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THE PRICE OF POLLUTION: A DUAL APPROACH TO VALUING SO_2 ALLOWANCES

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ABSTRACT

Under the 1990 Clean Air Act Amendments, a market-based scheme to reduce U.S. sulfur dioxide emissions will take effect in 1995. Early indications are that participation in the market will be light and that the price of an "allowance" will be lower than was first expected. Using an output distance function approach, for a dataset of 14 Wisconsin coal-burning utility plants we estimate the shadow price of reducing SO_2 emissions by one ton. This estimate can be interpreted as marginal abatement cost and should approximate the allowance price. The estimated average shadow price is considerably higher than the prices at which the few observed allowance trades have occurred. Wisconsin's unusually stringent state SO_2 legislation may explain a portion of this divergence.

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1. Introduction

Beginning in 1995, under Title IV of the 1990 Clean Air Act Amendments (CAAA), emissions of sulfur dioxide (SO_2) from U.S. coal-burning electric utilities are to be reduced dramatically. The overall aim of Title IV is to reduce aggregate SO_2 emissions. Total annual emissions are to decline in two increments; by 2000 the figure will be limited to 8.95 million tons, down from about 19 million tons in 1980. In the hope of achieving the reduction at the lowest possible cost, the law also creates a national market for SO_2 "allowances." Each allowance grants its bearer the right to pollute one ton of SO_2 on or after the year in which it was issued. Phase I of the law, which begins on January 1, 1995, affects 110 of the dirtiest coal plants, in addition to a few others that choose to participate. Each affected "unit" will be granted allowances in an amount based upon production levels during a 1985–87 base period. The annual endowment will be sufficient to permit units to emit SO_2 equalling 2.5 pounds per million Btu (mBtu) of base-period heat input. Phase II begins in the year 2000 and affects all coal-burning electric utility plants with capacity of at least 25 megawatts. The Phase II restriction is more stringent, with endowments of allowances equivalent to an emissions rate of 1.2 pounds per million Btu.[1]

Economists have long advocated the use of markets to control pollution. Since Pigou (1932), the cost savings potential of pollution taxes has been familiar. Dales (1968) elaborated upon Pigou's insight, advocating the use of tradable pollution permits in environmental control. Montgomery (1972) proved formally that when markets are competitive and information is perfect there is no alternative regulatory scheme that can achieve a given environmental standard at lower cost than can a permit-trading scheme. The literature following Dales and Montgomery is by now vast; for surveys see Tietenberg (1985) and Baumol and Oates (1988). For our purposes the striking feature of the CAAA is the fact that a preferred policy prescription of economists is to be put in practice on a national scale.

[1] The term "allowance" was chosen by Congress to describe the object that economists have usually called a pollution permit. We will use the newer term. A plant can consist of more than one "unit." This last can be thought of as a single boiler. See Lock and Harkawik (1991) for an overview of the CAAA.

How well will the market work? On the eve of the its formal opening, several crucial questions regarding the market's performance remain open. One is the effect that uncertainty will have on utilities' behavior in the market. Hahn and Hester (1989) argue that uncertainty about the institutional arrangements themselves has hampered previous attempts to implement market-based pollution control schemes. Another is the economic regulation of utilities by state public service commissions, whose ratemaking treatment of allowances promises to affect the market in important ways (Bohi and Burtraw 1992; Coggins and Smith 1993). Yet another is the differential regulatory treatment of utilities across states (Hahn and May 1994). The savings that are to be had if the allowance market works well appear to be sizable. By one account the market itself can yield cost savings as high as \$2 or \$3 billion annually (Portney 1990). In short, the stakes involved in the market are high and a great deal turns on whether it performs as hoped by its framers. If it does, the market should transmit price signals to participants that will cause abatement to be distributed across utilities optimally. At an equilibrium in a well-functioning allowance market, one might expect the observed allowance price to equal the marginal cost of achieving the last unit of abatement.[2]

But herein lies a conundrum for those—including utility compliance planners, state public service commissions, and the U.S. EPA—who must participate in or otherwise affect the allowance market. The conundrum is that compliance decision-making, including decisions regarding allowance market participation, requires knowledge of the allowance price. But the allowance price cannot be known with certainty before the market gets underway. How might one gather price information in a nascent market of this kind? Currently two primary sources are available: the handful of trades that have taken place to date for which prices are publicly available; and the allowance auctions conducted in 1993 on behalf of the EPA by the Chicago Board of Trade.[3] Allowances changed hands in actual trades through October 1993 at prices ranging from \$170 to \$400. The 1993 EPA allowance auctions yielded prices ranging from \$131 to \$450 for Phase I allowances (with an average of \$156.60); and from \$122 to \$310 for Phase II allowances (with an average of

[2] But see Chao and Wilson (1993). They argue that in a dynamic setting, because a decision to purchase allowances is reversible but a scrubber purchase is not, allowance prices should actually be *above* marginal abatement costs.

[3] A third source of information is the abatement cost estimates from large-scale utility industry models (EPRI 1993). These have, for the most part, been higher than recent observed prices. See Rose et al. (1993) or Hahn and May (1994) for a survey of all three data sources. Hahn and May (1994) also provide an interpretation of what the results have to say about probable behavior of allowance prices in the future.

\$136.19). Though these are useful figures, for a number of reasons it is difficult to treat them as definitive indicators of the actual value of an SO_2 allowance. The variability in observed prices, and the newness of the institutions themselves, make it difficult to predict allowance prices in future years.[4] On the whole, the allowance market has been less active than was once hoped. Some observers have warned that the apparent reluctance on the part of utilities to rely on allowance purchases to achieve compliance may cripple the market and drive up Title IV compliance costs.[5]

The purpose of this paper is to introduce into the SO_2 compliance literature a method, employed by Färe et al. (1993), for use in deducing the price of a pollutant from plant-level data on the underlying technical relationship between inputs and multiple outputs—including output of one or more pollutants. In an empirical application of the method we also provide an estimate of the average shadow price of SO_2 abatement for Wisconsin coal plants. This price, we shall argue, can be interpreted as the value of an allowance to the plants in the study. The technical approach to the problem of estimating shadow prices for a pollutant involves specifying a multiple-output production technology in which pollutants are considered to be (bad) outputs. Employing a weak disposability assumption, we specify and estimate a parametric distance function that can be used to calculate production efficiencies for each plant in our dataset. Using a duality argument the estimated distance function can be combined with electricity price information to derive a shadow price for SO_2, the undesirable output.

The paper is organized as follows. In section 2 the analytical model is developed and the empirical method for estimating shadow prices is laid out. In section 3 the dataset is described. Section 4 contains the empirical results. Section 5 provides an interpretation of the results, including a discussion of how they might bear upon the national allowance market. Concluding remarks appear in section 6.

2. The Distance Function and Shadow Prices

Suppose that a coal-burning electric utility plant employs a vector of inputs $x \in \mathcal{R}_+^N$ to produce a vector of outputs $u \in \mathcal{R}_+^M$. The relationship between inputs and the multiple outputs is captured by the firm's technology, which can be expressed as a mapping $\mathcal{P}(x) \subset \mathcal{R}_+^M$ from an input vector

[4] Cason (1993) shows that the EPA's allowance auction, by design, can be expected to exhibit prices that are biased downward.

[5] Rose et al. (1993) list several factors that appear to explain why utilities do not appear willing to trade allowances with one another. Prominent in their discussion are state-level regulatory treatment, tax treatment of allowances by the IRS, and uncertainty about the EPA's rulemaking. See also Bohi (1994).

x into the set of feasible output vectors. Suppose further that one of the firm's outputs is good or desirable, and that the others, indexed by $i = 2, \ldots, M$, are undesirable. Let u_1 denote the firm's good output, and let u_2 denote the vector of bad outputs. Formally, following Färe et al. (1989), to capture the idea that the firm cannot reduce its emissions of u_2 without reducing production of the good output, we assume that the technology satisfies weak disposability. The technology $\mathcal{P}(x)$ satisfies weak disposability if $[y \in \mathcal{P}(x)]$ implies that $[\theta y \in \mathcal{P}(x)]$ for every $\theta \in [0, 1]$. Figure 1 depicts a technology satisfying weak disposability. For a treatment of the properties that $\mathcal{P}(x)$ customarily satisfies, see Shephard (1970), Diewert (1982), or Färe (1988).

Figure 1 about here.

An alternative representation of the technology, conveying the same information, is the output distance function. For any (x, u) pair, the distance function is defined from the technology by

$$(1) \qquad D(x, u) = \min\{\theta : (u/\theta) \in \mathcal{P}(x)\}.$$

If $u \in \partial\mathcal{P}(x)$, the boundary of $\mathcal{P}(x)$, then $D(x, u) = 1$; if $u \in \operatorname{int}\mathcal{P}(x)$ then $D(x, u) < 1$. It must also be true that $D(x, u) \geq 0$. Thus, $D(x, u) \in [0, 1]$. In Figure 1 the value of $D(x, \tilde{u})$ is given by $D = 0\tilde{u}/0\text{A}$. The properties of the distance function and their relation to the technology are presented in Shephard (1970) and in Diewert (1982). In short, $D(x, u)$ is continuous; decreasing in u for each x; homogeneous of degree 1 in outputs; and concave and increasing in x.

Note that the distance function contains information about the efficiency of a given (x, u) pair. Indeed, one can take the inverse of $D(x, u)$ to be a measure of output efficiency (Farrell 1957). If $D(x, u) = 1$ then production is technically efficient; the set of output vectors for which there is an x at which $D(x, u) = 1$ traces out the production frontier in $\mathcal{R}^M_+$.

The technology representations $\mathcal{P}(x)$ and $D(x, u)$ rely only upon the data of input and output quantities. If one also knows one or more output prices then the duality between technology and revenue permits one to study the shadow prices of outputs. In a multi-output model in which both outputs are good, the familiar optimality condition requires that for any two outputs the slope of the production possibilities frontier should equal the ratio of the corresponding output prices. The same reasoning can be applied to the present problem, except that undesirable outputs will have negative shadow prices. Let $r \in \mathcal{R}^M$ denote a vector of output prices, and let the revenue function be defined from the distance function as $R(x,r) = \sup_u\{ru : D(x,u) \leq 1\}$. Shephard (1970) shows that under certain regularity conditions the following dual relationships will be satisfied.

(2a) $$R(x,r) = \sup_u\{ru : D(x,u) \leq 1\};$$

(2b) $$D(x,u) = \sup_r\{ru : R(x,r) \leq 1\}.$$

If both of these functions are differentiable then it is possible to solve the lagrangian problem for (2a), choosing u to satisfy the corresponding first order necessary conditions. Färe et al. (1993) show that the solution vector will satisfy

(3) $$r = R(x,r) \cdot \nabla_u D(x,u),$$

where ∇ denotes the gradient operator. Let $r_i^*(x,u)$ denote the shadow price of output i, normalized or deflated by the output price vector that solves (2a). Shephard's dual lemma, together with (2b), gives the vector expression $\nabla_u D(x,u) = r^*(x,u)$ which, combined with (3), gives

$$r = R(x,u) \cdot r^*(x,u).$$

We seek the actual (undeflated) shadow price for undesirable outputs, r_i with $i \neq 1$. In order to obtain this value it is necessary to know the actual value of r_1. Let us therefore assume that the price of u_1, the good output, is known and known to equal its undeflated shadow price.[6] Then for each output $i \neq 1$ we have

(4) $$r_i = r_1^0 \frac{\partial D(x,u)/\partial u_i}{\partial D(x,u)/\partial u_1}.$$

The familiar optimality condition (the equality between an output price ratio and the slope of the production frontier) contained in (4) is depicted in Figure 1 for the case in which u_2 is an undesirable output. Its shadow price is negative, capturing the notion that the output of u_2 can be reduced only with an accompanying reduction in u_1. For a pollutant the value $r_2(x,u)$ is the marginal abatement cost. Our aim in the following empirical section is to estimate SO_2 shadow prices for a collection of coal-burning electric utility plants, and to use this information to gain some insights into the performance and effects of the nascent allowance-trading market.

[6] Note that in this setting the shadow price is interpreted as marginal revenue: the distance function is a primal object whose dual is a revenue function. In our empirical application, the firms are rate-of-return regulated utilities, for whom output prices clearly equal marginal revenue, even though regulatory treatment can be expected to drive a wedge between output price and marginal cost.

Following Färe, et al. (1993) we choose a parametric form for the distance function. Though one could employ non-parametric methods, there are certain advantages to the parametric version.[7] Among them is the fact that $D(x,u)$ can be differentiated, allowing one to make use of (4). We suppose that the distance function takes the translog form

$$\begin{aligned}(5) \qquad \ln D(x,u) = \; & \alpha_0 + \sum_{i=1}^{M} \alpha_i \ln u_i + \sum_{j=1}^{N} \beta_j \ln x_n + \sum_{i=1}^{M}\sum_{i'=1}^{M} \alpha_{ii'}(\ln u_i)(\ln u_{i'}) \\ & + \sum_{j=1}^{N}\sum_{j'=1}^{N} \beta_{jj'}(\ln x_j)(\ln x_{j'}) + \sum_{i=1}^{M}\sum_{j=1}^{N} \gamma_{ij}(\ln u_i)(\ln x_j).\end{aligned}$$

This function is estimated as a nonstochastic linear programming problem using the method spelled out in Färe et al. (1993). Let $k = 1, \ldots K$ index the observations in a dataset. The objective function is $\sum_k \ln D(x^k, u^k)$. It is maximized subject to a number of constraints, including symmetry and homogeneity constraints.[8] Specifically, we require that (i) $\ln D(x^k, u^k) \leq 0$; (ii) $\partial \ln D(x^k, u^k)/\partial \ln u_i^k$ is non-negative for productive outputs and non-positive for undesirable outputs; (iii) $\sum_k \alpha_i = 1$ and $\sum_{i'} \alpha_{ii'} = \sum_i \gamma_{ij} = 0$; and (iv) $\alpha_{ii'} = \alpha_{i'i}$ and $\beta_{jj'} = \beta_{j'j}$. In each of these expressions the relevant indexes run over their respective ranges.

To sum up, an efficient firm in the sense used here is one with $D(x^k, u^k) = 1$. The restrictions on derivatives of $\ln D(x^k, u^k)$ require that as production of the good output increases, the distance function increases; that is, the firm becomes more efficient. As production of an undesirable output increases, on the other hand, we say the firm becomes *less* efficient. Another result of these restrictions is that the undesirable output—pollution—must have a non-positive shadow price.

3. The Data

The data for our empirical work are plant-level data taken from 14 coal-burning electric utility plants located in Wisconsin. The plants are owned and operated by the state's largest investor-owned utilities and one cooperative. For ratemaking purposes, utilities are required to maintain detailed records, to make them available to regulators, and thereby to place them in the public domain. Annual observations were collected for the three years 1990–92. The empirical model

[7]The advantage of being able to differentiate the distance function is useful for our purposes, but it is not critical. If one were to estimate a non-parametric version it would still be possible to estimate the shadow prices, at least within certain bounds.

[8]With $D(x^k, u^k) \leq 1$, it must be true that each $\ln D(x^k, u^k)$ is non-positive. By maximizing the sum of $\ln D$, one automatically minimizes the sum of deviations of the D from the frontier.

requires, for each plant, quantity information for two outputs and four inputs as well as an average electricity price. All of the data that we employ, with the exception of SO_2 emissions, can be gleaned from Forms 1 and 423, reports in the public domain that must be submitted by all regulated utilities to the Federal Energy Regulatory Commission (FERC). Information on SO_2 emissions was obtained from the Wisconsin Department of Natural Resources (WDNR). Summary statistics for the data are presented in Table 1.

Table 1 about here.

Output quantities and price

Electricity output is in kilowatt-hours per year (Kwh/yr), measured at purchasers' meters. Pricing of electricity is also based upon delivered quantities. Electricity prices are plant averages, weighted by quantities delivered to each ratepayer classification and deflated by the GDP price index to constant 1992 dollars. Prices for the investor-owned plants are retail prices. The cooperative-owned plants sell only to the wholesale market, so that only wholesale prices are available. Because production decisions are based upon these prices, however, we believe that marginal revenue and shadow prices are properly based upon them as well.

Annual emissions of SO_2, in tons, are recorded by the WDNR for each unit at each plant. Three methods of calculating emission levels are employed: engineering calculations; stack tests; and automatic determination from subsystem source classification codes. Because different methods can be used on different units at the same plant, it is difficult to summarize the emissions data by measurement method. Our data are taken directly from the WDNR sources.[9]

Input quantities

Four inputs to the electricity-SO_2 production process are included in the model: energy (in mBtu); sulfur (in tons); labor (in hours); and capital (in dollars). The unit-level coal throughput numbers (in tons) reported to the FERC were aggregated up to the plant level to obtain annual coal use. Each ton of coal contains both usable energy, in mBtu, and sulfur. Average mBtu and sulfur content are also available from the FERC, enabling us to calculate the levels of these two inputs at each plant.

The labor variable is calculated from FERC Form 1, which records the number of employees per plant. It was assumed that each employee is full-time and worked 2000 hours per year. Thus,

[9]See U.S. EPA (1990) for a more detailed description of the emissions measurement techniques and results.

we calculated total labor hours per plant by multiplying workers by 2000. The capital variable was taken from the same form, on which the value of total productive capital is recorded at the plant level. As with all of the dollar-denominated variables, the capital values were deflated using the GDP price index to constant 1992 dollars.

4. Empirical Results

Equation (5) was solved as a linear programming problem using the 42 observations and subject to the collection of constraints from section 2. The resulting parameter estimates are presented in Table 2. These estimates were used to calculate the output distance function for each observation. Three-year plant average distance function values (weighted by electricity output) appear in column 2 of Table 3. The average $D(x, u)$ across firms is approximately 0.946, indicating that productive efficiency in the sample plants could be increased by a little more than 5 percent given the technology currently in use. Figure 2 contains a plot of the 14 average output pairs.

Figure 2 and Tables 2 and 3 about here.

The third column of Table 3 presents the shadow price of SO_2 emissions for each plant, once again averaged across the three years. Our results show that the overall average shadow price of a marginal decrease in SO_2 emissions is \$292.70 in constant 1992 dollars. This is perhaps the leading finding of the paper. If the state of Wisconsin were to institute an allowance market for our sample of plants, at the same time requiring them to limit their annual aggregate sulfur dioxide emissions to the average 1990–92 level, the average value of an allowance should equal approximately \$292.70. By way of comparison, we note once again that actual trades between utilities have occurred at prices ranging from \$170 to \$400. The average price for Phase I allowances on the EPA's 1993 allowance auction was \$156.60; for Phase II allowances \$136.19 (Hahn and May 1994).

Table 3 also presents the average SO_2 emission rates by plant, expressed in pounds of SO_2 per mBtu of heat consumption. Note that firms with relatively high SO_2 shadow prices have the lowest emission rates, while the "dirty" plants have lower shadow prices. As one would expect, investments or operating decisions that cause a plant's emission rate to fall appear to cause an increase in the marginal cost of abatement.

The SO_2 shadow prices vary widely across plants. Industry-wide, any number of factors might help to explain this variation, including the vintage of plants, coal sources, or the presence of scrubbers in some plants. It happens that none of Wisconsin's coal plants have been fitted with scrubbers, so the variation cannot be traced to that cause.[10] Another possible explanation for variation in shadow prices is the type of boiler employed. Our plants have boilers of two types: cyclone and dry bottom. The former is a newer technology than the latter, and for comparable fuel sources and plant vintages might be expected to offer an advantage in SO_2 emissions. Table 4 presents average output-weighted distance functions and shadow prices by boiler type. The 3 plants fitted with cyclone boilers are indeed slightly more efficient than the dry-bottom plants, as measured by the distance function. Shadow prices for SO_2 are lower at the three cyclone plants than at the dry-bottom plants. This indicates that abatement could be achieved at a lower cost at the plants with newer technology, as was expected. In an allowance-trading setting, these plants should be *sellers* of allowances; the older dry-bottom plants, on average, should be *buyers* of allowances.

Table 4 about here.

There is considerable evidence that economic regulation of utilities in the form of rate-of-return controls has an effect on production decisions in the industry (Courville 1974; Spann 1974; see Joskow and Rose 1989 for a survey). The question arises, then, as to whether the estimation technique used here is still legitimate. We believe firmly that it is, for the plants in our sample all face the same regulatory authority—the Wisconsin PSC. The regulatory framework, for which we do not seek to account explicitly, is nevertheless embedded in our data. But this presents no difficulty if one supposes, as we do, that the efficient plants are employing inputs in an optimal manner subject to the regulatory constraint. If one were to estimate the model using data from more than one state, it would become possible to study the differential effect of regulatory treatment across states. This is a question that we defer to a later study.

Table 5 provides a summary of the derivatives properties of the distance function, and also reveals something about the parameter estimates. The derivatives of $\ln D$ with respect to the two output variables, evaluated at the means of the data, have the expected signs. As electricity output increases with all else held constant, efficiency *increases*; as SO_2 output increases efficiency *decreases*. It is not easy to interpret the magnitudes of these numbers because the function is in logged form. The estimated distance function does not behave quite as well where inputs

[10] The presence of scrubbers on some plants might have important effects on the distance function estimation itself, a possibility that warrants further study.

are concerned. Monotonicity is satisfied if the distance function declines as input use increases. Evaluated once again at the means of the data, only the labor input fails to display this property.

Table 5 about here.

5. Regulation and the SO_2 Allowance Market

Given the current shortage of allowance price information, we believe our finding concerning the average shadow price of SO_2 emissions for Wisconsin electric utilities, and the method for calculating it, will prove to be useful to compliance planners and others with an interest in the market. The method yields an estimate of the shadow price of SO_2 for each plant, information that utility managers might use in devising compliance strategies. Perhaps the leading virtue of the method is its relatively modest data requirements. In particular, there is no need to gather price and quantity information from the allowance market. As the allowance market begins to operate in earnest shortly and Phase I of the acid rain title of the CAAA comes into effect, it will become possible to estimate allowance demand and supply relationships econometrically. Until then, approaches like ours can yield at least a hint of the prices that will prevail.

Our results are specific to the Wisconsin utility industry. How much can be said, based upon them, about the national allowance market? There are quite naturally some qualifications that must be kept in mind when one attempts to illuminate the larger market with our work. One important example is the lack of scrubbers at Wisconsin coal plants. This has a direct bearing on our technology model, for the presence of scrubbers on some plants would certainly affect estimation of the distance function. If data for plants with scrubbers were included, a comparison akin to that in our Table 4—this time aggregating plants according to the presence or absence of scrubbers—would be possible. The results would yield insights into the effect of scrubbers on both technical efficiency and emission rates and levels.

Our results are also influenced by Wisconsin's own innovative and relatively stringent acid rain legislation. Since the beginning of 1993, each of the state's major utilities have been required emit, on average, no more than 1.2 pounds of SO_2 per mBtu *across all plants*. Recall that in Phase I of the CAAA, affected units will be given enough allowances to emit at the rate of 2.5 pounds per mBtu; in Phase II, 1.2 pounds. Though the Wisconsin law appears to match the Phase II restriction, in fact it is intermediate between Phases I and II. The key difference is that emission rates are averaged across all of a utility's plants, including nuclear and gas-fired plants, which emit almost no SO_2. Utilities can meet the requirements of the state law while emission rates from coal-fired plants are well above 1.2 pounds. Wisconsin's law also permits emissions trades between utilities on a one-to-one basis, subject to certain mild restrictions on total emissions after the trade.[11]

Table 6 contains annual average emission rates for the three years covered by our sample. It is apparent that the utilities were on a trajectory toward compliance with the state law during this time. Emission rates fell from 2.10 in 1990 to 1.82 in 1992. These figures explain why Wisconsin utilities have been significant sellers of Phase I allowances: in order to meet the state restriction, Phase I units overcomplied with the CAAA restriction.[12] At the same time, at least one Wisconsin utility has begun to *purchase* allowances for use in Phase II.

Table 6 also contains annual average SO_2 shadow prices. As expected, these have increased as emission rates have fallen over the study period. If one views the shadow price as akin to (the negative of) marginal abatement costs, then our results are comparable to the EPRI (1993) estimates of marginal abatement cost in the region including Wisconsin. The EPRI number for Phase I abatement was $332/ton in 1992 dollars. By the year 2000, when Wisconsin's coal-fired plants must reach 1.2 pounds/mBTU, we would expect shadow prices (and marginal abatement costs) to rise above their current levels. At their current observed prices, it would appear that allowance purchases are an attractive compliance alternative. Given the average price of $136.19 for Phase II allowances in the 1993 EPA auction, the Wisconsin utilities appear to be getting a bargain.

In the absence of input price information, there is a limit to what one can claim from our results about exactly which plants should reduce their SO_2 emissions. Though we can say roughly which plants should increase and which should reduce emissions, we cannot say how abatement would be distributed across plants in a least-cost outcome. At an equilibrium in the SO_2 allowance market, $r_2(x, u)$ should be approximately equal across plants. Methods extending those we have used can be employed to examine the equilibrium properties of a utility industry with allowance trading. If input

[11]The CAAA are driven by an aggregate cap on emissions, while the Wisconsin law has only a "goal" of reducing emissions from coal-fired utility plants to not more than 250,000 tons annually (Wisconsin statute 144.388 (2)(b)).

[12]Of the 726,384 Phase I allowances that were exchanged in publicly-announced private trades through November 1993, Wisconsin utilities sold 110,000, or 20.2% (Rose et al. 1993). By comparison, Wisconsin's Phase I units are to receive 143,380 allowances annually through 1999.

price information were known, plant-level cost functions could be constructed using nonparametric methods. These objects could be used to devise an industry-wide abatement cost function, which could in turn be minimized subject to an aggregate emissions constraint and possibly some firm-specific capacity constraints. The resulting solution would constitute a complete description of optimal environmental compliance decision-making. It would also yield the equilibrium allowance price and a description of allowance market-behavior, complementing the abatement cost function results of Atkinson and Tietenberg (1991).

6. Conclusions

As the U.S. electric utility industry prepares to meet the requirements of Title IV of the 1990 CAAA, many things are unknown. Yet utilities have been asked to make compliance decisions that can involve investments of hundreds of millions of dollars. Their decisions depend in an essential way upon the price at which allowances will trade. In this paper we have employed a distance function technique to extract the shadow price of SO_2 emissions from a dataset containing production information for a collection of Wisconsin coal-burning electric utilities. The empirical approach uses the distance function, which captures the technological relationship between inputs and outputs, and the corresponding dual information contained in a revenue function.

From the estimated distance function parameters we found that for the Wisconsin utilities in our dataset the average shadow price of SO_2 emissions is \$292.70 per ton. This number is in the neighborhood of other recent estimates of the marginal cost of abatement for coal plants in the Midwest region. However, as Phase II of the CAAA draws near, the plants in our sample will need to reduce their emissions still further. We expect that shadow prices will be driven up, and the purchase of Phase II allowances at current prices will become a better bargain still.

The methodology we have employed may find use in other industries facing new or newly stringent environmental restrictions. One advantage to our approach lies in its modest data requirements. It relies only on observed output and input data that are readily available. It does not require information concerning individual plant production functions. Consequently, similar studies could be conducted for other states or regions throughout the U.S. Perhaps more importantly, by extending the model one could study the relative effect of different abatement choices such as fuel switching or scrubbing. As utility operators anticipate future regulation, our results may prove useful in ongoing compliance planning.

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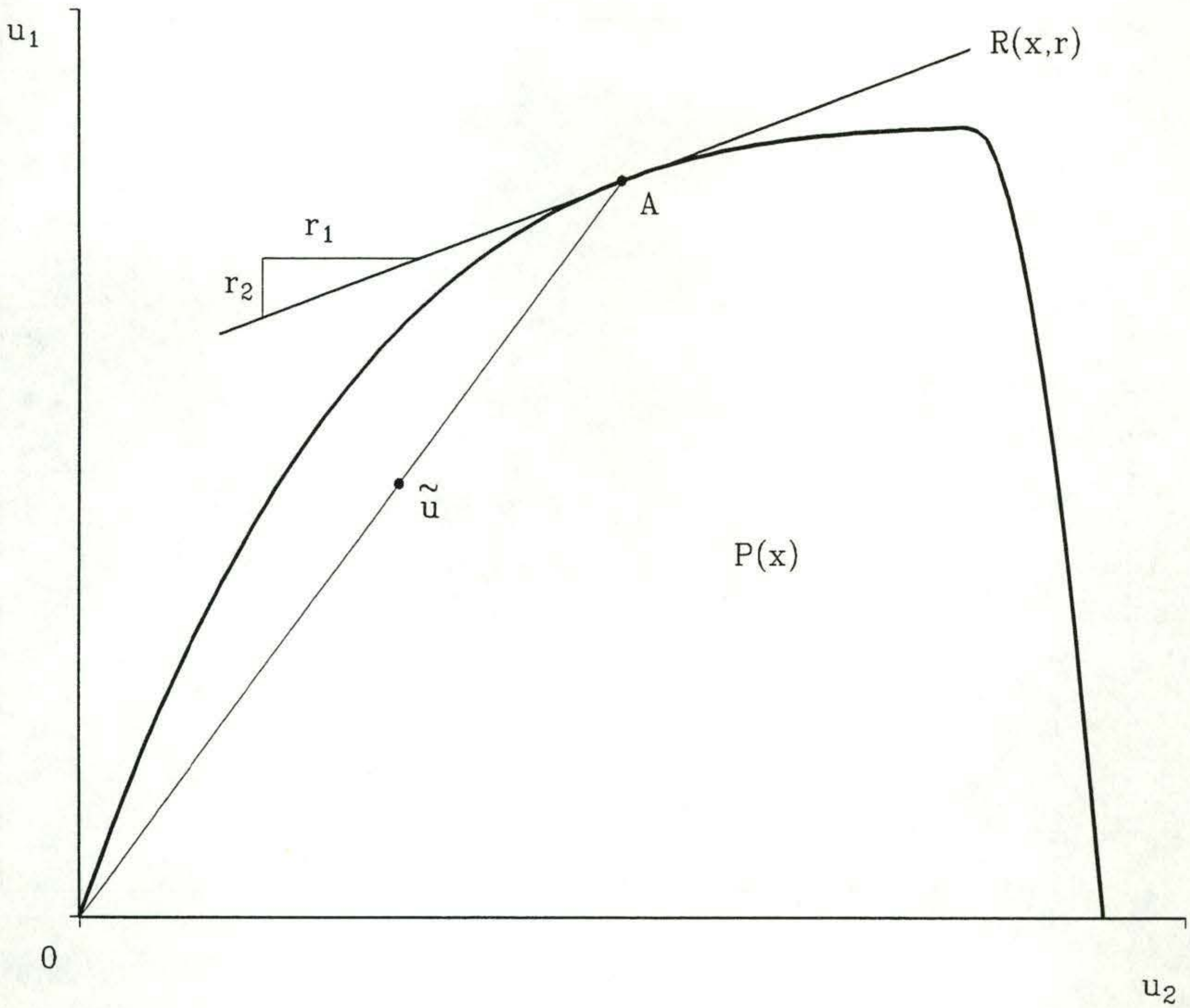

Figure 1. Technology $P(x)$ and revenue $R(x, r)$ with weak disposability.

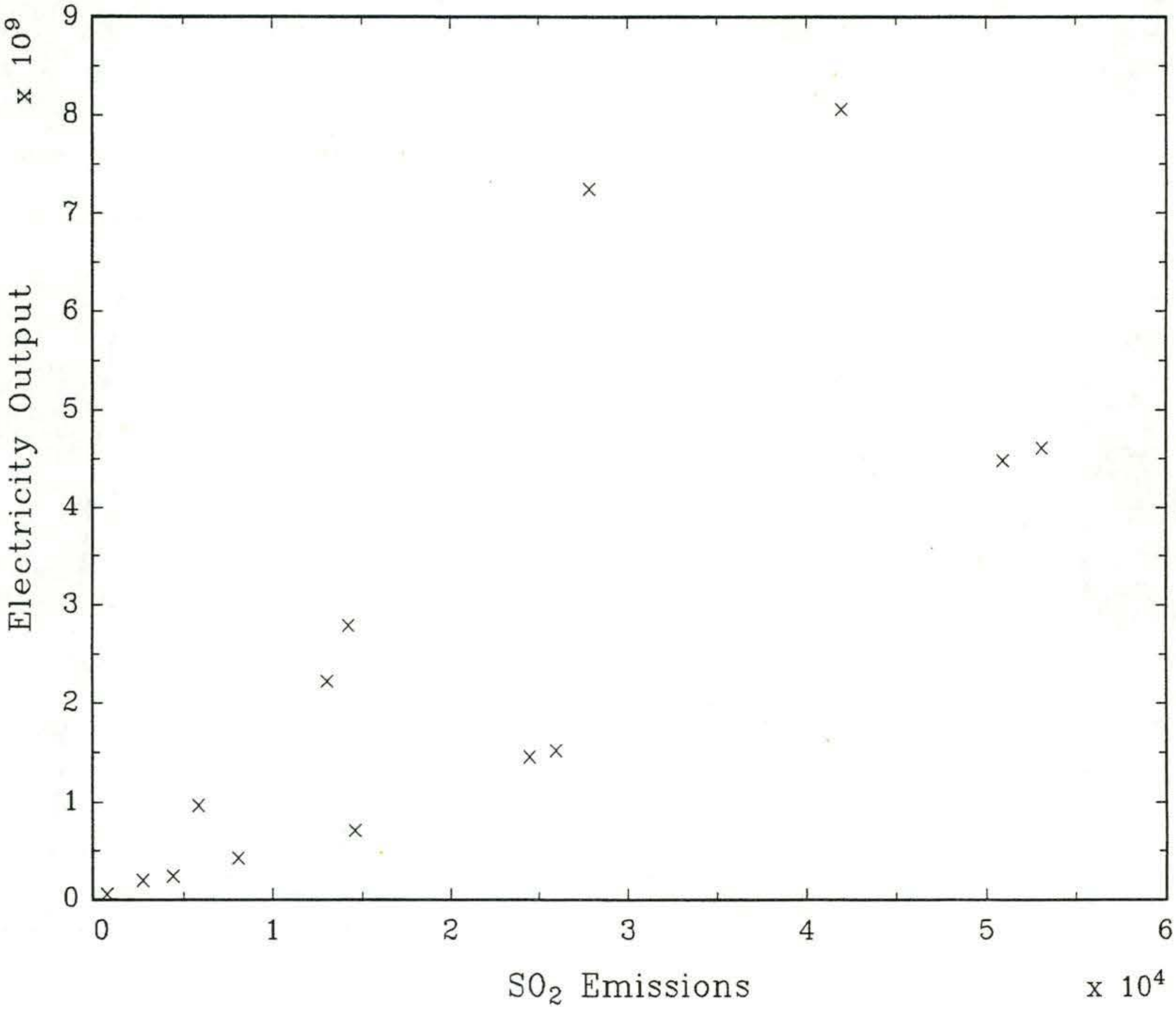

Figure 2. Output pairs by plant, average 1990–92.

Table 1. Descriptive statistics ($K = 42$).

Variable	Units	Mean	Std Dev	Minimum	Maximum
Electricity	Kwh/yr	2496494107	2572496186	35115000	9204967619
SO_2	tons/yr	20588.00	17115.88	465.56	60040.00
Sulfur	tons/yr	11013.80	9516.62	226.53	35695.25
Energy	mBtus/yr	27307582.0	27096312.3	471377.0	96910161.0
Labor	hours/yr	282333.3	171011.5	58000	828000
Capital[a]	$	204072351	208758507	12694737	796570753
Price	cents/Mwh	5.13897	0.79171	3.638	6.587

[a] Constant 1992 dollars.

Table 2. Parameter Values.

Parameter	Value	Parameter	Value
α_0	-4.8952	β_{22}	-1.1392
α_1	0.9621	β_{23}	0.2481
α_2	0.0379	β_{24}	0.6888
β_1	1.1085	β_{33}	0.2108
β_2	-1.7145	β_{34}	-0.1852
β_3	1.7169	β_{44}	-0.4067
β_4	-1.0128	γ_{11}	-0.0266
α_{11}	0.0200	γ_{12}	0.0266
α_{12}	-0.0200	γ_{21}	0.0464
α_{22}	0.0200	γ_{22}	-0.0464
β_{11}	0.0097	γ_{31}	-0.0261
β_{12}	0.3699	γ_{32}	0.0261
β_{13}	-0.4963	γ_{41}	-0.0193
β_{14}	-0.0571	γ_{42}	0.0193

Table 3. Three-year Average Distance Function and Shadow Prices.

Plant	$D(x,u)$	$r_2(x,u)^a$	lb. SO_2/mBtu
1	0.96197	-6.223	2.942
2	0.96134	-15.824	2.452
3	0.99140	-897.034	0.697
4	0.90609	-7.439	2.505
5	0.65360	-67.057	2.447
6	0.90786	-48.327	3.038
7	0.95084	-595.777	0.866
8	0.93429	-692.416	0.997
9	0.95769	-123.759	2.102
10	0.99769	-767.214	1.159
11	0.96268	-72.783	3.353
12	0.83776	-399.940	0.904
13	0.91603	-112.349	2.210
14	1.00000	-78.533	3.490
Average	0.94599[b]	-292.698[c]	2.016[c]

[a] Constant 1992 dollars.
[b] Weighted by electricity output.
[c] Weighted by SO_2 emissions.

Table 4. Mean Distance Function and Shadow Prices by Boiler Type.

	Boiler Type			
	Dry Bottom ($n = 11$)		Cyclone ($n = 3$)	
	$D(x,u)$	$r_2(x,u)$	$D(x,u)$	$r_2(x,u)$
Mean	0.942232	-326.733	0.964618	-175.483
SD	0.104536	90.665	0.048468	68.126

Table 5. Derivatives of $\ln D$, evaluated at global means.

	Variable (z)	$\partial \ln D / \partial \ln z$
Outputs:	Electricity	1.0388
	SO_2	-0.0388
Inputs:	Sulfur	-0.2444
	mBtu	-0.7789
	Labor	0.3065
	Capital	-0.2700

Table 6. Annual average shadow values and emission rates.

Year	$r_2(x, u)$	lb. SO_2/mBtu
1990	-305.010	2.1009
1991	-251.635	2.1133
1992	-322.869	1.8247