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Abstract
The introduction of scrubbers as a means of controlling sulfur dioxide pollution from stationary sources coincided with the implementation of the Clean Air Act of 1970. Since that time, there have been many policy changes affecting the electricity generation industry. These changes may be characterized as moving from direct regulation toward market-based incentives, both in deregulation or restructuring of power markets and adoption of market-based environmental regulation. These changes provide natural experiments for investigating whether the form of regulation can alter the rate of technological progress. Previous literature (Popp 2003, Lange and Bellas 2005) is mixed on whether advancements as a result of the switch to market-based environmental incentives have led to lower costs. This paper extends this literature by analyzing changes in scrubbers' use of electricity (also known as parasitic load) in relation to regulatory policy regimes. Results show that restructured electricity markets have led to a considerable (30-45%) decrease in parasitic load. Conversely, the change to a cap-and-trade system for sulfur dioxide has not led to a decrease.

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Subject Area: Costs of Pollution Control (17), Electric Power (34), Environmental Policy (52)

I. Background

Most proponents of market-based regulation point to the incentives for cost savings as an important justification for their use. When pollution (in the case of environmental policy) or electricity (in the case of generation policy) is priced at the margin, plants act to minimize the cost of producing a certain level of output. Many coal-fired power plants have flue gas desulfurization units (also known as scrubbers) to control the release of sulfur dioxide, and to a lesser extent, mercury. Scrubbers draw electricity from the plant, known as parasitic load, which is estimated to be between 0.7% and 2.3% of total generation (Keohane, 2006 and EPA, 2000). This load would be valued at approximately $2.0 million per scrubber, annually, at $0.05/KWh. Färe et al (2004) show the parasitic load does vary substantially from plant to plant. While market-based environmental regulation may have spurred reductions in scrubber electricity consumption to better compete with other abatement options**,** a similar argument can be made for restructured (or deregulated) electricity markets in that they allow a generator to profit from any savings in parasitic load. Concurrently, both changes have provided plants incentives for energy saving innovation in their use of scrubbers. This paper tests the hypothesis that these market-based regulations have reduced scrubber electricity use.

Electricity Market Regulation

Until the early 1990s, power plants generally operated as regulated monopolies. States, through public utility commissions (PUCs), allowed firms (both investor-owned and municipal) to build power plants and provide electricity to the grid sufficient to meet demand.[1] In return, firms were allowed to earn a specified rate of return on the cost of

[1] Federal projects like the Tennessee Valley Authority were not subject to state level regulation.

supplying electricity, also known as cost of service regulation. States differed in how quickly the cost of service could be adjusted. Some had routine meetings or specific provisions allowing for rate changes while others required the utility to ask for approval of rate changes at a hearing of the PUC (Bushnell and Wolfram, 2005). As a result, reducing the electricity devoted to the scrubber likely reduced the price of electricity as the costs also fell. Beginning with the Energy Policy Act of 1992, federal and state regulators have attempted to deregulate the generation and transmission of electricity. The Federal Energy Regulatory Commission has issued a number of Orders (888, 889, and 2000) to encourage more market-based incentives in generation policy. Seventeen states and the District of Columbia have passed legislation that restructured electricity generation policy that was still in effect as of February 2003 (EIA, 2003). A list of these states is given in Table 1. Not all of these states contain coal-fired power plants and their associated scrubbers. Many issues have held up or complicated the transition to market-based generation policy this decade including the California experience of 2001.

The empirical literature on the efficiency effects of restructured electricity markets clearly shows that traditional regulated electricity markets did not provide the correct incentives for efficiency. Markiewicz, Rose, and Wolfram (2004) find that investor-owned plants in restructured markets reduced their labor and non-fuel expenses by 5% relative to investor-owned plants in traditional markets. The gain was even larger when compared to non-investor-owned plants. Bushnell and Wolfram (2005) analyze the impact on fuel efficiency of a change to restructured electricity markets. Using a sample of coal and gas plants in both traditional and restructured markets, they find a 2%

increase in fuel efficiency for plants in restructured markets, a fuel cost savings of $550 million at 2003 prices, which they attribute to the incentive effects of a restructured market. Douglas (2004) shows that low-cost coal power plants are more utilized in states with restructured markets compared to those with traditional markets. Simulations show cost savings on the order of 2%. Newbery and Pollitt (1997) conduct a social cost-benefit analysis for the restructuring of the U.K. electricity market. They find the main benefits of restructuring come from improvement in generation efficiency (in both fuel and labor inputs) and they were largely captured by the power plants (and their shareholders) and not distributed to consumers in the form of lower prices.

Environmental Regulation

Scrubbers were widely adopted after implementation of the Clean Air Act Amendments (CAAA) of 1970, although a handful had been installed prior to federal regulation. They remain the only option for significant post-combustion abatement of sulfur dioxide (SO2) emissions. The CAAA of 1970 included new source performance standards (NSPS) that mandated plants, for which construction commenced after 1971, comply with an emissions standard that they were free to meet using any means. Most plants adopted low-sulfur coal while a smaller fraction installed scrubbers. The CAAA of 1977 added to the emissions standard a "percent reduction clause" which called for 90% abatement of SO2 emissions. This was in essence a technological standard as only scrubbers could achieve the mandated removal rate.[2] With adoption of the Clean Air Act Amendments of 1990, regulation began moving away from the command-and-control approach of the

[2] An exception was made to allow a removal rate of 70% if low-sulfur coal was burned by the boiler. However, a scrubber was still necessary to meet this removal rate.

CAAA of 1970 and 1977. The 1990 CAAA created a national permit market for SO2 emissions. Unlike NSPS, this market would apply to all boilers regardless of the year they entered service. The 1990 CAAA created a larger potential customer base for scrubbers, but those potential new customers also had more options than past customers, who were effectively mandated to purchase a scrubber. The most popular option for these new potential customers was to switch to low-sulfur coal and the number of new scrubber installations was smaller than expected.

There is an extensive theoretical literature looking at the relationship between the form of environmental regulation and innovation in pollution control technology. Early papers (Downing and White 1986, Millman and Prince, 1989, Zerbe 1970) show that the incentives offered by market-based regulation in general, and permit systems specifically, provide stronger incentives for innovation and adoption of cost-reducing technological changes than do abatement standards.

The state of the empirical literature is not as clear. Bellas (1998) estimated a scrubber cost model in which lifetime scrubbing costs (capital costs plus 15 times the annual operating costs) are found not to have fallen significantly through 1992, implying no advancement in scrubber technology under the CAAA of 1970 and 1977. Another finding is that plants “learn by doing” as operating costs fell significantly as the age of the scrubber increased. Popp (2003) set forth the hypothesis that the nature of innovation is dependent on the form of the regulation. Under command-and-control regulations, utilities may attach no value to advances that increase removal efficiency. Thus, innovation might be directed to reducing quality-adjusted costs. With a market-based system, improvements in removal efficiency and quality-adjusted costs are valuable. Using data on patent activity and the operating costs of scrubbers, he finds evidence supporting the theory that cost saving innovations occurred under the CAAA of 1977 while removal efficiency innovations occurred under the CAAA of 1990. Based on an analysis of capital and operating costs, Lange and Bellas (2005) extend these papers using data from 1985-2002 and find that scrubber technology experienced a one-time improvement shortly after passage of the CAAA of 1990. They find no evidence of technical progress prior to the 1990 CAAA. It should be noted here that operating costs in these papers include the value of the parasitic load. As a result, previous analyses will be unable to differentiate between changes in scrubber labor costs (for example) and parasitic load.

This analysis links the areas of electrical market regulation and environmental regulation by testing for advances in the design and use of scrubbers in terms of their parasitic load. Testing for a relationship between market-based policies and electricity saving scrubber innovations is important for two reasons. First, it is expected that scrubbers will be installed on a large number of coal-fired boilers in order to comply with the Clean Air Interstate Rule and the Clean Air Mercury Rule in 2010. In addition, coal-fired electricity generation is expected to remain the largest part of the U.S. electricity generation portfolio for at least the next 20 years. This analysis will reveal whether restructuring of electricity markets and adoption of market-based environmental regulations can help reduce the economic burden of pollution control as more scrubbers come into use.

II. Data

Data are taken from the Energy Information Administration's Form 767 from 1996 through 2003. This form collects information on design, regulation and operation of U.S. steam-electric plants with net generating capacity ratings of 10 megawatts or greater. Only plants with 25 megawatts or greater capacity are used in this analysis as recordkeeping for smaller plants began in 2001. The data include information at the level of the individual boiler and the associated flue gas desulfurization (FGD) unit. All scrubbers in the sample have one associated boiler, thus each observation is a scrubber-boiler pair, although a plant may have more than one scrubber-boiler pair.

The variables used in the analysis fall into three broad categories. The first are time varying scrubber-boiler characteristics. The first of these, which is the dependent variable in the analysis, is the rate of electricity used per hour in-service (i.e., parasitic load rate). This is the total electricity-consumed by the scrubber in kWhs during the year divided by the number of hours the scrubber was in-service. Scrubbers operating less than 100 hours in a given year are dropped for that year. The second variable is operating costs per hour in-service, which is equal to total operating cost during the year divided by the hours in-service. Three variables describe the coal whose emissions the scrubber treated. Total coal is the quantity, in short tons, of coal burned during the year by the boiler. Average heat/sulfur content is the average BTU/sulfur content of coal burned during the year by the scrubber-boiler unit. The data also include the sulfur level for which the scrubber was designed. A new variable equal to the square of the difference between the average sulfur content and the design sulfur content was created to test whether deviations from the design level have a significant impact on electricity usage. The removal efficiency is the percentage of SO_2 the scrubber removes from the flue gas. This analysis uses the removal efficiency at annual operating factor, which is the most common metric given in the data.[3] Finally, the year the scrubber was installed and the age of the scrubber for each year of operation are variables used in this analysis.

The second category of variables is policy regime variables. The first of these is a dummy variable indicating boilers that were part of Phase I of the 1990 CAAA while Phase I was in effect. After 1999, Phase II of the 1990 CAAA came into effect and all plants in the sample would have faced the same SO_2 constraint. This dummy is equal to one for those boilers that were either mandated or volunteered to participate for the entire Phase I period (1996-1999) and is zero otherwise. The second of these is a dummy variable indicating a restructured electricity market, which takes a value of one beginning in the year following passage of legislation to restructure the electricity market in the state where the plant is located and continuing through the sample period; it is zero otherwise.

The third and final category of variables is time-invariant dummy variables. Dummies are created for each year from 1996 through 2003. A dummy variable is included

[3] Results for the analysis using removal efficiency at 100% operating load show little difference for the policy variables and are available from the authors by request.

indicating whether the scrubber produces a sellable by-product, generally gypsum. The number of scrubber trains, compartments where the exhaust (flue) gas and the sorbent mix to collect the SO_2, is included as a measure of the level of redundancy built into the scrubber. The flue gas exit rate is included as a measure of size or capacity of the scrubber and measures how much flue gas passes through the scrubber per minute. Scrubbers are categorized into eight different types of scrubber as given by the EIA in the Form 767 instructions. A table of summary statistics for the variables used in this analysis is found in Table 2.

III. Analysis

A model based on Lange and Bellas (2005) is used to test the hypothesis of decreased parasitic load under market-based environmental regulation and restructured electricity markets. A linear model and a double log, or multiplicative, model are used to estimate a model of scrubber electricity consumption per hour in-service. The double log model allows for economies of scale with respect to various explanatory factors and is more flexible than the linear model. Both functional forms use a fixed effects estimator grouped by plant (plants can have more than one boiler-scrubber unit) to control for unobserved heterogeneity in this panel dataset[4]. In addition, each model is estimated using two-samples for a total of four regressions. The first sample includes only plants in states that restructured their electricity markets. The second sample includes plants in all states regardless of whether the state restructured its electricity market.

[4] A Hausman specification test of fixed vs random effects rejected the null of random effects at the 1% significance level.

One important aspect of the model is the relationship between removal efficiency and electricity usage. It is formalized through the use of a standard engineering model that expresses removal efficiency as the number of standard scrubbing units (Perry and Green, 1997). The first standard unit removes $1 - e^{-1}$, or approximately 63.2% of the incoming sulfur. The number of standard units is expressed as the following function of the removal efficiency[5]:

$$n(x) = \ln \frac{1}{1-x} \qquad [1]$$

Where

x is the removal efficiency, ($0<x<1$).

The models estimated are:

$$ParasiticRate_{jt} = \alpha_i + \beta_1 \left(\ln \frac{1}{1-x_{jt}} \right) + \beta_2 P_{jt} + \beta_3 X_{jt} + \beta_4 S_{ji} + \beta_5 Y_t + \varepsilon_{jt} \qquad [2a]$$

$$\ln ParasiticRate_{jt} = \alpha_i + \beta_1 \ln \left(\ln \frac{1}{1-x_{jt}} \right) + \beta_2 P_{jt} + \beta_3 \ln X_{jt} + \beta_4 S_j + \beta_5 Y_t + \varepsilon_{jt} \qquad [2b]$$

Where α_i is the plant-specific constant, x_{jt} is the removal efficiency of boiler-scrubber unit j in period t, the equation in parenthesis is the number of standard scrubbing units for boiler-scrubber unit j in period t, P_{jt} is a vector of policy regime dummy variables, X_{it} is a vector of time-varying scrubber-boiler characteristics, S_i is a vector of non-varying

[5] Perry & Green (1997), pp 14-9. For simplification we assume there is no back pressure of SO_2.

scrubber-boiler dummy characteristics, Y_t is a vector of year dummies, and ε_{it} is an error term.

Our model is specified to differentiate between innovations in the design of scrubbers and innovations that occur after the scrubber is installed at the plant. The estimated coefficient on the year of installation helps to identify changes in electricity consumption that result from technological innovations while the scrubber age coefficient identifies learning-by-doing innovations at the plant. Finally, the estimated coefficient on the restructured markets dummy identifies innovations from the incentive effect of restructured markets.

IV. Results

Estimation results for model 2a are presented in Table 3. Higher removal efficiency is not associated with a significantly higher parasitic load rate. Larger scrubbers (as measured by flue gas exit rate) are also not associated with higher load rates for restructured markets, but do have significantly higher rates of use when looking at all markets. In both samples, evidence of decreased parasitic load rate is found for restructured electricity markets. Innovations in restructured markets produced savings of 30%. There is no evidence of learning-by-doing, as indicated by the insignificant estimated coefficients on age, or technological innovations, as indicated by the estimated coefficients on the year of installation. In fact, when looking at all states, the parasitic load rate for newer scrubbers has increased at an average rate of 3% per year.

Estimation results for model 2b are presented in Table 4. The results on removal efficiency and flue gas exit rate are the same as in model 2a. Again, both samples find that restructured electricity markets are associated with decreased parasitic load rate. The savings are on the order of 45%[6]. At wholesale electricity prices of $0.05/Kwh, states with restructured markets save an average of $990,000 per year per scrubber. The lack of a significant estimated coefficient on year of installation suggests no technological advance related to parasitic load. In total three out of the four analyses point to no technological advancement in parasitic load. The evidence on learning-by-doing is mixed as the restructured markets sample shows a significant decrease per year in parasitic load. However, this result disappears in the full sample. These results, combined with those in Table 3, suggest that the incentive effect of restructured markets is the main driver behind the reduced parasitic load, with weak evidence that learning-by-doing may also contribute.

V. Conclusion

The movement to market-based regulation in the electricity industry is meant to encourage more efficient resource use. Two of the biggest changes in the industry have come from environmental regulation and generation policy. The 1990 CAAA established a cap-and-trade permit system for the control of SO2 while the restructuring of electricity generation deregulated what had been a regulated monopoly. This paper tests whether these policy changes led to electricity-saving innovations in the design and operation of a scrubber. Results reveal that the 1990 CAAA and learning by doing had little impact on

[6] Since this is a semi-log model with respect to dummy variables, the percentage change is calculated using Halvorsen and Palmquist (1980).

parasitic load rate**s**. Restructured electricity markets, however, yielded a 30-45% reduction in parasitic load rates, depending on the model estimated. With 52 scrubbers in restructured markets in our sample, this amounts to a savings of approximately $50 million per year (assuming $0.05 KWh price of electricity). These savings likely arose from the incentive effect in restructured electricity markets where electricity prices are not guaranteed, compared to traditional markets where costs of generation are reliably reimbursed.

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VI: Appendix

Table 1: Restructured Electricity Markets

States with Restructured Electrcity Markets through 2003
Arizona, Connecticut, Delaware, District of Columbia, Illinois, Maine, Maryland, Massachusetts,Michigan, New Hampshire, New Jersey, New York, Ohio, Oregon, Pennsylvania, Rhode Island, Texas, and Virginia.

Table 2: Summary Statistics

Variable	Mean	S.D.
Electricity Usage/Hours in Service, KWh	6,552.1	7,219.3
Operating Costs/ Hour in Service, $	3.0	4.6
Avg-Designed Sulfur Difference Sq	1.4	3.8
Total Coal, 1000 Short Tons	1,644.7	1,066.6
Avg BTU Content	10,391.5	1,966.1
Avg Sulfur Content, %	1.5	1.2
Year Installed	83.5	6.7
Hours in Service	7,603.8	1,017.9
Removal Efficiency, Annual Operating Load, %	81.2	15.6
Flue Gas Exit Rate, cu. Ft. per minute	1,601,950.0	926,791.1
# of Scrubber Trains	3.3	1.9
Restructured Market Dummy	0.2	0.4
Saleable Byproduct Dummy	0.2	0.4
Age, years	16.0	7.0

Table 3: Regression Results-Linear Model

Dependent Variable: Scrubber Energy Usage per Hour
Time Period : 1996-2003
Estimation: Fixed Effects   Group: Plant

Sample:	Restructed States Only		All States	
Explanatory Variable	Coefficient	P-Value	Coefficient	P-Value
Operating Costs/ Hour	36.93	0.69	45.94	0.32
Phase I Dummy	1011.80	0.50	1185.16	0.05
Year Installed	123.74	0.79	214.02	0.04
Restructured Market	-2338.58	0.06	-2410.79	0.00
Age	46.16	0.88	73.98	0.38
Salable	1034.34	0.65	736.01	0.51
Removal Efficiency-Annual	79.68	0.83	179.80	0.31
Flue Gas Exit Rate	-0.04	0.54	0.01	0.00
# of Scruber Trains	17579.90	0.52	861.45	0.01
Total Coal	2.42	0.12	-0.13	0.79
Avg. Heat	-0.96	0.50	0.00	0.99
Avg. Sulfur	-3419.87	0.20	-689.83	0.43
Hours in Service Sq	0.00	0.05	0.00	0.18
Avg-Designed Difference Sq	-481.65	0.63	-110.45	0.63
N	310		1093	
Groups (Plants)	33		103	
R2	0.08		0.29	
Rho	0.98		0.79	

Year and Scrubber Type Estimates Removed for Brevity

.

Table 4: Regression Results-Double Log Model

Dependent Variable: Ln Scrubber Energy Usage per Hour

Time Period : 1996-2003

Estimation: Fixed Effects   Group: Plant

Sample:	Restructed States Only		All States	
Explanatory Variable	Coefficient	P-Value	Coefficient	P-Value
Ln Operating Costs/ Hour	-0.05	0.75	-0.05	0.29
Phase I Dummy	-0.43	0.36	0.05	0.75
Year Installed	-4.88	0.60	-0.02	0.99
Restructured Market	-0.66	0.06	-0.68	0.00
Ln Age	-0.87	0.06	-0.18	0.33
Salable	0.43	0.48	0.17	0.54
Ln Removal Efficiency-Annual	0.01	0.98	0.10	0.40
Ln Flue Gas Exit Rate	-2.72	0.89	0.81	0.00
Ln # of Scruber Trains	2.78	0.93	-0.20	0.46
Ln Total Coal	1.81	0.02	0.18	0.38
Ln Avg. Heat	-21.93	0.00	-2.40	0.11
Ln Avg. Sulfur	-0.30	0.64	-0.24	0.40
Ln Hours in Service Sq	-1.56	0.01	-0.20	0.22
Ln Avg-Designed Difference Sq	0.14	0.07	0.00	0.92
N	295		1037	
Groups (Plants)	33		103	
R2	0.04		0.09	
Rho	0.96		0.7	