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ABSTRACT

Electric utilities can reduce sulfur dioxide emissions through a variety of strategies such as adding scrubbers, switching to low-sulfur coal, or shifting output between generating plants with different emissions. The cost of achieving a given emission target can be minimized using a market for emission allowances, as under the Clean Air Act Amendments of 1990, if firms with high abatement costs buy allowances while those with low abatement costs reduce emissions and sell allowances. However, public utility commissions regulate which costs can be passed to customers.

Previous theoretical work has analyzed effects of regulations on a utility's choice between permits and a single continuous "abatement technology." Here, we consider three abatement technologies and the discrete choices among them. Our numerical model uses market and engineering information on permit prices, scrubber cost and sulfur removal efficiency, alternative fuel costs and sulfur content, plus generating plant costs and efficiency. Using illustrative sets of parameters, we find that regulatory rules could more than double the cost of sulfur dioxide compliance.

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Sulfur Dioxide Compliance of a Regulated Utility

Total sulfur dioxide (SO_2) emissions in the United States must be reduced by more than 40 percent from their 1980 level, according to Title IV of the Clean Air Act Amendments of 1990 (CAAA).[1] Virtually all of this abatement must be undertaken by electric utilities using a variety of technologies such as flue-gas desulfurization equipment (scrubbers), switching to more-expensive low-sulfur coal, or switching output to plants with lower emission rates. To provide flexibility in these abatement activities, the CAAA institutes a system of tradable emission allowances. In theory, with competitive markets, this allowance system can induce utilities among themselves to find cheaper means to control emissions than would a conventional command-and-control approach such as a technology standard or uniform performance standard.

However, almost all utilities are regulated by state public utility commissions (PUCs) that decide what costs can be passed on to customers through electricity prices. By allowing some costs and not others to be passed to electricity customers, these regulatory rules can affect the decisions of utilities about how to comply with the CAAA. As a result, actual compliance decisions may not minimize the cost of compliance.

This paper illustrates the extent to which actual compliance costs can exceed minimum compliance costs. We first discuss the reasons that PUC rules may intentionally or unintentionally provide differential incentives to abate emissions or buy allowances, and we describe three possible PUC ratemaking scenarios. We then model the abatement decisions of a utility that must comply with the CAAA while facing those PUC rules, and we do so in a way that captures the discrete nature of choices among multiple abatement technologies. We use the model to calculate both cost-minimizing compliance choices and the other compliance choices under PUC rules.

Previous research has clarified how emission trading can achieve minimum compliance costs (Montgomery, 1972, and Tietenberg, 1985), and how PUC regulations

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[1] Phase I, from 1995 to 2000, requires 110 of the dirtiest electric utilities to reduce SO_2 emissions to an average of 2.5 pounds per million Btu. Phase II starts in 2000, affects all utilities over 25 megawatts (MW), and limits emissions to 1.2 pounds per million Btu. For an update on how the CAAA is working, see Burtraw (1995) or Rico (1995).

affect those compliance decisions (Bohi and Burtraw, 1992, and Rose et al., 1992). Using their theoretical model, Bohi and Burtraw (1992) show that the utility's minimization of compliance cost is not affected by "symmetric" regulatory treatments that assign to shareholders the same fraction of all costs and benefits from allowance trading and abatement activities. They show how asymmetric regulations affect compliance. Coggins and Smith (1993) develop a similar model, and use it to measure effects on social welfare. Both of these papers capture the Averch and Johnson (1962) effect as well. If the rate of return to capital allowed by regulators exceeds the market rate of return required by investors, for example, then the utility may face differential incentives to buy whatever abatement technology counts as capital in the rate base. For simplicity, these papers consider the choice between trading allowances and a single continuous "abatement technology." Bernstein et al. (1994) and Winebrake et al. (1995) consider effects of regulations on multiple compliance choices. These economic models use cost functions that are convex, continuous, and twice differentiable, which is useful to obtain analytical solutions that characterize tradeoffs at the margin.[2] Abatement proceeds until its marginal cost equals marginal benefit (the price of an allowance, saved by reducing emissions).

We also model the effects of PUC rules while assuming utility managers comply with the CAAA by maximizing their shareholders' profits. We extend previous efforts, however, by considering discrete decisions about multiple abatement technologies.[3] In our model, the utility might buy allowances, sell allowances, install a flue-gas desulfurization (FGD) unit, switch to low-sulfur fuel, or switch output between plants with different emission characteristics. Each of those activities may receive a particular regulatory treatment, and some of those activities are highly discontinuous.

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[2] Bernstein et al. (1994) focus on results, using a "dynamic linear program," in which decision variables are continuous. Winebrake et al. (1995) provide more detail on their model. Firms can switch fuels and install scrubbers, but output at each plant is fixed. They consider all 110 plants subject to Phase I and an aggregate variable for other firms in Phase II. They find that trading can save over \$4 billion during 1995-2005, and they calculate an allowance price of \$143 per ton SO_2.

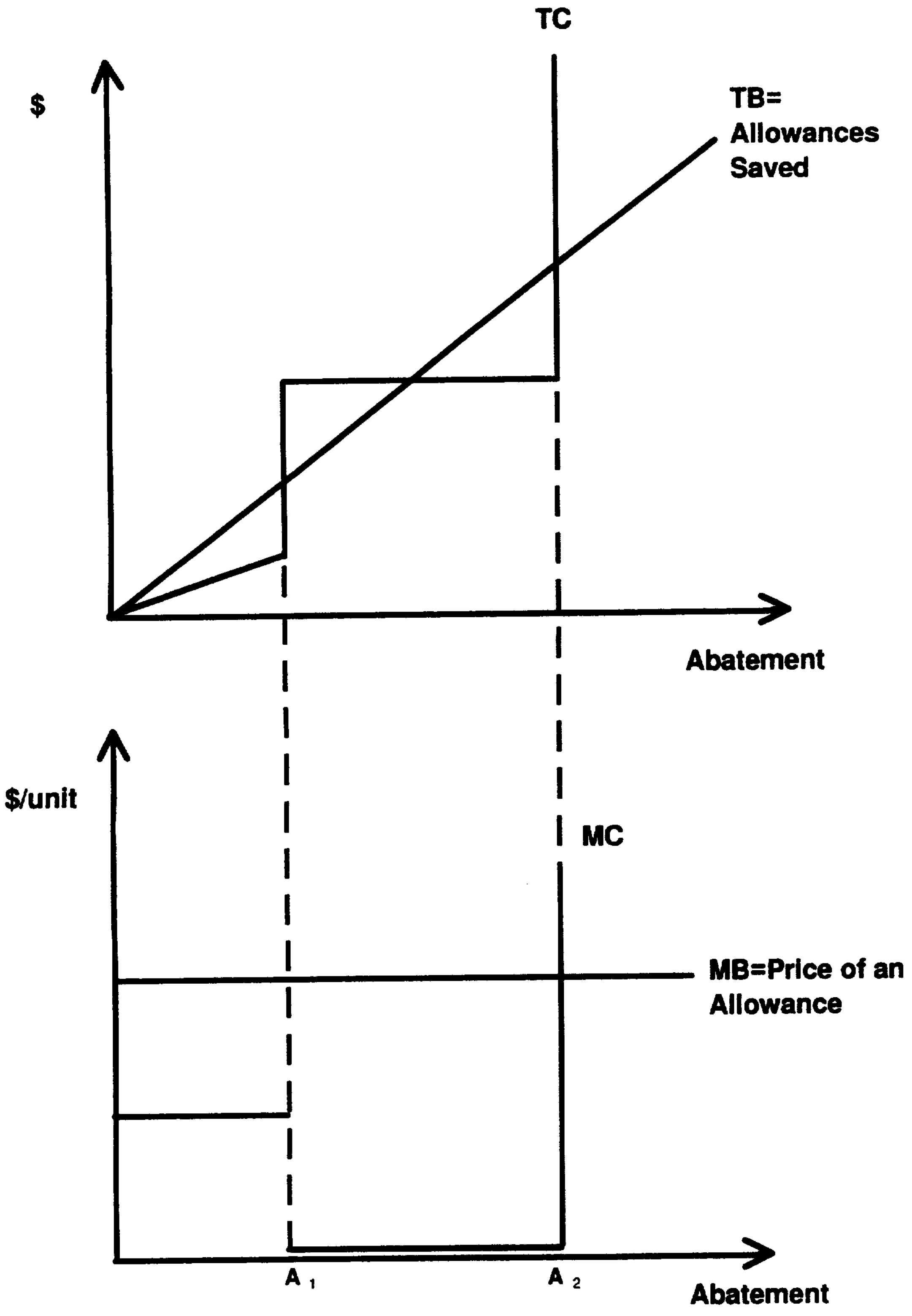
[3] Palmer et al. (1995) consider discrete choices among multiple options, in a model similar to ours, but they are concerned with "social costing" regulations rather than CAAA compliance.

To illustrate, Figure 1 shows the total cost (TC) and the corresponding marginal cost (MC) of abatement. For initial increments, the utility might switch toward low-sulfur coal at a constant marginal cost given by the price differential between low- and high-sulfur coal. At some point like A_1, after all coal is low-sulfur, further abatement can be achieved only by installing an FGD unit (scrubber) at a substantial jump in cost. Yet the scrubber also provides a substantial jump in abatement, up to A_2. (With the scrubber to remove sulfur, the utility can also switch back to the cheaper high-sulfur coal, and it can switch output to the plant with the scrubber.) Finally, at some point, further abatement is not possible, and the cost curves are vertical. The marginal benefit (MB) of abatement is the price of an allowance saved. In this model, MC may be undefined at some levels of abatement, and may not intersect MB. We calculate total costs and benefits and find the option where (TB-TC) is largest (in this figure, A_1 or A_2). Thus we account for more of the compliance decisions made be utility managers, but the model must be solved by numerical rather than analytical methods.

An advantage of this approach is that we can use specific economic and engineering information about each abatement technology. Each plant in our model has a generating capacity, production efficiency, and emission characteristic. Each type of fuel has a heating value, sulfur content, and market price. Each scrubber has a capital cost, economic life, and discount rate.

Our model has some limitations. It is not designed to address issues about how PUC regulations are formed (Joskow and Schmalensee, 1986), how these policies affect electricity production (Coggins and Smith, 1993), how PUC regulations affect allowance prices (Winebrake et al., 1995), or how actual allowance markets might be affected by such factors as market power (Hahn, 1984), manipulation (Misolek and Elder, 1989), non-compliance (Keeler, 1991), transactions costs (Stavins, 1995), and state sulfur dioxide limits (Coggins and Swinton, 1996). We ignore reasons for banking allowances, such as regulatory uncertainty (Lober and Bailey, 1995) and price uncertainty (Bohi and Burtraw, 1992). Instead, the model is designed to address issues and provide intuition about the possible effect of PUC regulation on the cost of CAAA compliance, using the abstraction

Figure 1: An Illustration of Discrete Decisionmaking



of a fully-informed, profit-maximizing utility manager who faces a *given* PUC regulation, output requirement, and allowance price. Later in this paper we vary these exogenous parameters to test the sensitivity of results. We discuss these limitations and the possibility of extending the model to multiple utilities.

The model is designed to consider multiple distortions in a second-best world. In this case, the effects of federal environmental policy depend heavily on a separate policy undertaken by a state government with a different agenda. For tractability, however, we ignore other distortions such as taxes or monopoly power in markets for allowances, fuels, or technologies. All environmental costs of mining are assumed to be reflected in the price of coal. Since aggregate emissions are fixed by the CAAA through the total number of allowances, we can ignore benefits of changes in the overall pollution level. This fixed total pollution is re-allocated by allowance trading, however, so we implicitly ignore differences in the effects of pollution by location. Thus, our measure of compliance cost does not include all possible social costs, but it does include all compliance costs borne either by shareholders or by electricity customers. This measure is called "social" cost to distinguish it from the purely private cost faced by shareholders that forms the basis of utility decisionmaking.

Using the model, we demonstrate five important results. First, although Bohi and Burtraw (1992) show that symmetric regulatory treatment is *sufficient* to induce cost-minimizing compliance choices, we show that it is not *necessary* for such behavior. Because compliance choices are discrete, rather than continuous, small to moderate changes in one of the regulatory parameters do not necessarily induce any change in compliance at all. At some point, however, the utility may jump to a different more-expensive abatement technology. Second, PUC regulatory rules can have unintended effects. One set of rules designed to encourage allowance trading does have the intended effect, but another set of rules designed to discourage local emissions does not. Thus an "environmentally conscious" PUC might end up polluting its state more than the "market advocate" PUC. Third, we show how regulatory rules can provide artificial incentives for mergers and acquisitions. If two utilities are discouraged from pooling their abatement resources by trading allowances, they might pool all of their resources to achieve the same result. Thus an unfettered allowance market might help leave the electric generating industry more competitive as it looks toward possible deregulation in wholesale and distribution markets. Fourth, we use illustrative parameter values and regulatory scenarios to calculate social costs of compliance with the Clean Air Act Amendments. Under certain asymmetric PUC regulations, when our stylized utility minimizes private cost of compliance, the resulting social cost of compliance is often twice the minimum social cost and sometimes nine or ten times the minimum social cost. Finally, we show that asymmetric PUC rules can make the allowance trading provisions of the CAAA even more expensive than the alternative federal command-and-control regulation.

The first section below provides more background on the CAAA and reasons that actual PUC regulations might provide asymmetric compliance incentives. Section II describes the model and data used to set parameter values. Section III uses the model to calculate effects of particular PUC ratemaking rules, while Section IV analyzes the sensitivity of results to alternative parameter values. The last section discusses possible extensions of the model, summarizes results, and explores some policy implications.

I. The CAAA and PUCs

The Clean Air Act Amendments set a national limit on annual sulfur dioxide emissions and created an annual number of emission allowances equal to that limit. An allocation system endows each electric utility with an annual number of allowances based on its historical sulfur dioxide output. These allowances are free to the utility. Each allowance grants the holder the right to emit one ton of sulfur dioxide during or after the year in which the allowance is issued. Electric utilities that burn fossil fuels -- primarily coal -- must match each ton of sulfur dioxide emissions with an allowance.[4] When the utility's current sulfur dioxide output is greater than the number of allocated allowances, as is commonly the case, the utility may achieve compliance either by abating emissions or by

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[4] Under CAAA provisions, penalties for noncompliance are high enough that effectively utilities must match each ton of sulfur dioxide output with an emission allowance.

purchasing additional allowances from other holders. A utility that switches fuels or uses other technologies to reduce emissions to a level below its endowment may sell (or bank) the excess allowances. Thus it can balance the market-determined price of an allowance against the cost of abatement technologies that directly reduce sulfur dioxide emissions.

This balancing will be affected by PUC regulations that change the utility's perception of compliance costs and benefits. State PUC regulators set the price of electricity, effectively controlling utility shareholders' recovery from customers of spending on capital equipment and operating costs necessary for electricity production. In this sense, PUC ratemaking amounts to deciding how production costs and occasional gains on asset sales should be divided between shareholders and electricity customers. This regulatory problem applies to sulfur dioxide compliance, as well. PUC regulators must decide how to allocate gains on allowance sales and spending on emissions abatement and allowance purchases.

Many state public utility commissions have not yet decided how they will treat sulfur dioxide compliance for ratemaking purposes, and industry analysts have widely cited "regulatory uncertainty" as an impediment to trades (Hahn and May, 1994; Electric Light & Power, 1994; Rose et al., 1993). Thus, the purpose of this paper is to illustrate some potential consequences of suggested regulatory rules.

In our model, we reduce the sharing of compliance costs and benefits between ratepayers and shareholders to its rudiments, using only four regulatory parameters. Each parameter represents the portion, between zero and one, of a cost or gain that the PUC allocates to shareholders (as opposed to ratepayers):[5]

parameter:	shareholders' portion of:
α	cost of allowance purchases
β	gain on allowance sales
γ	extra cost of fuel (from fuel switching or plant switching)
δ	cost of investment in FGD units (scrubbers)

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[5] Similar exogenous cost-sharing parameters are used to model incentives in Bohi and Burtraw (1992). We also use our model below to calculate the effects of more direct PUC actions such as the prohibition of allowance trading or mandated FGD installation, as in Winebrake et al. (1995).

In traditional ratemaking, the PUC assigns all prudent costs of electric operations to electric customers. With respect to sulfur dioxide compliance, this "cost-plus" regulation would assign FGD capital costs fully to utility customers as part of the ratebase necessary for the provision of electric service. One standard treatment of compliance fuel costs would involve the "fuel clause," a mechanism by which changes in fuel expense are recovered from ratepayers through automatic adjustments to electricity prices. Cost-plus regulation would deem allowances to be the property of ratepayers, and would therefore direct all trading costs and benefits to electric customers.[6]

Cost-plus regulation could be represented in our model by setting all four regulatory parameters to zero. In this way, all compliance costs and benefits are allocated to electricity customers. In a model with strictly profit-maximizing behavior by utility managers, however, the utility's compliance decision is then indeterminate. Since the effect of compliance on profit is always zero, the manager has no criterion for choosing one compliance strategy over another. Possible nonfinancial motives are discussed below.

This result reflects not just a modeling problem, but a more general policy problem faced by PUC regulators with respect to utility production as well as compliance decisions. If shareholders have no stake in the financial outcome of these decisions, and if utility managers consider only shareholder profits, then they have no direct incentive to minimize any of these costs. Furthermore, in general, the regulators cannot perfectly observe utility costs or managerial efforts to reduce them. Joskow and Schmalensee (1986) review the design of "incentive regulations" that best maximize consumer welfare given asymmetric information and the utility's profit maximization.

In the context of our model, this dilemma has a simple solution. By giving shareholders a small stake in *all* of the costs and benefits of compliance, the PUC can give utility managers incentive to make compliance decisions that minimize social cost. This "symmetric regulatory treatment" is represented by setting all four parameters to a single nonzero value. We use this case to calculate the minimum social cost of compliance.

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[6] Wisconsin and West Virginia adopt this approach to allowance transactions (Rose et al., 1993).

This symmetric regulatory outcome is not guaranteed, however, for a variety of reasons. First, utility managers may fear changes in the government's allocation of allowances, or in the future market price of allowances. To guarantee the utility's continued ability to comply with the CAAA, utility managers may shun reliance on the uncertain allowance market in favor of known abatement technologies. To overcome this natural disinclination, PUCs may deliberately skew the allocation of compliance costs and benefits to create incentives for utilities to participate in the allowance market. Such "allowance trading incentives" are much discussed in the literature (Rose et al., 1992; Rose and Burns, 1993; Bohi and Burtraw, 1991). In our model, allowance trading incentives can be represented by assigning to shareholders a positive fraction of all gains or losses from trading. These incentives may well be combined with traditional cost-plus regulations that assign all FGD and fuel costs to electricity customers.

Second, state regulators balance these economic objectives against other social and political objectives. For example, they seek to protect electricity customers, and to encourage economic development. States that mine high-sulfur coal may decide to protect local mining employment by encouraging the use of local coal or requiring the use of scrubbers.[7] Other state PUC regulators may wish to protect the local environment by discouraging the purchase of allowances relative to other compliance strategies. We simulate effects of such regulations below.

Third, even if a PUC wishes to minimize social costs by promulgating symmetric regulatory treatment of all options, they may be thwarted by the sheer complexity of ratemaking procedures. Actual ratemaking involves complicated accounting conventions, the effects of taxes, measuring the utility's true cost of capital, and dealing with the time value of money. These complexities can obscure the true nature of the division of costs between electric customers and utility shareholders. An important question, then, is how far can regulatory parameters deviate from symmetry without changing the utility's compliance choices away from social-cost-minimizing choices. To explore this issue, we

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[7] Such rules appear in Illinois, Indiana, Kentucky, Ohio, and Pennsylvania (Lober and Bailey, 1995).

test the sensitivity of total compliance costs to incremental changes in particular regulatory parameter values.

II. The Model

We represent the compliance decision as a constrained optimization problem for one firm with multiple generating plants and fuel alternatives. Exogenous parameter values are set to reflect current information on generating plants, abatement technologies, fuel costs, FGD capital costs, and the allowance price. The utility is a price-taker in the allowance market. We assume a fixed total demand for electricity, and a fixed electric generating capacity at each plant. Thus, we avoid the need to account for any of the fixed costs or even variable costs of production, so long as those costs do not vary with compliance choices. We assume total labor and maintenance costs are unaffected by switching a given amount of electricity generation from one plant to another, or by using low-sulfur instead of high-sulfur coal. Thus, managers consider only the *change* in profits from adding a scrubber, paying more for low-sulfur coal, using more of the less-efficient plant, or trading allowances.

The full range of sulfur dioxide compliance strategies is broad and complex, but for practical purposes the major options can be reduced to the four considered here: allowance trading, coal switching, plant switching, and FGD installation.[8] Under the CAAA so far, around 60 percent of compliance involves coal switching or blending, nearly 30 percent involves allowance trading (and intra-utility offsets or plant-switching), and about 10 percent involves FGD installation (Bretz, 1994; Rico, 1995; and Burtraw, 1995). The model represents only coal-fired generating plants and the demand on those plants.

The analysis here is based on one time period, a year, with no intertemporal decision making by the utility. We also assume perfect information and perfect certainty. Thus, with no changes in technologies or market prices, the firm would continue to make the same compliance choices period after period. These assumptions also allow us to

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[8] Compliance strategies not considered here include plant re-powering, fuel switching to natural gas, coal washing, and demand-side (energy conservation) options. Over time, the utility may also shift the composition of its generating resources away from technologies that use fossil fuels.

ignore the CAAA provisions for banking allowances and the associated regulatory issues about whether banked allowances should be included in the utility's rate base and what return these allowance assets should earn.

The purpose of the model is to compare the total cost of compliance at differing compliance choices, with and without the effects of PUC ratemaking. We first establish baseline sulfur dioxide emissions and fuel costs, finding the utility's choice of fuels and plant usage to meet electricity demand in the absence of restrictions on sulfur dioxide emissions. We then use the model to solve for social-cost minimizing choices that meet compliance and capacity constraints while generating the required total amount of electricity. The calculated minimum social cost of compliance includes the change in fuel expense from its baseline level, the cost of FGD installation(s), and the net financial effects of allowance trading. Using the same model, we can then set regulatory parameters to reflect particular PUC ratemaking rules. We then use the model to find the new profit-maximizing compliance decisions and the new total compliance cost. The difference between this total compliance cost and the earlier-calculated minimum compliance cost is the additional cost attributable to PUC regulations.

A. Parameters and Variables

Diverse economic and engineering information is summarized into parameters for use in our model. Table 1 presents our notation and definitions of these parameters and other variables.[9] It divides exogenous parameters into four types: generating plant characteristics; fuel characteristics; regulatory parameters; and market parameters.

Each generating plant (p=1,...,P) is assigned a net capacity C_p and a heat rate V_p at which it converts fuel energy to electric energy. FGD characteristics are plant-specific and include capaital outlay K_p, economic life L_p, and sulfur dioxide removal efficiency R_p. Each fuel (f=1,...F) has a price P_f, a heating value H_f which specifies its energy

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[9] The table does not show some simple conversions for consistency of units.

Table 1: Model Parameters and Variables

Generating Plant and FGD Parameters (p=1,...,P)		Units
C_p	Net generating capacity at plant p	MW
V_p	Heat rate (an inverse measure of efficiency)	Btu/KWh
K_p	Capital cost of FGD at plant p	$/plant
L_p	Economic life of FGD at plant p	years
R_p	SO2 removal efficiency of FGD at plant p	fraction [0,1]
r_p	Annual capital recovery factor for FGD at plant p	fraction [0,1]
Fuel Parameters (f=1,...,F)		
P_f	Price of fuel f	$/ton
H_f	Heating value of fuel f	MBtu/ton
S_f	Sulfur content of fuel f	fraction [0,1]
Regulatory Parameters		
α	Allowance purchase cost to shareholders	share [0,1]
β	Allowance sale gain to shareholders	share [0,1]
γ	Fuel cost change to shareholders	share [0,1]
δ	FGD capital cost to shareholders	share [0,1]
Market and Other Exogenous Parameters		
A_d	Endowed allowances	tons of SO2/year
D	Demand for electricity	MWh/year
P_A	Price of SO2 emission allowance	$/ton of SO2
ρ	Discount rate (required rate of return)	rate of return [0,1]
m	Conversion constant, sulfur (S) to SO2	1.9 units SO2/unit S
n	Conversion constant, MW to MWh/year	8,760 hours/year
Decision Variables		
A_b	Allowances bought for SO2 compliance	tons of SO2/year
A_s	Allowances sold for SO2 compliance	tons of SO2/year
X^o_{pf}	Fuel f burned at plant p, without SO2 compliance	tons/year
X'_{pf}	Fuel f burned at plant p, with SO2 compliance	tons/year
Y_p	Binary variable for FGD at plant p	0 no, 1 yes
E	Total firm SO2 emissions	tons of SO2/year
Q_p	Net generation at plant p	MWh/year

Notes: Megawatt (MW) is a million watts, a measure of generating capacity or power. Multiplication by 8,760 hours/year gives megawatt hours per year (MWh). Multiplication by 1,000 gives kilowatt hours per year (KWh). British thermal unit (Btu) and millions of Btu (MBtu) are measures of heat energy. Sulfur dioxide is abbreviated as SO_2.

content, and a sulfur content S_f. The mix of fuels determines both fuel cost and sulfur dioxide emissions.

The four regulatory parameters have already been discussed. Other exogenous parameters include the number of endowed allowances A_d given to the utility each year by the EPA, and the annual demand for electricity D. Endowed allowances can be matched with sulfur dioxide emissions or sold at the market price P_A. Since endowed allowances have no cost to the utility, the gain on the sale of each allowance is the full market price. Parameters and decision variables are given in annual units, so we need the utility's discount rate ρ to convert the total capital cost of each scrubber K_p into its annual equivalent r_p. We do not model the Averch-Johnson (1962) effect explicitly, with separate variables for the allowed rate of return and the market rate of return. However, we can account for that effect implicitly by assigning differential regulatory incentives to any compliance technology that appears in the rate base.[10]

The model utility controls four variables. It can buy A_b allowances or sell A_s allowances, but not both.[11] The model utility also selects X_{pf}, the amount of each fuel burned at each plant. If the aggregate sulfur content of the compliance fuel mix X'_{pf} is lower than that of the non-compliance fuel mix X^o_{pf}, then fuel switching contributes to sulfur dioxide abatement. Lower-sulfur coals are generally more expensive than high-sulfur coals, which provides a fuel cost contribution to compliance cost. Finally, the model utility chooses whether or not to install FGD equipment at each plant. This binary decision variable is Y_p. Together, these four control variables effectively determine total sulfur dioxide emissions, E, and electric generation at each plant, Q_p.

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[10] If scrubbers but not allowances are treated as capital with an allowed return that exceeds the market return, that effect can be captured through the parameters that divide the costs of those two compliance methods between shareholders and customers. This assumption allows us to abstract from an issue over which PUC has little control. The utility's required return changes continually and is very difficult to measure. As a practical matter, neither the PUC nor the utility may know whether the allowed return is actually larger or smaller than the required return.

[11] Simultaneous buying and selling is prohibited in this single-period model to preclude a money pump made possible if PUC rules were to allow differential effects on utility profits.

B. The Objective Function and Constraints

The model consists of a set of profit equations and three types of constraints: the demand constraint, the sulfur dioxide compliance constraint, and plant capacity constraints (Table 2).[12] The objective function is the change in shareholder profit due to the four compliance activities, as affected by regulatory parameters. First, shareholders bear a fraction α of the cost of allowance purchases. Second, they receive a fraction β of the value of any endowed allowances that are sold. Third, if the fuel mix chosen for compliance is more expensive than the fuel mix chosen in the absence of compliance, then shareholder profit is reduced by a fraction γ of the additional fuel cost. Fourth, the installation of an FGD unit creates annualized capital costs, and profits are reduced by a fraction δ of the sum of these costs taken across all plants having FGD equipment.

The extra fuel cost includes not only the cost of switching fuel types, but also the cost of switching output to the less efficient plant that uses more fuel per unit of electricity. The utility might choose to produce more electricity at the less efficient plant, even in the social-cost minimizing compliance solution, if the cost of adding a scrubber at that plant is sufficiently smaller than other compliance options. Partitioning extra fuel cost into these two components is somewhat arbitrary. We calculate the cost of "fuel-switching" as total fuel cost minus the cost of the cheapest fuels that would produce the same level of output at each plant. The cost of "plant-switching" then is the calculated change in fuel cost minus the cost of fuel-switching.

Table 2 also shows three constraints on the utility's choices. First, the sum of electricity production at all plants must meet fixed annual demand. Each plant's output depends on plant efficiency, fuels used, and fuel heating values. The capacity constraints ensure that each plant's annual output does not exceed its electric generating capacity. The compliance constraint, imposed by the CAAA, holds that allowances must match sulfur dioxide emissions. The last equation shows how total emissions depend on scrubber choices, removal efficiency, and the sulfur contents of fuels used.

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[12] The model is coded in the GAMS (General Algebraic Modeling System) language (Brooke et al., 1992). Our mixed integer programming problem is solved by a version of the ZOOM solver.

Table 2: Objective Function and Constraints

Maximize:

$$\Pi_{TOTAL} = \Pi_{BUY} + \Pi_{SELL} + \Pi_{FUEL} + \Pi_{FGD}$$

the total change in shareholder profits attributable to allowance purchases, allowance sales, fuel-switching, and FGD (scrubber) installation, where:

$$\Pi_{BUY} = -\alpha \cdot A_b \cdot P_A$$

$$\Pi_{SELL} = \beta \cdot A_s \cdot P_A$$

$$\Pi_{FUEL} = \gamma \sum_p \sum_f (X^o_{pf} - X'_{pf}) \cdot P_f$$

$$\Pi_{FGD} = -\delta \sum_p Y_p(r_p \cdot K_p) \qquad \text{where} \qquad r_p \equiv \left[\frac{\rho(1+\rho)^{L_p}}{(1+\rho)^{L_p} - 1} \right]$$

Subject to:

demand constraint $D = \sum_p Q_p$ where $Q_p \equiv \sum_f (H_f \cdot X_{pf} \cdot 1000 / V_p)$

capacity constraints $Q_p \le C_p \cdot n$ for p=1,...,P

compliance $E = A_d + A_b - A_s$ where $E \equiv \sum_p [(1 - Y_p \cdot R_p) \sum_f (X_{pf} \cdot S_f \cdot m)]$

C. Exogenous Parameter Values

The parameter values are chosen to illustrate a typical situation for utilities that must comply with the CAAA (Table 3). The model utility employs two coal-fired plants to meet demand: a large plant (1000 MW) and a small plant (300 MW). The large plant is more efficient than the small plant, as is typically the case. The capital costs of flue gas desulfurization equipment for both plants are based on a unit cost of $200 per kilowatt of capacity, an average figure for the wet FGD systems that have been the most frequently used to date (Keeth et al., 1992). The sulfur dioxide removal efficiency for this type of FGD equipment is typically 95 percent (Keeth et al., 1992).

For simplicity, the model utility is limited to two fuel choices: a medium-sulfur coal and a low-sulfur coal. These coal types and their characteristics are available to most utilities faced with CAAA compliance (Electric Power Research Institute, 1993). Table 3 shows mine-mouth prices for these two types of coal, so we add the cost of transportation from the mine to the utility. In "fuel case 1" we add the same transport cost to both types of coal, to represent a utility in the central U.S. that is equidistant between Eastern sources of medium-sulfur coal and Western sources of low-sulfur coal. More generally, results for compliance costs depend only on the difference between the two fuel prices. Thus, "fuel case 1" can be taken to represent any utility facing gross fuel prices that differ by $3.50 per ton. We also report results for "fuel case 2" with a difference of $10 per ton, which might represent an Eastern utility paying extra transport costs for low-sulfur coal.

The utility faces fixed demand of 7.7 million MWh/year, which reflects utilization rates of 70 percent at the larger plant and 60 percent at the smaller plant. These capacity factors are typical of actual operations at plants of these sizes (Fink et al., 1992). Both plants are necessary to meet total demand. The utility is endowed with 44,305 allowances per year, based on the unrestricted levels of plant operation and the CAAA Phase II emission limit of 1.2 pounds of sulfur dioxide per million Btu. Engineering data and relationships necessary to model electricity production are taken from El-Wakil (1984). The allowance price of $150 per ton of sulfur dioxide is based on the 1994 Environmental Protection Agency auction (Hoske, 1994).

Table 3: Central Parameter Values

Generating plants (P=2)	Large Plant	Small Plant
Net generating capacity	1,000 MW	300 MW
Efficiency (heat rate)	9,500 Btu/KWh	10,500 Btu/KWh
FGD capital cost	$200 million	$60 million
FGD economic life	15 years	15 years
SO2 removal efficiency	95 %	95 %
Fuels (F=2)	Medium Sulfur	Low Sulfur
Price	$22.00 /ton	$25.50 /ton
Heating value	25 MBtu/ton	25 MBtu/ton
Sulfur content	1.5 %	1 %
Other Parameters		
Endowed allowances	44,305 tons SO_2	
Demand for electricity	7.7 million MWh	
Allowance price	$150 /ton SO_2	
Discount rate	10 %	

III. Results

With no restrictions, baseline sulfur dioxide emissions are 84,180 tons. The utility adds no scrubbers, and it burns only the cheaper, higher-sulfur coal at both plants. In the model, this utility uses the larger, more-efficient plant to the maximum capacity.[13]

With emission restrictions, compliance choices depend on the four regulatory parameters. If two (or more) of those parameters were zero, then the utility would face none of the costs or benefits of those compliance options and would have no basis to choose between them. The solution would be indeterminate. In those cases, even if profits are unaffected, we suppose that the utility may have public-relations or other nonfinancial reasons to choose the alternative with lower social costs. To represent these other social pressures, we use an arbitrarily small positive value (0.001), instead of zero, for any one of these parameters for any simulation in which that portion of cost or benefit goes to customers. We now look at special cases.

A. Minimum Social Costs of Compliance

The profit-maximizing utility in this model will minimize the total (social) cost of compliance as long as it faces any nonzero but symmetric regulatory parameters (Bohi and Burtraw, 1992). Column A of Table 4 shows private profits when all costs and benefits go to shareholders ($\alpha=\beta=\gamma=\delta=1$), but the same choices obtain for any single nonzero value for those parameters ($0<\alpha=\beta=\gamma=\delta\leq 1$).

With this regulatory treatment, the model utility suffers the smallest decrease in shareholder profit by maintaining the baseline 84,180 tons of sulfur dioxide emissions. It therefore complies with the CAAA by using all 44,305 endowed allowances, and it purchases an additional 39,875 allowances (at $150 each) for a cost of $5.98 million.[14]

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[13] We set total demand by assuming average capacity factors of 70 percent at the large plant and 60 percent at the small plant, but we set the model to allow maximum capacity factors 10 percent higher. In the simulated baseline, the utility uses the larger, more-efficient plant to the maximum 80 percent of capacity, and it meets remaining demand by running the smaller plant at 27 percent of capacity.

[14] This purchase of allowances is only permissible under the law if it does not violate local ambient standards (for sulfur dioxide as well as other pollutants).

Table 4: Compliance Choices and Costs, for Alternative Parameter Values

	Cost Min	**Fuel Case 1** ($3.50 difference/ton)		**Fuel Case 2** ($10 difference/ton)	
	A	**B**	**C**	**B**	**C**
	$\alpha=\beta=\gamma=\delta>0$	$\alpha=\beta=0.15$ $\gamma=\delta=0.001$	$\alpha=0.15$ $\beta=\gamma=\delta=0.001$	$\alpha=\beta=0.15$ $\gamma=\delta=0.001$	$\alpha=0.15$ $\beta=\gamma=\delta=0.001$
Compliance Choices, tons of SO_2	*(Note 1)*	*(Note 2)*	*(Note 3)*	*(Note 2)*	*(Note 3)*
Fuel Switching	-	Both plants	Large plant	Both plants	-
Plant Switching	-	-	Yes	-	-
Scrubbing	-	Both plants	Small plant	Both plants	Large plant
Allowances Bought (Sold)	39,875	(41,499)	0	(41,499)	(32,227)
Total SO_2 Emissions	84,180	2,806	44,305	2,806	12,078
Change vs. cost-min	n/a	-81,374	-39,875	-81,374	-72,102
Utility Profit (Loss), $millions	($5.98)	$0.93	($0.02)	$0.87	($0.02)
Change vs. cost-min *(Note 1)*	n/a	+$6.92	+$5.97	+$6.85	+$5.96
Social Cost of Compliance, $millions					
Allowance Cost (Gain)	$5.98	($6.23)	0	($6.23)	($4.83)
Fuel Switching Cost (*Note 4*)	0	$10.34	$7.47	$29.54	0
Plant Switching Cost (*Note 4*)	0	0	$1.01	0	0
Scrubbing Cost	0	$34.18	$7.89	$34.18	$26.30
Total Social Cost of Compliance	$5.98	$38.30	$16.36	$57.50	$21.46
$ per household	$23	$147	$63	$220	$82
$ per ton of SO_2 (*Note 5*)	$150	$952	$410	$1,429	$538
Actual Cost vs. Minimum Cost					
Change in social cost, $millions	n/a	+ $32.32	+ $10.38	+ $51.51	+ $15.48
Percentage change	n/a	+ 640%	+ 274%	+ 961%	+ 359%
$ per household	n/a	+ $124	+ $40	+ $197	+ $59
as % of average electric bill ($840)	n/a	14.8%	4.8%	23.5%	7.0%
$ per ton of SO_2 (*Note 5*)	n/a	+ $802	+ $260	+ $1,279	+ $388

Note 1: Although the same compliance solution holds for any $\alpha=\beta=\gamma=\delta>0$, private profits are shown only for $\alpha=\beta=\gamma=\delta=1$. Thus private profits for other regulatory scenarios are compared to this figure.

Note 2: Values of the regulatory parameters $\alpha=\beta$ greater than 0.15 yield the same compliance solution. Utility profit increases to $6.18 and $6.16 million when $\alpha=\beta=1$ for fuel cases 1 and 2, respectively.

Note 3: Values of the regulatory parameter α greater than 0.15 yield the same compliance solution, with utility profit remaining at -$0.02 million for both fuel cases.

Note 4: Fuel switching cost is total fuel cost less fuel cost calculated using the cheapest fuel of the same amounts at the same plants. Plant switching cost is total increase in cost of fuel less fuel switching cost.

Note 5: For cost calculations per-ton of SO_2, the denominator is the difference between unconstrained emissions and initial allowance endowment, which must be covered by allowance purchases plus SO_2 abatement.

Profits fall by $5.98 million only if all costs are allocated to shareholders, but the actual (social) cost of this compliance action is still $5.98 million.

To put this magnitude in perspective, we translate it into an amount per household. For this purpose, we wish to know how many households would live in the region covered by this utility if it served the average U.S. mix of residential, commercial, and industrial customers. Total electricity generation by investor-owned utilities in the U.S. is about 2.8 billion MWh annually (Edison Electric Institute, 1993). Therefore, the model utility's 7.7 million MWh production represents 0.275 percent of total U.S. generation. If this utility served 0.275 percent of the 95 million households that live in this country, it would serve 261,250 households. On this basis, the $5.98 million annual compliance cost represents $23 per household.[15]

B. Allowance Trading Incentives

Because allowance trading is relatively new to a conservative industry, many utility managers consider it risky. They do not know future allowance endowments, or prices, and they may want to guarantee their capability for future compliance by using known abatement technologies. To help overcome this reluctance to participate in allowance markets, PUC regulators may wish to provide incentives that would assign to shareholders some portion of net gains from allowance trading (Rose et al., 1993; Bohi and Burtraw, 1991). These "allowance trading incentives" would be represented in our model by positive values for α and β.

In one of the few precedents actually set for state regulatory treatment of CAAA compliance thus far, the Connecticut Department of Public Utility Control has ruled that United Illuminating Company shareholders should be responsible for 15 percent of the gains on allowance sales and costs of allowance purchases (Rose et al., 1993). We therefore use the Connecticut rule as a representation of the trading-incentives scenario,

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[15] In a sensitivity test with the allowance price doubled to $300, the utility in this model would still choose to buy allowances. Annual compliance cost would also double, to $46 per household.

setting α and β to 0.15. With respect to other compliance options, traditional cost-plus ratemaking would still allow the utility to recover all FGD equipment and fuel costs from ratepayers. We set γ and δ to 0.001, instead of zero, to break the utility's indifference between fuel-switching and scrubbing.

With these incentives, we would expect the managers to invest aggressively in abatement technology (because these costs are virtually irrelevant to their shareholders) and to sell as many allowances as possible (because shareholders receive 15 percent of the proceeds). Indeed, this is what the model finds (column B of Table 4).[16] In "fuel case 1," the model utility chooses to install FGD units at both plants and to switch entirely to low-sulfur coal. This compliance strategy yields the maximum possible reduction of emissions, freeing the maximum number of allowances for sale. Sulfur dioxide emissions fall by 81,374 tons (from the baseline 84,180 tons), and the utility sells 41,499 of its 44,305 endowed allowances. At $150 each, these allowances sell for $6.23 million. Shareholders keep 15 percent of this amount, which is $0.93 million. Relative to the "cost-min" solution with a $5.98 million loss, this $0.93 million profit represents a $6.92 million increase in private profits.[17]

The social cost of this outcome, however, is substantially higher than the minimum social cost of the previous solution. The extra cost of using the more expensive, lower-sulfur coal is $10.34 million. The annual cost of the FGD units is $34.18 million. Net of the $6.23 million for selling allowance (split between shareholders and ratepayers), the social cost of compliance under the "incentive" regulatory solution is $38.30 million, or $147 per household, more than six times as large as the minimum compliance cost.

Relative to that minimum compliance cost, this utility spends an extra $32.32 million, or $124 per household. This excess social cost represents a 14.8 percent increase

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[16] In this section, we discuss only columns of the table for the first fuel case ($3.50/ton cost difference). The next section discusses columns for the second fuel case ($10/ton difference).

[17] In order to sell allowances, at $\alpha=\beta=0.15$, the utility's choices maximize abatement. Therefore the use of higher values for α and β has no effect on the compliance solution but only increases the profit to shareholders from abatement and allowance sales.

in the average annual expenditure on electricity ($840 per household, according to the U.S. Department of Energy, 1995). A state PUC may choose this regulatory approach to encourage trading, for the sake of benefits not measured here, but it might do so only at a substantial cost to its jurisdiction.

C. Concern for Local Pollution

State Public Utility Commissions are charged with multiple and sometimes conflicting economic and political objectives. These goals might include the protection of the local environment as well as the local economy. The PUC might want utilities in its jurisdiction to undertake true pollution abatement, rather than to buy allowances. It might especially want to avoid becoming known as the dumping grounds for pollution problems from other regions. Environmental advocates and policy makers in New York, for example, have sought to limit in-state utilities' purchase of allowances. To represent these incentives, we use regulatory parameters that put at least a fraction of allowance purchase costs on shareholders but maintain traditional "cost-plus" treatment of other costs and benefits. Specifically, α is set to the same 0.15 as above, while $\beta=\gamma=\delta=0.001$ to pass other costs and benefits to customers.

Under these regulatory rules, the utility's primary objective is to avoid buying allowances. We expect the utility to undertake at least enough abatement technology to get allowance purchases to zero, since the cost of that abatement can be passed to customers. Any further abatement is less important, but would depend on actual abatement costs compared to the price that could be received for sold allowances.

This intuition is reflected by the results in column C of Table 4. The model utility chooses to switch fuels at the large coal plant and to scrub at the small coal plant. In addition, the utility shifts electricity generation to the plant with the scrubber. This combination of abatement technologies is just enough to eliminate allowance purchases, and further abatement is not justified by the price for selling allowances.

These results illustrate the multiple abatement technologies with discrete decision-making. The model utility has no desire to buy an expensive scrubber at the large plant, and thus pays only $7.98 million per year to scrub the small plant. It does not pay for fuel-switching at the small plant with the scrubber, since sulfur at that plant can effectively be removed. The model utility achieves part of the target abatement by switching output to the small plant with the scrubber, even though it is less efficient at producing electricity, because the extra $1.01 million of fuel cost can be passed to customers.

The annual social cost of compliance in this case is $16.36 million, or $63 per household, which is 274 percent of the minimum social cost for this utility.[18] The state PUC may achieve some benefit not measured here, but the extra cost amounts to $10.38 million per year, or $40 per household.

This policy has some other perverse consequences. First, it may not best advance its own stated goal of reducing local pollution. It prevents the utility from buying allowances, and importing pollution, but it provides no further incentive to reduce pollution and sell allowances. Emissions in this case match the endowed allowances, 44,305 tons of sulfur dioxide, but emissions in the prior "incentive ratemaking" case were reduced to only 2,806 tons of SO_2 in order to sell allowances.[19]

A second perverse consequence relates to incentives for mergers and acquisitions. An unfettered emission-permit market allows two firms to take advantage of different comparative efficiencies by shifting abatement to the lower-cost location. Asymmetric regulatory rules restrict external trades, but two such firms can achieve the same overall cost reduction without external trades as a single firm with internal shifts of abatement activities. In the current example, the firm in column C in Table 4 undertakes costly abatement to avoid buying allowances, but it could merge with another firm that has lower abatement cost. The regulatory constraint on buying allowances is relaxed if the two firms can share their endowed allowances.

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[18] Similarly, Winebrake et al. (1995) find that such restrictions on allowance trades can increase costs by 220-240 percent.

[19] In any case, local pollution is not necessarily related to local emissions. Acid rain in the Adirondack Mountains of New York is more affected by emissions in the midwest than by emissions in New York.

D. Forced Scrubbing

The results for asymmetric incentives in Table 4 can be compared to a different case in which the PUC or state legislation simply requires utilities to purchase a scrubber for every plant. To save local coal-mining jobs, a state might require scrubbers.[20]

In this case we do not need to "find" the solution that maximizes private profits (but we use $\alpha=\beta=\gamma=\delta=0.001$ to calculate those private profits, assuming other traditional cost-plus regulation). With two scrubbers, and no fuel-switching, the model utility's sulfur dioxide emissions fall by 79,971 tons, to 4,209 tons. Under the CAAA, it could sell 40,096 of its endowed allowances (at $150 each) for $6.01 million, but the two scrubbers cost $34.18 million (as in column B). Thus the total compliance cost is the difference, $28.17 million, which represents $108 per household. Relative to the minimum compliance cost ($5.98 million to buy allowances), the excess cost is $22.19 million.

This state rule makes CAAA compliance almost five times as expensive as the cost-minimizing solution of buying allowances. It costs the jurisdiction an extra $85 per household, the equivalent of a 10.1 percent increase in the average electric bill.

E. Command-and-Control Regulation

Although our paper is primarily about the effects of PUC regulation on the cost of compliance with the CAAA, our results can be used to shed light on the cost savings from the CAAA relative to alternative command-and-control (CAC) regulation of two sorts. Without the allowance trading provisions of the CAAA, the federal government might have had a technology standard or a performance standard.

One kind of technology standard might require a scrubber on every plant. Thus the results for "forced scrubbing" above can be re-interpreted to represent a federal CAC regulation. With this interpretation, the cost of compliance under the command-and-control policy (the $28.17 million just cited) is almost five times the minimum that is

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[20] Such a rule was passed by Illinois in 1992, but it was subsequently struck down by the Seventh Circuit Court. Bernstein et al. (1994) find that the Illinois rule would cost the state a half billion dollars over 5 years, or $60,000 annually per job saved.

possible under the CAAA ($5.98 million) Even if the price of an allowance were doubled to $300, the CAC rule is more than twice as expensive as trading.[21]

The remaining uncertainty is whether the CAAA can achieve the minimum possible cost, given PUC rules. If the state PUC requires scrubbing, then the CAAA makes absolutely no difference (relative to a federal policy of forced scrubbing). If the PUC employs "allowance trading incentives" (column B of Table 4), then we have the surprising result that the use of tradable permits under the CAAA might be even more costly than federal CAC regulation. With cost parameters selected to represent a "typical" hypothetical utility, we find that CAC regulations generate costs that are almost five times the minimum, but we also find that tradable permits with PUC "allowance trading incentives" (column B) generate costs that are more than six times the minimum. The reason is that "allowance trading incentives" induce the utility to fuel-switch, as well as scrub both plants, in order to sell allowances.

Instead of this technology standard, federal CAC regulation might employ a performance standard. For example, emissions of each utility might be limited to the number of tons of sulfur dioxide represented by the initial endowment of allowances (without trades). In this case, the results in column C of Table 4 can be re-interpreted to represent a federal CAC regulation, because in those results the utility used its endowed allowances with no trades. With this interpretation, the cost of compliance under the command-and-control policy (the $16.36 million in column C) is almost three times the minimum that is possible under the CAAA.

Again we have the result that PUC interference *can* make the allowance trading provisions of the Clean Air Act *more* costly than a simple federal CAC regulation. The cost of the CAAA with PUC "allowance trading incentives" ($38.30 million, column B) is more than twice the cost of the federal performance standard ($16.36 million, column C). Or, if the PUC used rules like our "concern for local pollution" case (column C), then the costs under the CAAA are identical to the federal CAC policy. The point is certainly not

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[21] Similarly, Bernstein et al. (1994) and Burtraw (1995) find that the cost of the command-and-control alternative is two or three times the cost that is possible under the CAAA.

that allowance trading will generate no cost savings, but that PUC rules will be crucial in determining the extent of cost saving under the CAAA.

IV. Sensitivity Analysis

To test the robustness of these results, we used the model to calculate alternative outcomes for many different values of parameters. Changes in the allowance price and the discount rate clearly affect the dollar cost of buying allowances or buying abatement technology, and thus the dollar cost of compliance, but they do not affect this utility's choices under any of the regulatory scenarios. Therefore, in this section, we describe results only for changes in fuel costs and regulatory parameters.

The general conclusion from these sensitivity tests is related to the discrete nature of decisions in our model. In some cases a substantial change in a cost or other parameter value may have no effect on compliance decisions, and in other cases a small change in one parameter may have a substantial effect on compliance decisions.

A. The Fuel Cost Differential

Table 4 shows outcomes for two different assumptions about the fuel cost differential. In fuel case 1, the difference between low-sulfur coal and higher-sulfur coal was \$3.50 per ton, and in fuel case 2 it is \$10 per ton. For "incentive" ratemaking rules (columns B), the model utility chooses the same compliance solution, with the same FGD units and fuel-switching at both plants. The cost of fuel-switching nearly triples, however, so the social cost of compliance rises from \$147 to \$220 per household. This last figure is almost ten times the minimum social cost.

For the other regulatory scenario, where the utility is discouraged from buying allowances, the fuel cost differential does affect behavior (columns C). With the low fuel cost differential, the utility scrubs the small plant and switches just enough fuel at the large plant to use exactly the endowed allowances. With the \$10/ton cost differential, however, the utility avoids fuel-switching by scrubbing the large plant. This discrete increment to abatement leaves 32,227 excess allowances that can be sold.[22] Adding another scrubber to the small plant would produce additional allowances for sale, but the gain from that sale does not offset the cost of the scrubber.[23]

The change in the excess social cost of compliance is more than the change in fuel cost. Indeed, the utility avoids the extra fuel cost by investing in a scrubber that is even more expensive. The last column of Table 4 shows that this new compliance solution costs society an extra $59 per household, instead of $40 per household.

B. Other Asymmetric Regulatory Rules

In general, our results show how regulatory parameter asymmetries can cause the utility's profit-maximizing compliance decision to deviate from the social-cost minimum solution. As just demonstrated, however, small to moderate changes in parameters might not induce any change in behavior. This raises the question: how much can regulations deviate from perfect symmetry without inducing the firm to deviate from cost-minimizing compliance? Obviously the answer depends on the assumed parameters, but the following calculations may help illustrate the relationships.

Consider a symmetric regulatory treatment where $\alpha=\beta=\gamma=\delta=0.15$, such that 85 percent of all compliance costs and benefits are passed to ratepayers. Then, in Figure 2, we vary only α, the fraction of allowance purchase cost assigned to shareholders, while holding all other regulatory parameters fixed. The vertical axis of Figure 2 shows the excess social cost of compliance. The horizontal axis shows α in increments of 0.05 between zero and one. When α is 0.15, of course, the excess social cost is zero. As it turns out, however, α can lie anywhere between zero and 0.35 with no change away

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[22] In a more general model, depending on regulatory treatment, this utility might decide to bank allowances instead of selling them.

[23] The fuel cost differential does not have to triple (from $3.50/ton to $10/ton) to induce this discrete change in behavior. Starting at $3.50/ton, we can raise the fuel cost differential gradually with no change in behavior, until a particular point (around $8.63/ton) at which the model utility decides to abandon fuel-switching and to scrub the large plant instead of the small plant.

Figure 2: Change in Social Cost of Compliance for Different Allocations of Allowance Purchase Cost to Shareholders (all other parameters are 0.15)

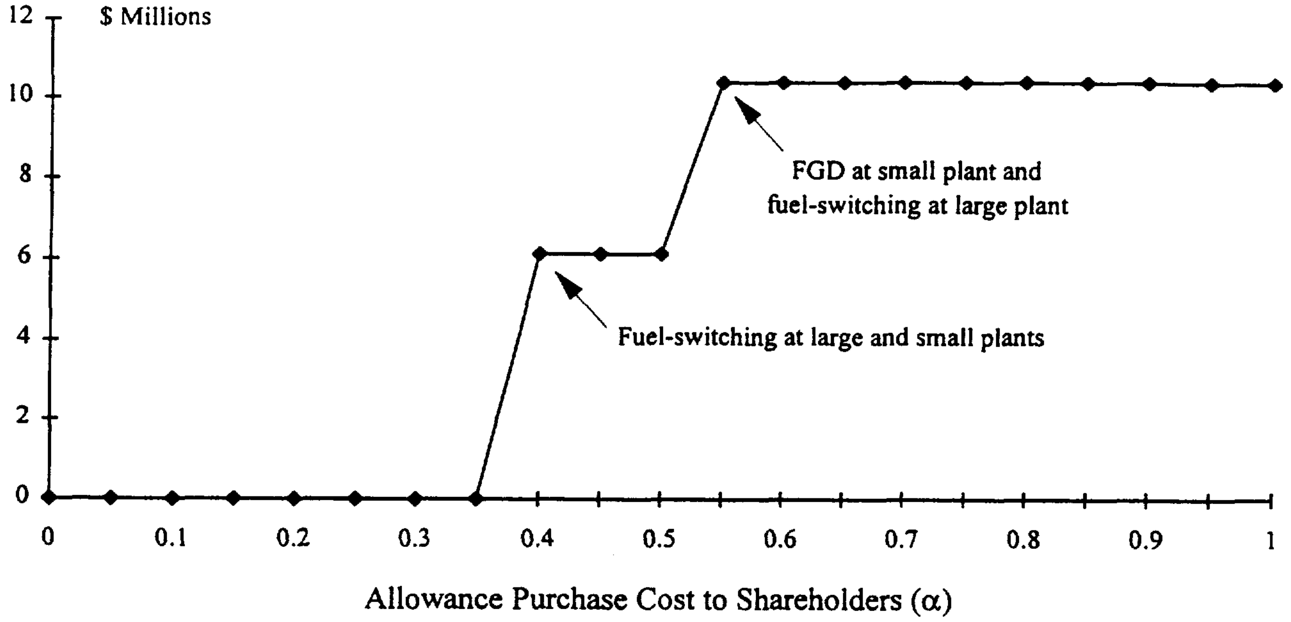
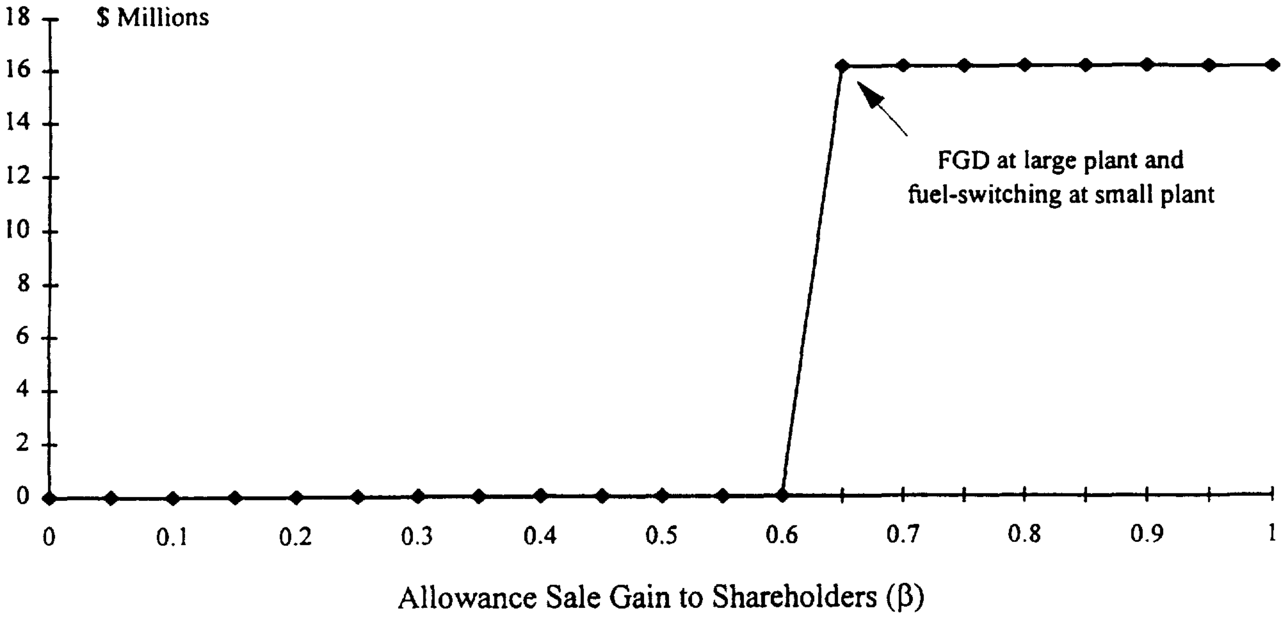


Figure 3: Change in Social Cost of Compliance for Different Allocations of Allowance Sale Gain to Shareholders (all other parameters are 0.15)



from the minimum compliance cost.[24] At $\alpha=0.40$, the utility combines some fuel-switching with its allowance purchases, increasing the cost of compliance by $6.1 million (from $6.0 to $12.1 million). For α of 0.55 and greater, the profit-maximizing compliance strategy includes FGD installation and fuel-switching with no allowance purchases -- a change that increases the social cost of compliance by $10.4 million.

Similar results hold for variations of the other regulatory parameters. Figure 3 depicts the change in social cost of compliance for deviations in β around its symmetric setting of 0.15. The model utility stays with cost-minimizing compliance until the portion of allowance sale allocated to shareholders reaches 65 percent. For β values of 0.65 or greater, the utility chooses to scrub the large plant, fuel-switch at the small plant, and sell allowances -- increasing social cost of compliance by $16.08 million.

An increase in γ, the portion of fuel cost allocated to shareholders, has no effect on compliance. In this case, however, a decrease changes compliance. In Figure 4, with $\gamma=0.05$, the model utility switches fuels at both plants. It buys fewer allowances than at the "cost-min" solution, and increases social cost of compliance by $6.13 million. A similar decrease in δ, the FGD costs allocated to shareholders, also changes compliance. Figure 5 shows that δ at 0.05 induces the model utility to scrub the large plant, and δ at zero induces scrubbing at both plants. In neither Figure 4 nor 5 does a value of γ or δ greater than 0.15 induce a change from the cost-minimizing solution.

IV. Extensions and Policy Conclusions

We now turn to possible extensions of the model. In each case we consider how that extension might refine the numerical outcomes, or expand our understanding, but we emphasize that none of these extensions would overturn the basic conclusion: small deviations from perfect regulatory symmetry may have no effect on compliance choices, while specific asymmetric incentives for allowance trading or to discourage allowance purchases may have unintended effects and may substantially increase compliance costs.

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[24] Other utilities face other technological and market price parameters, however, and therefore may undertake large, discrete compliance changes for only a small deviation from symmetry.

Figure 4: Change in Social Cost of Compliance for Different Allocations of Fuel Cost to Shareholders (all other parameters are 0.15)

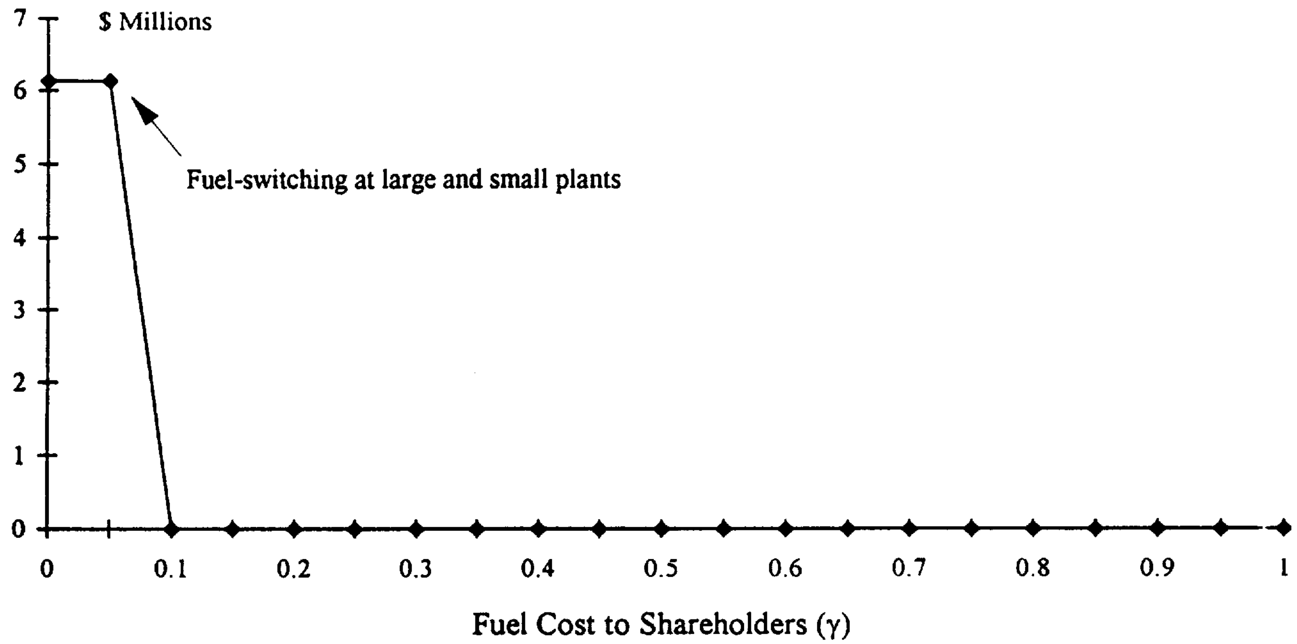
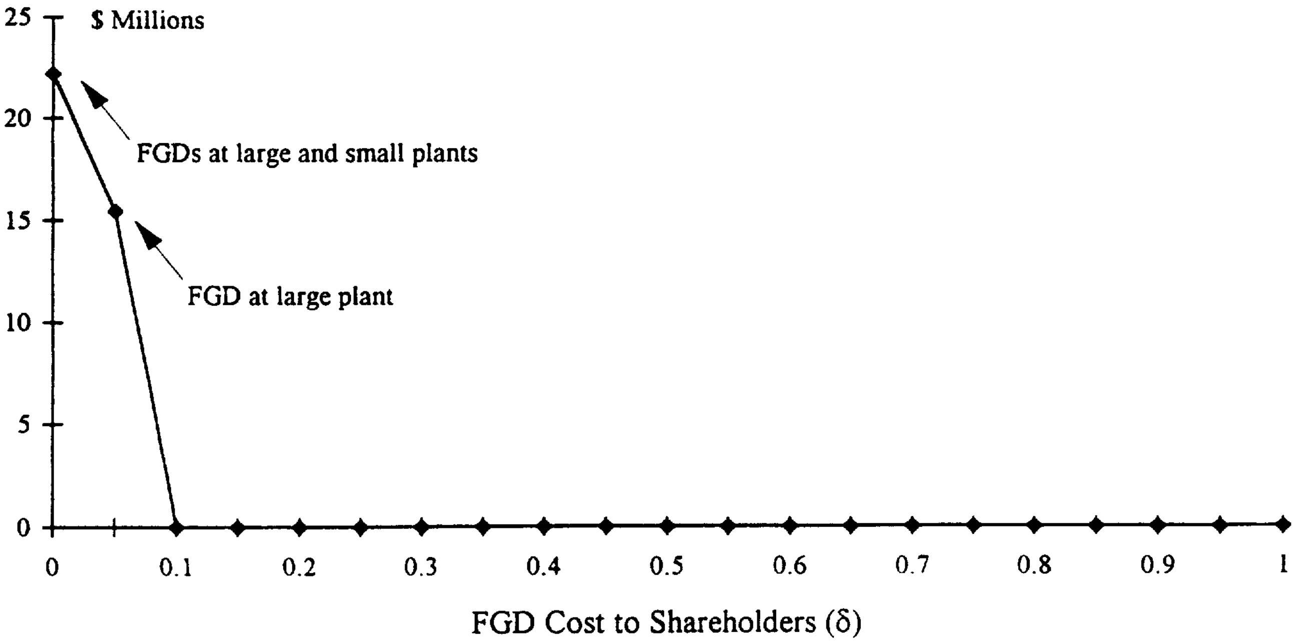


Figure 5: Change in Social Cost of Compliance for Different Allocations of FGD Cost to Shareholders (all other parameters are 0.15)



The model in this paper could be extended to multiple utilities. With two or more utilities facing different abatement cost parameters, we could calculate endogenously the price of allowances that would clear the market, under each set of regulatory rules. Economists naturally think in such terms, and several have undertaken such models (Coggins and Smith, 1993, Winebrake et al., 1995). This step is not taken here, for a number of reasons. First, calculations for just a few such utilities would not accurately represent the actual allowance market. Utilities all across the U.S. can trade in this market, so a reasonable price calculation would require data on the actual abatement costs facing all U.S. utilities. Second, utilities across the U.S. will face different regulatory rules that are not yet determined. Some PUC jurisdictions may encourage trades while others discourage them. For calculations of excess social cost for the entire U.S. that are more than illustrative, we must await further research on the size and number of utilities facing each set of cost parameters and each set of regulatory rules.

This paper is not intended to address questions about the determination of price in a national market. This extension would only be important for our purposes if it affected our excess cost calculations. It would not. Even in a model of the whole U.S., the market price facing any single utility is exogenous. Therefore, as long as we choose a valid allowance price, we get a valid calculation of excess compliance cost for a single utility. Results for several utilities facing that allowance price can even be added together.

Another question involves the importance of our discrete decision-making. If a thousand utilities each faced slightly different abatement costs, then incremental changes in the allowance price might reveal a nearly-continuous aggregate demand for allowances. Thus, the use of continuous cost and benefit curves might not be a bad approximation. Nonetheless, we think it is important to analyze the decisions of individual firms before aggregating them. Moreover, our results might be useful for a PUC that is contemplating alternative rules for its own jurisdiction with a limited number of utilities.

Other extensions might provide additional insight. Most importantly, perhaps, a model with uncertainty about future regulations (Winebrake et al., 1995) or future prices (Bohi and Burtraw, 1992) might provide utilities with reasons to bank allowances for a future year. The introduction of uncertainty would undoubtedly change compliance choices. The model might be amended to consider transactions costs (Stavins, 1995), noncompliance (Keeler, 1991), or imperfect competition (Hahn, 1984). These amendments would certainly refine the numerical results of our model, but they would not alter the conclusion that PUC regulations can fundamentally alter the intended effects of the Clean Air Act. Specifically, allowance trading incentives combined with traditional "cost-plus" treatment of spending on abatement can substantially increase the social cost of compliance. Other asymmetric regulatory treatments may have other unintended effects and also can substantially increase costs. Yet, utilities facing other technological and market price parameters might not change their behavior at all.

Finally, although deviations from symmetry can be quite costly, we show that exact symmetry among the regulatory parameters is not necessary to induce cost-minimizing compliance. Thus, PUC regulators may have some latitude in their ratemaking decisions. Small discrepancies in their treatment of abatement and allowance trading are hard to avoid, as a practical matter, but will not necessarily undermine the cost-minimizing compliance solutions intended by the CAAA.

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