EIA (2003), the capital cost for a wet scrubber installed on unit size greater than 400 MW was between 100 and 250 dollars per kW in 2001. The operation and maintenance costs were about 2-8 dollars per kW. The capital cost increased substantially throughout the 2000s. The wet FGD capital cost for a 500 MW unit retrofit during 2004-2006 increased from \$342 to \$407 per kW, meaning the average capital cost for a 500 MW unit is about 187 million US dollars (Cichanowicz, 2010). FGD is an important technology in reducing SO<sub>2</sub> emissions, and yet, its installation and maintenance impose a substantial financial burden on power plants. Their decision to adopt is hardly a trivial one. It is important, as well as interesting, to understand the leading factors affecting coal-fired electric power plants' decisions on adopting this device. Among others, we are particularly interested in the impact of policy variables such as electric utility industry restructuring and environmental regulations.

Using data between 2002 and 2012, this paper applies survival analysis framework to estimate the effects of environmental regulations and electricity market restructur-

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1990, and accounted for 32% of US total greenhouse gas emissions in 2012 (EIA, 2013).

<sup>2</sup>FGD systems are also used in process plants such as refineries, and pulp and paper mills.

ing as well as firm size, fuel costs, quality of coal, on the likelihood of FGD installation. The estimation unit is boiler. A total of 327 coal-fired power plants and their 917 boilers are included in the sample. The study makes two contributions to the literature. First, we show that electricity market restructuring is strongly associated with the power plants' adoption of FGD. Although plenty of research has been written about the influence of electricity market restructuring on power plants, none of them directly estimates the relationship between restructuring and FGD installation. We find that still-regulated power plants are much more likely to install the emission control device compared to their deregulated counterparts. Second, the environmental regulatory stringency has a strong impact on power plants' propensity to install FGD. Inspections by state and local agencies, whether carried out in the electric utility industry or not, have a strong influence on FGD adoption by power plants. A one percentage point increase in the state-level inspection rate of all polluters in the previous year increases the probability of FGD installation this year by about 1.3-2.7%. Additionally, the empirical results find a strong positive influence of plant size on the propensity to invest in this emission control technology. Boiler age, on the other hand, is negative associated with the technology adoption.

The paper is organized as follows. Section two provides background information on the literature and relevant regulations. Section three outlines the empirical model. Section four describes the data and summary statistics. Section five presents the empirical results. Section six contains our conclusions.

## 2 Literature and Regulatory Background

Closely related to this paper are two strands of research, focusing on restructuring of the electric utility industry and environmental protection regulations respectively.

### Restructuring of the electric utility industry

In the US, restructuring of the electric utility industry mainly took the form of deregulation in terms of ownership, rate-making, cost recovery, and entry of new competitors into the market. The restructuring movement was not nationwide in that, to this day, fifteen states have restructured their electricity industry, twenty seven states are still regulated, and the rest have once started but then suspended restructuring. Even in states that undertook the reform, restructuring does not mean complete deregulation, as the government continues to regulate some services of the industry.

In still-regulated states, utilities continue to be able to seek the recovery of prudently incurred operating costs from Public Utility Commissions (PUCs) and receive rate-of-return on capital investments. In contrast, utilities in states that completed restructuring can no longer resort to such cost recovery. For a more detailed discussion of the regulatory history of electricity market restructuring, refer to White (1996), Joskow (1997), EIA (2000), Wolfram (2005), and EPA (2011).

Most studies in this field examine the impact of rate-or-return regulations or deregulations on two things: cost savings and the pricing of electricity output. First, deregulated power plants appear to be more capable of cutting expenses on labor, fuel, and operations. Fuel efficiency at plants following restructuring improved by

about 2% during the sample period of 1997-2003 (Bushnell and Wolfram, 2005). Power plants in restructured states reduced labor and non-fuel expenses by roughly 5% or more relative to plants unaffected by restructuring incentives (Markiewicz, Rose, and Wolfram, 2004; Wolfram, 2005). Procurement cost of coal input drops by 12% at deregulated plants relative to matched plants that were not subject to any regulatory change (Cicala, 2013). Other studies contributing to the impact on cost savings include Rose and Joskow (1990), Newbery and Pollitt (1996), Joskow (1997), and Bellas and Lange (2008). Second, the electricity output price tends to be higher in regulated states than that in deregulated ones, and new entrants can consistently underprice the projects proposed by regulated power plants (White, 1996). The higher rates were attributed to historical reasons that regulators forced utilities to purchase power from high-cost independent suppliers under the Public Utilities Regulatory Policy Act of 1978, as well as the industry's expensive foray into nuclear power.

So far, no research has directly measured the relationship between regulatory status and the installation of capital-intensive emission control devices like FGD<sup>3</sup>. Whether such relationship is positive or negative is unknown a priori. On one hand, regulated power plants may be more inclined to install FGD because (i) rate-of-return regulations incentivize plants to expand their capital stock (the "Averch-Joshson effect"); and (ii) regulated units may be able to recover the investment cost of emission control device, if the investment is deemed prudent by the local PUC. On the other hand, regulated power plants may be less likely to install FGD because in regulated states, PUCs require power plants to obtain pre-approvals prior to installation of con-

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<sup>3</sup>With one exception, Cicala (2013), which touched on sulfur compliance strategy by regulated and deregulated power plants. The main results of Cicala (2013) show the effect of deregulation on fuel procurement price and import status, both of which are convincing. However, for FGD adoption, his results are unsatisfactory with  $R^2$  as low as 0.017.



trol technologies. As shown in Figure (7.1), regulated power plants generally resort to pre-approvals (more frequently) or periodic rate adjustments when seeking cost recovery. Such pre-approvals create hurdles for regulated power plants, in that they are time-consuming with average length exceeding seven months. The uncertainty may lead to utilities be denied a loan or be required to pay a higher interest rate. In contrast, deregulated units would be able to begin installation of control equipment more quickly (PUC, 2011). This paper will test whether the electricity market restructuring is positively or negatively associated with FGD installation.

### Environmental Regulations

Environmental protection was not always a pressing issue in the United States. A series of events in the 1960s, including the publication of *Silent Spring* in 1962, the *National Wild and Scenic River Act* in 1968, and the Cuyahoga River fire in 1969 caused by oily waste and industrial pollution, heightened the awareness of ordinary Americans who demanded new legislation to protect the environment. In 1970, President Nixon established the EPA as an autonomous regulatory body to oversee the enforcement of environmental policy (Environmental Protection Agency, 1992). During the 1970s, environmental protection enforcement was largely carried out in a centralized framework along with passage of the Clean Air Act of 1970 and 1977, and the Clean Water Act of 1972. Under the influence of "New Federalism" advocated by President Reagan, environmental regulations were gradually delegated by the federal government to states in the 1980s. The regulatory authority of states was more clearly spelled out in the Clean Air Act Amendment of 1990, which mandated that states

should make constant progress in reducing emissions while the federal government provides the technical guidance for the state to monitor stationary sources.

Researchers in this field have recognized that environmental regulations can be a double-edged sword. Environmental regulations increase firms' costs, such as abatement costs, costs associated with entry and exit, production costs, and investment costs (Christiansen and Haveman, 1981; Gray and Shadbegian, 1993; Greenstone, List and Syverson, 2012; Ryan, 2012). Meanwhile, well-designed environmental regulations induce innovation in green technology and improve environmental as well as business performance in the long run (Porter, 1991; Jaffe and Palmer, 1996; Dechezlepretre and Sato, 2014). FGD is a mature emission technology that demands a significant financial commitment. In that case, do environmental regulations exert a positive or negative impact on FGD installation? The literature is silent on this question, and this paper attempts to fill the gap.

### **3 Empirical Model: Survival Analysis**

This paper applies a survival analysis to analyze the time a power plant takes to install the emission control technology FGD. Survival Analysis (also called Time to Event Analysis) is used to model the probability that an event occurs as a function of time. In biomedical science, it is used to analyze the time to an event such as death. In social science, researchers use survival analysis to study time to events such as unemployment, marriage, customers' switching to an alternative electricity provider (Kleit, Shcherbakova and Chen, 2012), or firms' adoption of a new technology (Rose and Joskow, 1990; Cabral and Leiblein, 2001; Fuglie and Kascak, 2001; Bellas and

Lange, 2008)<sup>4</sup>. Compared to traditional regression models, survival analysis demonstrates its strength in analyzing censored data. For instance, when researchers study the effect of a drug, patients may (i) die within the study period; (ii) survive at the end of the study; or (iii) drop out of the study for reasons unrelated to the research. In the context of this paper, we are interested in power plants' adoption of FGD. During a finite sample period, power plants may (i) install FGD at some point; (ii) not install; or (iii) drop out of the study. In the following, we briefly review how the survival analysis is constructed and how it can be applied to the estimation.

**Model Construction** First, an *event* is defined as an FGD installation. Denote *duration*,  $T$ , as a random variable that represents the time until a plant experiences an event. The probability that the duration will be less than  $t$  is given by

$$F(t) = Pr(T < t) = \int_0^t f(s)ds, \quad (1)$$

where  $f(s)$  is the probability density function of duration. Second, the *survival function*,  $S(t)$ , is defined as the probability of the *duration* that is at least  $t$ :

$$S(t) = Pr(T \geq t) = \int_t^{\infty} f(s)ds \quad (2)$$

Thus, for any  $t$ ,  $F(t) + S(t) = 1$ . Lastly, the hazard rate,  $\lambda(t)$ , is defined as the probability that an individual subject will experience an event at time  $t$ , given that the subject is at risk for having an event. In other words, the hazard rate indicates the probability that the duration will end at time  $t$ , given that it has lasted until time

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<sup>4</sup>UCLA Statistical Computing Seminars: Survival Analysis with Stata

t:

$$\lambda(t) = f(t)/S(t). \quad (3)$$

In the context of this paper, a power plant "survives" at time  $t$  if it hasn't installed FGD by that time. A plant is "at risk" if it continues to be surveyed/observed and is considering whether to adopt the technology. The hazard rate is the likelihood that a plant will install FGD at time  $t$ , given that the plant is at risk for adopting this technology.

In this paper, we use four specifications for the hazard rate,  $\lambda(t)$ : exponential, Weibull, Gompertz, and Cox proportional hazard models. The survival analysis model is estimated by maximum likelihood estimator. The log-likelihood function is as follows:

$$\begin{aligned} \log L &= \sum_{i=1}^N [d_i \log \lambda(t_i) + \log S(t_i)] \\ &= \sum_{i=1}^N [d_i \log \lambda(t_i) - \Lambda(t_i)], \end{aligned} \quad (4)$$

where  $d_i$  is an indicator variable which takes value one if plant  $i$  does not survive and zero otherwise.  $\Lambda(t_i) = \int_0^{t_i} \lambda(t) dt$  is the *cumulative hazard*. The mathematics details about hazard rate and likelihood function are included in the appendix.

## 4 Data and Summary Statistics

Having reviewed the empirical model, we now turn to data and summary statistics. The statistical models are estimated with data on coal-fired electric power plants, gathered from forms EIA-423, 767, 860, 861, and 923 between 2002 and 2012, all

available from the EIA website with the exception of fuel cost at deregulated plants<sup>5</sup>. The year 2002 is chosen as the starting year because detailed power plant fuel cost data are unavailable prior to that<sup>6</sup>, and the year 2012 is chosen as the ending year because it is the most recent year available. The data are restricted to power plants with 1 megawatt or greater of combined generating capacity, as EIA-860 and EIA-923 only survey those meeting this criterion. EIA-767 was terminated in 2005 and its data collecting duty was continued to be fulfilled by EIA-860 and EIA-923 after 2006. As a result, several important variables such as nameplate capacity and fuel usage in boilers were not collected during the transition period of 2006-2007. For this reason, this study does not cover these two years.

Since FGD is installed on boilers to control emissions, the empirical analysis is conducted at the boiler level. A plant may have more than one boiler, thus we focus on plant-boiler pairs. During 2002-2005 and 2008-2012 period, a total of 448 unique coal-fired power plants with 1 megawatt or greater, giving 1254 unique plant-boiler pairs. For the purpose of survival analysis, only power plants that had not installed FGD by the end of 2001 are included (as the ones that installed FGD by the end of 2001 did not survive at the onset of the study and should not be included). Therefore, the final sample includes 327 power plants<sup>7</sup> and their 917 boiler. Table (7.1) reports means and standard deviations of the variables used in the analysis for the full sample period and by year.

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<sup>5</sup>Plant-level fuel cost at deregulated plants are confidential data, which were obtained from EIA directly.

<sup>6</sup>Although FERC and EIA forms 423 on fuel price data go back to 1972 on the EIA website, the fuel price data from deregulated plants are only available after 2002. Since the analysis is restricted to the post-2002 period, there are limitations on how to interpret and generalize the empirical results, which are discussed at the end of this section.

<sup>7</sup>To put things in context, there were 572 coal-fired power plants (with no restrictions on generating capacity) in the United States as of 2012.

### (1) Boiler level variables

The average age of boilers, *Boiler Service*, is 44 years. As of 2012, boilers in coal-fired electric power plants have served about 48 years, on average. Boilers tend to have decreased efficiency after about 30 years of operation, and may be subject to retirement (Campbell, 2013). Power plant operators thus face the decision between installing FGDs on boilers to reduce emissions, or retiring the aging equipment.

The variable *Total Coal Usage* represents the total physical quantity of coal used in a boiler. Total coal usage is not normalized by plant size, as plant size is another explanatory variable included in the analysis. In our data, a boiler uses 725 thousand short tons of coal per year on average. The coal usage increased during 2002-2008, but dropped to less than 600 thousand short tons in 2012. This is consistent with the overall effort on reducing coal consumption in the US, where coal consumption (for all purposes) was reduced by 195 million short tons over the period of 2000-2012 (EIA, International Energy Statistics).

*Average Sulfur Content* represents the percentage of sulfur by weight contained in coal used in the previous year. Sulfur content differs across coals. In the data, the most frequently used coal are bituminous coal, subbituminous coal, and lignite coal, accounting for 66.65%, 30.59%, and 1.89%, respectively. The typical sulfur content is about 0.4-6.0% in bituminous coal, 0.2-1.5% in subbituminous coal, and 0.4-3.0% in lignite coal. Between 2002 and 2012, power plants switched slightly from bituminous coal (69.24% to 64.86%) to the cleaner lower-sulfur subbituminous coal (27.7% to 33.06%). The average sulfur content of all coal used is 0.91% during the whole sample period, and the sulfur content has experienced continuous decline from

0.975% to 0.88%.

## **(2) Plant level data**

Firm size is another variable of interest. The total *Nameplate Capacity* of a power plant is an appropriate measure of plant size. *Nameplate Capacity* refers to the value on the generator nameplate in megawatts, representing the technical full-load sustained output of a generator without exceeding design thermal limits. A power plant can have more than one generator, and its size is determined by the *combined* nameplate capacity of all generators. Alternatively, one may consider using the capacity of each generator, rather than that of all generators in a plant. This study uses the combined nameplate capacity for two reasons: first, individual capacity data are not available. Second, the combined capacity better describes the plant size, which is usually associated with the ability to invest. The average size of power plants is 1,026 megawatts in the full sample period, ranging from 989 megawatts in 2002 to 1,065 megawatts in 2012.

*Fuel Cost* is the delivered cost of coal, including all costs incurred in the purchase and delivery to the plant. It also includes maintenance and depreciation costs of coal delivered in railcars owned by the plant (EIA-923 Report Instructions). In the data, the average cost of coal is about 228 cents per million Btu during 2002-2012. The fuel cost has increased from 139 cents per million Btu in 2002, to 243 cents per million Btu in 2008, to 290 cents per million Btu in 2012<sup>8</sup>. This is consistent with other sources of coal price data. According to EIA Annual Energy Review (2012), the F.O.B. prices (at the point of first sale, excluding freight or shipping and insurance)

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<sup>8</sup>About \$44 per short ton of coal.

of bituminous coal increased from about 26 dollars per short ton in 2002, to over 57 dollars per short ton in 2011. Similarly, the price of subbituminous coal more than doubled between 2002 and 2012.

The variable *Regulatory Status* represents the public regulatory category of electric power plants. This paper follows Fowlie (2010) to categorize all plants into either deregulated (*Regulatory Status* = 1), regulated (*Regulatory Status* = 2), or public (*Regulatory Status* = 3). Regulated utilities can file rate cases with local Public Utility Commissions to recover costs from major new infrastructure projects (e.g., a pollution control retrofit or plant fuel conversion) or an unexpected increase in operating or maintenance expenses. Deregulated plants are those in restructured electricity markets and they must recover capital investments through competitive wholesale electricity markets (Fowlie, 2010). In other words, deregulated plants lack the channel of recovering capital costs from PUCs. The last category, public power plants, are owned and operated by public entities, including federal and state governments, municipalities, political subdivisions, rural cooperatives, and the Tennessee Valley Authority (TVA). Although public power plants cannot seek reimbursement from PUCs like their regulated counterparts do, they may benefit from lower-interest bank loans made available to them. Over the period of 2002-2012, the percentage of power plants in each regulatory status stayed roughly the same. About 31.45% are deregulated, 54.4% are still regulated, and the remaining 14.15% are public.

Dummy variables are created for regions and regulation status of sulfur. In terms of location, the Midwest is the baseline region (*Region* = 1). The South, Northeast, and West are coded *Region* = 2, 3, and 4 respectively. The dummy variable *Federal Regulation* equals 1 if the most stringent sulfur dioxide regulation on a boiler<sup>9</sup> was a



federal regulation, and 0 if the most stringent regulation was a state or local regulation. During the sample period, about 17.49% of the boilers face more stringent federal regulations, and the remaining 82.51% face more stringent state and local regulations.

### **(3) State and local level data**

In order to capture the effect of state-level regulatory stringency on the adoption of emission control technology, *Average Inspection Rate* is included as an explanatory variable. While all other variables are from the EIA database, the inspection variable is from Air Facility System (AFS) maintained by the US EPA. AFS contains compliance data for stationary polluting sources regulated by Environmental Protection Agency and state and local air pollution agencies. The state and local agencies inspect polluting sources for violation with regard to emission and/or procedural compliance, compliance status for a facility with regard to pollutants regulated by an air program (such as SO<sub>2</sub> emissions regulated by Acid Rain Program, hazardous air pollutants regulated by Maximum Achievable Control Technology (MACT)), or by a procedural requirement of a permit. Unfortunately, the inspection data are not perfect for the purpose of this paper. The most ideal data would be the inspection records for all coal-fired electric power plants; however, the AFS data actually cover a wide spectrum of facilities, from large industrial facilities to relatively small operations such as dry cleaners. Only a subset of coal-fired power plants under consideration are covered by the AFS survey. With no other data sources providing information on regulatory stringency, the AFS data are used as an approximate measure of state-wide regula-

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<sup>9</sup>The original description of this variable is "the most stringent type of statute or regulation under which the boiler is operating for sulfur dioxide."

tory effort, but the limitations should be kept in mind. *Average Inspection Rate* is defined as the percentage of regulated facilities being inspected by state and local authorities. Over the full sample period, 48% of facilities in a state are inspected. The three states with the highest inspection rates are Massachusetts, Virginia, and Maryland. The states with the lowest inspection rates are Wisconsin, Minnesota, and Oregon.

Before moving on to estimation, it is useful to examine the two-way relationship between FGD adoption and explanatory variables. Figure (7.2) shows such associations. On the horizontal axis, group 0 represents electric power plants that have not installed FGD, while group 1 represents those that have. As shown in the figure, power plants with FGD installed have newer boilers. They use more coal, and their coal has a higher content of sulfur. Plants with FGD appear to be larger than those without.

Figure (7.3) plots the nonparametric Kaplan-Meier estimates of the survival function. Starting with all boilers that had not installed FGD by the end of 2001, the survival rate decreased moderately between 2002 and 2005, meaning a relatively small number of boilers installed FGD during this period. Between 2005 and 2012, the survival rate experienced steady decline, from about 95% in 2005 to under 70% in 2012, reflecting an increased pace of FGD adoption among coal-fired power plants.

As discussed above, only boilers that had not installed FGD by the end of 2001 are included in the survival analysis due to data availability constraints. One might wonder whether large differences exist between plants having and having not installed FGD by the end of 2001. A comparison between these two groups of power plants is presented in Table (7.2). In 2002, a total of 128 power plants had installed FGD

by 2001, while 327 had not. The two groups of power plants are fairly comparable in terms of fuel cost, nameplate capacity, inspection rate, and their public regulatory status. The early installers have newer boilers, use more coal, and their coal has higher sulfur content.

## 5 Estimation Results

Having described the data, we now turn to estimation results. The survival model is estimated in terms of coefficients and hazard rates. Only the hazard rate estimates are presented in Table (7.3), because hazard rate is just an exponential transformation of the coefficient.<sup>10</sup> If variable  $X$  is estimated to have a hazard rate of  $h$ , then for one unit increase in the  $X$  variable, the probability of FGD installation changes by  $(h-1)\%$ . The survival model is estimated using four commonly used parametric distributions: exponential, Weibull, Gompertz, and Cox Proportional Hazard (PH) models. The estimation results obtained from these models are interpreted as follows.

Boiler age appears to have a negative impact on the probability of FGD installation. The hazard rate for this variable is about 0.98, meaning as a boiler's service year increases by one, the likelihood of FGD installation decreases by 2%. This is consistent with a priori expectations. Given the fact that many boilers in coal-fired power plants in the US have been in service for a long time (the average age of boilers is around 40 years in the 2000s), plants may consider the alternative of retiring an aged boiler instead of installing expensive FGD.

Sulfur content of coal is positively associated with the probability of FGD instal-

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<sup>10</sup>A positive coefficient is corresponding to a hazard rate greater than one; a negative coefficient is corresponding to a hazard rate between zero and one.

lation. The hazard rate estimates vary from 1.65 to 1.93, depending on the model, all strongly significant. As the average sulfur content in the previous year increases by 1%, the probability of FGD installation this year increases by about 0.65-0.93%.<sup>11</sup>

The total amount of coal used is also positively associated with the likelihood of installing FGD. Different models yield similar estimates for hazard rates, between 1.61 and 1.84, and are all statistically significant. When coal usage increases by 1%, the probability of FGD installation increases by about 0.61-0.84%.

The estimated coefficient for fuel cost are positive across all models; however, none of them are statistically significant.

The size of electric power plants, measured by nameplate capacity, has a positive effect on the FGD installation probability. The hazard rate estimates vary from 1.48-1.64, depending on the model, all statistically significant. This suggests that as the generating capacity enlarges by 1%, a power plant will be more likely to install FGD by about 0.48-0.64%. This result is consistent with the literature that suggests larger firms tend to invest in FGD sooner than smaller firms.

The regulatory status has three categories: deregulated (*Regulatory Status=1*), regulated (*Regulatory Status = 2*), and public (*Regulatory Status=3*). Deregulated power plants are taken as the baseline category. Across the four models, the indicator variable *Regulatory Status=2* has positive and significant estimates for the hazard rate, ranging from 1.51 to 1.92. The indicator variable *Regulatory Status = 3* has positive but insignificant estimates for the hazard rate. The results show that, compared to deregulated power plants, regulated plants are about 51-92% more likely to

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<sup>11</sup>When X increases to 1.01X,  $\log(X)$  increases to  $\log(1.01X) = \log(1.01) + \log(X) \approx 0.01 + \log(X)$ . Therefore, a hazard rate estimate of 1.65 means the probability of FGD installation will increase by  $65\% \times 0.01 = 0.65\%$ , if X increases by 1%.

install FGD. Recall the discussion of restructuring movements in section two: a priori, it is unknown the direction of relationship between regulation and FGD installation. Two opposing forces are at work. On one hand, still-regulated power plants can be motivated to invest in FGD because the costs can be recovered if the local PUC deems the project *prudent*. On the other hand, still-regulated power plants need to jump through more administrative and regulatory hoops before the investment is approved or pre-approved. The length of approval process as well as the uncertainty of outcome can adversely affect the plants in borrowing from banks and/or increase the interest rate on the loan. Our results confirm that the first effect (the "Averch-Johnson" effect) overtakes the second one.

The average inspection occurrence in the previous year has a strong positive effect on the probability of FGD installation. The hazard rate estimates vary from 2.3 to 3.7 across different models, all statistically significant. This suggests that when state-level average inspection rate in the previous year increases by 1 percentage point (or 0.01), the probability of FGD installation increases by 1.3%-2.7%.<sup>12</sup> As discussed in the data section, the state-level inspection data actually cover a wide spectrum of facilities, from large industrial facilities to small operations like dry cleaners. Only a subset of electric power plants in this study are reflected in the inspection data. Therefore, the inspection data represent the stringency of a state's regulatory efforts on fighting pollution *in general* (i.e., not enforcement on electric utility industry only). From the inspection data, we can gather some idea of whether a state is "tight" or "loose" on environmental issues. Power plants in tighter states appear to be more likely to

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<sup>12</sup>One unit increase in X variable is associated with (hazard rate - 1)% change in the estimated probability of FGD. The variable *Average Inspection Rate* has values between 0 and 1, so the change in the probability is interpreted as when inspection rate increases by 0.01, instead of 1.

install FGD, according to our results. The strength of environmental protection may cast both direct and indirect effects on electric power plants. Directly, more frequent inspections impose an imminent threat of financial penalty to polluters. Indirectly, offenders face more pressure from the media and general public in states less tolerant of pollution.

## 6 Conclusion and Policy Implications

Flue-gas desulfurization (FGD) is one of the most effective emission control technologies available for established coal-fired electric power plants to reduce sulfur dioxide emissions. Due to high costs of installation, operation, and maintenance, the decision making process for investing in FGD is not trivial. This paper contributes to the literature by examining a wide array of possible determinants affecting power plants' adoption of FGD, including factors at boiler level, plant level, and state level. The empirical analysis is carried out using data on coal-fired electric power plants in the US during the period of 2002-2012, in a survival analysis framework.

At boiler level, results show that boiler age is negatively associated with the likelihood of FGD installation. On the other hand, sulfur content of coal and total coal usage are both positively associated with the likelihood of FGD installation.

At plant level, plant size has a strong positive effect on the probability of FGD installation – a 1% increase in plant size is associated with a 0.48-0.64% increase in the likelihood of FGD investment. This finding is consistent with the literature on firm size and technology diffusion.

After the electric power industry restructuring, power plants fall into three reg-

ulatory categories: deregulated, regulated, and public. Along the lines of "Averch-Johnson effect", regulated utilities may be more likely to expand their capital stock and thus more likely to install FGDs. On the other hand, utilities in regulated states must go through many hurdles in order to obtain cost recovery, and for that reason, regulated utilities may be less inclined to install FGDs. This paper concludes that the former effect is stronger: Compared to deregulated power plants, the ones still regulated by Public Utility Commissions are about 51-92% more likely to install FGD.

Lastly, the frequency of environmental protection enforcement appears to stimulate FGD installation. Our results show that power plants in states with tighter regulatory efforts on environmental issues are more inclined to install FGD. Inspections, whether carried out within electric utility industry or not, have a strong influence on FGD adoption by power plants. A one percentage point increase in the state-level inspection rate of all polluters in the previous year increases the probability of FGD installation this year by about 1.3-2.7%.

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## 7 Appendix

### 7.1 Appendix 1 - Abbreviations

AFS	Air Facility System
EIA	Energy Information Agency
EPA	Environmental Protection Agency
FGD	Flue-gas Desulfurization
MACT	Maximum Achievable Control Technology
PUC	Public Utility Commission
TVA	Tennessee Valley Authority
SO <sub>2</sub>	Sulfur dioxide
NO <sub>x</sub>	Nitrogen oxides

### 7.2 Appendix 2 - Hazard Rate and the Likelihood Function in Survival Analysis

**Hazard Rate** To estimate this model, the form of the hazard rate,  $\lambda(t)$ , needs to be specified. Four of the most commonly used parametric models are considered: exponential, Weibull, Gompertz, and Cox proportional hazard models. The exponential duration distribution simply assumes the hazard function to be a constant,  $\gamma$ , which doesn't vary with time. The Weibull and Gompertz distributions are more generalized than the exponential one, as they both depend on time<sup>13</sup>. The hazard functions are  $\lambda(t) = \gamma\alpha t^{\alpha-1}$  for Weibull, and  $\lambda(t) = \gamma e^{\alpha t}$  for Gompertz ( $\gamma > 0, \alpha > 0$ ). Finally, the Cox proportional hazard model is perhaps the most widely used formulation in survival analysis. The hazard function is  $\lambda(t) = \lambda_0(t, \alpha)e^{x'\beta}$ , so that the hazard function

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<sup>13</sup>The hazard rate of the Weibull distribution is monotonically increasing if  $\alpha > 1$ , and monotonically decreasing if  $0 < \alpha < 1$ . The hazard rate of the Gompertz distribution is monotonically increasing.

$\lambda(t)$  is proportional to the baseline hazard  $\lambda_0$ , with scale function  $e^{x/\beta}$  not a function of time.

**Likelihood function** Consider  $N$  power plants with duration until FGD installation governed by a survivor function  $S(t)$  and hazard rate  $\lambda(t)$  as discussed above. A power plant  $i$  is observed at time period  $t_i$ . There are two scenarios for this plant. If the plant survives (i.e., it hasn't installed the technology) at time  $t_i$ , then its contribution to the likelihood function is just the probability of survival:

$$p_i = S(t_i). \tag{5}$$

If the plant doesn't survive (i.e., it installs the technology) at time  $t_i$ , then its contribution to the likelihood function is the density at that duration:

$$p_i = f(t_i) = S(t_i)\lambda(t_i). \tag{6}$$

The two contributions share the survivor function  $S(t_i)$ . A plant that doesn't survive multiplies this contribution by the hazard rate  $\lambda(t_i)$  while a survived plant does not. Thus an indicator variable can be used to simplify the likelihood function. Let an indicator variable,  $d_i$ , take value one if plant  $i$  doesn't survive and zero otherwise. The likelihood function is the multiple of likelihood of plants ( $i = 1, 2, \dots, N$ ) observed at different times  $t_1, t_2, \dots, t_N$ :

$$L = \prod_{i=1}^N p_i = \prod_{i=1}^N \lambda(t_i)^{d_i} S(t_i). \tag{7}$$

From definition of  $f(t)$  and  $S(t)$ , it's known that  $f(t) = -\frac{dS(t)}{dt}$ . Thus,  $\lambda(t) = \frac{f(t)}{S(t)} = -\frac{d \log S(t)}{dt}$ , and  $\log S(t) = -\int_0^t \lambda(t) dt$ . If  $\Lambda(t) = \int_0^t \lambda(t) dt$  is defined as the *cumulative hazard*, then  $\Lambda(t) = -\log S(t)$ . The log-likelihood function is therefore

$$\begin{aligned} \log L &= \sum_{i=1}^N [d_i \log \lambda(t_i) + \log S(t_i)] \\ &= \sum_{i=1}^N [d_i \log \lambda(t_i) - \Lambda(t_i)], \end{aligned} \tag{8}$$

For a more detailed discussion of survival analysis, please refer to Rodriguez (2007).

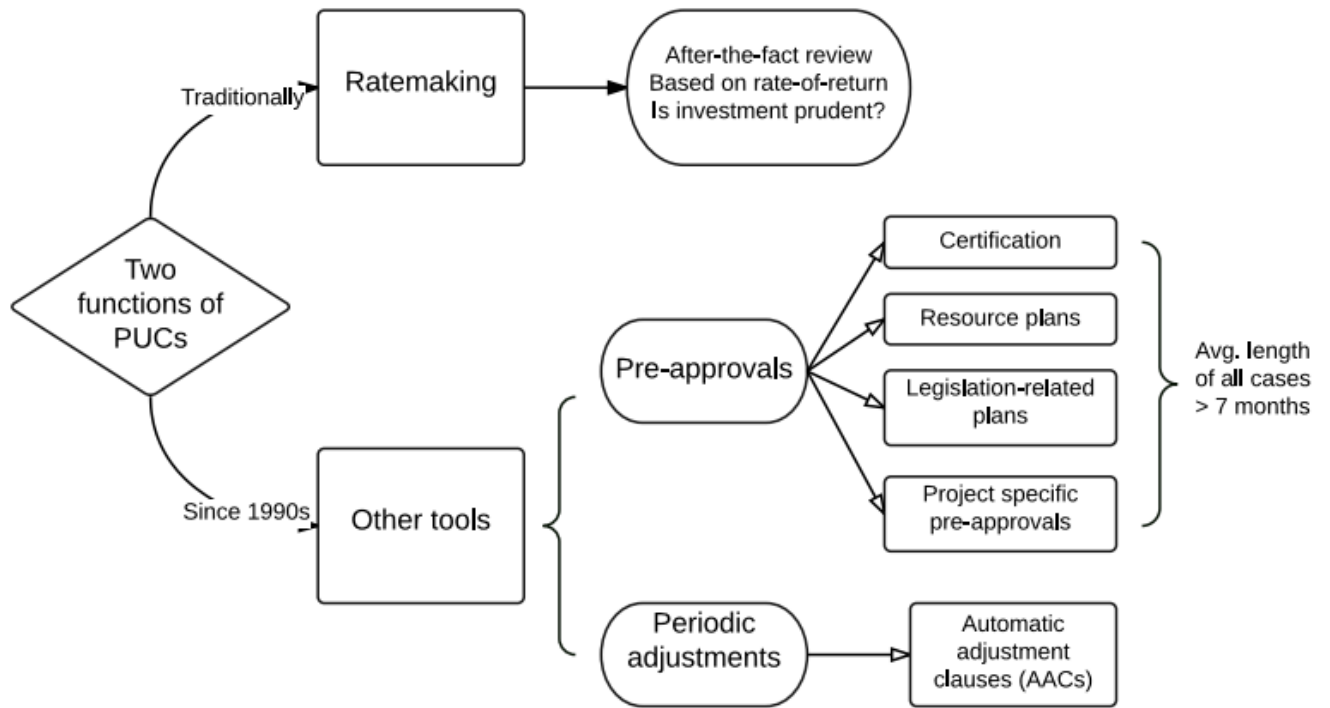


Figure 7.1: Regulatory Approvals by Public Utility Commissions (PUCs)



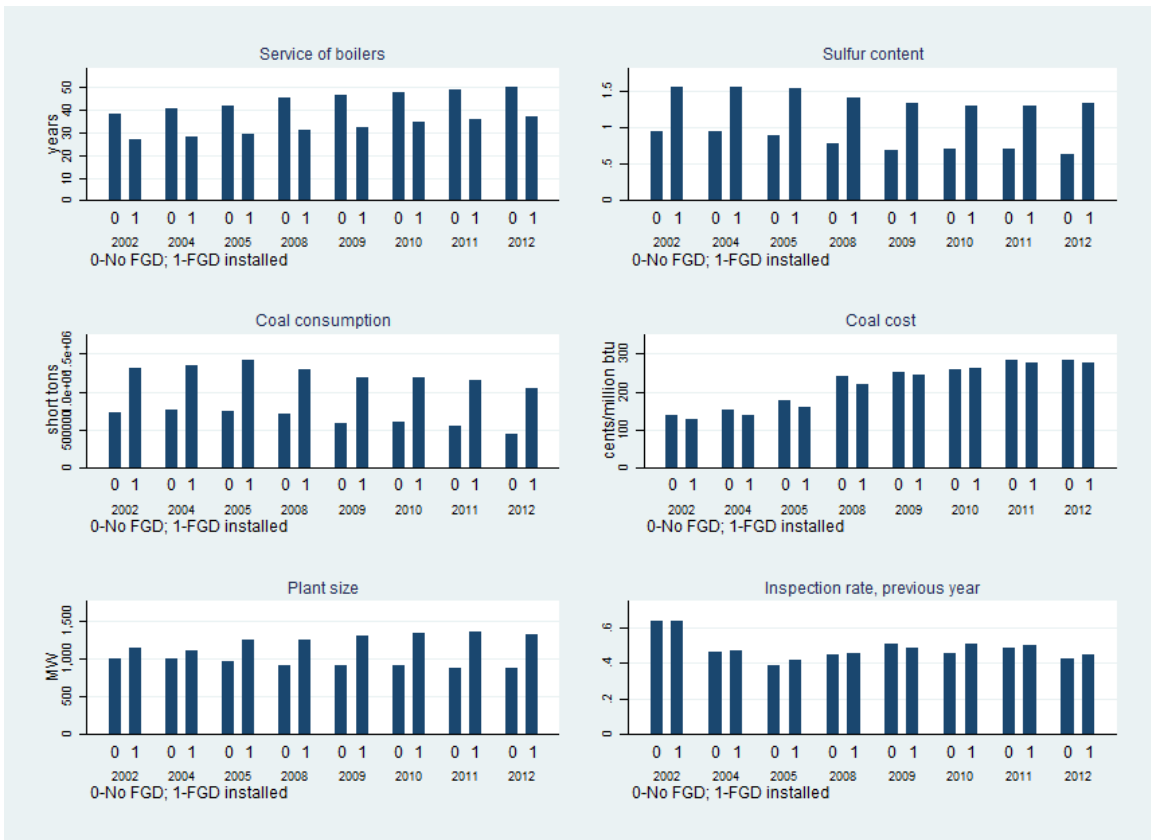


Figure 7.2: Relationship between FGD and major variables

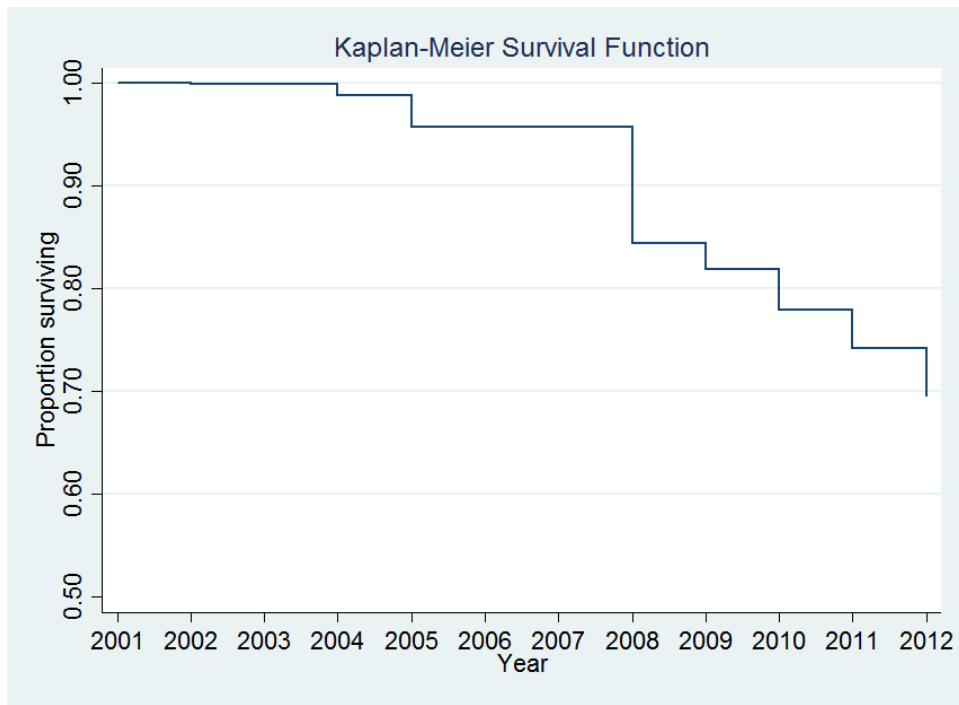


Figure 7.3: Kaplan-Meier Survival Function

Table 7.1: Summary Statistics

Variable	Full Sample 2002-2012	By Year		
		2002	2008	2012
<b>(1) Boiler level data</b>				
Boiler Service (years)	44.14 (12.49)	38.45 (11.23)	44.46 (11.42)	48.30 (12.68)
Total Coal Usage (short tons per year)	725,022 (846,183)	730,220 (814,137)	795,312 (896,390)	597,397 (783,016)
Average Sulfur Content (%)	0.91 (0.69)	0.975 (0.56)	0.93 (0.44)	0.88 (0.60)
<b>(2) Plant level data</b>				
Fuel Cost - Coal (cents per million btu)	228 (99.99)	139 (33.51)	243 (79.36)	290 (91.90)
Nameplate Capacity (MW)	1026 (844.21)	989 (844.17)	1007 (846.44)	1065 (841.76)
Deregulated (Regulatory Status = 1)	31.45%	29.66%	33.21%	30.40%
Regulated (Regulatory Status = 2)	54.40%	55.88%	53.91%	52.14%
Public (Regulatory Status = 3)	14.15%	14.46%	12.88%	17.46%
Midwest (Region = 1)	49.06%	60.06%	62.13%	38.42%
South (Region = 2)	36.25%	30.98%	28.89%	42.24%
Northeast (Region = 3)	6.63%	1.72%	2.04%	10.35%
West (Region = 4)	8.06%	7.24%	6.93%	8.99%
Federal regulation is more stringent (Federal Regulation = 1)	17.49%	18.74%	17.05%	19.16%
State/local regulation is more stringent (Federal Regulation = 0)	82.51%	81.26%	82.95%	80.84%
<b>(3) State and local level data</b>				
Average Inspection Rate	0.48 (0.20)	0.64 (0.25)	0.45 (0.18)	0.43 (0.19)

Standard deviations are in parentheses.

Table 7.2: In 2002: Compare Plants Having or Having Not Installed FGD by 2001

Variable	Had the plant installed FGD by the end of 2001?	
	Yes	No
Boiler Service (year)	27.37 (12.6)	38.45 (12.9)
Total Coal Usage (short tons per year)	1,319,765 (1,111,646)	730,220 (729,443)
Average Sulfur Content (% , previous year)	1.55 (1.11)	0.97 (0.67)
Fuel Cost - Coal (cents per million btu)	127 (39.26)	139 (39.30)
Nameplate Capacity (MW)	1145 (842.90)	989 (828.46)
Average Inspection Rate	0.641 (0.23)	0.646 (0.25)
Deregulated	31.60%	29.66%
Regulated	48.11%	55.88%
Public	20.28%	14.46%
Number of power plants	128	327
Number of plant-boiler pairs	251	917

Note: Standard deviations are in parentheses.

Table 7.3: Hazard Rate Estimation - Survival Analysis

Variable	Exponential	Weibull	Gompertz	Cox PH
<i>(1) Boiler-level variables</i>				
Boiler Service (years)	0.987* (0.008)	0.977*** (0.008)	0.975*** (0.008)	0.979** (0.008)
(log) Average Sulfur Content	1.656*** (0.165)	1.931*** (0.194)	1.932*** (0.196)	1.856*** (0.186)
(log) Total Coal Usage	1.607*** (0.159)	1.806*** (0.187)	1.835*** (0.189)	1.739*** (0.177)
<i>(2) Plant-level variables</i>				
(log) Fuel Cost - Coal	1.097 (0.196)	1.055 (0.150)	1.083 (0.155)	1.054 (0.177)
(log) Nameplate Capacity	1.482*** (0.186)	1.629*** (0.207)	1.641*** (0.209)	1.583*** (0.200)
<i>Deregulated (Regulatory Status = 1): baseline</i>				
<b>Regulated (Regulatory Status = 2)</b>	<b>1.506**</b> (0.321)	<b>1.914***</b> (0.407)	<b>1.924***</b> (0.409)	<b>1.781**</b> (0.379)
Public (Regulatory Status = 3)	1.404 (0.389)	1.439 (0.402)	1.426 (0.397)	1.428 (0.398)
Federal regulation is more stringent	0.864 (0.177)	0.653** (0.142)	0.636* (0.139)	0.714 (0.152)
<i>Midwest (Region = 1): baseline</i>				
South (Region = 2)	1.014 (0.173)	1.196 (0.201)	1.186 (0.199)	1.140 (0.194)
Northeast (Region = 3)	2.381*** (0.737)	2.806*** (0.883)	2.950*** (0.986)	2.721*** (0.854)
West (Region = 4)	1.421 (0.597)	1.503 (0.618)	1.509 (0.649)	1.470 (0.627)
<i>(3) State and Local-level variables</i>				
<b>Average Inspection Rate</b>	<b>2.252**</b> (0.918)	<b>3.532***</b> (1.522)	<b>3.702***</b> (1.601)	<b>3.040***</b> (1.292)

\*\*\*: p-value<1%; \*\*: p-value<5%; \*: p-value<10%. Standard errors are in parentheses.

To interpret hazard rate: if variable X is estimated to have a hazard rate of  $h$ , then for one unit increase in the X variable, the probability of FGD installation changes by  $(h-1)\%$ .  
Hazard rate  $> 1 \rightarrow$  An increase in X is associated with an increased probability of FGD installation.  
Hazard rate  $< 1 \rightarrow$  An increase in X is associated with a decreased probability of FGD installation.