

**Sulfur Dioxide Control by Electric Utilities:
What are the Gains from Trade?**

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SULFUR DIOXIDE CONTROL BY ELECTRIC UTILITIES: WHAT ARE THE GAINS FROM TRADE?

Abstract

Title IV of the 1990 Clean Air Act Amendments (CAAA) established a market for transferable sulfur dioxide (SO₂) emission allowances among electric utilities. This market offers firms facing high marginal pollution abatement costs the opportunity to purchase the right to emit SO₂ from firms with lower costs; as such, it is expected to yield cost savings compared to a command-and-control approach to environmental regulation. This paper uses econometrically estimated marginal abatement cost functions for power plants affected by Title IV of the CAAA to evaluate the performance of the SO₂ allowance market. Specifically, we investigate whether the much-heralded fall in the cost of abating SO₂, compared to original estimates, can be attributed to allowance trading. We demonstrate that, for plants that use low-sulfur coal to reduce SO₂ emissions, technical change and the fall in low-sulfur coal prices have lowered marginal abatement cost curves by over 50% since 1985. This is the main source of cost reductions rather than trading per se. In the long run, allowance trading may achieve cost savings of \$700-\$800 million per year compared to an “enlightened” command and control program characterized by a uniform emission rate standard. However, a comparison of potential cost savings in 1995 and 1996 with actual emissions costs suggest that most trading gains were unrealized in the first two years of the program.

Key Words: acid rain, sulfur dioxide, air pollution, Clean Air Act, Title IV, permit trading

JEL Classification Nos.: H43, Q2, Q4

SO₂ CONTROL BY ELECTRIC UTILITIES: WHAT ARE THE GAINS FROM TRADE?

I. Introduction

For years economists have urged that policy makers use market-based approaches to control pollution (taxes or tradable permits) rather than relying on uniform emission standards or uniform technology mandates (command-and-control). This advice was largely ignored until the 1990 Clean Air Act Amendments (CAAA) established a market for sulfur dioxide (SO₂) allowances. Coupled with a cap on overall annual emissions, the SO₂ allowance market gives electric utilities the opportunity to trade rights to emit SO₂ rather than forcing them to install uniform SO₂ abatement technology or emit at a uniform rate. By equalizing marginal abatement costs among power plants, trading should limit SO₂ emissions at a lower cost than the traditional command-and-control approach.

The SO₂ allowance market presents the first real test of the wisdom of economists' advice, and therefore merits careful evaluation. Has the allowance market significantly lowered the costs of abating SO₂, as economists claimed it would? An answer in the affirmative would strengthen the case for marketable permits to control other pollutants, such as greenhouse gases. Conversely, if cost savings are small, this would have implications for the design (or even the adoption) of market-based approaches to controlling pollution in the future.

The purpose of this paper is to evaluate the performance of the SO₂ allowance market. Specifically, we ask two questions: (1) How much can the trading of permits reduce the costs of controlling SO₂, compared to command and control, i.e., what are the potential gains from trade? (2) Were these trading gains realized in the first years of the allowance market? The answers

require that we estimate marginal abatement cost functions for generating units at all power plants in the allowance market and compute the least cost solution to achieving the cap on SO₂ emissions. The difference between the least cost solution and the cost under our counter-factual command-and-control policy represents the potential static efficiency gains from allowance trading. We compute these gains for 1995 and 1996, the first two years of the allowance market, and the expected savings in 2010, when the emissions cap will be stricter and applied more broadly and when the allowance market should be functioning as a mature market.

The command-and-control baseline against which we measure gains from allowance trading is key to the analysis. A policy that would have imposed end-of-the-stack abatement technology (scrubbing) would have been significantly more expensive than the baseline we adopt, which is an emission rate standard applied uniformly to all facilities¹. The baseline we adopt is “enlightened” because it would provide firms with considerable flexibility, including the opportunity to take advantage of technological change that may have been precluded under a more rigid technology standard; hence it is a favorable characterization of a command-and-control approach.² From this baseline we evaluate the contribution of formal trading within the allowance market.

Our approach to evaluating the allowance market is very different from the approach used by other observers to assess market performance. Both the Administrator of the USEPA and the

¹ The Sikorski/Waxman bill in 1983 sought to reduce emissions, by about the same amount as eventually required under Title IV, by requiring the installation of scrubbers (flue gas desulfurization equipment) at the fifty dirtiest plants. Studies estimate that the annual cost of this proposal would have ranged from \$7.9 (OTA, 1983) to \$11.5 billion (TBS, 1983; 1995 dollars).

² Our baseline may be optimistic even as a characterization of a uniform emission rate regime. To the extent that technological improvements in scrubbing and fuel blending reflected in our data for the mid 1990s might not have been observed under an emission standard approach, we may be underestimating the costs of the baseline against which we compare an allowance trading approach.

chair of the Council of Economic Advisors have proclaimed the success of the allowance market based on a comparison of current allowance prices (circa \$100 per ton in 1997) with estimates of marginal abatement costs produced at the time the CAAA were written (as high as \$1500).³ Since the former are much lower than the latter, it is concluded that the trading of SO₂ allowances has greatly reduced the cost of curbing SO₂ emissions.

This argument is flawed for two reasons. First, it is inappropriate to judge how well the allowance market is performing simply by comparing current allowance prices with ex ante estimates of marginal abatement costs. Even if the allowance price was equal to marginal abatement cost in the least cost solution, it would not follow that all trading gains were realized. Price can equal marginal abatement cost even if many utilities who might benefit from trading fail to participate in the market. Second, comparing current allowance prices with ex ante estimates of marginal abatement costs shows only that the latter were too high; it does not mean that the allowance market was responsible for the fall in marginal abatement costs.⁴

Our analysis suggests that the above claims for the allowance market are misleading — especially the suggestion that formal trading has significantly lowered the cost of SO₂ abatement. In contrast, we reach the following conclusions:

³ On March 10, 1997 EPA Administrator Carol Browner argued: "...During the 1990 debate on the acid rain program, industry initially projected the cost of an emission allowance to be \$1500 per ton of sulfur dioxide...Today, those allowances are selling for less than \$100." ("New Initiatives in Environmental Protection," *The Commonwealth*, March 31, 1997.) Likewise, in testimony before Congress, CEA Chair Janet Yellen noted, "Emission permit prices, currently at approximately \$100 per ton of SO₂ are well below earlier estimates Trading programs may not always bring cost savings as large as those achieved by the SO₂ program" (Yellen 1998).

⁴ It should also be noted that the ex ante estimates of marginal abatement costs were generally for the second phase of the program, and cannot, therefore, be compared with current allowance prices unless they are discounted to the present.

(1) Marginal abatement costs for SO₂ are much lower today than were estimated in 1990.

Technical improvements including advances in the ability to burn low-sulfur coal at existing generators, as well as improvements in overall generating efficiency, lowered the typical unit's marginal cost function by almost \$50 dollars per ton of SO₂ over the decade preceding 1995. The decline in fuel costs lowered marginal abatement costs by about \$200 per ton.

(2) This decline in marginal abatement costs has lowered the cost of achieving the SO₂ emissions cap under *both* the least cost solution and under enlightened command and control, e.g., under a uniform emission rate standard. This implies that the gains from trade—the cost savings attainable from an allowance trading program—have also fallen over time. We estimate the potential cost savings to be \$250 million annually during the first phase of the allowance program (1995-2000, which covers the dirtiest power plants) and \$784 million annually during the second phase of the program (beginning in 2000, which covers all plants), about 43% of compliance costs under our command and control baseline.

(3) A comparison of the least cost solution for witnessed emission reductions with actual abatement costs indicates that actual compliance costs exceeded the least cost solution by \$280 million in 1995, and by \$339 million in 1996 (1995 dollars). This suggests that the allowance market did not achieve the least cost solution, even though marginal abatement costs under that solution were approximately equal to allowance prices. The failure to realize potential savings is not surprising. The 1990 Clean Air Act Amendments represent a dramatic departure from the pollution regulations to which utilities were previously subject; and taking full advantage of their flexibility may require time. As participants become more familiar with the opportunities the allowance market presents, and ongoing deregulation of the electricity industry provides greater

incentives to reduce costs, the volume of trading will no doubt increase and cost savings are more likely to be realized.

The remainder of the paper is organized as follows. Section II provides institutional background on the CAAA. Section III presents the methodology we employ to evaluate the allowance market, including our estimation of marginal abatement cost curves. Section IV estimates potential gains from allowance trading in the long run, and explains why these estimates are lower than were predicted when the CAAA were written. Section V evaluates the performance of the allowance market in 1995 and 1996, and section VI concludes the paper.

II. Institutions

Since 1970 the SO₂ emissions of electric utilities have been regulated in order to achieve federally mandated local air quality standards (the National Ambient Air Quality Standards). For plants in existence in 1970 these standards, codified in what are called State Implementation Plans, have typically taken the form of maximum emission rates (pounds of SO₂ per million Btus of heat input). Plants built after 1970 are subject to New Source Performance Standards (NSPS), set at the federal level. Since 1978, NSPS for coal-fired power plants have effectively required the installation of capital intensive flue gas desulfurization equipment (scrubbers) to reduce SO₂ emissions, an attempt to protect the jobs of coal miners in states with high-sulfur coal. This regulation has significantly raised the costs of SO₂ abatement at new plants in areas where emissions could have been reduced more cheaply by switching to low-sulfur coal.

During the 1980s over 70 bills were introduced in Congress to reduce SO₂ emissions from power plants. Some would have forced the scrubbing of emissions by all electric generating units,

while others would have provided limited flexibility by imposing uniform emission rate standards while giving firms the opportunity to choose a compliance strategy.

The innovation of Title IV is to move away from these types of uniformly applied regulations. Instead, reductions are to be achieved by setting a cap on emissions while allowing the trading of marketable pollution permits or *allowances*. Each generating unit in the electricity industry is allocated a fixed number of allowances each year, and is required to hold one allowance for each ton of sulfur dioxide it emits.⁵ Utilities are allowed to transfer allowances among their own facilities, sell them to other firms, or bank them for use in future years.

The eventual goal of Title IV of the CAAA is to cap SO₂ emissions of electric utilities at 8.95 million tons—about half of their 1980 level. This is to be achieved in two phases. In the first phase, which began in 1995, each of the 110 dirtiest power plants (with 263 generating units) is to reduce its emissions to an annual tonnage equivalent to 2.5 pounds SO₂ per mmBtu of heat input. Firms can voluntarily enroll additional generating units (“Compensation and Substitution” units) in Phase I, subject to the constraint that the average emission rate of all units not increase. The second phase of emissions reductions, which begins in the year 2000, requires all fossil fueled power plants larger than 25 megawatts to reduce their emissions to an average of 1.2 pounds of SO₂ per mmBtu.

Allowance trading takes advantage of the fact that emission control costs vary across different generating units, and encourages firms with the cheapest control costs to undertake the greatest emission reductions. Unfortunately, firms may not have had adequate incentives to

⁵ Allowances are allocated to individual facilities proportional to emissions during the 1985-1987 period. About 2.8% of the annual allowance allocations are withheld by the EPA and distributed to buyers through an annual auction run by the Chicago Board of Trade. The revenues are returned to the utilities that were the original owners

minimize SO₂ compliance costs, because of decisions made by some state public utility commissions (Rose (1997); Bohi (1994); Bohi and Burtraw (1992)). For instance, to protect the jobs of miners in high-sulfur coal states, some regulators pre-approved the recovery of investment in scrubbers, while leaving it uncertain whether the cost of other possible compliance measures would be similarly recoverable. The allowance program itself encouraged scrubbing by allocating 3.5 million “bonus” allowances to firms that installed scrubbers as the means of compliance, for the explicit purpose of protecting jobs in regions with high-sulfur coal. In addition, investments in scrubbers can be depreciated as soon as the scrubber is installed. In contrast, the cost of purchased allowances cannot be recovered until they are used for compliance. These facts suggest that — through no fault of its own — the allowance market might not succeed in capturing the potential gains from emission trading, a hypothesis that we investigate below.⁶

III. Methodology

To investigate whether the allowance market has operated efficiently and to estimate the size of potential gains from trading versus other forms of regulation, we estimate marginal abatement cost functions for generating units. These functions can be used to calculate the least cost solution to achieving an aggregate level of emissions, as well as the expected costs of alternative regulatory approaches.

A. Calculation of the Gains from Allowance Trading

of the allowances. The failure of the program to raise revenue has been identified as an important source of additional social cost not reflected in firm compliance cost (Goulder, Parry and Burtraw, 1997).

⁶ Fullerton, McDermott and Caulkins (1997) and Winebrake *et al.* (1995) provide estimates of the potential magnitude of inefficiencies that may result but no author has attempted to estimate actual performance.

The least cost solution to achieving the SO₂ cap requires minimizing the present discounted value of compliance costs for all generating units over time, subject to constraints on the banking of allowances. Because the SO₂ cap shrinks between Phase I and Phase II, the banking of allowances will, in general, be optimal, and emissions should be less than allowances in the early years of the program (Rubin 1996). Eventually, however, a steady state will be reached in which annual emissions equal annual allowances.

Rather than solve this inter-temporal problem, we side step the banking question by taking the banking behavior of firms as given. We also side-step the investment question by taking investments in retrofit scrubbers in Phase I as given, though we evaluate whether additional scrubber investments are likely. We also ignore potential future environmental legislation, e.g., for control of particulates, ozone or greenhouse gases.

Our primary goal is to compute how much more cheaply the chosen level of emissions could be achieved through trading than by command and control. We calculate the long run gains from trade by computing the least cost solution to achieving the emissions cap in the year 2010, when annual allowances should equal annual emissions (EPA, 1995; EPRI, 1997). We then contrast this with the cost of achieving the cap in 2010 via a uniform emissions rate standard (command and control).⁷ For 1995 and 1996, the first two years of the allowance market, we compute the potential gains from trade as the difference between the least cost solution to achieving *actual* emissions and the cost of achieving these emissions via command and control.

⁷ The uniform performance standard that we assume as our command and control form of regulation represented a dramatic departure, in 1990, from previous pollution control policies that generally dictated the use of a particular technology. Thus our command and control scenario may be an optimistic representation of the form of pollution control that would have happened in the absence of SO₂ allowance trading.

We calculate the costs *actually incurred* in these two years to learn whether the potential gains from trading have been realized.

The Role of Scrubbing v. Fuel Switching

To calculate the least cost solution to limiting SO₂ emissions we must estimate the marginal abatement cost curves of all generating units in the allowance market. In estimating marginal abatement cost functions we separate plants into those that reduce SO₂ emissions via fuel switching (substituting low-sulfur for high-sulfur coal) and those that have installed scrubbers. As noted above, fuel switching is the chief method of reducing emissions for most power plants. In 1995 only 17 percent of all generating units used scrubbers. Of these, most installed scrubbers to comply with New Source Performance Standards (61%) or to comply with more stringent state or local standards (21%). Twenty-eight Phase I generating units were retrofitted with scrubbers to comply with Title IV of the Clean Air Act Amendments.

In calculating the least cost solution, we treat the number of scrubbers in existence as of 1995 as fixed. This assumes that no further scrubbers will be installed, i.e., that it will be cheaper for units to reduce emissions by fuel switching than by scrubbing, an assumption that we subsequently validate by comparing the cost of scrubbing to the marginal cost of abatement in the least cost solution.

From the perspective of abating SO₂ emissions, the chief difference between units that fuel switch and units that scrub is the shape of their marginal abatement cost (MAC) functions. Holding electricity output constant, plants that fuel switch can reduce the tons of SO₂ they emit by varying the sulfur content of their fuel. Assuming that a premium must be paid for low-sulfur coal, this implies a downward-sloping marginal abatement cost curve for SO₂. For plants that scrub, emissions of SO₂ are almost entirely determined by electricity output (heat input). Because

scrubbers remove about 95% of the sulfur content of coal, emissions are relatively insensitive to the sulfur content of coal burned. Conditional on output, therefore, the marginal abatement cost curve for scrubbed units is a point. In computing the least cost solution we therefore subtract the emissions of scrubbed units from the emissions cap and solve for the least cost solution using the marginal abatement cost curves of units that fuel switch. To compute total costs under the least cost solution, the observed capital and variable costs of retrofit scrubbing are annualized over twenty years using a 6% discount rate. These costs are added to the costs of fuel switching.

Computation of the Gains from Trade

We compute the cost of the least cost solution for all units that fuel switch as the area under their marginal abatement cost (MAC) curves from baseline emissions--emissions that would have obtained absent the 1990 Clean Air Act Amendments--to emissions under the least cost solution. For firms whose MAC curves are positive over all relevant emissions levels, the computation is straightforward. For firms whose marginal abatement curves are negative over some range of emissions, we compute the cost of moving from baseline emissions to emissions in the least cost solution as the area under the portion of the MAC curve that lies above the positive quadrant.⁸

B. Estimation of Marginal Abatement Cost Curves

To estimate marginal abatement cost functions for plants that fuel switch, we assume that the manager of each power plant minimizes the cost of producing electricity at the generating

⁸ To incorporate units in the least cost solution for which we have not estimated MAC curves we allocate allowances, A , to units for which MAC curves are available, solve the least cost solution, and then multiply total cost by the ratio of total allowances to A . This in effect assumes that the aggregate MAC curve for omitted units is identical to that for the units in our dataset.

unit, subject to its production technology and a constraint on SO₂ emissions.⁹ This constraint represents the emissions standard facing the plant because of the National Ambient Air Quality Standards (NAAQS) for SO₂. We have chosen the generating unit as the unit of analysis because SO₂ emissions standards apply to individual generating units.¹⁰ An alternative approach would be to assume the manager minimizes the cost of producing a fixed level of output at the plant level, equating the marginal cost of electricity generation across generating units, but this would force us to average emission standards across units faced with different standards. Since the order in which units are brought into service is usually pre-determined, we treat output as fixed at the generator level.

Our approach to estimating marginal abatement cost functions at fuel switching units is to estimate a cost function and share equations for electricity generation that treat generating capital as variable. Because the firm's capital stock is instantaneously achievable, the estimates we obtain are estimates of long-run abatement costs. This is similar to the approach taken by Gollop and Roberts (1983, 1985) who estimated marginal abatement costs at the firm level for 56 coal-fired

⁹ Throughout, we assume that electric utilities are compliant: their emissions never violate the emissions standard. This assumption appears to be justified by USEPA data, which show fewer than 5% of the plants in our database are ever in violation of emission regulations during the period of our study.

¹⁰ Generating units consist of a generator-boiler pair. For over 85% of the generating capacity there is a one-for-one match between generators and boilers. For the remaining 15%, there are multiple generators attached to a boiler or visa versa. Emission standards and allowance allocations apply to the boiler. The continuous emission monitoring system used under Title IV measures emissions at the stack level where it is often the case that several generating units are attached to one emission stack. For those units that share boilers and/or stacks we assign emissions based on the percentage of total heat input consumed by each boiler. For generators that share a single boiler we assign emissions based on the percentage of total electricity output from each generator.

electric utilities. They examined firms' responses to SO₂ regulations between 1973 and 1979 for firms that met emission requirements through fuel switching.¹¹

Econometric Model

The manager's problem is to choose labor (l), generating capital (k), inputs of high- and low-sulfur coal (fhs and fls , respectively) to minimize the cost of producing output (q) and achieving an emission rate (e), subject to emissions and production constraints. Observations are indexed by unit (i) and time period (t), which are suppressed for convenience.

$$\begin{aligned}
 \text{Min}_{k,l,fls,fhs} C &= p_k k + p_l l + p_{ls} fls + p_{hs} fhs \\
 \text{subject to} & : \\
 Q(k,l,fls,fhs,t) &\geq Q \\
 E(k,l,fls,fhs,t) &\leq E^*
 \end{aligned} \tag{1}$$

In (1), E^* represents the emissions standard, typically stated as an emission rate, e.g., pounds of SO₂ per million Btus of heat input, averaged over a specified time interval.¹² In deriving the cost function to be estimated, one approach would be to replace the chosen values of inputs with the expressions for the optimal input demands as a function of input prices, the level of output and E^* . For policy purposes, however, we wish to estimate a marginal abatement cost

¹¹ The econometric estimation of marginal abatement cost functions may be contrasted with the approach taken in other analyses of Title IV which rely on engineering estimates of marginal abatement cost functions (Fullerton, McDermott and Caulkins (1997), Siegel (1997), Kalagnanam and Bokhari (1995), Burtraw *et al.* (1998), EPA (1995, 1990), EPRI (1995), and GAO (1994)).

¹² Almost 85% of standards are stated as pounds of SO₂ or sulfur per million Btus of heat input. Other standards include percent of sulfur content of fuel, pounds of sulfur dioxide emitted per hour and parts per million of sulfur dioxide in stack gas. When estimating the cost function all standards were converted to pounds of SO₂ per million Btus of heat input. Dummy variables were included to distinguish different averaging times.

function that describes the cost of meeting the emission rate actually achieved. For this reason we write costs as a function of e , the actual emission rate. Because e is an endogenous variable in the cost function, we simultaneously estimate the cost function and an equation to predict e as a function of the emissions standard and other exogenous variables. The cost function to be estimated is thus,

$$C = C(p_k, p_l, p_{ls}, p_{hs}, q, e, t). \quad (2)$$

The econometric model (equations (3) - (6)) consists of the cost function, input share equations and an equation for the firm's mean annual emission rate. We use a translog form for the cost function, adding dummy variables for each plant in the database to measure fixed effects that vary among plants.¹³ A quadratic function of time is added to the cost function to capture technical change. Linear time trends enter the input share and emissions rate equations. Dummy variables are included to indicate the type of emission standard the plant faces (m_j) and the time period over which emissions are averaged (v).

$$\begin{aligned} \ln c = & \alpha_0 + \sum \lambda_m d_m + \alpha_t t + \sum \alpha_j \ln p_j + \alpha_q \ln q + \alpha_e \ln e \\ & + 1/2 \sum \sum \alpha_{jk} \ln p_j \ln p_k + \sum \alpha_{jq} \ln p_j \ln q + \sum \alpha_{jt} (\ln p_j) t \\ & + \sum \alpha_{je} \ln p_j \ln e + 1/2 \gamma_{qq} (\ln q)^2 + 1/2 \phi_{ee} (\ln e)^2 + 1/2 \delta_{tt} t^2 \\ & + \gamma_{lq} t (\ln q) + \phi_{te} t (\ln e) + \beta_{qe} \ln q \ln e + \varepsilon_c, \end{aligned} \quad (3)$$

$$\begin{aligned} s_l = & \alpha_l + \alpha_{ll} \ln p_l + \alpha_{lfhs} p_{hs} + \alpha_{lfls} p_{ls} \\ & + \alpha_{lk} p_k + \alpha_{lq} \ln q + \alpha_{lt} t + \alpha_{le} e + \varepsilon_l, \end{aligned} \quad (4)$$

$$\begin{aligned} s_k = & \alpha_k + \alpha_{kk} \ln p_k + \alpha_{lk} p_l + \alpha_{fhs k} p_{hs} \\ & + \alpha_{flsk} p_{ls} + \alpha_{kq} \ln q + \alpha_{kt} t + \alpha_{ke} e + \varepsilon_k, \end{aligned} \quad (5)$$

¹³ The following conditions are imposed to insure the cost function is linearly homogeneous in input prices: $\sum_i \alpha_i = 1$ and $\sum_j \alpha_{ij} = \sum_j \alpha_{jq} = \sum_j \alpha_{je} = \sum_j \alpha_{jt} = 0$, $i, j = l, k, fls, fhs$.

$$\ln e = \alpha_e + \alpha_{e^*} \ln e^* + \sum \beta_i m_i + \sum \gamma_i m_i (\ln e^*) + \delta_i v + \delta_i t + \sum \lambda_i \ln p_i + \delta_i t + \varepsilon_e, \quad (6)$$

The estimated model includes input share equations only for labor and capital. This is necessary because of the large number of zero values for inputs of low-sulfur and high-sulfur coal. At the level of the generating unit only one type of coal is typically used, implying a zero cost share for the alternative fuel type. To avoid the bias that zero shares would introduce in our estimates we include only the share equations for generating capital and labor.

The estimation of abatement cost functions is further complicated by the fact that over half of the units in our database exhibit non-cost-minimizing behavior in their choices of fuel at some time during the sample period. Either as a result of long-term fuel contracts or of other unobservable transaction costs associated with fuel switching, these units did not immediately switch to low-sulfur coal when it appeared to be economic for them to do so.¹⁴ In some cases remaining in long-term contracts may have provided a hedge against price fluctuations. In other cases utilities may have had little incentive to respond to price changes if fuel prices could be passed on to consumers (Atkinson and Kerkvliet, 1989). In any event, these observations violate the assumption of cost minimization implicit in the specification of the model and are therefore excluded when we estimate the cost function.¹⁵

¹⁴ We tested to see if firms that are apparently violating cost minimizing behavior are bound by older contracts relative to other firms, on the assumption that the older the contract the less likely it is to reflect current prices facing the firm. Although, the contract age of plants that are apparently not cost minimizing is longer, 6 months out of a average contract age of 5 years, this does not seem to be a large enough difference to account for all of the non-cost minimizing behavior.

¹⁵ This results in eliminating some units for certain years, but still enables us to estimate a cost function for these units. They are therefore included in our calculation of the least cost solution.

The cost function, corresponding share equations and the emission rate equation are estimated by Full Information Maximum Likelihood methods using panel data for the period 1985-1994. The stochastic disturbances in the estimating equations for any observation are assumed to be correlated across equations.

Our interest centers on the marginal cost of achieving emissions rate e , which can, in turn, be translated into a marginal cost function for tons of SO_2 . In general terms, the marginal cost of emissions function is given by MC/Me , which is usually negative over observed ranges of emissions. The negative of this function, $-\text{MC}/\text{Me}$, will henceforth be referred to as the marginal abatement cost function. To describe the marginal cost of abating a ton of SO_2 , the cost of a given percentage reduction in the emissions rate can be converted into the equivalent reduction in tons of SO_2 .¹⁶

Data

Our data set consists of virtually all privately and publicly owned Phase I coal-fired generating units, and all privately owned Phase II coal-fired units.¹⁷ These units are responsible for 87% of all SO_2 emissions produced by coal-fired power plants in 1985 and 85% of all emissions in 1994. For each generating unit we compiled data on generating capital, abatement capital, labor, and inputs of high and low-sulfur coal for 1985-94. The data also include the SO_2

¹⁶ The marginal cost of a change in the SO_2 emissions rate, e , at a particular value of e is defined as negative one times the product of the elasticity of total cost with respect to the emission rate, and the ratio of total cost to the observed emissions rate, or $-\text{MC}/\text{Me} = (-\text{MlnC}/\text{Mlne})(\text{C}/e)$. The marginal cost of abating an additional ton of SO_2 emissions, may be derived from the fact that $e = \text{SO}_2/\text{MMBTU}$, where MMBTU is millions of BTUs of heat input. It follows that, $-\text{MC}/\text{MSO}_2 = -\text{MC}/\text{Me} (1/\text{MMBTU}) = (-\text{MlnC}/\text{Mlne})(\text{C}/(\text{SO}_2/\text{MMBTU})) (1/\text{MMBTU}) = -(\text{MlnC}/\text{Mlne})(\text{C}/\text{SO}_2)$.

¹⁷ The data set excludes all cooperatively-owned plants, which are subject to different reporting requirements than either privately or publicly owned plants.

emission rate standard facing the generating unit, its mean annual emission rate in pounds of SO₂ per million Btus of heat input (mmBtu) and output in kilowatt hours. The input prices facing each power plant complete the data set. (See Appendix A for a more complete description.)

To describe sulfur content we distinguish two classes of coal. Coal that when burned in a standard boiler generates no more than 1.2 pounds of sulfur dioxide per million Btus of heat input is defined as low-sulfur coal; all other is high-sulfur coal. This distinction is not entirely arbitrary. Coal resulting in 1.2 pounds of sulfur dioxide or less is termed "compliance coal" due to its ability to meet the original NSPS, in effect from 1971-1978. It also will meet Phase II emission standards, on average.¹⁸ For a firm that purchased only high-sulfur coal, we use the average price of high-sulfur coal in the state where the plant is located. In all cases, we use the contract price rather than the spot price of coal.¹⁹

Results of the Estimation

To summarize the results of our estimation we evaluate the marginal abatement cost function for each unit at 1985 and 1994 emission levels. Table 1 presents the mean and standard deviation of the marginal cost of abating a ton of SO₂, when marginal abatement costs for different units are weighted by SO₂ emissions. In the 1994 time period, 89% of all the predicted marginal abatement costs are significantly different from 0 at the 5% level.

¹⁸ An alternative approach to modeling the sulfur content of coal, used by Kolstad and Turnovsky (1995), is to allow plants to select sulfur content as a continuous attribute, given a hedonic price function for coal. We attempted this approach, but were unable to obtain reliable estimates of hedonic price functions for each state and year.

¹⁹ In 1985, 89% of all coal was purchased through long-term contracts rather than on the spot market. Although this percentage has declined through time, 80% of all coal was still purchased through long-term contracts in 1995. For this reason we use contract prices throughout the analysis.

Table 1 sheds light on differences in marginal abatement costs between Phase I units (including both Table A units and Compensation and Substitution units) and Phase II units, and shows how marginal abatement costs have changed over time. As Table 1 indicates, marginal abatement costs are, on average, substantially higher for Phase II units than for Phase I units. This is not surprising given the much lower emission rates of Phase II units. The range of marginal abatement costs is also much higher for Phase II than for Phase I units. In 1994 marginal abatement costs range from about -\$90 per ton for low-cost Phase II units to about \$2700 per ton. The range for Phase I units is narrower: from approximately -\$260 per ton to \$710 per ton.²⁰

[Insert Table 1 here]

It is also clear from Table 1 that marginal abatement costs have fallen over time for both Phase I and Phase II units. Indeed, the mean marginal abatement cost has fallen by nearly 50% for Phase I units and almost 20% for Phase II units. Since emission rates have fallen over time, this suggests that the marginal abatement cost curve for each unit has itself fallen between 1985 and 1994.

There are at least two reasons why marginal abatement cost curves have fallen. One is that coal prices, both for high- and for low-sulfur coal, have declined over the period. This is illustrated by Figure 1, which shows the nominal prices for each type of coal, by year, averaged across all units in our sample, together with national average coal prices, by sulfur content,

²⁰ Table 1 indicates that marginal abatement costs are negative for at least 10% of the units in each category in 1994. As noted above, this failure to take advantage of cost-saving opportunities to switch fuel may be the result of inability to escape from long-term fuel contracts or insufficient incentives to find the lowest priced fuel as a result of regulatory fuel adjustment clauses.

computed for all utilities.²¹ Figure 1 indicates that the prices of both types of coal fell between 1985 and 1995; however, the price of low-sulfur coal fell faster. What Figure 1 does not show is that the price of low-sulfur coal was lower than the price of high-sulfur coal for 20% of the units in our sample in 1985 and for 25% of the units in our sample in 1994. Over the same period the quantity of low sulfur coal delivered to electric utilities rose significantly. The second reason for a fall in the marginal abatement cost curve is technical progress in abating sulfur dioxide emissions, resulting in part from more general technical progress in electricity generation.

[Insert Figure 1 here]

How important are price changes and technical progress in explaining the fall in marginal abatement cost curves? To answer this question Figure 2 plots marginal abatement cost curves for a generating unit with average Phase I input and output characteristics using (a) 1985 fuel prices and 1985 time trend, (b) 1985 fuel prices and 1995 time trend, (c) 1995 fuel prices and 1985 time trend (d) 1995 fuel prices and 1995 time trend and (e) 1995 fuel prices and 2010 time trend. In all five curves output (Q) as well as all non-fuel input prices are held constant. The effect of technological improvements, represented by the vertical distance between curves (a) and (b) accounts for about 20 percent of the change of the MAC function, or a decline of about \$50 per ton between 1985 and 1995. The effect of changes in fuel prices, represented by the vertical

²¹ The bars in this chart reflect differences in coal prices as they appear in our dataset. In computing the price of low- (high-) sulfur coal we have weighted the price actually paid by plants that purchase low- (high-) sulfur by their heat input and have similarly weighted the *predicted* price of low- (high-) sulfur coal for plants that purchased only high- (low-) sulfur coal. The lines represent national average coal prices, which are computed by averaging the prices paid only by firms that actually purchased each type of coal, including firms excluded from our dataset. The resulting low-sulfur coal prices are slightly lower than our estimates. Our higher low-sulfur coal prices result from the fact that many plants in our data set faced with higher than average low-sulfur coal prices do not actually purchase low-sulfur coal. Therefore the average low-sulfur coal price in our dataset should be higher than the national average.

distance between curves (b) and (d) accounts for the remaining 80 percent of the fall in the marginal abatement cost function, a decline of about \$200 per ton.

[Insert Figure 2 here]

This figure also demonstrates why marginal abatement costs computed at the plant's actual level of emissions have fallen even as emissions have themselves declined. Without technological change or changes in fuel prices, an average plant would move from point A in 1985 to Point B in 1995. MAC would increase as emissions were reduced by 6,000 tons. With changes in fuel prices and technology, however, the unit moves to Point C where its marginal abatement cost is only about half as large as it was originally.²² If the current trend in technological improvements continues until the year 2010, this *average* unit's marginal abatement cost will fall by an additional \$100 ((d) to (e)).

IV. The Least Cost Solution and Potential Gains from Trade in the Long Run

A. Preferred Estimates of the Least Cost Solution

To estimate potential gains from allowance trading in the long run, we compute the least cost solution to achieving the 8.95 million ton SO₂ cap in the year 2010. This requires that we make assumptions about parameters that will shift the marginal abatement cost functions over time—the rate of growth of electricity production (Q), fuel prices (pls and phs), and the rate of technical progress. We must also determine the rate at which coal plants in existence in 1995 will be retired from service, and must determine what SO₂ emissions would have been in 2010 in the absence of the CAAA.

²² It is important to keep in mind that the relative importance of technological change and fuel prices on an individual unit's marginal abatement cost function depends greatly on where the unit is located. Generating units located in areas that have had access to relatively inexpensive low-sulfur coal for some time would not see a substantial drop in their marginal abatement cost functions due to changes in coal prices.

Electricity Output. We assume that electricity production averaged over all coal-fired units increases at the rate of 1.49% per year.²³ Output is, however, likely to increase more rapidly at scrubbed units, which we assume will be utilized at 80 percent of capacity by 2010.²⁴ This fixes the emissions of scrubbed units. We allocate remaining generation and emissions under the cap to fuel switching units.

Input Prices and Technical Change. In parameterizing the marginal abatement cost functions of fuel switching units we assume that the real prices of high- and low- sulfur coal remain at 1995 levels and that the rate of technical change experienced between 1985 and 1994 continues through 2010.²⁵

Retirement of Coal-Fired Power Plants. Any coal-fired units that are retired between now and 2010 will either be replaced by coal-fired units with scrubbers (to satisfy NSPS) or by natural gas plants. This will reduce the emissions of these units to negligible levels, thus freeing up allowances and reducing compliance costs for units that remain in the market. We assume 11 gigawatts of coal-fired capacity in place in 1995 will be retired by the year 2010 and that all of that coal-fired capacity will be replaced by natural gas plants.²⁶

²³ EPRI (1997) assumes annual increase in generation from coal-fired facilities of 1% per year through 2005 and flat thereafter; EPA (1995) assumes an average annual increase of 1.3% for thirty years; US EIA (1996) assumes increase in coal-fired generation of 1.1% annually through 2015, but this estimate is revised in US EIA (1997) to 1.49%.

²⁴ Utilization rates at scrubbed units have been increasing over time. There were 19 generating units with retrofit scrubbers in place by the beginning of 1995. The highest utilization rate in 1995 was 88%, and four were above 80% utilization.

²⁵ The fuel price assumption is consistent with the US EIA (1996), while US EIA (1997) revised the forecast to indicate the sulfur premium would shrink slightly further.

²⁶ The US EIA (1997) predicts that 22 GW of coal-fired capacity will be retired between 1995 and 2010. Given recent experience with coal plant life extension and developments in monitoring technology that have lowered maintenance costs (Ellerman 1998), we expect substantially fewer coal plants to actually retire over that 15 year horizon.

Baseline Emissions. We compute baseline emissions—those that would have prevailed absent Title IV—using 1993 emissions *rates* applied to 2010 levels of electricity production. We believe that the declines in emission rates that occurred between 1985 and 1993 were primarily the result of decreases in the price of low sulfur coal and would have happened in the absence of Title IV.

Continuous Emissions Monitoring Data. An important feature of the 1990 CAAA is that SO₂ emissions must be measured by a continuous emissions monitoring system (CEMS) rather than being estimated based on fuel consumption. Previous studies all use engineering estimates of SO₂ emissions. A comparison of the two measurement techniques reveals that, in 1995, CEMS emissions were about 7 percent higher than estimated emissions, implying that the SO₂ cap is, in effect, 7 percent below the cap based on engineering formulas. To be consistent with actual practice, we use CEMS data.

Compliance Costs in the Preferred Case

Under the above assumptions, the total annual cost of achieving the SO₂ cap of 8.95 million tons in 2010 is \$1.04 billion (1995 dollars). Of this total, \$380 million represents the cost incurred by plants that fuel switch, which account for about 60% of reductions from baseline emissions.²⁷ For plants that have installed scrubbers, annualized capital costs are \$382 million per year and variable costs \$274 million per year.

The marginal cost of emissions reduction, which should approximate long run permit price, is \$291 per ton of SO₂. This assumes that the marginal ton of SO₂ is reduced via fuel

²⁷ We have investigated the implied transportation of low-sulfur coal and found it to be a modest extension of recent trends in the increased use of low-sulfur coal.

switching, an assumption that is justified if one compares the cost of reducing SO₂ by installing retrofit scrubbers with the cost via fuel switching. Though the useful life of a retrofit scrubber is likely to be close to 20 years (EPA, 1995), the investment decision should reflect current financial and regulatory uncertainties in the industry, which call for a 10 year payback life (EPRI, 1997). With this decision rule, the average cost per ton of reducing SO₂ through additional retrofit scrubbers is \$406, which exceeds the marginal cost of SO₂ reduction via fuel switching.

B. Comparisons and Sensitivity Analyses

Annual compliance costs of \$1 billion per year are far lower than originally predicted when the 1990 Clean Air Act Amendments were drafted. In fact, they are less than half of the estimates of compliance costs expected by the EPA (1989, 1990). This raises two questions: Are our estimates of compliance costs biased downward? If not, why are they so much lower than EPA's original estimates of such costs?

The assumptions made above with regard to electricity generation and fuel prices are likely to overstate, rather than understate costs. We assume, for example, the same rate of growth in electricity generated by coal and a slower rate of retirement of coal-fired plants than official predictions (US EIA 1997). The assumption that high- and low- sulfur coal prices remain at their 1995 is also conservative—the Energy Information Administration (1997) predicts a reduction in the low-sulfur premium below 1995 levels.

The one assumption that might bias our cost estimates downward is that technical progress will continue from 1995 until 2010 at the same rate as between 1985 and 1994. If we assume, at the other extreme, that technical progress stops in 1995, our estimate of compliance costs rises to \$1.51 million (1995 dollars) and our estimate of long-run allowance price to \$436 per ton of SO₂. Even this extreme assumption puts our estimates of total compliance costs below

EPA's (1990) estimate of \$2.5 - \$6.0 billion (Table 2), and our estimate of marginal cost below EPA's estimate of \$579-\$760 per ton.²⁸

[Insert Table 2 here]

It is important for two reasons to understand why these estimates differ. One is to see whether there is a systematic tendency to over-estimate the cost of environmental regulations. That costs are systematically over-estimated has been alleged both by economists (Hammitt 1997) and environmentalists, and is an especially timely issue in light of debates over the cost of reducing greenhouse gases. The second reason is that the factors that explain why estimates of compliance costs have fallen also explain why the costs of command-and-control approaches to reducing SO₂ have fallen and why the potential gains from allowance trading are also lower than originally anticipated.²⁹

One reason for EPA's high estimates of compliance costs is failure to foresee the continued fall in the low-sulfur coal premium, as well as continuing technical progress in fuel switching. To estimate the magnitude of these effects we re-compute the least cost solution using 1989 prices and technology.³⁰ Both total and marginal abatement costs rise by about 90% (Table 2). When fuel switching determines the marginal cost of compliance, using 1989 fuel prices and technology can produce marginal cost estimates approximately as large as those predicted when Title IV was written. Total costs also increase, in part because a higher sulfur premium lowers

²⁸ Recent engineering studies that acknowledge the use of low-sulfur coal for compliance have also identified the declining trend of marginal and annual costs of compliance (EPA (1995) and EPRI (1995,1997)).

²⁹ Even in the absence of trading, Title IV allows firms unprecedented flexibility in selecting a method for complying with SO₂ emission reduction goals. This increased flexibility is believed to have contributed to recent declines in low-sulfur fuel prices and the pace of innovation in fuel switching and scrubbing (Burtraw 1996).

³⁰ We also assume that emissions are estimated based on fuel consumption, as they were in studies prior to the passage of Title IV.

the percent of emissions reductions that can be obtained for free. Using 1989 prices and technology only 21 percent of emissions reductions from plants that fuel switch are obtained by realizing negative marginal abatement costs. This figure, however, rises to 57 percent in the preferred scenario.³¹

Failure to foresee changes in prices and technical progress, however, does not explain all of the difference in total cost estimates. Also important are differences in the baseline from which emissions reductions are measured. In all of our calculations, we assume that the emission *rates* (lbs. of SO₂/mmBtu) that would have prevailed absent the 1990 Clean Air Act Amendments are those that prevailed in 1993. These are much lower than 1989 emission rates, hence the reductions in emissions necessary to achieve the 8.95 million ton cap, by our calculations, are much lower than imagined in 1989 (specifically, about 2 million tons lower). Holding MAC curves constant, lowering the necessary reduction in emissions will lower total compliance costs.

Finally, EPA's estimates of compliance costs are higher than ours because they assumed that more retrofit scrubbers would be built (37) than were actually constructed (28), because they failed to foresee a 50% fall in the cost of scrubbing that we identify.

C. Potential Gains from Trade

We now consider the cost of meeting the SO₂ cap using a command and control approach, and compute the potential gains from trade as the difference between this cost and the cost of compliance under the least cost solution. Since the goal of Title IV is to achieve an average emissions rate of 1.2 pounds of SO₂ per million Btus of heat input, we model command and

³¹ While this estimate may seem high, we have evidence from 1995 and 1996 that utilities are realizing such economic cost savings. In 1995 one-quarter of a potential \$443 million in savings from fuel switching were realized. In 1996, half of \$644 million in potential savings were realized. We believe that increased competition in the electric utility industry will motivate generators to take advantage of these savings.

control as a uniform performance standard that is designed to achieve the same level of emissions as the trading program.³²

For our preferred case, we estimate the potential gains from trade compared to the command and control scenario to be \$784 million (43% of the cost of command and control). While these gains constitute a substantial fraction of the cost of command and control, they are not as large as were originally predicted. The GAO (1994), for example, estimated that a per-unit cap on emissions would cost approximately \$5.3 billion annually and the reduction in costs from efficient trading to be \$3.1 billion (about 60% of this figure).

The explanation for our more modest estimates of trading gains is clear—the factors that have caused marginal abatement costs to fall to a large extent also would have lowered the costs of achieving the SO₂ emissions cap via command and control. These include the fall in the price of low sulfur coal and, to some extent, technical improvements that have facilitated fuel switching.³³ It should also be noted that, in addition to *lowering* marginal abatement cost curves (see Figure 3), the fall in low sulfur coal prices has made marginal abatement cost curves *more homogenous*. This is because costs of transporting low sulfur coal to more distant locations, for example, the East and Southeast, has fallen rendering differences in transportation cost a less important component of the overall cost of fuel switching. Since a major source of trading gains

³² The uniform emission rate standard does not take into account the fact that some units may face unrealized "economic" emission reductions beyond those mandated by the standard. Therefore, emissions are lower under the uniform standard than they are under a trading program, which provides firms with higher abatement costs the flexibility to capture the slack in the effective emission constraint at other firms (Oates, Portney and McGartland 1989).

³³ Some of the technological developments in fuel blending may not have occurred under a uniform emissions standard since blending of coals with different sulfur contents by itself, i.e. without the option of purchasing allowances, generally would not be sufficient to achieve the required emission reductions. Similarly, there would have been less incentive to improve the performance of scrubbing equipment under a uniform emission rate standard and the witnessed improvements may not have been realized. To the extent that the effects of the allowance trading program on technological change in emissions reduction are reflected in our data, our estimates

is differences in marginal abatement cost curves among units in the market, this increased homogeneity is also responsible for low gains from trade.

The relatively modest potential trading gains reflected in our results should not be interpreted as a criticism of the allowance market, but they are likely to have an impact on market performance. If potential gains from trade are small and transactions costs of using the market are substantial, utilities will be less eager to trade allowances. In the next section, we analyze the performance of the SO₂ allowance market in 1995 and 1996 to determine both the potential gains from trade under a perfectly functioning market and how much of these gains actually have been realized.

V. The Performance of the Allowance Market in 1995 and 1996

In 1995 the aggregate emissions of Phase I units were approximately 5.3 million tons, rising to 5.44 million tons in 1996. To compute the least cost method of achieving these emissions levels we parameterize marginal abatement cost functions for each unit using actual output levels and input prices. Technical progress is assumed to occur at the same annual rate as observed between 1984 and 1995. We take as our baseline 1993 emission *rates*, which we apply to 1995 and 1996 electricity generation to predict emissions in the absence of Title IV.

The least cost solution yields a common marginal abatement cost for the last ton emitted among units that fuel switch and a set of efficient emission levels for all generating units. To compute total costs we integrate each unit's marginal abatement cost curve from baseline emissions to emissions under the least cost solution. The total cost of *actual* emissions in each

of the costs of a uniform emission rate standard and the potential gains from trade are likely understated.

year is computed analogously, except that integration under the MAC curve occurs from baseline emissions to actual 1995 and 1996 emissions.³⁴

[Insert Table 3 here]

The least cost solution to achieving 1995 emissions, including the capital and variable costs of scrubbing (\$496 million), is \$552 million (1995 dollars) (see Table 3). The estimated *actual* cost of achieving 1995 emissions is considerably higher—\$832 million. This suggests that \$280 million of potential cost savings were unrealized in the first year of the allowance market. Our estimate of the actual costs is close to estimates obtained by Ellerman *et al.* (1997) of actual compliance costs (\$728 million) based on a survey of the industry. We consider the difference between these estimates and the least cost solution as evidence that there were unrealized gains from trade in 1995.

In 1996 performance under the program did not change dramatically. The least cost solution to achieving 1996 emissions is \$571 million (1995 dollars). The estimated *actual* cost of achieving 1996 emissions increased slightly from the previous year, partly due to increased utilization of scrubbed units. This suggests that \$339 million of potential cost savings were unrealized in the second year of the allowance market.

We note that the marginal cost of the last ton emitted in the least-cost solution (\$101 in 1995 and \$71 in 1996) is close to the price at which allowances were trading (around \$90). The equality of these numbers does not, however, demonstrate that the market was operating efficiently: The two could be equal even if many participants opted out of the market, which was in fact the case.

³⁴ Emission rates are based on DOE-EIA engineering estimates not CEMS data. Because both the heat input and SO₂ emissions estimated by the DOE-EIA are lower than the CEMS measurements the estimated emission rates are equal on average.

Although the allowance market in its first years of operation failed to achieve the least cost solution, it is possible that it was more efficient than a command and control approach to achieving emissions. The cost of the uniform emissions rate standard necessary to achieve actual 1995 emissions is approximately \$800 million, slightly less than our point estimate of actual emissions costs (Table 3). What this suggests is that the uniform performance standard, although it fails to equalize MAC per ton of SO₂, is no less efficient than the actual pattern of emissions chosen by utilities. It also implies potential gains from trade (potential cost savings of trading over command and control) of \$250 million, or about one-third of the costs of command and control.

The failure of the allowance market to achieve the least-cost solution in 1995 and 1996 is neither surprising nor alarming. Title IV represents a dramatic departure from traditional environmental regulation. It requires utilities to manage a financial asset--emission allowances--for which there is no precedent. It also requires a well-functioning market in allowances, which takes time to establish. There is evidence that allowance trades are growing in volume. Economically significant trades between separate utility holding companies have doubled every year since the inception of the program through 1997, which suggests that utilities are increasingly taking advantage of the allowance market as a means to reduce compliance costs (Kruger and Dean, 1997). In addition the number of allowances used for compliance that were obtained through inter-firm transactions increased by 50% between 1995 and 1996.

VI. Conclusions

When the market for sulfur dioxide allowances was envisioned in the late 1980's, the cost of complying with the proposed SO₂ cap was thought to be much higher than it has, in fact, turned out to be. Likewise, the potential trading gains associated with the market were predicted

to be much higher than the estimates presented above. The lower trading gains that we predict for the allowance market in the long run are largely the result of two factors--declines in the price of low sulfur coal and improvements in technology that have lowered the cost of fuel switching. These factors have lowered the gains from trade in two ways. First, they have lowered marginal abatement cost curves for most generating units, which has lowered the cost of achieving the cap via a uniform performance standard, as well as the cost of achieving the cap through allowance trading. Second, because spatial differences in coal prices have been reduced, marginal abatement cost curves have become more homogeneous, which has also lowered the gains from trade.

Our results have several important lessons for policy makers as they consider adopting an allowance trading approach to regulating other utility emissions such as nitrogen oxides (NO_x) and greenhouse gases. First, our findings lend support to the theory that the costs of compliance with regulation are often overestimated *ex ante*. We show that estimates of the costs of compliance with the SO₂ reduction goals under Title IV have fallen substantially over time due to a combination of unanticipated declines in coal prices and technical change. This suggests that attempts to estimate the future costs of other pollution control programs may be similarly flawed, especially given the difficulty in forecasting future trends in technological change. This technology forecasting task is made more complicated by the introduction of greater competition in electricity markets, which is expected to accelerate the pace of technical change.

Second, our results suggest that, in designing an allowance market, it is important for policy makers to consider the source of trading gains and how these gains might change over time. The source of trading gains in the SO₂ allowance market is spatial differences in the price of high v. low sulfur coal. As these price differences have diminished, so have potential trading gains. In the market for CO₂ there are, initially, likely to be large trading gains because coal-fired

power plants, by converting to natural gas, can reduce their CO₂ emissions at a lower cost than oil- and gas-fired plants. Once this conversion is completed, however, trading gains within the electric utility industry will diminish.

Lastly, our results suggest that it will take time for allowance markets to mature and, therefore, for the potential gains from trade to be realized. We show that, on the whole, the market failed to realize potential gains from trade in 1995 or 1996. The reluctance of many firms in the utility industry to take advantage of the allowance market may be a result of features of utility regulation that have limited incentives to participate in the market. As competition increases within the generation segment of the industry, and as we enter the second phase of the allowance program, we expect to see greater use of the market to reduce the costs of environmental compliance. Formal trading in the SO₂ allowance market may not achieve large cost savings compared to a uniform performance standard. The flexibility of the trading program, though, has encouraged utilities to capitalize on advantageous trends, such as changing fuel prices and technological innovation that might have been delayed or discouraged by traditional regulatory approaches. The SO₂ program shows that a market in tradable emission rights is, indeed, feasible. As the electric utilities industry becomes more competitive, one would expect to see the advantage of emission trading programs for other pollutants to become more evident.

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Appendix A

Data for estimating the generator unit level cost function (information on the levels of inputs and output) come from the Energy Information Administration's form EIA-767 and the Federal Energy Regulatory Commission's Form 1 for the period 1985 to 1996. Electric utility plant capital stock comes from Form 1 for the period 1982 to 1996. Prior to this, capital stock data come from the Energy Information Administration's annual report *Electric Plant Cost and Power Production Expenses (Expenses)* and precursors to this report. Coal price information comes from the *Monthly Report of Cost and Quality of Fuels for Electric Plants (Monthly Report)*. The following list describes each of the individual variables needed in the cost function.

Q: Output. Electrical generation (kWh) by generating unit. **Source:** *EIA-767*.

p_{hs}: Price of high sulfur fuel. Following the example of Gollop and Roberts (1983, 1985), the price of high sulfur fuel is the weighted average price, in cents per million Btus, of high sulfur fuel bought by the utility that owns the generator. An emission boundary of 1.2 lbs. of SO₂ per million Btus of heat input is used to differentiate low and high sulfur coal. If the utility bought no high sulfur fuel then the price is equal to the price of low sulfur fuel bought by the utility multiplied by the ratio of high to low sulfur coal prices in the state where the plant is located. **Source:** *Monthly Report*.

p_{ls}: Price of low sulfur fuel. Measured in the same manner as the price of high sulfur fuel. **Source:** *Monthly Report*.

p_l: Wage Rate. The utility's total labor expenditures divided by the sum of the total number of full-time employees and one-half of the number of part-time and temporary employees working for the utility. Publicly owned plants' wage rates are equal to the average wage rate of privately owned plants in the state where the plant is located or the region surrounding the state if no privately owned plants are located in the same state. **Source:** *Form 1*

p_k: The rental price of generation capital. The rental price of generation capital is equal to the utility's cost of capital plus depreciation rate, adjusted for changes in the cost of construction (Cowing et al. 1981). That is,

$$p_k = (R_i + DE)HW_j,$$

where R is the utility's cost of capital, and DE is the depreciation rate and HW is the Handy-Whitman index of electric utility construction costs adjusted to reflect a base year of 1990. The financial cost of capital for privately owned plants is estimated as the sum of the long-term debt interest rate, the preferred stock dividend rate, and the required return on equity capital, where each factor is weighted by its respective capital structure proportion. The financial cost of capital for publicly owned plants is equal to the long term debt interest rate reported in Moody's Municipal and Government Manual. Data for jointly owned plants comes from the utility

indicated as the operator by EIA-767. The depreciation rate is assumed to be 5 percent and it is applied to the undepreciated value of capital stock remaining in each year. This is based on a decay pattern defined by the 1.5 declining balance method and a 30 year asset life. **Source:** *Form 1 and The Handy-Whitman Index of Public Utility Construction Costs*.

e*: **Emission Standard.** The emission standard, in pounds of SO₂ per million Btu of heat input. **Source:** *EIA-767*.

e : **Average Emission Rate.** The annual average emission rate for each utility plant. **Source:** Calculated by the Energy Information Administration from information in *EIA-767*.

k: **Generation Capital Stock.** The capital stock for each plant is calculated as follows:

$$CS_i = (CS_{i-1}) + NI_i / HW_i \quad i = 1951, \dots, 1995,$$

where CS_i is the adjusted capital stock for year i. NI_i is the net investment for year i, DE is the depreciation rate and HW_i the Handy-Whitman index for year i adjusted to reflect a base year of 1990. The plant's net capital stock is equal to the initial investment in buildings and equipment plus the costs of additions minus the value of retirements, expenditures on flue gas desulfurization capital stock and depreciation. Each generator's capital stock is the product of the plant's capital stock and the generator unit's share of the plant's total generation capacity. **Source:** *Expenses, EIA-767 and Form 1*.

Generation Capital Expenditure. The product of the deflated generation capital stock and the rental price of generation capital.

Labor Expenditure: The product of the wage rate and the total number of employees working at the plant multiplied by the generator's share of the plant's total generation capacity.

High Sulfur Fuel Expenditure: The product of heat input from high sulfur coal, in millions of Btus, and the price of high sulfur fuel. The type of fuel burned by the generating unit is determined from the unit's SO₂ emission rate before SO₂ removal.

Low Sulfur Fuel Expenditure: The product of heat input from low sulfur coal, in millions of Btus, and the price of low sulfur coal.

Capital investments in scrubbing are amortized using the following formula:

$$F_t = \left(\frac{K_0}{T} + rK_t \right) (1+i)^t,$$

where F_t is the annual fixed cost for year t , K_0 is the initial investment cost, T is the life of the capital equipment, r is a real interest rate, K_t is the undepreciated investment at the beginning of each year, and i is the inflation rate. Based on this formula the annual capital charge is 11.33% of the capital investment.

Table 1: 1985 and 1994 Weighted Average Marginal Abatement Costs and Rates for Coal-Fired Units without Scrubbers

| | Emission Rate (lbs/mmBtu) | Mean MAC | Std. Dev. | 10th Percent |
|--------------|------------------------------|----------|-----------|--------------|
| 1985 Phase I | 3.65 | \$250 | \$485 | \$7 |
| Table A | 4.09 | \$164 | \$308 | -\$1 |
| Comp. & Sub | 1.97 | \$604 | \$812 | \$57 |
| Phase II | 1.33 | \$1332 | \$1836 | \$183 |
| Total | 2.45 | \$811 | \$1467 | \$51 |
| 1994 Phase I | 2.82 | \$121 | \$475 | -\$264 |
| Table A | 3.15 | \$104 | \$370 | -\$149 |
| Comp. & Sub | 1.47 | \$190 | \$763 | -\$293 |
| Phase II | 1.22 | \$1092 | \$2469 | -\$88 |
| Total | 1.90 | \$680 | \$1958 | -\$182 |

*Emission Rates are weighted by total heat input and Marginal Abatement Costs are weighted by total SO2 emissions. Figures are were included and excluded from the costs function estimation in order to make comparisons between years meaningful.

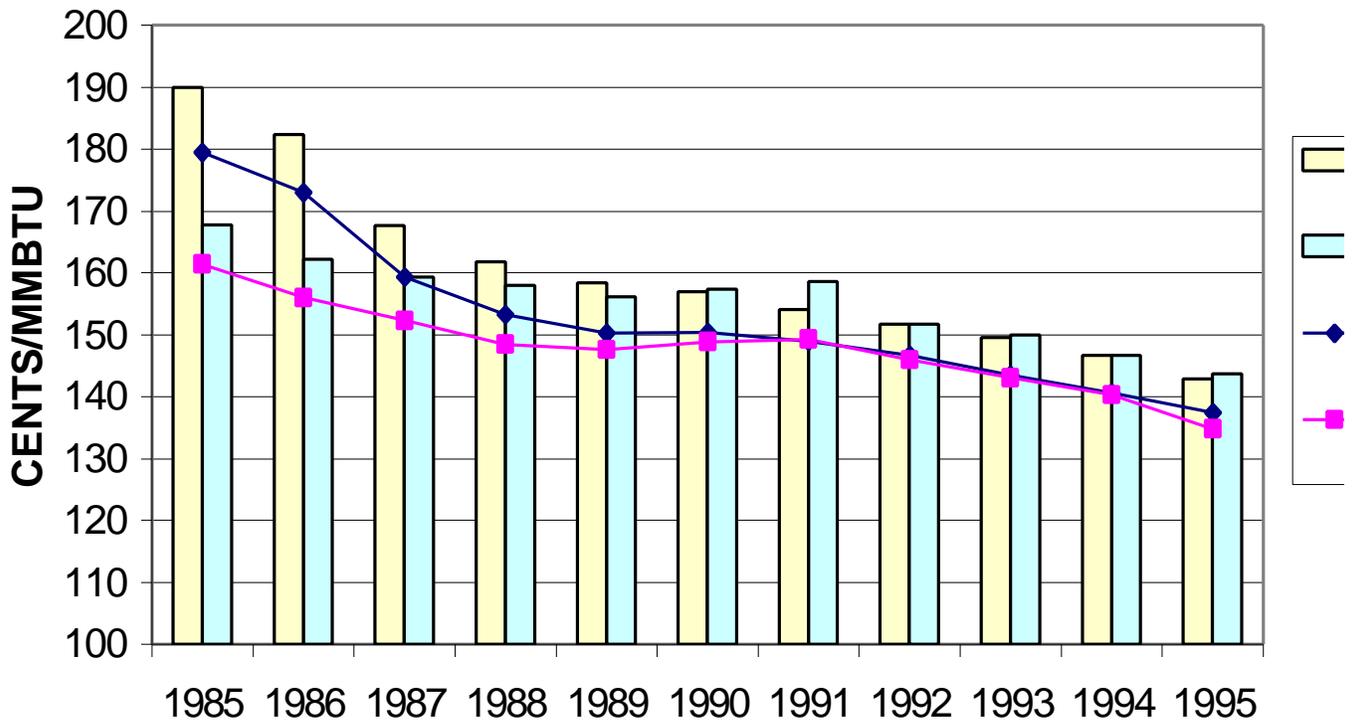
Table 2: Long-Run (Phase II, year 2010) Cost Estimates

| Scenario | Cost under Command and Control (billion 1995\$) | Cost Under Efficient Trading Cost (1995\$) | Marginal Cost per Ton SO2 (1995\$) | Average Cost per Ton SO2 (1995\$) | Potential Gains from Trade (1995\$) |
|--|--|--|--|---|---|
| <i>Preferred Estimate</i> | 1.82 | 1.04 | 291 | 174 | 0.78 |
| 1995 Technology | 2.23 | 1.51 | 436 | 198 | 0.72 |
| 1989 Prices and 1989 Technology | 2.67 | 1.90 | 560 | 236 | 0.77 |
| EPA (1990) | - | 2.3-5.9 | 579-760 | 348-499 | - |
| EPA (1989) | - | 2.7-6.2 | | 377-511 | - |

Table 3: Phase I (1995 and 1996) Annual Total Cost

| | Command and Control (million 1995\$) | Efficient Trading (million 1995\$) | MAC (1995\$) | Potential Gains from Trade (million 1995\$) |
|---------------------------|---|--|------------------------|---|
| 1995 | | | | |
| Preferred Estimate | 802 | 552 | <i>101</i> | 250 |
| Actual compliance | 832 | | <i>n/a</i> | 280 |
| 1996 | | | | |
| Preferred Estimate | 777 | 571 | <i>71</i> | 206 |
| Actual compliance | 910 | | <i>n/a</i> | 339 |

Figure 1: Low-Sulfur and High-Sulfur Coal Prices



**Figure 2: The Effect of Changes in Fuel Prices and Technica
Change on Marginal Abatement Cost Functions**

