

© Copyright 2005  
Ian Lange



Investigating the Effects of the 1990 Clean Air Act Amendments  
on Inputs to Coal-Fired Power Plants

Ian Lange

A dissertation submitted in partial fulfillment of the  
requirements for the degree of

Doctor of Philosophy

University of Washington

2005

Program Authorized to Offer Degree:  
Economics

UMI Number: 3178090

Copyright 2005 by  
Lange, Ian

All rights reserved.

### INFORMATION TO USERS

The quality of this reproduction is dependent upon the quality of the copy submitted. Broken or indistinct print, colored or poor quality illustrations and photographs, print bleed-through, substandard margins, and improper alignment can adversely affect reproduction.

In the unlikely event that the author did not send a complete manuscript and there are missing pages, these will be noted. Also, if unauthorized copyright material had to be removed, a note will indicate the deletion.

**UMI**<sup>®</sup>

---

UMI Microform 3178090

Copyright 2005 by ProQuest Information and Learning Company.

All rights reserved. This microform edition is protected against  
unauthorized copying under Title 17, United States Code.

ProQuest Information and Learning Company  
300 North Zeeb Road  
P.O. Box 1346  
Ann Arbor, MI 48106-1346

University of Washington  
Graduate School

This is to certify that I have examined this copy of a doctoral dissertation by

Ian Lange


and have found that it is complete and satisfactory in all respects,  
and that any and all revisions required by the final  
examining committee have been made.


Chair of Supervisory Committee:

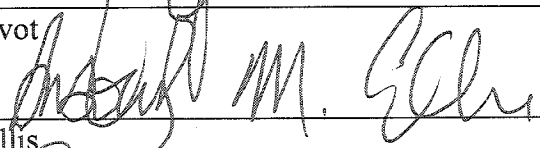
  
\_\_\_\_\_  
Robert Halvorsen

Reading Committee:

  
\_\_\_\_\_  
Robert Halvorsen

  
\_\_\_\_\_  
Neil Bruce

  
\_\_\_\_\_  
Eric Zivot

  
\_\_\_\_\_  
Greg Ellis

  
\_\_\_\_\_  
Allen Bellas

  
\_\_\_\_\_  
Marieka M. Klawitter

Date: 5-27-05

In presenting this dissertation in partial fulfillment of the requirements for the doctoral degree at the University of Washington, I agree that the Library shall make its copies freely available for inspection. I further agree that extensive copying of the dissertation is allowable only for scholarly purposes, consistent with "fair use" as prescribed in the U.S. Copyright Law. Requests for copying or reproduction of this dissertation may be referred to Proquest Information and Learning, 300 North Zeeb Road, Ann Arbor, MI 48106-1346, to whom the author has granted "the right to reproduce and sell (a) copies of the manuscript in microform and/or (b) printed copies of the manuscript made from microform."

Signature 

Date 6-8-05

University of Washington

Abstract

Investigating the Effects of the 1990 Clean Air Act Amendments  
on Inputs to Coal-Fired Power Plants

Ian Lange

Chair of the Supervisory Committee:  
Professor Robert Halvorsen  
Economics

This dissertation examines the effects of the 1990 Clean Air Act Amendments (CAAA) on inputs to coal-fired power plants. The 1990 CAAA established a system of tradable permits for sulfur dioxide (SO<sub>2</sub>) emissions for all power plants and granted utilities complete freedom in how they achieved compliance. While much of the literature has focused on the market for SO<sub>2</sub> emissions permits, the 1990 CAAA fundamentally altered the way power plants choose their inputs, especially those related to SO<sub>2</sub> emissions and control. Previously, many inputs were mandated or their true social value was distorted by command-and-control type regulation. The impact of a power plant's ability to efficiently choose its inputs will alter the way the input markets operate. The three empirical papers of this dissertation investigate the extent to which power plants are using their ability to choose inputs efficiently and the resulting impacts on input markets.

## TABLE OF CONTENTS

	Page
List of Figures .....	ii
List of Tables .....	iii
Chapter 1: Introduction .....	1
Chapter 2: Technological Change for Sulfur Dioxide .....	5
Scrubbers Under Market-Based Regulation	
2.1 Background .....	5
2.2 Data .....	13
2.3 Analysis .....	16
2.4 Results .....	21
2.5 Conclusion .....	24
Chapter 3: Coal Market Integration: The Effect of Pollution .....	31
Abatement Flexibility and Railroad Deregulation on the Markets for High and Low Sulfur Coal	
3.1 Background .....	31
3.2 Data .....	36
3.3 Analysis .....	37
3.4 Results .....	40
3.5 Conclusion .....	44
Chapter 4: An Estimate of the Implicit Price of Sulfur in Coal .....	55
Prior to Phase I of the 1990 Clean Air Act Amendments	
4.1 Background .....	55
4.2 Data .....	60
4.3 Analysis .....	64
4.4 Results .....	66
4.5 Conclusion .....	68
Chapter 5: Conclusion .....	76
Bibliography .....	79

**LIST OF FIGURES**

Figure Number	Page
3.1. Time Series of Coal Prices .....	46

## LIST OF TABLES

Table Number	Page
2.1. Descriptive Statistics .....	26
2.2. Expected Variable Signs .....	27
2.3. Regression Results .....	28
2.4. Coefficient Tests.....	30
2.5. HHI Index.....	30
3.1. States in each Region .....	47
3.2. Chow Tests .....	47
3.3. Hypothesis .....	47
3.4. Unit Root Tests I .....	48
3.5. Cointegration Results I.....	48
3.6. Speed of Adjustment Results I.....	49
3.7. Unit Root Tests II.....	50
3.8. Cointegration Results II.....	51
3.9. Speed of Adjustment Results II.....	52
4.1. Descriptive Statistics .....	70
4.2. OLS Results.....	71
4.3. OLS Results with Quadratic Terms.....	72
4.4. Fixed Effects Results.....	73
4.5. Fixed Effects Results with Quadratic Terms.....	74
4.6. Plant-Based Fixed Effects Results .....	75

## ACKNOWLEDGEMENTS

The author wishes to express sincere appreciation to my committee for their vast reserve of knowledge and helpful guidance. In particular, Professor Robert Halvorsen and Allen Bellas provided inspiration and support. This thesis would never have been completed without the encouragement and devotion of my parents, sister, significant other, and friends.

## DEDICATIONS

To my parents, Roy and Antoinette

## Chapter 1 Introduction

The Clean Air Act Amendments (CAAA) of 1990 fundamentally altered the way most coal-fired power plants operate. The changes inherent in this act allowed power plants to choose their method of sulfur dioxide (SO<sub>2</sub>) abatement while adding the option of a SO<sub>2</sub> permit trading market between plants. Federal regulation until the implementation of the 1990 CAAA in 1995 focused on boiler-specific regulation for those built after 1971. Boilers built before 1971 were unregulated at the federal level. The CAAA of 1970 required an emissions standard of no more than 1.2 lbs of SO<sub>2</sub> per million BTU for boilers built after 1971. The CAAA of 1977 essentially required that boilers built after 1978 use a piece of capital, known as a scrubber, to remove SO<sub>2</sub> from the waste stream.

Economic research regarding the 1990 CAAA has focused on the performance of the SO<sub>2</sub> permit trading market and the cost of complying with the new regulations. The effect of the 1990 CAAA reaches far beyond this newly-created permit market. Putting the history of regulation together, a majority of boilers until 1995 had little incentive to use the cost minimizing bundle of inputs (including SO<sub>2</sub>) to produce electricity. The effects of this inefficient bundle of inputs are not constrained to the electric generation industry. The performance of input markets, such as coal and scrubbers, are interconnected with the regulation of power plants. It is expected that altering the way power plants are allowed to choose their inputs will alter the way that the input markets perform. The chapters in this

dissertation are linked in that they provide empirical tests of the theoretical predictions that arise from the ability of power plants to choose their abatement technique.

The first input industry dealt with, and second chapter, in this dissertation is the scrubber industry. Scrubbers, also known as flue gas desulfurization units, remove  $\text{SO}_2$  from the waste stream (flue gas) of a boiler by trapping it with a type of sorbent. The 1990 CAAA introduced market-based incentives to power plants by allowing them to meet the given emissions standard as they see fit. In principle, the 1990 CAAA forced scrubbers to compete with other abatement options (mainly burning low-sulfur coal and the permit market) and increased the number of possible customers. The hypothesis proposed in this paper is that the competition of other abatement options has led to a reduction in the cost of purchasing (capital costs) a scrubber as well as the costs of operating a scrubber. Data listing the capital and operating costs as well as the characteristics of the scrubbers is used to determine the effect of different policy regimes. A hedonic model is estimated with policy regime dummies corresponding to what versions of the CAA were in effect when the scrubber was installed.

The second input market dealt with in this dissertation is the coal market. This market will be the subject of the third and fourth chapter. The third chapter examines the way plants exploit the difference in coal attributes to minimize the cost of compliance with an environmental regulation such as the CAA. The heat inherent in coal that power plants

use to generate electricity comes bundled with undesirable qualities such as sulfur and ash. Federal regulations gave older (pre-1971) power plants a false value of sulfur and did not allow newer power plants to substitute between high and low sulfur coal to minimize costs. In addition, railroad (the main mean of transportation for coal) rates and routes were regulated by the federal government until the early 1980's. Under these types of regulation, barriers to efficient trade hamper the ability of power plants to alter their purchases of coal when prices move and minimize the cost of meeting an environmental regulation. Railroad deregulation in the early 1980's and the 1990 CAAA introduction of a market for sulfur should reduce the barriers to efficient trade between different types of coal. This would result in an integration of the high and low sulfur coal markets. Price indices are created to test this hypothesis using cointegration tests.

The fourth chapter looks at long-term coal contracts and the manner in which their pricing changes with the changing of incentive of the CAAs. The 1990 CAAA created an implicit price on sulfur inherent in coal by establishing a market for emissions of  $\text{SO}_2$  through the distribution of pollution permits. This market created an implicit marginal willingness to pay for reductions in the sulfur content of coal as this would translate into fewer  $\text{SO}_2$  emissions, freeing permits to be sold. Previous versions of the CAA gave plants no incentive to value the sulfur content at the margin. A hedonic price model of coal purchases is estimated to determine the implicit price of sulfur inherent in the coal.

It is expected that contracts signed previous to 1990 would show no statistically significant price for sulfur content, while those signed after 1990 would.

## Chapter 2

**Technological Change for Sulfur Dioxide Scrubbers Under Market-  
Based Regulation****2.1 Background**

Flue gas desulfurization (FGD) units, commonly known as scrubbers, have been used at U.S. power plants since the late 1960s to control emissions of sulfur dioxide (SO<sub>2</sub>) and resulting acid rain. Use of scrubbers resulted largely from the implementation of regulations specific to new boilers, known as new source performance standards (NSPS). Prior to implementation of NSPS there were very few scrubbers. As NSPS were introduced and revised, use of scrubbers was at first optional and later essentially mandatory for new coal burning boilers. The first set of standards, NSPS-D, were included in the 1970 Clean Air Act (CAA) and specified only that new boilers not emit more than 1.2 pounds of SO<sub>2</sub> per million Btu (mm Btu) of heat input. The next set of standards, NSPS-Da, were included as part of the 1977 Clean Air Act Amendments (CAAA) and specified a limit of 1.2 pounds of SO<sub>2</sub> per mm Btu and a removal rate of 90% of SO<sub>2</sub> from the emission stream.<sup>1</sup>

---

<sup>1</sup> An exception was made to allow a removal rate of 70% if SO<sub>2</sub> emissions were less than 0.60 pounds per mm Btu. This effectively lowered the scrubbing requirement for units burning lower sulfur coal but still required scrubbing, even for low sulfur coal.

Title IV of the 1990 Clean Air Act Amendments (1990 CAAA) created a system of tradable permits for SO<sub>2</sub> emissions that would eventually apply to most coal burning power plants in the U.S. The eventual goal of the system was a 10 million ton reduction in SO<sub>2</sub> emissions, about 50% of 1985 emissions, by the year 2000. Phase I of the permit system began in 1995 with the inclusion of approximately 263 older, previously unregulated boilers whose participation was mandated plus 174 boilers that would have been brought in under Phase II but voluntarily entered during Phase I (EIA, 1997). These 263 older boilers, also known as Table A, generally emitted large amounts of SO<sub>2</sub> and nitrogen oxide (NO<sub>x</sub>), burned high sulfur coal, were unregulated at the federal level, and lacked scrubbers. Boilers included in Phase I were granted permits at the rate of 2.5 pounds of SO<sub>2</sub> per mm Btu of average annual heat input over 1985-87. In Phase II, all boilers with a generating capacity at or greater than 25 megawatts were included and were granted permits at the rate of 1.2 lbs of SO<sub>2</sub> per mm Btu measured over the same time period.

While the 1990 CAAA does not eliminate the mandatory scrubbing associated with the NSPS of the 1977 CAAA, it does allow units to achieve compliance with the permit system by whatever means they choose. Additionally, older units that previously had no incentive to install and operate scrubbers gained that incentive as a result of the tradable permit system. The effects of the 1990 CAAA on scrubbing were to make scrubbing voluntary while offering every unit an incentive to scrub. They also allowed greater

flexibility in meeting SO<sub>2</sub> requirements, thus providing the possibility of more efficient use of new and existing scrubbers, further increasing their attractiveness and adding potential for cost savings. This combination of effects exposes scrubbing to competitive forces while offering it expanded opportunities for use. Under these conditions, we would expect to see scrubbing cost reductions associated with the 1990 CAAA. The relevance of this research can be found in Ellerman et al (2000), when they note that, “if subsequent research is able to confirm the suggested relation between regulatory regime and innovation, the implication will extend far beyond Phase II and Title IV.” Our motivation will be to explore this relationship.

The 1990 CAAA deviated from the historical approach to pollution control in that they sought to control emissions even from older units that were generally not subject to NSPS. This was particularly important because older units released a large percentage of total emissions, both in aggregate and relative to the quantity of electricity they generated (GAO, 1997). Units that began operating prior to 1972 emitted 59 percent of the sulfur dioxide released by power plants in the year 2000 despite generating only 42 percent of the electricity, an emission rate roughly twice that of new plants. In addition, the 1990 CAAA effectively required compliance at the utility-level rather than boiler-level, allowing utilities to reduce emissions using boilers with a comparative advantage.

The effect of permits is to create an implicit cost per ton of SO<sub>2</sub> emissions equal to the prevailing permit price. Plants have a number of potential responses to this implicit cost. They can continue to operate as they had previously and purchase permits to cover their emissions, switch to blends of coal with lower sulfur content, perhaps requiring some modification of the affected boiler, or install scrubbers to remove most of the SO<sub>2</sub> from their waste stream. Other more drastic options include adapting boilers to burn either oil or natural gas instead of coal or shutting down generating units entirely and transferring the unit's permits within the utility or selling them to another utility. Of these options, coal switching or blending was done at 136 or 52% of the Table A boilers and accounted for 59% of the emissions reductions achieved, scrubbers were installed at 27 or about 10% of the units and accounted for approximately 28% of the emissions reductions, and continued operation was chosen by 83 or 32% of the Table A boilers. Shut down or refueling with oil or gas was done for a total of 8 boilers, about 3% of the Table A boilers (EIA, 1997).

There is an extensive literature looking at the relationship between environmental regulations and pollution control technology and costs. Numerous theoretical papers have shown that market-based regulation offers greater incentives for innovation in pollution control technology. Early papers (Downing and White 1986, Milliman and Prince, 1989, Zerbe 1970) as well as more recent work (Jung et al, 1996) describe the incentives offered by market-based regulation in general and permit systems specifically.

Permit systems provide stronger incentives for innovation and adoption of cost-reducing technological changes than do abatement standards, the method of SO<sub>2</sub> regulation under the 1970 CAA and 1977 CAAA.<sup>2</sup>

Several papers have discussed the overall savings in compliance costs as a result of the 1990 CAAA. Ellerman et al (2000) take a comprehensive look at the cost of compliance and found substantial cost savings due to the CAAA of 1990. Part of this cost savings is found to be a drop in scrubbing costs relative to expectations prior to implementation of the 1990 CAAA. Schmalensee et al. (1998) find that Phase I compliance costs have been lower than expected while SO<sub>2</sub> reductions have been greater than expected. Carlson et al (2000) estimate marginal SO<sub>2</sub> abatement costs and show that the lower cost of low sulfur coal was a large contributor to the decline. While these studies have found reduced or lower than expected compliance costs, this does not imply that scrubber technology has advanced. It may simply be that the greater flexibility allowed by the 1990 CAAA has enabled firms to minimize costs with existing technology.

The first empirical paper looking at innovations in the scrubber market was Bellas (1998), which estimates a hedonic scrubbing cost model using installation year as a proxy

---

<sup>2</sup> Malueg (1989) offers a possible violation of this result, depending on whether firms are net buyers or sellers of permits and would thus stand to gain or lose (respectively) from decreased permit prices resulting from improved abatement technology.

for vintage. Data on scrubbers in use from 1985-1992 are used to determine if advances in scrubber technology have occurred. Lifetime scrubbing costs (capital costs plus 15 times the annual operating costs) are found not to have fallen significantly over time, implying no advancement in scrubber technology. Another finding is that plants “learn by doing” as operating costs fell significantly as age of the scrubber increased. A more qualitative look at innovation in the scrubber market is found in Taylor et al (2003) with the finding that government regulation or anticipation of government regulation, more than research subsidies, stimulates innovation. For a standardized scrubber (500 MW plant, coal containing 3.5% sulfur and removal efficiency of 90%), capital costs are estimated over the 1976-1995 time period. Results show capital costs falling by half over this time period. Additional results also confirm results in Bellas (1998) that plants “learn by doing” in operating their scrubbers. Evidence that government action in setting up national SO<sub>2</sub> control symposiums helps facilitate the diffusion of knowledge throughout the industry is another important finding of this paper.

Burtraw (1996, 2000) discusses some of the improvements made by scrubber manufacturers since the passage of the 1990 CAAA, including elimination of flue gas (the boiler waste gas) reheat and better instrumentation. He also notes that the existence of a permit market allows reduced redundancy in the physical capital of a scrubber as firms may purchase permits for emissions during scrubber downtime. Under NSPS-Da, firms were required to have redundant, parallel scrubbing systems that would allow them

to continue scrubbing even when one scrubber module was inoperative, a requirement effectively relaxed with CAAA of 1990. This resulting reduction in redundancy is estimated by the Energy Information Agency (EIA) (1994) to reduce capital costs by approximately one third. Other work supports the idea that scrubbers have become less expensive. The General Accounting Office (GAO) (1994) cites trade papers as saying that scrubber prices have halved since 1990.

Keohane (2003) estimates the effect of the CAAA of 1990 on abatement technique choice and abatement costs based on boiler-level data. Using probit analysis to predict scrubber installation and costs, he finds that scrubbers would have been more prevalent and significantly more expensive in the absence of this change in regulatory regime. Popp (2003) takes a different approach to innovation by looking at trends in scrubber related patent applications. The data, surprisingly, show that the rate of SO<sub>2</sub> control patent applications has not increased since the CAAA of 1990 was implemented, as theory would predict. The argument put forward by Popp is that the nature of innovation changed when the regulation changed. Under command-and-control type regulation, utilities attach no value to advances that increase the removal efficiency of a scrubber. Thus, innovation is directed to cost-reducing improvements. With a market-based system, improvements in removal efficiency are valuable. To test this theory, he constructs a stock of knowledge variable and an interaction term with a 1990 CAAA dummy variable to account for patent data. Data from 1972-1997 for two dependent

variables, scrubber efficiency and operating costs, were used to test the above hypothesis. These dependent variables were regressed on a knowledge stock and other explanatory variables using a hedonic scrubbing cost model similar to that of Bellas (1998). The operating cost regression uses a random effects estimator because the data is panel. The regression results support his argument that operating costs fell prior to the passage of the CAAA of 1990 and removal efficiency increased after passage the CAAA of 1990. The operating cost result runs counter to that of Bellas (1998), which found no change in operating costs over time.

The aim of this paper is to more rigorously investigate the relationship between regulatory regime and abatement technology using data that extend well past implementation of the 1990 CAAA. While it is important that overall compliance costs have fallen under 1990 CAAA, our goal is to focus on the effects on scrubbing costs. More specifically, when scrubbing costs are adjusted for a boiler's design and operating characteristics and the coal burned, what are the effects of a changing policy regime? This is different from examining compliance costs. Compliance costs have almost certainly fallen with implementation of the 1990 CAAA for a variety of reasons, particularly because of increased flexibility relative to earlier policy regimes. This is also different from scrubbing costs. A decrease in scrubbing costs doesn't necessarily imply an advance in scrubber technology if the 1990 CAAA permit greater flexibility in scrubber use. Only through adjusting costs for design and operating parameters can

technological advances related to policy changes be identified. This paper also acts as an empirical test of the environmental innovation literature (Downing and White 1986, Millman and Prince, 1989, Zerbe 1970, Jung et. al. 1996) predictions about which type of policy regime, command and control versus marketable permits, provides stronger incentives to innovate.

## 2.2 Data

The data used are from the Energy Information Administration (EIA) Form 767 from the years 1985 through 2002. This form collects information on design and operation of U.S. steam-electric plants with ratings of 10 megawatts or greater. The data are provided at the level of individual boilers and include design specifications for each boiler within a plant, the quantity and characteristics of coal burned in each boiler, the environmental regulations to which the boiler is subject, and the design characteristics, installation cost, and operating costs of any associated scrubbers. Of the 1009 boilers operating in the year 2002 that specified coal as their primary fuel, 213 had associated scrubbing units. Eight of these scrubbers were retired after 1995. Descriptive statistics are given in Table 2.1.

The variables are divided according to their use in analysis of either annual operating costs or capital costs, although there is some overlap. Real annual operating costs<sup>3</sup>,

---

<sup>3</sup> The price index used is the Producer Price Index, Intermediate materials, supplied and components, Total, with 1982=100.

expressed in thousands of dollars, are the total operation and maintenance expenditures during the year, excluding electricity but including feed materials and chemicals, labor and supervision related to scrubber operation, waste disposal, maintenance and all other related costs. Real capital costs<sup>4</sup>, also in thousands of dollars, are the FGD unit's installed cost for structures and equipment, also known as the price of a scrubber.

A variable of primary importance is the removal efficiency of the FGD unit. This variable is used in both the real operating and capital costs analysis. The data contain three measures of removal efficiency: efficiency at annual operating factor, tested efficiency, and design efficiency. Efficiency at annual operating factor is the efficiency based on the percent of capacity at which the associated boiler was operated. Tested efficiency is the tested removal efficiency of the scrubber. Design efficiency is the level of removal efficiency that the scrubber was initially designed to achieve. In modeling operating costs our primary measure was efficiency at the annual operating factor in each year of operation. If this measure was not available for a scrubber in the year in question, an adjacent year's annual operating factor efficiency was used.<sup>5</sup> Tested efficiency or design efficiency was used if annual operating factor efficiency was unavailable. In

---

<sup>4</sup> The price index used is Producer Price Index, Finished goods, Excluding foods and energy, Capital equipment, with 1982=100.

<sup>5</sup> These two options covered approximately 85% of our observations. For the remaining observations, tested efficiency or design efficiency was used. If none of these was available the scrubber was excluded from this analysis.

modeling capital costs, design efficiency was used as that is the information plants would have had when making purchase decisions.

Two other characteristics of scrubbers are included in both models as explanatory variables. The flue gas exit rate is the rate at which flue gases pass through the scrubber in cubic feet per minute; this serves as a measure of size or capacity. The flue gas pass-through percentage is the percentage of flue gases that pass through the scrubber rather than being diverted directly to the stack. The overwhelming majority of FGD units process 100% of the flue gas from the associated boiler. A value of less than 100% means that the FGD unit scrubs only a portion of the gases coming from the boiler and indicates that scrubbing capacity is less than would otherwise be the case.

Several variables were specific to modeling operating costs. Average sulfur is the average sulfur content of the coal burned in the associated boiler in that year. Total coal burned is the total amount of coal burned in the associated boiler in that year. The percent operating hours gives the scrubber's operating hours as a fraction of its associated boiler's hours. While scrubbers are generally in operation when their associated boilers are, utilities may rely on other compliance options if the scrubber is shut down.

We used the following variables specifically to model the capital costs. Designed sulfur is the scrubber's design specification for coal to be burned in the associated unit. The

number of scrubber trains, chambers of components that prepare the sorbent for mixture with the flue gas, was used as a measure of the number of parallel scrubbing units that constitute a scrubber and serve as a measure of the level of redundancy. Scrubbers installed under the 1977 CAAA policy regime average approximately twice as many trains as those installed under the 1990 CAAA policy regime as seen in Table 2.1.

Several dummy variables are used in both models. Federal regulation is a dummy variable taking the value 1 if the most stringent SO<sub>2</sub> regulation faced by the boiler was a federal regulation rather than a state or local regulation. Saleable product is a dummy variable where a value of 1 indicates that the scrubber in normal operation generates a byproduct that may be recovered and sold. South, Northeast and West are regional dummy variables; Midwest is the region coded to zero. The retrofit dummy takes a value of 1 if the scrubber came on line at least a year after the associated boiler. The CAA and CAAA dummy variables specify the regulatory era in which the scrubber came on line and are described in more detail below.

### 2.3 Analysis

To determine whether scrubber technology has advanced since the passing of the 1990 CAAA, we follow the model laid out by Bellas (1998). We examine two dependent variables, real annual operating costs and real capital costs, which are modeled as functions of scrubber, boiler, coal, and policy characteristics. The operating costs

regression uses a random effects estimator to control for unobserved boiler-scrubber characteristics over time in this panel data set. A random effects estimator is used because the policy variables of interest do not vary over time. The capital costs data set is cross sectional thus an OLS estimator with White-corrected standard errors is used.

Removal efficiency is the percentage of SO<sub>2</sub> that the scrubber removes from the flue gas. The relationship between removal efficiency and scrubber cost is formalized through the use of a standard engineering model that expresses removal efficiency as a number of standard scrubbing units (Perry and Green 1997, 14-1 - 14-10). Each 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<sup>6</sup>:

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

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

A scrubber with a removal efficiency of 86.4%, for example, would be the equivalent of two standard units. Assuming a constant cost per standard scrubbing unit implies increasing marginal costs of removal efficiency.

---

<sup>6</sup> Perry & Green (1997), pp 14-9. For simplification we assume there is no back pressure of SO<sub>2</sub>.

A multiplicative or double log model is used to estimate costs. This allows for economies of scale with respect to various explanatory factors and is more flexible than a linear model would be. For analysis of operating costs the model estimated is:

$$\ln \text{RealCosts}_{jt} = \ln \beta_0 + \beta_1 \ln \left( \ln \frac{1}{1 - x_{jt}} \right) + \sum_{i=2}^M \sum_{t=1}^T \beta_i \ln X_{ijt} + \sum_{i=M+1}^{M+N} \beta_i D_{ij} + v_j + \varepsilon_{jt} \quad [2]$$

where  $x_{jt}$  is the removal efficiency of unit  $j$  in period  $t$ ,  $\ln \frac{1}{1 - x_{jt}}$  is the number of

standard scrubbing units equivalent to the removal efficiency of unit  $j$  in period  $t$ ,  $X_{ijt}$  are the observed values of the  $M-1$  scrubber-boiler characteristic variables  $X_i$  for unit  $j$  in period  $t$ ,  $D_{ij}$  are values of the  $N$  dummy variables for unit  $j$  and  $v_j$  is the random effects

parameter. In addition, the models estimated include policy regime dummy variables and time trends as described in the text and indicated in the results. For analysis of capital costs, the model estimated is:

$$\ln \text{RealCosts}_j = \ln \beta_0 + \beta_1 \ln \left( \ln \frac{1}{1 - x_j} \right) + \sum_{i=2}^M \beta_i \ln X_{ij} + \sum_{i=M+1}^{M+N} \beta_i D_{ij} + \varepsilon_j \quad [3]$$

The variables are as described above except that they are values observed or reported in 2002 and  $x_j$  is the design efficiency of the FGD unit. Again, policy regime dummy

variables and time trends are included as explanatory factors as described in the text or in the results. The expected effects of each independent variable on the two dependent variables are given in Table 2.2.

To test for the effect of policy regime on real operating costs and real capital costs, we use three specifications of the model, yielding a total of six regressions. The first specification includes policy regime dummies based on the year of scrubber installation. The coding of these variables reflects a lag from passage of different versions of CAA and CAAA. The 1970 CAA dummy indicates scrubbers installed between 1973 and 1979, the 1977 CAAA dummy indicates scrubbers installed between 1980 and 1991 and the 1990 CAAA dummy indicates scrubbers installed in 1992 and beyond.<sup>7</sup> These years were chosen as breakpoints because they were the first years in which boilers subject to those CAAs had scrubbers installed.<sup>8</sup> Scrubbers installed prior to 1973 were coded to zero, thus the coefficients on the policy regime dummies will be relative to these early scrubbers. Due to the relatively small number of earlier scrubbers, our analysis of capital costs will involve only the 1977 and 1990 CAAA dummies, thus the reference group here is all scrubbers installed before 1980.

---

<sup>7</sup> Results were similar if the first year of the 1990 CAAA policy regime dummy was 1991, 1993 or 1994.

These results are available upon request from the authors.

<sup>8</sup> It is worth noting that requirements of CAAs applied to boilers, not scrubbers.

The second specification breaks the 1990 CAAA scrubbers into two sets: early and late 1990 CAAA. As mentioned above, Taylor (2003) finds that anticipated government regulation is a stimulus to innovation. To determine whether pre-regulation effects differed from post-regulation effects, the 1990 CAAA dummy was split in two. An early 1990 CAAA dummy is created for scrubbers installed between 1992 and 1995, while the late 1990 CAAA dummy corresponds to scrubbers installed in 1996 and after. All other variables are as given above.

The first two specifications of policy regime dummies allow for discrete changes in relevant costs across regimes, but constrain the rate of change in costs within a regime to be zero. To allow greater flexibility, we expanded the model to include the year of scrubber installation and an interaction variable of year of scrubber installation and the 1990 CAAA policy regime. We transform the year of scrubber installation variable by subtracting 1992 from each observation so that the 1990 CAAA policy regime dummy determines the discrete change in costs in the year 1992.<sup>9</sup> The estimated annual rate of change in costs of scrubbers installed after 1992 is the sum of the estimated coefficients on the year of scrubber installation and the interaction term. Including this interaction variable and the 1990 CAAA policy regime variable allows for a discrete change in costs

---

<sup>9</sup> Again, results were similar if the first year of the 1990 CAAA policy regime dummy was 1993 or 1994, although the 1990 CAAA dummy did lose significance if 1991 was the first year. These results are available upon request from the authors.

in 1992 (the first year of the 1990 CAAA policy regime dummy) as well as different annual rates of change starting in 1992 compared to pre-1992. This specification allows for differentiation between a one-time reduction in costs and a continual reduction over time. We drop the 1970 CAA and 1977 CAAA policy regime dummies in this specification, thus the comparison is between scrubbers installed before 1992 and those installed in 1992 and later.

## 2.4 Results

Regression results, presented in Table 2.3, are generally consistent with expectations. Flue gas exit rate and total coal, two measures of scale, have estimated coefficients that are positive but less than one, reflecting economies of scale. Scrubbers in the northeast had significantly higher capital and operating costs and those in the west had significantly higher capital costs than did those in the midwest (the excluded region). These regional effects may be due to differences in relative costs of living or other regional differences that are outside the primary focus of this paper. Retrofit units do not differ significantly from original units in either operating or capital costs. Regression results are consistent across specifications. For the operating costs regressions, the portion of variation explained by the random effects parameter,  $v_j$ , is given by rho in Table 2.3.

The estimated coefficients on regulatory variables confirm the hypothesized relationship between regulatory regime and innovation. We find that scrubbers installed under the

1990 CAAA are cheaper to purchase and cheaper to operate than those installed under any other policy regime. In addition, costs of scrubbers installed under the 1977 CAAA were not significantly different from the costs of those installed under the 1970 CAAA or earlier. Again, these results are consistent across specifications of the model.

The first specification includes dummy variables for each policy regime. Results of the first regression (Table 2.3, column 1) suggest that operating costs are significantly lower for scrubbers installed under the 1990 CAAA policy regime than for those installed under the NSPS of the 1970 CAA and 1977 CAAA. These results are consistent with those of Bellas, in that the estimated effects of the two older policy regimes are not significantly different from zero, implying no technological progress through 1991. These results were robust to exclusion of the eight scrubbers retired after 1995.

Results of the second regression (Table 2.3, column 2) suggest that capital costs are significantly lower for scrubbers installed under the 1990 CAAA policy regime than for those installed under the 1977 CAAA and earlier, controlling for the redundancy in physical capital (scrubber trains). Scrubbers installed under the 1977 CAAA are no cheaper than those installed earlier. As expected, provision of a saleable product and inclusion of a larger number of scrubber trains increase the price of a scrubber.

The second specification divides the 1990 CAAA into earlier and later periods. Results of the third regression (Table 2.3, column 3) suggest that operating costs fell further in the later portion of the 1990 CAAA, although a Chi-square test suggests that the estimated coefficients on the early and late 1990 CAAA dummy are not significantly different. Results from the fourth regression (Table 2.3, column 4) suggest that capital costs fell further in the early phase of the 1990 CAAA, a difference that an F-test showed to be significant at the 10% level. Results from these two tests are given in Table 2.4.

The third specification added a time trend variable and an interaction term between the time trend and the 1990 CAAA. Results of the fifth regression (Table 2.3, column 5) suggest that operating costs fell discretely with adoption of the 1990 CAAA but have held steady since then. There is no significant time trend for operating costs for scrubbers installed prior to 1992, and no significant time trend for those installed from 1992 on. Results of the sixth regression (Table 2.3, column 6) suggest that the path of capital costs takes a similar form. While there is a discrete drop in capital costs from previous regulatory regimes to the 1990 CAAA regime, the annual rate of change is not significantly different between regimes. Neither regression shows a significant trend over time in the costs of operating or purchasing a scrubber.

A possible confounder for our results is a change in the organization of the scrubber market. If the market concentration decreases, we may expect costs to fall or quality to increase regardless of regulatory regime due to increased competition between firms. We

compute the Herfindahl-Hirschman Index (HHI) of market concentration for each of the last three decades to determine how the market has evolved. The results, given in Table 2.5, suggest that, if anything, the market has become more concentrated in the 1990s. This suggests that changes in the structure of the scrubber market are not driving our results.<sup>10</sup>

## 2.5 Conclusion

While market-based environmental regulations offer greater flexibility and opportunities for reduced compliance costs given existing technology, the more important long run effect might be their impact on technological change and the costs associated with individual compliance options. We look at the effect of the 1990 CAAA, a market-based approach to SO<sub>2</sub> regulation, on scrubber costs. Compared to previous regimes, the 1990 CAAA expanded the potential market for scrubbers but also increased the level of competition they faced. Theoretical models have long predicted that market-based regulation will provide greater incentives to innovate than command-and-control regulations. We test this theory by analyzing the effect of the 1990 CAAA on real

---

<sup>10</sup> An anonymous reviewer suggests that over-capacity in the scrubber industry in anticipation of 1990 CAAA may have contributed to decreases in capital costs when coal switching materialized as a more cost-effective option for many plants.

operating and capital costs. Both operating and capital costs took a discrete fall with the CAAA of 1990, but demonstrated no statistically significant difference in the annual rate of change subsequently. A time trend variable showed no statistically significant change in either costs over the sample period. Comparing the scrubbers installed under the first couple years of the 1990 CAAA with those installed later show that the capital costs fell more in the early part of the 1990 CAAA. To some extent our results are mixed, suggesting that adoption of policies that offer greater incentives for innovation provides for a great leap forward in cost reductions, but not necessarily subsequent ongoing progress.

Table 2.1: Descriptive Statistics

Mean Values for Operating and Capital Cost Variables by Boiler		
Variable	Pre 1990 CAAA	Post 1990 CAAA
<b>Operating</b>	n=128	n=40
Real Annual Operating Costs, \$1000	2621.51	2185.35
Tested Removal Efficiency	80.36	84.91
Hours Boiler Under Load	7791.24	7520.88
Flue Gas Exit Rate, cu ft per minute	1571369	1719716
Flue Gas Pass-Through (%)	92.41	100
Average Sulfur Content, % x 100	154.9	169.01
Total Coal, 1000 tons	16081.6	15690.38
Boiler Inservice Hours	7707.08	7338.33
Percent Operating Hours	0.99	0.97
Federal Regulation	0.3	0.25
Saleable Byproduct	0.17	0.3
South	0.36	0.33
Northeast	0.05	0.13
West	0.31	0.28
Age	12.97	3.57
Retrofit	0.25	0.82
<b>Capital</b>	n=157	n=56
Real Capital Costs, \$1000	58747.01	42630.31
Designed Removal Efficiency	82.28	86.68
Designed Sulfur	2.15	2.4
# of FGD Trains	3.4	1.61
FGD Trains Operating at 100%	2.95	1.55

Source: EIA-767 (2002).

Table 2.2: Expected Signs of Independent Variables

Expected Sign of Independent Variables, by Dependent Variable		
Variable	Annual Operating Costs	Capital Costs
Removal Efficiency	+/-	+
Flue Gas Exit Rate	+	+
Flue Gas Pass-Through (%)	+	+
Average Sulfur	+	NA
Total Coal Burned	+	NA
Percent Operating Hours	+	NA
Designed Sulfur	NA	+
# of FGD Trains	NA	+
Federal Regulation	+/-	+/-
Saleable Product	+	+
South	+/-	+/-
Northeast	+/-	+/-
West	+/-	+/-
70 CAA	+/-	NA
77 CAAA	+/-	+/-
90 CAAA	-	-
Age	-	NA
Retrofit	+/-	+
NA = Not Applicable	+/- = Ambiguous	

Table 2.3: Regression Results

Dependent Variable	Column 1 In Real Operating Costs	Column 2 In Real Capital Costs	Column 3 In Real Operating Costs
R <sup>2</sup>		0.391	
N	2345	212	2345
In Removal Efficiency	0.012	0.411	0.013
In Flue Gas Exit Rate	<b>0.273*</b>	<b>0.367*</b>	<b>0.268*</b>
In Flue Gas Pass-Through (%)	<b>0.835*</b>	0.336	<b>0.842*</b>
In Average Sulfur	<b>0.431*</b>		<b>0.429*</b>
In Total Coal	<b>0.428*</b>		<b>0.431*</b>
In Percent Operating Hours	<b>0.378*</b>		<b>0.377*</b>
In Designed Sulfur		0.117	
# of Scrubber Trains		<b>0.177*</b>	
Federal Regulation	<b>0.102</b>	0.15	<b>0.104</b>
Saleable Product	-0.056	<b>0.794*</b>	-0.076
South	-0.078	0.073	-0.091
Northeast	<b>0.658*</b>	<b>1.33*</b>	<b>0.639*</b>
West	-1.680	<b>0.619</b>	-0.159
70 CAA	-0.138		-0.143
77 CAAA	-0.231	-0.073	-0.229
90 CAAA	<b>-1.00*</b>	<b>-1.24*</b>	
Year FGD Installed			
90 CAAA* Year FGD Installed			
Early 90 CAAA			<b>-0.900*</b>
Late 90 CAAA			<b>-1.076*</b>
Age	<b>-0.018*</b>		<b>-0.018*</b>
Retrofit Dummy	0.056	-0.248	0.040
Constant		2.650	
Rho	0.565		0.565

Estimates significant at the 10% level are in bold, 5% level denoted with a "\*\*\*"

Table 2.3: Regression Results continued

Dependent Variable	Column 4	Column 5	Column 6
	In Real Capital Costs	In Real Operating Costs	In Real Capital Costs
R <sup>2</sup>	0.400		0.400
N	212	2345	212
In Removal Efficiency	0.401	0.016	0.360
In Flue Gas Exit Rate	<b>0.357*</b>	<b>0.273*</b>	<b>.359*</b>
In Flue Gas Pass-Through (%)	0.294	<b>0.840*</b>	0.192
In Average Sulfur		<b>0.430*</b>	
In Total Coal		<b>0.435*</b>	
In Percent Operating Hours		<b>0.377*</b>	
In Designed Sulfur	0.132		0.151
# of Scrubber Trains	<b>0.175</b>		<b>0.181*</b>
Federal Regulation	0.094	<b>0.108</b>	0.124
Saleable Product	<b>0.814*</b>	-0.078	<b>0.767*</b>
South	0.118	-0.097	0.102
Northeast	<b>1.43*</b>	<b>0.628*</b>	<b>1.41*</b>
West	<b>0.552</b>	-0.155	<b>0.554</b>
70 CAA			
77 CAAA	-0.066		
90 CAAA		<b>-0.466</b>	<b>-1.74*</b>
Year FGD Installed		-0.961	0.543
90 CAAA* Year FGD Installed		-0.039	0.105
Early 90 CAAA	<b>-1.52*</b>		
Late 90 CAAA	<b>-0.868*</b>		
Age		<b>-0.0184*</b>	
Retrofit Dummy	-0.286	0.048	-0.253
Constant	3.000		0.997
Rho		0.561	

Estimates significant at the 10% level are in bold, 5% level denoted with a ""

Table 2.4: Coefficient Tests

Testing Difference Between Early and Late 1990 CAAA			
Null:	Early 1990 CAAA - Late 1990 CAAA = 0.0		
	Operating Costs		Capital Costs
Chi (1)	0.85	F(1,197)	2.77
Prob	0.355	Prob	0.097

Table 2.5: Herfindahl-Hirschman Index Results

Herfindahl-Hirschman Index of Scrubber Market Concentration		
1970s	1980s	1990s
0.1110	0.0984	0.1352

## Chapter 3

### **Coal Market Integration: The Effect of Pollution Abatement Flexibility and Railroad Deregulation on the Markets for High and Low Sulfur Coal**

#### **3.1 Background**

The use of coal as an energy source has stabilized in the U.S. after rising appreciably in the late 1970's. Coal currently accounts for roughly half of the electricity generated in the U.S. Coal is a bundled input, with the desirable quality of heat bundled with undesirable qualities such as sulfur, which becomes sulfur dioxide (SO<sub>2</sub>) when burned. The history of regulation tied to coal comes largely from the regulation of railroads, which is the primary mode of transportation from mine to power plant, and power plant SO<sub>2</sub> abatement technique choice. Railroads were deregulated by the Staggers Act of 1980 and permissible techniques for SO<sub>2</sub> abatement were liberalized by the Clean Air Act Amendments (CAAA) of 1990, which instituted a cap-and-trade program for SO<sub>2</sub> emissions. Due to the flexibility inherent in these regulations, we expect to see changes in the markets for coal consistent with cost minimization. The change relevant here is that the markets for high and low sulfur coal should become more integrated as power plants are able to substitute between the two. The rest of this section is broken into a history of SO<sub>2</sub> abatement regulation, a history of railroad regulation, and the effect of deregulation on the coal market.

*SO<sub>2</sub> Regulation*

The market-based approaches of the 1990 CAAA are different from past air pollution regulation. Initially, much of the SO<sub>2</sub> regulation was of the command and control type where power plants were mandated to use certain inputs (scrubbers, etc) to meet boiler specific requirements. The earliest regulation was the CAAA of 1970, which required new boilers not to exceed emissions of 1.2 pounds of SO<sub>2</sub> per million Btus. Boilers that came online under these regulations were free to meet this performance standard as they please; most power plants either scrubbed or purchased low-sulfur coal. Next, the CAAA of 1977 added requirements that, for all purposes, required the installation of scrubbers for all boilers that came online between 1977 and 2000. Boilers built prior to 1970 were unregulated at the federal level. As a result, the only boilers with an incentive to use low-sulfur coal were those that came online between 1970 and 1977 (Burtraw, 1996).

In Phase I of the 1990 CAAA, which began in 1995, permits were handed out at a rate of 2.5 pounds of SO<sub>2</sub> per million Btu for 263 boilers which were previously unregulated at the federal level. Phase II, which began in 2000, lowered the rate to 1.2 pounds of SO<sub>2</sub> per million Btu for all boilers with a capacity of 25 megawatts and higher. Options available to meet the emissions standard include purchasing low-sulfur coal, installing a scrubber, and/or buying permits. The tradable permit market has been of much interest in the applied economics literature since its inception. Most of the literature to this point dealing with the CAAA of 1990 has focused on the performance of the SO<sub>2</sub> permit

market<sup>11</sup>. The transition from command and control to market-based regulation has a much broader reach into the workings of a market economy than the SO<sub>2</sub> permit market. When the federal government drops its mandates on how a power plant abates SO<sub>2</sub>, it drastically alters the value of attributes inherent in the inputs used. It also allows power plants to better use inputs that are fairly substitutable in the production process, such as different types of coal, to meet the emissions cap.

### *Railroad Regulation*

The cost of coal at the mine can vary substantially from the price of delivered coal to a power plant. This is due to the geographical distribution of coal and power plants in the U.S. The majority of low-sulfur coal is found in the Powder River Basin (PRB) of northern Wyoming and southern Montana, generally classified as part of the Western Basin. The other major coal basins in the U.S. are the Interior Basin including Illinois, Kentucky, and Indiana and the Appalachian Basin including West Virginia, Pennsylvania, and Tennessee. The Interior Basin has the highest sulfur content while the Appalachian Basin has a mix of sulfur contents. A majority of coal-fired power plants are located east of the Mississippi. The Energy Information Agency (EIA) estimates that in 1997, transportation costs of coal account for 35% of the price of delivered coal and that 70% of coal is shipped by rail exclusively<sup>12</sup>. Both the percentage of cost attributed to

---

<sup>11</sup> See Schmalensee et al (1998) for an example

<sup>12</sup> Available at <http://www.eia.doe.gov/cneaf/coal/ctrdb/natlrends.html> as Cost as a Percentage of Delivered Price and Tonnage by Mode, respectively.

transportation costs and the use of rail have increased over time. An important factor then in determining what coal a customer buys is the price of shipping by rail.

Railroad deregulation started in 1976 with the Railroad Revitalization and Regulatory Reform Act and was extended and largely completed with the Staggers Act of 1980. Prior to these laws, maximum railroad rates were set by the Interstate Commerce Commission (ICC) based upon the Interstate Commerce Act (ICA) of 1887. A detailed history of railroad regulation can be found in Keeler (1983) with an emphasis on Chapter 5<sup>13</sup>. The ICC set rates that were just and reasonable. As can be expected, just and reasonable rates have little reason to be in line with efficient rates. In addition, transportation by rail often requires coal to move from one firm's tracks to another's. The ICC set the rates one rail firm could charge other rail firms to switch between tracks. These rates did not vary based on supply and demand. Abandoning unprofitable lines and starting new lines of service were often not allowed by the ICC. Burlington Northern Railroad had a monopoly on shipments from the PRB until 1983 when Union Pacific was allowed to service lines (Keeler, 1983). The result of the federal regulation of railroad was restricted competition among rail firms for delivery of low-sulfur coal (Burtraw, 1996).

The Staggers Act of 1980 largely deregulated rail rates and allowed firms to alter the lines serviced. The Staggers Act of 1980 stated that, except where a railroad had "market

---

<sup>13</sup> Detailed descriptions of railroad regulation used in this paper are based on Keeler.

dominance,” it was free to set rates as it pleased. It defined market dominance as a ratio of revenues to variable costs higher than a certain number. This number started at 160 and was set to rise as the ICC saw fit.

Railroad firms were then able to compete for the service of transporting coal from the PRB to power plants. The amount of western coal produced increased from 334 million tons in 1990 to 550 million tons in 2002, a 65 percent increase. Higher sulfur content coal basins, such as the Interior Basin, have seen their production decrease from 205 million tons to 146 million tons over the same time period, a 30 percent decrease. (EIA, Various Years) The rail industry implemented many innovations to meet the increased demand for PRB coal such as laying double tracks, increasing the number of locomotives, and increasing the car fleet size (Burtraw, 1996). As a result, the average rate per ton-mile of contract coal rail shipment between the PRB and Midwest power plants fell by half between 1979 and 1993. (Ellerman and Montero, 1998) The EIA found that the average contract coal rate per ton-mile fell from 2.81 cents to 1.36 cents between 1979 and 1997<sup>14</sup>. This decrease in per ton-mile rail rates may be deceiving as Busse and Keohane (2003) show that railroads lowered per ton-mile rates to increase a fixed fee that allows them to capture a larger amount of the rents created by the CAAA of 1990.

---

<sup>14</sup> Available at <http://www.eia.doe.gov/cneaf/coal/ctrdb/natlrends.html> as Rate Per Ton-Mile

*Effect of Deregulation*

These two cases of government deregulation should have a major effect on the market for coal. The CAAA of 1990 allows power plants to substitute between low and high sulfur coal and railroad deregulation allows plants to substitute between coals from different regions. A power plant would then see low-sulfur coal and high-sulfur coal as fairly close substitutes and would be free to purchase the cheaper one (taking into account the price of a permit). Theoretically, we would expect that the two coal markets (high and low sulfur) would become more integrated as power plants exploit price differentials between the two to minimize the cost of compliance. Efficient trade should bring about a difference in the price of high and low sulfur coal that approximates the value of sulfur. If sulfur is correctly priced and the markets are integrated, then power plants should be indifferent to purchasing high or low sulfur coal. The law of one price would, in essence, hold in this situation. If markets are not integrated, thus the law of one price does not hold, then there are gains to be made by buying whichever coal is cheaper, increasing demand for that type and causing its price to rise. This process would continue until the difference between the two prices equaled the value of sulfur.

**3.2 Data**

Data come from the Federal Energy Regulatory Commission (FERC) Form 423: Monthly Report of Cost and Quality of Fuels for Electric Plants. The sample used is from July 1972 to December 2002. The data are a fairly detailed breakdown of every coal purchase

for plants 50 megawatts and larger, which represents 99% of electric utility coal deliveries. The prices used are the log of cents per million BTU deflated to 1982 prices using the PPI for all commodities.

In order to carry out an analysis of whether a coal market is integrated, a time series of prices (a price index) needs to be created. The data are given as the amount of coal purchased by a given plant from a given mine for a given price at a given time. The price index used is the mean of all transactions in a given month that fit a given category<sup>15</sup>. Since the data are denoted in months, a monthly index of coal prices is created.

### **3.3 Analysis**

Coal transactions are first separated by the level of sulfur. Following Stanton (1992), low sulfur coal is defined as coal having less than 1.2 lbs of SO<sub>2</sub> per million BTU; high sulfur coal is defined as coal with greater levels of sulfur. After separating coal transactions by sulfur level, indices are next created by the location of the purchasing plant. Three coal demand regions (CDR) were formed: the East, East Midwest, and West Midwest. The number of transactions by plants located in the West was insufficient for inclusion in this analysis. A list of states that make up each CDR is given in Table 3.1. This set-up looks for evidence of market integration between plants in these three regions. Ideally,

---

<sup>15</sup> A second type of price indices is created using the weighted mean based on the quantity (in tons of coal) purchased for all transactions in a given month that fit a given category but the results did not vary.

the CDRs would be finer than these, but too few transactions occur on a consistent basis for both sulfur types. A graph of the price indices by region is given in Figure 3.1.

The above history of regulation in the coal market separates the years analyzed by the level of barriers to efficient trade. In addition, Figure 3.1 shows that prices were greatly affected by the Arab Oil Embargo of 1973-74. During this time of large price increases, it is expected that plants would find it difficult to arbitrage between the three coal regions thus we would like to exclude this time period from our analysis. To determine the years during which regulatory change had the greatest impact on the price index, segments of the time series are tested for evidence of a structural break using a Chow Breakpoint test. A simple model of high sulfur coal prices regressed against a constant and low sulfur coal prices is used to determine the structural break dates. All combinations of the years 1974/1975, 1982/1983, and 1994/1995 were used as possible breakpoints for all three regions. The combination of years with the largest sum of F-statistics across the three regions is used to break the data into three time periods (Hansen 2001). The results of the Chow Breakpoint test can be found in Table 3.2. Each time period corresponds to varying levels of barriers to efficient trade between coal markets, thus varying opportunities for arbitrage. A breakdown of time periods, regulatory regimes, and integration hypothesis is given in Table 3.3.

The price indices are analyzed for evidence of cointegration to test the integration hypothesis. The theory of market integration using cointegration tests is based on an error correction mechanism. This error correction mechanism states that two time series (the price of high and low sulfur coal) will not deviate persistently from an equilibrium condition (Walls, 1994). The equilibrium condition that does not allow persistent deviation is presumed to be the no arbitrage condition. If the two time series of prices deviate from the law of one price, arbitrage would force the prices back into equilibrium.

Testing for cointegration between two time series is straightforward. Cointegration tests are a two-step process. First, the time series is tested for a unit root to insure that the time series is non-stationary (also known as integration of level 1,  $I(1)$ ), which would imply that the mean and variance are time dependent. In addition, tests are run on the first difference of the time series to insure that they are stationary. An augmented Dickey-Fuller (ADF) unit root test is used with a constant, no time trend, and a maximum of 12 lags. The significance levels are provided by MacKinnon (1991). The second step is to determine the number of cointegrating vectors in a system of time series. Johansen's (1995) maximum likelihood multivariate cointegration tests are used to determine how integrated the given markets are. This multivariate cointegration test evaluates the long-run equilibrium relationship in prices simultaneously (Nagubadi et al., 2001). If there are  $N$  time series in the market, then integration would require  $N-1$  cointegrating vectors. The tests were conducted assuming a model with an intercept and no time trend in the

cointegrating equation. A variable autoregressive (VAR) lag length test using the Akaike Information criterion was used to determine the optimal number of lags in the cointegration tests. All estimations were performed in Eviews. The VAR estimated is:

$$\Delta P_t = \mu + \Gamma_1 \Delta P_{t-1} + \dots + \Gamma_k \Delta P_{t-k} + \Pi P_{t-1} + \epsilon_t \quad [1]$$

where  $\Delta$  is the first difference operator,  $\Delta P_t$  is a (2x1) vector of coal prices,  $\Gamma$  and  $\Pi$  are coefficient matrices,  $\mu$  is a constant, and  $\epsilon_t$  is a (2X1) vector of normally distributed iid error terms. The number of cointegrating vectors is determined by the rank of the  $\Pi$  matrix.

### 3.4 Results

Results of unit root tests for price indices are listed in Table 3.4. All of the price indices failed to reject a unit root at the 10% significance level and all of the first differences rejected a unit root at the 1% significance level. Thus, all price indices are non-stationary and I(1). Results of the Johansen cointegration tests are given in Table 3.5.

Results based on the type of regulation show a discrepancy between periods that does not follow theoretical expectations. Of most interest from a policy perspective is the 1996-2002 time period. The West Midwest and East CDR is integrated at the 10% significance level, while the East Midwest is not. Results for the 1983-1994 time period find the West

Midwest CDR integrated at the 1% significance level and the East Midwest CDR integrated at the 10% significance level. In the 1976-1981 time period, only the West Midwest CDR is integrated at the 10% significance level. The fact that the West Midwest CDR is integrated for all three time periods is likely due to its location between the high sulfur Interior Basin and the low sulfur Western Basin. Overall, the evidence is not compelling for increased integration over time, although the 1996-2002 has two integrated regions (at the 10% significance level) as opposed to one in the 1976-1981 time period.

The results for the 1996-2002 time period suggest that some power plants are not minimizing the costs of complying with the 1990 CAAA by arbitraging between coal of different sulfur levels. Although this result does not match what was expected, there is other evidence that this is the case. Previous research such as Swinton (2002, 2004) and Carlson (2000) come to similar conclusions. Swinton finds that the marginal abatement cost of sulfur for plants are not equal using an output distance function between power plants. Carlson reaches a similar conclusion by econometrically estimating the marginal abatement cost of sulfur for all Phase I boilers. In addition, Rose (1997) notes that state-level regulation of power plants by public utility commissions often favors a self sufficient compliance strategy, such as buying low sulfur coal, which involves no purchase of permits for compliance. This seems to have caused power plants to buy low sulfur coal over cheaper (including the permits needed for compliance) high sulfur coal.

Each cointegration test estimates speed of adjustment parameters, which provide information concerning how one time series responds to changes in the other. Table 3.6 gives the speed of adjustment parameters for the cointegration tests reported in Table 3.5. These parameters tell us how quickly the price of one time series responds to changes in the price of the other. The larger the magnitude of the parameter, the quicker the given price adjusts to a one unit change in the other price. If two times series are not cointegrated, then the speed of adjustment parameters does not have any economic meaning. The numbers underlined are those whose series are not cointegrated, thus they should be ignored. Of most interest here is the West Midwest CDR. After railroad deregulation, low sulfur coal prices are driving the price dynamics with high sulfur coal prices responding to changes in low. This is a result of the parameters being significant for the price of high sulfur coal but insignificant for the price of low sulfur coal in the West Midwest CDR. This is expected given the large increase in Western Basin coal purchases after 1990 relative to those basins with higher sulfur content. The magnitude of adjustment for high sulfur coal is largest in the 1996-2002 time period suggesting that adjustments in prices are quicker than in previous periods.

To further investigate the effects of deregulation on the coal market, the CDR price indices were further broken down by contract type. Contracts for coal delivery that were less than one year in duration were labeled spot market transactions while those over one year in duration were labeled contract market transactions. As examined in Joskow

(1990) most contract market transactions specify a price adjustment mechanism that determines how the price adjusts over time. This price adjustment mechanism can lead to price rigidity depending on the components of the adjustment formula. Power plants often contract for the majority of their coal purchases and use the spot market for demand fluctuations. The increased price sensitivity of the spot market relative to the contract market makes the deregulation of railroads (and the resulting drop in rail price) important factors for changes in the spot market. This framework will test whether one of the transaction types has been differentially affected by the changes in regulation. Results of the unit root tests and cointegration tests for the price indices separated by contract type are listed in Table 3.7 and 3.8, respectively.

The pattern over time found when separating transactions by contract type is similar to that of the combined analysis. The 1996-2002 time period has one integrated CDR spot market (East) at the 10% significance level and two CDRs contract markets (East Midwest and West Midwest). This is in contrast to the 1983-1994 time period where all of the contract market CDRs were integrated and the East Midwest and the West Midwest CDR spot markets were also integrated. The earliest time period has only two integrated CDRs (East and West Midwest contract) out of the eight. Based on these results, railroad deregulation seems to have greatly improved the integration of the coal market, although the 1996-2002 time period does not continue this level of integration. One point to note is that for the West Midwest CDR, the contract market is integrated

throughout. This, again, is likely due to the relative location of the West Midwest CDR and coal regions.

The speed of adjustment parameters for this framework are given in Table 3.9. Surprisingly, the contract markets tend to adjust quicker than the spot market to changes in the price dynamics. For each time period, the magnitude of adjustment by high sulfur coal prices is larger in the contract market than in the spot market. The West Midwest CDR contract purchases show that the price of high sulfur coal is reacting to changes in the price of low sulfur coal. The magnitude of adjustment for high sulfur coal is largest for all time periods in the West Midwest CDR. The East Midwest CDR has its largest adjustment parameter in the 1996-2002 time period also.

### **3.5 Conclusion**

Regulation of the coal market has undergone various levels of impediments to efficient trade. Railroad deregulation began in 1983 and SO<sub>2</sub> pollution abatement technique deregulation began in 1995. Using regulatory regimes to separate the last thirty years of coal purchases, we look for evidence of increased market integration over time. Price indices are created by taking the mean of all coal purchases by sulfur level for three CDRs. Cointegration tests are run to determine if regional high and low sulfur markets are integrated. Evidence suggests that the time period 1996-2002 is less integrated than theoretically expected. Transactions within each CDR and sulfur level are next separated

by spot or contract market. Results show that the West Midwest CDR contract market was integrated over the entire sample. Also the spot market became more integrated in the 1983-1994 time period, but this result does not hold for the 1996-2002 time period. Speed of adjustment parameters show that the West Midwest CDR price dynamics are driven by the price of low sulfur coal for all time periods, with the magnitude of adjustment being largest for the 1996-2002 time period.

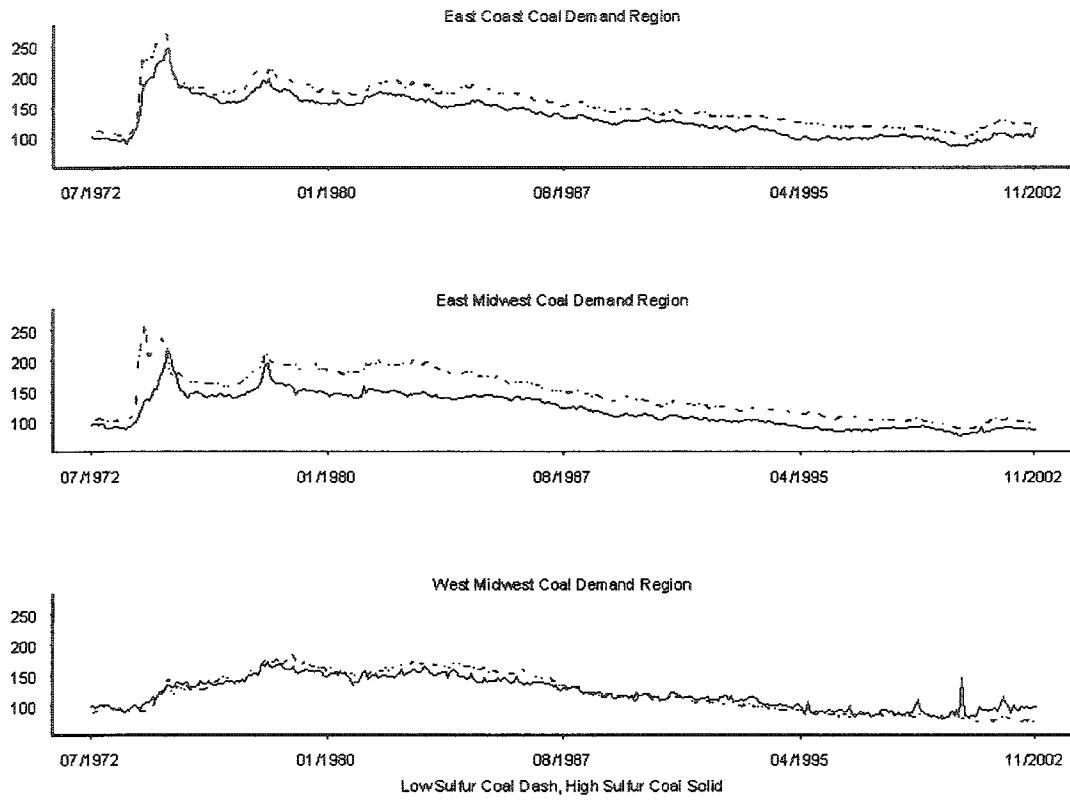


Figure 3.1: Time Series of Coal Prices

Table 3.1: Guide to States in each Coal Demand Region

Coal Demand Region	States
East	Maine, Vermont, New Hampshire, Massachusetts, Rhode Island, Connecticut, New York, New Jersey, Pennsylvania, Delaware, West Virginia, Maryland, Virginia, North Carolina, South Carolina, Georgia, Florida
East Midwest	Michigan, Wisconsin, Illinois, Indiana, Ohio, Kentucky, Tennessee, Mississippi, Alabama
West Midwest	Minnesota, Iowa, Missouri, Arkansas, Louisiana, North Dakota, South Dakota, Nebraska, Kansas, Oklahoma, Texas

Table 3.2: Chow Test to Determine Breakpoints

Chow Breakpoint Test F-Statistic				
	East	East Midwest	West Midwest	Summation
75/82/94	42.5	31.5	14.2	88.2
75/82/95	39.1	31.8	19.7	90.7
75/83/94	43.5	28.6	14.7	86.8
75/83/95	39.2	29.2	20.0	88.4
74/82/94	37.8	26.3	14.2	78.3
74/82/95	34.6	26.5	19.7	80.8
74/83/94	39.5	26.0	14.7	80.2
74/83/95	35.6	26.5	20.1	82.2

Table 3.3: Hypothesis

Time Period	Barriers to Efficient Trade	Integration Hypothesis
1976-1981	Strong (Railroad & SO <sub>2</sub> )	Least Integration
1983-1994	Modest (SO <sub>2</sub> )	Modest Integration
1996-2002	Weak	Most Integration

Table 3.4: Unit Root Tests Results I

Unit Root Tests Null Hypothesis: Series has a unit root	Level		First Difference	
	ADF T-Statistic	Probability	ADF T-Statistic	Probability
High Sulfur East Coast	-2.394	14.41%	-6.978	0.00%
High Sulfur East Midwest	-1.231	66.21%	-15.438	0.00%
High Sulfur West Midwest	-1.183	68.31%	-16.102	0.00%
Low Sulfur East Coast	-2.309	16.96%	-11.286	0.00%
Low Sulfur East Midwest	-1.778	39.10%	-13.782	0.00%
Low Sulfur West Midwest	-0.223	93.26%	-17.044	0.00%

All times series are from 07/1972 to 12/2002

Table 3.5: Cointegration Results I

## Johansen Cointegration Test: 1996-2002

By Sulfur Level	# of Cointegrating Equations	Eigenvalue	Trace Statistic	P-Value	# of Lags
East Coast	None	0.14	19.07	0.07	8
	At most 1	0.07	6.53	0.15	
East Midwest	None	0.14	15.70	0.19	5
	At most 1	0.03	2.83	0.61	
West Midwest	None	0.18	18.97	0.07	2
	At most 1	0.02	1.88	0.80	

## Johansen Cointegration Test: 1983-1994

By Sulfur Level	# of Cointegrating Equations	Eigenvalue	Trace Statistic	P-Value	# of Lags
East Coast	None	0.04	10.22	0.62	2
	At most 1	0.03	4.25	0.38	
East Midwest	None	0.07	19.30	0.07	2
	At most 1	0.06	8.44	0.07	
West Midwest	None	0.17	34.61	0.00	1
	At most 1	0.05	7.70	0.09	

## Johansen Cointegration Test: 1976-1981

By Sulfur Level	# of Cointegrating Equations	Eigenvalue	Trace Statistic	P-Value	# of Lags
East Coast	None	0.15	16.71	0.14	3
	At most 1	0.07	5.39	0.24	
East Midwest	None	0.09	9.58	0.68	2
	At most 1	0.04	3.02	0.58	
West Midwest	None	0.20	21.06	0.04	1
	At most 1	0.06	4.81	0.30	

Table 3.6: Speed of Adjustment Results I

Speed of Adjustment Parameters 1996-2002	East	East Midwest	West Midwest
Change in Price of Low Sulfur	0.068	<u>-0.146</u>	0.042
T-Stat	3.390	<u>-3.174</u>	1.000
Change in Price of High Sulfur	-0.011	<u>-0.099</u>	-0.624
T-Stat	-0.262	<u>-1.833</u>	-4.132
1983-1994			
Change in Price of Low Sulfur	<u>0.000</u>	0.102	0.114
T-Stat	<u>-0.002</u>	2.856	1.642
Change in Price of High Sulfur	<u>-0.098</u>	-0.028	-0.371
T-Stat	<u>-2.299</u>	-0.943	-4.960
1976-1981			
Change in Price of Low Sulfur	<u>0.490</u>	<u>0.005</u>	0.233
T-Stat	<u>0.660</u>	<u>0.100</u>	2.060
Change in Price of High Sulfur	<u>-0.271</u>	<u>-0.161</u>	-0.352
T-Stat	<u>-3.010</u>	<u>-2.330</u>	-3.350

Results underlined are not from cointegrated series thus they should be ignored.

Table 3.7: Unit Root Tests II

Unit Root Tests	Level		First Difference	
Null Hypothesis: Series has a unit root	ADF T-Statistic	Probability	ADF T-Statistic	Probability
High East Contract	-1.463	55.135%	-8.572	0.000%
High East Midwest Contract	-0.480	89.193%	-24.791	0.000%
High West Midwest Contract	-1.265	64.685%	-17.647	0.000%
High East Spot	-2.525	11.031%	-9.585	0.000%
High East Midwest Spot	-2.267	18.343%	-9.034	0.000%
High West Midwest Spot	-1.906	32.946%	-16.948	0.000%
Low East Contract	-1.715	42.273%	-7.230	0.000%
Low East Midwest Contract	-0.496	88.885%	-9.876	0.000%
Low West Midwest Contract	-0.716	83.984%	-21.386	0.000%
Low East Spot	-2.545	10.571%	-11.716	0.000%
Low East Midwest Spot	-2.346	15.832%	-14.590	0.000%
Low West Midwest Spot	-1.111	71.265%	-18.087	0.000%

All times series are from 07/1972 to 12/2002

Table 3.8: Cointegration Results II

Johansen Cointegration Test: 1996-2002					
By Sulfur Level	# of Cointegrating Eq.	Eigenvalue	Trace Statistic	P-Value	Lags
East Contract	None	0.14	16.69	0.14	8
	At most 1	0.05	4.20	0.38	
Emdws Contract	None	0.24	27.01	0.01	3
	At most 1	0.05	4.30	0.37	
Wmdws Contract	None	0.25	27.94	0.00	2
	At most 1	0.05	4.33	0.37	
East Spot	None	0.15	18.28	0.09	8
	At most 1	0.05	4.19	0.38	
Emdws Spot	None	0.10	10.93	0.55	1
	At most 1	0.03	2.25	0.73	
Wmdws Spot	None	0.13	15.14	0.22	3
	At most 1	0.04	3.49	0.49	
Johansen Cointegration Test: 1983-1994					
By Sulfur Level	# of Cointegrating Eq.	Eigenvalue	Trace Statistic	P-Value	Lags
East Contract	None	0.10	22.58	0.02	5
	At most 1	0.05	6.67	0.15	
Emdws Contract	None	0.11	24.44	0.01	2
	At most 1	0.06	8.26	0.07	
Wmdws Contract	None	0.18	35.44	0.00	1
	At most 1	0.05	6.81	0.14	
East Spot	None	0.07	13.77	0.31	2
	At most 1	0.02	3.27	0.53	
Emdws Spot	None	0.14	25.38	0.01	1
	At most 1	0.03	4.27	0.37	
Wmdws Spot	None	0.13	23.29	0.02	4
	At most 1	0.02	3.27	0.53	

Table 3.8: Cointegration Results II, continued

Johansen Cointegration Test: 1976-1981

By Sulfur Level	# of Cointegrating Eq.	Eigenvalue	Trace Statistic	P-Value	Lags
East Contract	None	0.24	22.39	0.03	1
	At most 1	0.04	3.05	0.57	
Emdws Contract	None	0.06	8.51	0.78	2
	At most 1	0.05	3.90	0.43	
Wmdws Contract	None	0.21	23.69	0.02	1
	At most 1	0.08	6.39	0.16	
East Spot	None	0.16	15.71	0.19	3
	At most 1	0.05	3.46	0.50	
Emdws Spot	None	0.09	9.90	0.65	2
	At most 1	0.05	3.34	0.52	
Wmdws Spot	None	0.12	10.94	0.55	1
	At most 1	0.02	1.43	0.89	

Table 3.9: Speed of Adjustment Results II

Speed of Adjustment 1996-2002	East Con	Emdws Con	Wmdws Con
Change in the Price of Low Sulfur	<u>0.087</u>	-0.116	0.026
T-Statistic	<u>3.230</u>	-1.450	0.763
Change in the Price of High Sulfur	<u>-0.067</u>	-0.501	-0.879
T-Statistic	<u>-0.985</u>	-4.912	-4.966
<b>1983-1994</b>			
Change in the Price of Low Sulfur	-0.006	0.229	0.085
T-Statistic	-3.452	2.617	1.530
Change in the Price of High Sulfur	-0.006	-0.167	-0.400
T-Statistic	-2.578	-2.380	-5.380
<b>1976-1981</b>			
Change in the Price of Low Sulfur	<u>0.209</u>	0.092	<u>0.102</u>
T-Statistic	<u>3.260</u>	1.022	<u>0.810</u>
Change in the Price of High Sulfur	<u>-0.240</u>	-0.195	<u>-0.496</u>
T-Statistic	<u>-3.85</u>	-1.79	<u>-4.06</u>

Results underlined are not from cointegrated series thus they should be ignored.

Table 3.9: Speed of Adjustment Results II continued

Speed of Adjustment 1996-2002	East Spot	Emdws Spot	Wmdws Spot
Change in the Price of Low Sulfur	0.117	<u>0.067</u>	<u>-0.073</u>
T-Statistic	3.440	<u>1.136</u>	<u>-3.310</u>
Change in the Price of High Sulfur	0.050	<u>-0.121</u>	<u>-0.248</u>
T-Statistic	1.042	<u>-1.980</u>	<u>-9.530</u>
<u>1983-1994</u>			
Change in the Price of Low Sulfur	<u>0.061</u>	0.162	0.277
T-Statistic	<u>1.280</u>	3.050	3.020
Change in the Price of High Sulfur	<u>-0.116</u>	-0.118	-0.199
T-Statistic	<u>-2.350</u>	-2.660	-2.990
<u>1976-1981</u>			
Change in the Price of Low Sulfur	-0.029	0.077	0.227
T-Statistic	-0.309	0.958	2.800
Change in the Price of High Sulfur	-0.268	-0.161	-0.051
T-Statistic	-3.26	-1.784	-1.04

Results underlined are not from cointegrated series thus they should be ignored.

## Chapter 4

### An Estimate the Implicit Price of Sulfur in Coal Prior to Phase I of the 1990 Clean Air Act Amendments

#### 4.1 Background

The 1990 Clean Air Act Amendments (CAAA) created an implicit price on sulfur inherent in coal. This was done by establishing a market for emissions of sulfur dioxide (SO<sub>2</sub>) through the distribution of pollution permits to coal-fired power plants. This market created an implicit marginal willingness to pay for reductions in sulfur content as this would translate into fewer SO<sub>2</sub> emissions, freeing permits to be sold. Sulfur in coal combines with oxygen to form SO<sub>2</sub>, a precursor to acid rain and a source of particulates. The 1990 CAAA was quite different from previous federal regulation of coal-fired boilers in that it employed a decentralized, market-based approach instead of a command-and-control approach using emissions standards or technological mandates.

The economic hypothesis of this research focuses on the implicit price of sulfur in long-term coal contracts. Changes over the history of regulation gave power plants varying incentives to value sulfur. Power plants generally sign long-term contracts for a majority of their coal demand and use the spot market to cover fluctuations in demand (Kerkvliet and Shogren, 1992). Thus the implicit price of sulfur in these contracts is a good measure of what power plants expect the price of sulfur to be. The implicit price of sulfur should be close to zero for contracts initiated or renegotiated before passage of the 1990 CAAA.

as sulfur was not priced by any market mechanism. After passage, new or renegotiated contracts should begin to show an implicit price of sulfur comparable to the expected permit price.

Federal regulation of SO<sub>2</sub> emissions from coal-fired boilers began with the 1970 Clean Air Act, under which existing boilers were regulated by the states and new boilers were federally regulated under the New Source Performance Standards (NSPS). State regulation of existing boilers varied greatly by region, including some nonbinding regulation<sup>16</sup> (Ackerman and Hassler, 1981). The first set of NSPS, NSPS-D, applied to new boilers for which construction commenced after August 17, 1971, and specified only that boilers not emit more than 1.2 pounds of SO<sub>2</sub> per million Btu (mm Btu) of heat input. The next set of standards, NSPS-Da, were included as part of the 1977 CAAA and applied to new boilers for which construction commenced after September 18, 1978, and specified a limit of 1.2 pounds of SO<sub>2</sub> per mm Btu and a removal rate of 90% of SO<sub>2</sub> from the emission stream. An exception was made to allow a removal rate of 70% if SO<sub>2</sub> emissions were less than 0.60 pounds per mm Btu. This effectively required scrubbing, even for units burning low sulfur coal. Importantly, all of these regulations left firms with no marginal incentive to pay for reductions in the sulfur content of coal.

---

<sup>16</sup> Some boilers, especially in the Midwest, were given an emissions standard of 16 lbs of SO<sub>2</sub> per million BTU. The highest level of sulfur that we have seen in this or other data sets is around 8 lbs.

Title IV of the 1990 CAAA created a system of tradable permits for SO<sub>2</sub> emissions that would eventually apply to most coal burning power plants in the U.S. The eventual goal of the system was a 10 million ton reduction in SO<sub>2</sub> emissions, about 50% of 1985 emissions, by the year 2000. Phase I of the permit system began in 1995 with the inclusion of approximately 263 older boilers whose participation was mandated plus 174 boilers that would have been brought in under Phase II but voluntarily entered during Phase I. These 263 older boilers, also known as Table A, generally burned high sulfur coal and emitted large amounts of SO<sub>2</sub>. Boilers included in Phase I were granted permits at the rate of 2.5 pounds per mm Btu of average annual heat input over 1985-87. In Phase II, all boilers with a generating capacity equal to or greater than 25 megawatts were granted permits at the rate of 1.2 lbs/mm Btu as measured over the same period.

One goal of this research is to determine what information plants actually used to guide their decisions prior to implementation of permit trading. A permit market puts an explicit price on emissions, creating an economic incentive for abatement. Economic theory suggests that the permit price will equal the marginal cost of abatement as each power plant looks to minimize the cost of compliance. At the time the law was being debated in Congress, a study done for the EPA that mimicked the prevailing legislation estimated that the long-run (Phase II) marginal cost of SO<sub>2</sub> abatement was between \$579 and \$760 per ton (Burtraw 1998). The Phase I projection was between \$250 and \$350 per ton (Joskow et al 1998). The first two inter-utility trades were in May and July of

1992 with prices of \$265 and \$300 per ton, respectively (Joskow et al 1998). A 1993 study by the Electric Power Research Institute (EPRI) found long-run marginal abatement costs of \$520 per ton. EPRI is an independent, non-profit center for electricity research through which “all sectors of the U.S. electricity industry” contribute to support research and development.<sup>17</sup> In 1995, two studies, one by EPRI and one by the EPA, estimated the long-run marginal costs of SO<sub>2</sub> abatement at \$543 and \$532 respectively (Burtraw and Palmer, 2003). It is the long-run marginal costs that one would expect plants to utilize in making decisions concerning their willingness to pay in the long-term contracts analyzed here. In contrast to what these studies predicted, permits began trading in 1995 at \$150 per ton, fell to \$70 in 1996, and were below \$175 until 2004. The issue of setting an emissions cap based on estimated marginal costs will come up again as Phase II is set to expire in 2010 when the CAAA will need to be reauthorized.

A related goal of this research is to test the efficiency of the permit market. Joskow et al (1998) look at many aspects of the permit market, bid/ask spreads for private inter-utility trades and the EPA auction results, to conclude that the market is efficient and competitive. Here we will test a different type of efficiency. Theoretically, we would expect power plants to arbitrage between paying more for lower sulfur coal and buying permits. If the permit market was operating efficiently, these arbitrage opportunities should be exhausted, but there are a couple of reasons why they might still exist and why the cost of reaching this emissions reduction might not be minimized. Rose (1997) and

---

<sup>17</sup> [http://www.epri.com/corporate/discover\\_epri/epri\\_facts/index.html](http://www.epri.com/corporate/discover_epri/epri_facts/index.html)

Arimura (2002) both give evidence that state public utility commissions (PUCs) interfere with permit markets by favoring certain compliance strategies. Rose (1997) explains that some PUCs often favor a self-sufficient compliance strategy, such as buying low sulfur coal, which involves no purchase of permits. Arimura (2002) finds that plants located in states that acted to protect local high sulfur coal interests are less likely to switch to low sulfur coal. Swinton (2002, 2004) uses an output distance function to show that marginal abatement costs are not equated across plants.

While there are barriers to perfect efficiency, if markets are operating relatively efficiently, the premium paid for lower sulfur coal (the sulfur premium) should be related to the permit price. The first paper to estimate a sulfur premium was Kolstad and Turnovsky (1998), which used coal purchase data from 1976 through 1985 for NSPS-D boilers to estimate a non-linear price function for coal based on sulfur content and ash content. Although the authors used a non-linear form for the price function they failed to reject the null assumption of linearity. They find a mean implicit price of sulfur of \$0.071 per pound, which is approximately equal to \$284 per ton of SO<sub>2</sub>. Unfortunately, no standard errors are estimated thus there is no way to know if this is statistically different than zero. More recently, two papers have looked at the coal spot market for evidence of a sulfur premium. Arimura (2002a), estimates a hedonic coal price model using spot market transactions from 1985-1998. The sulfur premium in this study is given in terms of pounds of sulfur per million BTU rather than tons of SO<sub>2</sub>, making it

difficult to compare to the price of a permit. The paper does state that for 1995 and 1996, the 95% confidence interval sulfur premium does not contain the permit price. However, 1997 and 1998's 95% confidence interval does. Keohane and Busse (2004) estimates a sulfur premium while looking for changes in the price of rail transportation from the largest low sulfur coal basin, the Powder River Basin (PRB). Using a hedonic coal price model with a random effects estimator to control for unobserved heterogeneity, they find mixed evidence of a sulfur premium in the spot market<sup>18</sup>.

#### **4.2 Data**

The data come from the Coal Transportation Rate Database (CTRB), which is maintained by the Energy Information Agency (EIA). The EIA compiles the CTRB largely from the Federal Energy Regulatory Commission (FERC) Form 580 "Interrogatory on Fuel and Energy Purchase Practices." FERC Form 580 is a survey of investor-owned, interstate electric utility plants with steam-electric generating stations of more than 50 megawatts. The survey is given every two years. The dataset contains information on coal transactions for the years 1979-1999 such as the type of contract, cost, quality, and origin of coal purchases as well as the year of contract inception and year of modification. We use the data on coal deliveries as well as contract characteristics and the unit of observation is each coal delivery. Each contract has a number of deliveries associated with it thus the number of observations is a multiple of the number of contracts. This

---

<sup>18</sup> Interestingly, they find that rail rates rose for plants within 1000 miles of the PRB while they fell for plants further than 1000 miles away.

survey is more detailed than other surveys (FERC 423, for example) but it uses a smaller sample of plants.

The data allow plants to keep some aspect of their cost data confidential. The data potentially list the price at the mine (known as F.O.B or Free on Board mine rate), the price of transportation, and the delivered price. For our analysis we focus on contracts that list the price at the mine or list the delivered price and all relevant transportation prices so that a mine rate can be calculated. Delivered prices may vary greatly from the mine price and the price of transportation can vary depending on distance from the mine (Keohane and Busse, 2004). We used a calculated mine price (obtained by subtracting the transportation price from the delivered price) rather than a reported mine price) for 64 of the 2594 observations, which come from 23 of the 744 contracts in our dataset.

Contracts are separated by the year of signing or latest year of renegotiation because the information available at this time is what firms use to decide on pricing. We separate the contracts into three regulatory regimes: Pre-1989, 1989-1990, and 1991-1994. The pre-1989 regime was a time of command-and-control regulation for power plants. The 1989-1990 regime was a transition time as Congress and the Bush administration were debating and finalizing the 1990 CAAA. The 1991-1994 regime was an adjustment period for power plants as they then knew what regulation they would face in 1995 and could adjust their behavior accordingly. All deliveries from a contract signed or

renegotiated in one of the time periods are included in the analysis, even if the delivery occurred in another regime. This is because the pricing decisions are usually made at the time of signing, not at the time of delivery. As a result, the price of coal in new contracts can vary significantly from those signed a number of years in the past. (Joskow, 1990) Thus a delivery in 1992 for a contract signed in 1988 will be included in the analysis of the pre-1989 regime. As noted in Joskow (1988, 1990) each coal contract has its own price adjustment mechanism that may impact the price of a given delivery. The dataset lists the type of price adjustment mechanism specified by each contract. We create price adjustment mechanism dummies to control for price variation that is inherent in each contract.

All coal characteristic variables used in the analysis below were translated into per ton units. Prices were adjusted for inflation using the Producer Price Index for crude energy materials to account for changes in inflation (Economic Report of the President, 2004). Seventeen observations of prices above \$999 per ton of coal were removed from the sample as these were suspected to be coding errors. BTU, sulfur, ash, and moisture content define the quality, and thus the price, of coal. Each of these coal characteristics are present in all observations. BTU content is the heat inherent in the coal that power plants demand. It is expected that a higher BTU content is associated with a higher price. Sulfur is an impurity that causes the emission of a regulated pollutant ( $\text{SO}_2$ ) and can alter the performance of the boiler. It is expected that the sign of the estimated effect of sulfur

on price will not be significantly different than zero for the pre-1989 time period as plants are not priced at the margin for SO<sub>2</sub> emissions, negative if plants could foresee the type of legislation that would make up the 1990 CAAA for the 1989-1990 time period, and negative for the 1991-1994 time period as plants adjust to marginal cost pricing of SO<sub>2</sub> emissions. The data give the sulfur content by weight of the coal. This was transformed into an amount of sulfur per ton of coal and converted to SO<sub>2</sub> by multiplying by two (Arimura, 2002). In theory, one ton of sulfur in coal becomes two tons of SO<sub>2</sub> through the combustion process. However, some amount of sulfur will bond with other chemicals in the boiler and not form SO<sub>2</sub>, resulting in an overestimate of the amount of SO<sub>2</sub> produced. Our estimate of the price of SO<sub>2</sub> can be adjusted for this by scaling it by the reciprocal of the percentage of sulfur that does form SO<sub>2</sub>. For example, if only ½ of the sulfur becomes SO<sub>2</sub>, our estimate of the inherent price of SO<sub>2</sub> should be multiplied by 2. Ash is an impurity that causes the emission of a regulated pollutant (particulate matter) and can alter the performance of the boiler. It is expected that higher ash content is associated with a lower price of coal although not at the margin. Particulate matter is regulated under the National Ambient Air Quality Standards and most plants are required to install equipment to limit emissions. Moisture is an impurity that alters the performance of the boiler. It is expected that the price of coal is negatively associated with the moisture content, possibly at the margin. Descriptive statistics of the data can be found in Table 4.1.

Finally, contracts are separated by the presence of a scrubber at the plant. Using data from the EIA Form 767 (2002) we separate plants with a scrubber, a piece of capital that removes SO<sub>2</sub> from the waste stream, as their willingness to pay for lower sulfur coal would be different from those without a scrubber. The scrubber dummy variable takes a value of 1 if the plant the contract delivers to has at least one scrubber.

### 4.3 Analysis

We use a hedonic price model to determine the impact that coal characteristics, such as sulfur content, have on the price of coal. The dependent variable is the real price per ton of coal at the mine. The first model estimated uses dummy variables for the price adjustment mechanism specified by the contract along with coal character. This model will use an OLS estimator and takes the following form:

$$P_t = a + X_{j,t} B_j + A_{j,t} \theta_j + e_t \quad [1]$$

Where  $a$  is a constant,  $X_{j,t}$  is coal characteristics  $j$  at delivery  $t$ , and  $A_{j,t}$  are dummies for the price adjustment mechanism specified in the contract. Fixed price contracts are withheld thus the  $\theta$ 's are price effects relative to a fixed price contract.

A second model will utilize a fixed effects estimator to control for contract heterogeneity and the correlation problem that would follow if we assumed each observation was

independent. This heterogeneity may come from the price adjustment mechanism of the contract, but may also originate from various unobservable factors such as plant characteristics, the relative negotiating ability of the mine, plant and transportation firm (generally rail) and/or other aspects. The model estimated takes the form:

$$P_t = a_i + X_{j,t} B_j + e_t \quad [2]$$

Where  $i$  denotes contracts,  $a_i$  is the fixed effect parameter for each contract,  $X_{j,t}$  is coal characteristic  $j$  at delivery  $t$ , and  $e_t$  is an error term.

The sample of contracts is broken up into three time periods corresponding to different regulatory regimes. The first is the pre-1989 time period from 1979-1988 during which plants had no marginal cost of SO<sub>2</sub> emissions. The second time period is 1989-1990. During this time, the 1990 CAAA was being debated in Congress and the press but the outcome was uncertain. The third time period is 1991-1994. During this time, the 1990 CAAA had become law but was not implemented. Both model specifications are estimated for each time period.

#### 4.4 Results

Regression results for model 1, given in Table 4.2, generally fit the expectations of the model. The included observations are all plants without a scrubber. Column 1 gives the pre-1989 results, Column 2 gives the 1989-1990 results, and Column 3 gives the 1991-1994 results. All regressions have an  $R^2$  above 0.90, implying that the model explains a large percentage of the variation in price. There seems to be a decreasing real price of BTU over these time periods. While a statistically significant sulfur premium arises for the pre-1989 period, as we will see this result is not particularly robust. As expected, a statistically significant sulfur premium is found for the 1991-1994 time period, but it is much lower than the initial permit market price.

A second version of model 1 was estimated with squared terms for the three coal impurities (sulfur, ash, and moisture) to account for any non-linearity in plants' willingness to pay. An F-test failed to reject the null hypothesis that all squared terms were jointly equal to zero for the 1989-1990 and 1991-1994 time periods. The null was rejected at the 10% level for the pre-1989 time period. It is likely that omitting the squared terms is causing the statistically significant result for sulfur content in the pre-1989 estimation. The results from the OLS regression with squared terms are presented in Table 4.3.

Regressions results for model 2, given in Table 4.4, are generally consistent with expectations. Again the observations included are all plants without a scrubber. As

before, the model explains a large percentage of the variation in the data. Rho, the percentage of variation described by the contract's fixed effects parameter, rose from approximately 0.45 in the first two periods to 0.669 for the 1991-1994 period. The larger rho in the 1991-1994 period is likely explained by the fact that plants with Phase I boilers are more willing to pay for a lower sulfur content relative to plants without Phase I boilers and this is being captured by the fixed effects term. The BTU content is the main attribute plants are purchasing in coal, but its implicit price seems to have fallen over time. There is no statistical evidence of a sulfur premium before 1991. A statistically significant premium of \$150 per ton of SO<sub>2</sub> arises in the third period. \$150 is approximately the price permits began trading at in 1995. This would imply that plants saw the long-run marginal abatement costs of SO<sub>2</sub> emissions as much lower than estimates made at that time. Additionally, the permit market seems to be efficient in that plants are successfully arbitraging between buying a permit and paying the sulfur premium.

These three regressions were also estimated with quadratic terms for coal impurities to account for possible non-linearity in the willingness to pay. An F-test of joint significance for all three squared coefficients is unable to reject the null hypothesis that they equal zero for each of the three time periods. The results of these regressions can be found in Table 4.5.

The above fixed effects estimator groups observations of deliveries by corresponding contract. As mentioned above, this will control for unobserved heterogeneity in the contract, one of which may be the impact of plant characteristics. As a robustness check to ensure that the above results are not influenced by plant-specific characteristics, we re-estimated model 2 grouping the observations by plant instead of contract. To control for the contract price adjustment mechanism, we include the price adjustment dummies in the model. Results for this analysis can be found in Table 4.6. The results remain unchanged for the 1989-1990 and 1991-1994 time periods. Results for the pre-1989 time period follow a similar pattern as the OLS results.

#### **4.5 Conclusion**

This analysis estimates the sulfur premium in long-term coal contracts over three different time periods that correspond to three different regulatory regimes. Contract deliveries are divided according to which regulatory regime was in place at the time the contract was signed or last renegotiated. The first time period, pre-1989, corresponds to the 1970 and 1977 CAAA, which used command-and-control type regulation of emissions standards or technological mandates for the control of SO<sub>2</sub>, giving plants little incentive to value marginal reductions in the sulfur content of their coal. The second time period, 1989-1990, corresponds to the deliberation and passage of the 1990 CAAA. The third time period, 1991-1994, corresponds to the pre-implementation stage of the 1990 CAAA. The 1990 CAAA introduced a tradable permit market for SO<sub>2</sub> emissions

that gave plants an implicit marginal price of sulfur content in coal. Using a hedonic price model with a fixed effects estimator to control for contract heterogeneity, we find that indeed plants were not paying a statistically significant premium for lower sulfur prior to the 1990 CAAA passage. After passage, but before implementation, plants began paying a statistically significant premium of \$150 per ton of SO<sub>2</sub> for lower sulfur coal. This amount matches the initial permit price and is much lower than the price predicted by numerous studies. This gives evidence that the permit market is efficient in that plants are arbitraging between the costs of alternative abatement options. In addition, these results provide an improvement over marginal abatement cost estimates of the price of a permit in an emission trading program and evidence of how power plants respond to market-based regulation.

Table 4.1: Descriptive Statistics

Regulatory Regime	Pre-1989	1989-1990	1991-1994
Variable			
Observations	1464	536	594
Contracts	389	151	204
Price	32.987 (82.568)	29.389 (56.496)	27.120 (67.001)
BTU	0.200 (0.488)	0.211 (0.406)	0.202 (0.490)
SO <sub>2</sub>	0.031 (0.018)	0.034 (0.021)	0.032 (0.020)
Ash	0.097 (0.028)	0.093 (0.023)	0.095 (0.026)
Moisture	0.093 (0.072)	0.095 (0.058)	0.096 (0.059)

All statistics are per ton, Standard errors are in parenthesis

Table 4.2: OLS Regression Results

OLS Estimates	Column 1	Column 2	Column 3
Non-Scrubber Plants	Pre-1989	1989-1990	1991-1994
R <sup>2</sup> -Overall	0.943	0.954	0.978
N	1133	353	407
BTU (Heat)	163.76 (0.00)	146.50 (0.00)	134.12 (0.00)
SO <sub>2</sub>	-121.23 (0.01)	47.79 (0.36)	-67.51 (0.04)
Ash	22.52 (0.58)	38.58 (0.12)	117.17 (0.00)
Moisture	-40.98 (0.01)	-37.67 (0.12)	-15.88 (0.36)
Constant	7.53 (0.16)	-2.08 (0.50)	-8.84 (0.02)

For brevity, price adjustment dummies are not given here  
P-values in parenthesis, Robust standard errors used

Table 4.3: OLS Results with Quadratic Terms

OLS Estimates	Column 1	Column 2	Column 3
Non-Scrubber Plants	Pre-1989	1989-1990	1991-1994
R <sup>2</sup> -Overall	0.945	0.955	0.979
N	1133	353	407
Prob All Squared = 0	0.068	0.625	0.373
BTU (Heat)	163.72 (0.00)	146.45 (0.00)	134.03 (0.00)
SO <sub>2</sub>	-260.98 (0.17)	192.63 (0.30)	63.54 (0.52)
SO <sub>2</sub> Squared	3227.00 (0.14)	-2243.73 (0.36)	-1815.94 (0.11)
Ash	287.55 (0.06)	71.60 (0.79)	340.57 (0.28)
Ash Squared	-1223.51 (0.06)	-189.75 (0.89)	-1267.02 (0.44)
Moisture	-250.98 (0.00)	27.57 (0.63)	38.56 (0.38)
Moisture Squared	662.70 (0.00)	-186.40 (0.391)	-148.55 (0.35)
Constant	4.67 (0.54)	-8.84 (0.54)	-22.88 (0.16)

For brevity, price adjustment dummies are not given here  
P-values in parenthesis, Robust standard errors used

Table 4.4: Fixed Effects Regression Results

Fixed Effects Estimates	Column 1	Column 2	Column 3
Non-Scrubber Plants	Pre-1989	1989-1990	1991-1994
R <sup>2</sup> -Overall	0.939	0.941	0.976
N	1133	353	407
Groups	317	105	155
Rho	0.447	0.402	0.669
BTU (Heat)	165.20 (0.00)	150.51 (0.00)	135.57 (0.00)
SO <sub>2</sub>	172.42 (0.33)	-20.96 (0.87)	-149.87 (0.016)
Ash	-1.72 (0.981)	25.74 (0.74)	69.87 (0.28)
Moisture	-37.64 (0.422)	16.51 (0.88)	-41.69 (0.39)
Constant	-1.54 (0.850)	-4.133 (0.80)	0.910 (0.90)

Grouping by contract, P-values in parenthesis

Table 4.5: Fixed Effects Results with Quadratic Terms

Fixed Effects Estimates	Column 1	Column 2	Column 3
Non-Scrubber Plants	Pre-1989	1989-1990	1991-1994
R <sup>2</sup> -Overall	0.938	0.926	0.975
N	1133	353	407
Groups	317	105	155
Rho	0.462	0.519	0.686
Prob All Squared = 0	0.187	0.865	0.166
BTU (Heat)	165.32 (0.00)	150.40 (0.00)	137.68 (0.00)
SO <sub>2</sub>	1002.6 (0.04)	-277.55 (0.42)	-3.35 (0.99)
SO <sub>2</sub> Squared	-10100 (0.07)	3808.6 (0.41)	-1637 (0.65)
Ash	75.28 (0.75)	110.83 (0.81)	866.97 (0.02)
Ash Squared	-459.75 (0.68)	-489.72 (0.836)	-4175 (0.03)
Moisture	-217.71 (0.15)	-37.95 (0.89)	-73.26 (0.27)
Moisture Squared	747.69 (0.20)	275.49 (0.828)	323.12 (0.37)
Constant	-10.60 (0.45)	-2.68 (0.923)	-38.88 (0.04)

Grouping by contract, P-values in parenthesis

Table 4.6: Plant-Based Fixed Effects Regression Results

Fixed Effects Estimates	Column 1	Column 2	Column 3
Non-Scrubber Plants	Pre-1989	1989-1990	1991-1994
R <sup>2</sup> -Overall	0.942	0.947	0.972
N	1133	353	407
Groups	164	93	89
Rho	0.401	0.544	0.823
Prob All Squared = 0	0.014	0.86	0.67
BTU (Heat)	161.95 (0.00)	147.04 (0.00)	137.78 (0.00)
SO <sub>2</sub>	-230.36 (0.00)	32.39 (0.50)	-91.40 (0.00)
Ash	-3.29 (0.94)	82.11 (0.07)	29.01 (0.52)
Moisture	-40.23 (0.22)	-28.98 (0.31)	-18.73 (0.28)
Constant	11.68 (0.04)	-5.64 (0.41)	4.133 (0.43)

For brevity, price adjustment dummies are not given here

Grouping by Plant, P-values in parenthesis

Results of the regressions w/ squared terms available on request

## Chapter 5

### Conclusion

The three chapters of this dissertation begin to reveal the impact of a switch to market-based regulation on the industries that provides inputs to the regulated industry. The regulated industry, coal-fired power plants, is impacted considerably by the switch to market-based regulation. Under emissions standards and technological mandates, plants are unable to minimize the costs of production by equating the marginal rate of technical substitution (MRTS) with the input price ratio for all inputs. Once freed of these extra constraints, plants are expected to alter their decisions in manner that minimizes the cost of production. This resulting change in behavior impacts the way input markets operate.

The first input market examined is the scrubber market. The hypothesis of the second chapter is that the scrubber industry has a greater incentive to innovate when forced to compete with other abatement options. We should see greater cost reductions for a quality adjusted scrubber after the switch to market-based regulation. Results suggest that the variable and capital costs are both statistically significantly lower for scrubbers installed after the 1990 CAAA while they were constant during the period of the 1977 CAAA.

The second input market examined is the coal market. The third chapter investigates whether plants are taking full advantage of the difference in coal attributes to minimize

the cost of compliance. The hypothesis proposed in this paper is that the period after railroad deregulation and the 1990 CAAA should be the most integrated of all time periods followed by the period of solely rail deregulation and finally the period of rail regulation and non-market SO<sub>2</sub> regulation. Results find scant evidence of increased market integration for the period of both rail deregulation and the 1990 CAAA relative to the period of solely rail deregulation.

The fourth, and final, chapter looks at long-term coal contracts and the manner in which their pricing changes with the changing of incentive of the CAAs. The 1990 CAAA created an implicit price on the sulfur content of coal while previous versions of the CAA gave plants no incentive to value the sulfur content. It is expected that contracts signed previous to 1990 would show no statistically significant price for sulfur content, while those after 1990 would. This hypothesis is upheld by the results. In fact, contracts signed after 1990 show an implicit price of sulfur that is approximately equal to the initial permit price.

While these three chapters do not reveal all of the impacts to the inputs to coal-fired power plants, they do give a broad picture. This dissertation has found some economic success stories as well as some failures. This is the case with most predictions about the impacts of a change to market-based regulation. The information revealed in this dissertation can be used to improve future transitions to market-based regulation in the spirit of adaptive management. In addition, the CAA is up for reauthorization in 2009,

thus this dissertation is useful for policymakers in deciding how to alter the SO<sub>2</sub> permit market to improve its efficiency.

**Bibliography**

- Ackerman, Bruce and William Hassler. 1981. *Clean Coal/Dirty Air*. New Haven, CT: Yale University Press.
- Arimura, Toshi. 2002. "An Empirical Study of the SO<sub>2</sub> Allowance Market: Effects of PUC Regulations". *Journal of Environmental Economics and Management*. 44 (2): 271-289.
- Arimura, Toshi. 2002a. "Hedonic Prices of Sulfur in Coal under the U.S. SO<sub>2</sub> Allowance Market." Mimeo. Available at <http://pweb.sophia.ac.jp/~t-arimu/cv/working/papers-e.htm>.
- Bellas, Allen. 1998. "Empirical Evidence of Advances in Scrubber Technology." *Resource and Energy Economics* 20 (4): 327-343.
- Burtraw, Dallas. 1996. "The SO<sub>2</sub> Emissions Trading Program: Cost Savings Without Allowance Trades." *Contemporary Economic Policy* 14(2): 79-94.
- Burtraw, Dallas. 1998. "Cost Savings, Market Performance, and Economic Benefits of the U.S. Acid Rain Program." RFF Discussion Paper 98-28.
- Burtraw, Dallas. 2000. "Innovation Under the Tradable Sulfur Dioxide Emission Permits Program in the U.S. Electricity Sector." RFF Discussion Paper 00-38.
- Burtraw, Dallas and Karen Palmer. 2003. "The Paparazzi Take a Look at a Living Legend: The SO<sub>2</sub> Cap-and-Trade Program for Power Plants in the United States." RFF Discussion Paper 03-15.
- Busse, Meghan. and Keohane, Nathaniel. 2003. "Pollution Control and Input Markets: The Creation and Capture of Rents from Sulfur Dioxide Regulation" Working Paper. Available at: [http://www.som.yale.edu/faculty/nok4/files/papers/sulfur\\_penalty.pdf](http://www.som.yale.edu/faculty/nok4/files/papers/sulfur_penalty.pdf)

- Carlson, Curtis, Dallas Burtraw, Maureen Cropper, and Karen Palmer. 2000. "Sulfur Dioxide Control by Electric Utilities: What are the Gains from Trade?" *Journal of Political Economy* 108 (6): 1292-1326.
- Downing, Paul, and Lawrence White. 1986. "Innovation in Pollution Control." *Journal of Environmental Economics and Management* 13 (1): 18-29.
- Economic Report of the President. 2004. Table B-66
- Ellerman, Denny, and Montero, Juan-Pablo. 1998. "The Declining Trend in Sulfur Dioxide Emissions: Implications and Allowance Prices" *Journal of Environmental Economics and Management*. 36 (1): 26-45.
- Ellerman, A. Denny, Paul Joskow, Richard Schmalensee, Juan-Pablo Montero, and Elizabeth Bailey. 2000. *Markets for Clean Air: The U.S. Acid Rain Program*. New York: Cambridge University Press.
- Energy Information Administration. Various years. Form EIA-767: Steam Electric Plant Operation and Design Report.
- Energy Information Administration. Various Years. "U.S. Coal Supply and Demand", Washington DC
- Energy Information Agency. 1994. "Electric Utility Phase I Acid Rain Compliance Strategies for the Clean Air Act Amendments of 1990".
- Energy Information Agency. 1997. "The Effects of Title IV of the Clean Air Act Amendments of 1990 on Electric Utilities: An Update".
- Federal Energy Regulatory Commission. Various Years. Form FERC 423: Monthly Report of Cost and Quality of Fuels for Electric Plants.

- General Accounting Office. 1994. "Allowance Trading Offers an Opportunity to Reduce Emissions at Less Cost."
- General Accounting Office. 1997. Overview and Issues on Emissions Allowance Trading Programs."
- General Accounting Office. 2002. "Emissions from Older Electricity Generating Units."
- Hansen, Bruce. 2001. "The New Econometrics of Structural Change: Dating Breaks in U.S. Labor Productivity" *The Journal of Economic Perspectives*. 15(4): 117-128.
- Johansen, Soren. 1995. *Likelihood-based Inference in Cointegrated Vector Autoregressive Models*. Oxford University Press. New York.
- Joskow, Paul. 1988. "Price Adjustment in Long-Term Contracts: The Case of Coal." *Journal of Law & Economics*. 31 (1): 47-83.
- Joskow, Paul. 1990. "The Performance of Long-Term Contracts: Further Evidence from Coal Markets." *The RAND Journal of Economics*. 21(2): 251-274.
- Joskow, Paul, Richard Schmalensee, and Elizabeth Bailey. 1998. "The Market for Sulfur Dioxide Emissions" *American Economic Review*. 88 (4): 669-685.
- Jung, Chulho, Kerry Krutilla, and Roy Boyd. 1996. "Incentives for Advanced Pollution Abatement Technology at the Industry Level: An Evaluation of Policy Alternatives." *Journal of Environmental Economics and Management* 30 (1): 95-111.
- Keeler, Theodore. 1983. *Railroads, Freight, and Public Policy*. Washington, D.C., The Brookings Institution.

- Keohane, Nathaniel. 2003. "What did the market buy? Cost savings under the U.S. Tradable Permits Program for Sulfur Dioxide." Yale Center for Environmental Law and Policy Working Paper.
- Keohane, Nathaniel. 2004. "What Did the Market Buy? Cost Savings under the U.S. Tradable Permits Program for Sulfur Dioxide." Mimeo, available at [www.som.yale.edu/faculty/nok4/files/papers/cost\\_savings.pdf](http://www.som.yale.edu/faculty/nok4/files/papers/cost_savings.pdf).
- Keohane, Nathaniel & Megan Busse. 2004. "Market Effects of Environmental Regulation: Coal, Railroads, and the 1990 Clean Air Act." Mimeo, available at <http://www.som.yale.edu/faculty/nok4/files/papers/prbrail.pdf>
- Kerkvliet, Joe & Jason Shogren. 1992. "The Impacts of Environmental Regulation on Coal Procurement Strategies: Design Coal and Multi-attributed Quality" *Environmental Management*. 35 (2), 83-91.
- MacKinnon, James. 1991. "Critical Values for Cointegration Test." In *Long-Run Economic Relationships: Readings in Cointegration*, R.F. Engle & C. W. Granger, Ed. Oxford University Press, Oxford. 267-276.
- Malueg, David. 1989. "Emission Credit Trading and the Incentive to Adopt New Pollution Abatement Technology." *Journal of Environmental Economics and Management* 16 (1): 52-57.
- Milliman, Scott, and Raymond Prince. 1989. "Firm Incentives to Promote Technological Change in Pollution Control." *Journal of Environmental Economics and Management* 17 (3): 247-265.
- Nagubadi, Venkatarao, Munn, Ian, and Tahai, Alireza. 2001. "Integration of Hardwood Stumpage Markets in the Southcentral United States" *Journal of Forest Economics*. 7 (1) 69-98.

- Perry, Robert, and Don Green, editors. 1997. *Perry's Chemical Engineer's Handbook*, 7th Edition, McGraw-Hill.
- Popp, David 2003. "Pollution Control Innovations and the Clean Air Act of 1990." *Journal of Policy Analysis and Management* 22 (4): 641-660.
- Rose, Kenneth. 1997. "Implementing an Emissions Trading Program in an Economically Regulated Industry: Lessons from the SO<sub>2</sub> Trading Program." In *Market Based Approaches to Environmental Policy: Regulatory Innovations at the Fore*, R. F. Kosobud and J. Zimmerman, Ed. Van Nostrand Reinhold, New York. 101-124.
- Schmalensee, D. Ellerman, P. Joskow, J. Montero, and E. Bailey. 1998. "An Interim Evaluation of Sulfur Dioxide Emissions Trading." *Journal of Economic Perspectives* 12 (3): 53-68.
- Stanton, Timothy. 1992. "Did the 1977 Amendments to the Clean Air Act Eliminate the Low-Sulfur Coal Incentive for Electric Power Plants?" *Journal of Energy and Development*. 16 (1): 91-108.
- Swinton, John. 2002. "The Potential for Cost Savings in the Sulfur Dioxide Allowance Market: Empirical Evidence from Florida" *Land Economics*. 78 (3): 390-404.
- Swinton, John. 2004. "Phase I Completed: An Empirical Assessment of the 1990 CAAA" *Environmental and Resource Economics*" 27 (3): 227-246.
- Taylor, Margaret, Edward Rubin, and David Hounshell. 2003. "Effect of Government Actions on Technological Innovation for SO<sub>2</sub> Control." *Environmental Science and Technology* 37 (20): 4527-4534.
- Walls, David. 1994. "Price Convergence across Natural Gas Fields and City Markets" *The Energy Journal*. 14 (4) 37-48.

Zerbe, Richard 1970. "Theoretical Efficiency in Pollution Control." *Western Economic Journal* 8 (4): 364-376.

## VITA

Ian Lange was born in Arlington Heights Illinois, a suburb of Chicago. He lived in the suburbs throughout his childhood. At the University of Illinois at Chicago he earned a Bachelor of Arts degree in Economics as well as a Master of Arts in Economics. In 2005 he earned a Doctor of Philosophy at the University of Washington in Economics.