Marketable pollution permits and acid rain externalities

SCOTT E. ATKINSON / University of Wyoming

Abstract. This paper examines the economic implications of currently proposed marketable pollution right (MPR) systems for attaining ambient air quality standards in local airsheds. We show that (1) the magnitude of local control costs for one MPR system must be less than or equal to that under the current pollution control system and (2) if this MPR system significantly reduces local costs of control, it must significantly increase local ambient degradation and, with high probability, the extent of long-range sulfate (SO_4) deposition. A simulation for a region of the Ohio River Basin indicates that the cost saving and increased ambient degradation and sulfate deposition in the North-east and Canada should be large.

Le marché pour les droits de pollution et les effets externes des pluies acides. Ce mémoire examine les conséquences économiques de la mise en place de systèmes de marchés de droits de pollution (MPR) comme mécanisme pour assurer certains standards de pureté de l'air dans certaines zones locales. L'auteur montre que (1) les coûts du contrôle local pour un tel système doivent être moindres ou égaux tout au plus à ceux du système de contrôle de pollution existant, et (2) si un tel système réduit de façon substantielle les coûts locaux du contrôle de la pollution, il s'ensuit cependant qu'il y a dégradation ambiante substantielle au niveau local et accroissement à long terme des dépôts de SO_4. Un exercice de simulation pour la région du bassin de la rivière Ohio montre que tant les réductions de coûts que la dégradation ambiante et la taille des dépôts de sulfate dans le Nord Est américain et le Canada devraient être considérables.

INTRODUCTION

This paper examines the economic implications of currently proposed marketable pollution right (MPR) systems for attaining ambient air quality standards in local airsheds. We show that the magnitude of local control costs for one MPR system must be less than or equal to that under the current pollution control system. We also show that if this MPR system significantly reduces local costs of control, it must significantly increase local ambient degradation and, with high probability, the extent of long-range sulfate (SO_4) deposition (popularly termed 'acid rain'). Further, internal-

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ization of this externality may significantly reduce the cost advantage of this MPR system. To determine the magnitudes involved we simulate two MPR systems and the current system for a region of the Ohio River Basin.

The dramatic increase in acid rain deposition in the North-east United States and large parts of Canada over the past few decades has been well documented.[1] Although most of this increase has been traced to midwestern sources,[2] it is not primarily due to increased levels of SO_2 emissions, as is widely thought; these emissions have remained relatively constant. Instead, the major causes appear to be the more complete oxidation of SO_2 into sulfuric acid, through the greater use of coal to produce electricity during summer months, and an approximate threefold increase in the height of emission stacks.[3] Under the current system of controls based on State Implementation Plans (SIPs), most midwestern sources are allowed to increase stack heights in lieu of installing SO_2 flue gas desulfurization (FGD) equipment (popularly termed 'scrubbers').[4] Increased stack heights sufficiently reduce ambient SO_2 concentrations at ground level to satisfy federal ambient standards in a local airshed. However, taller stacks result in a greater percentage of emissions travelling longer distances, greater conversion of SO_2 to SO_4 in transit, and therefore greater long-range acid deposition.

In spite of increased stack heights, many urban areas appear unable to attain the 1982 federal ambient standards for ozone, SO_2, particulate matter, nitrogen oxide, and carbon monoxide. In fact, many of these areas are projected to be in non-attainment of standards for more than one of these pollutants.[5]

Consistent with the increased political popularity of decentralized pollution control, and in an effort to reduce the costs of meeting ambient standards, the Environmental Protection Agency (EPA) has recently proposed the trading of MPRS within local airsheds.[6] Economists have long argued that systems using MPRs are more cost-effective to achieve federal ambient standards in a local airshed than the current system of controls based on SIPS.[7]

Local MPR systems employ either emission discharge permits (EDPS) or ambient discharge permits (ADPs). Under the local EDP strategy, each source minimizes its cost of control plus its expenditure on permits for uncontrolled emissions. Sources with lower marginal emission removal costs will control a greater percentage of their

1 See National Commission on Air Quality (1981) and Committee on the Atmosphere and Biosphere (1981).
2 See the National Commission on Air Quality (1981), 3.9-19
3 See the National Commission on Air Quality (1981), 3.9-1 to 3.9-35.
4 Based on discussions with Robert Hodanbosi, Chief, Division of Air Quality Modelling and Planning of the Ohio Environmental Protection Agency, sources are allowed to construct taller stacks up to what is termed 'good engineering practice' (GEP) levels in lieu of controlling emissions. For a cubic building, GEP implies stack heights approximately 2.5 times building height. Since few mid-western point sources have installed scrubbers, building tall stacks has clearly been more cost effective.
5 See the National Commission on Air Quality (1981), 3.4-21 to 3.4-34.
6 See the National Commission on Air Quality (1981), 4.1-41 to 4.1-42.
7 See Crocker (1966) and Dales (1968) for an early discussion of the advantages of these systems as alternatives to direct administrative control. Also, see Tietenberg (1980) for a survey and synthesis of the literature on MPRS.

emissions in lieu of purchasing EDPS. Each source's decision is independent of its degradation of local air quality. Under the local ADP strategy, each source minimizes its cost of control plus its expenditure on permits for local ambient degradation. Sources with lower marginal emission removal costs per unit improvement of local air quality will control a greater percentage of their emissions in lieu of purchasing ADPS. The contribution to long-range acid deposition is ignored by both systems.

The relative costs of local MPR systems have been modelled, using mathematical programming techniques for St Louis by Atkinson and Tietenberg (1982), where particulate control was considered, and for Chicago by Anderson et al. (1979), where nitrogen dioxide control was examined. These studies indicate an order-of-magnitude reduction in local control costs under the ADP system and a factor of five reduction under the EDP system compared with the current SIP system.

However, these studies ignore two important characteristics of MPR systems, which have received little or no attention elsewhere in the literature. The first is that in a local airshed there is no guarantee that an EDP system will be more cost-effective than an SIP system to achieve ambient standards. The second characteristic, which is the major focus of this paper, is described by the following proposition: the local ADP system, which guarantees that the cost to attain local ambient standards is at least as low as under the SIP system, also guarantees at least as much degradation of local air quality.[8] This implies a high probability of greater long-range acid deposition by the local ADP system. If local cost savings under this system are substantial, political pressure for its adoption may be great. However, the increased long-range acid deposition may lead to a Pareto inferior solution. Further, when externalities are internalized under a global ADP system, by limiting the amount of long-range acid deposition the cost-advantage of this system may be reduced sufficiently to make its adoption non-optimal relative to a global SIP system.

This proposition, however, does not enable us to determine the magnitude of control cost savings or increased long-range acid deposition under these local and global systems. Thus, we simulate these systems using a non-linear program and data on SO_2 control and dispersion for major point sources in the Cleveland region (Cuyahoga County) of the Ohio River Basin. This region is projected to be in non-attainment of ambient standards for SO_2 and is presumed to contribute significantly to acid deposition in Canada and the north-east United States. The results indicate that the local EDP strategy is far more costly and the local ADP strategy far less costly than the local SIP strategy to achieve local ambient SO_2 standards. The former result is consistent with the Rose-Ackerman (1973) proposition stating that an emissions fee system is not guaranteed to be more efficient than an SIP system. However, the more cost-effective ADP system loads the local environment more heavily with SO_2 and substantially reduces the control burden of power plants with tall stacks. Both contribute to substantially increased long-range acid deposition by the local ADP system relative to the current SIP system. When constraints requiring 'optimal' levels of acid deposition are introduced to achieve global solutions, we

8 See Atkinson and Tietenberg (1982) for empirical evidence of the importance of this proposition.

observe a significant reduction in the cost-savings of the ADP relative to the EDP and SIP strategies. The remaining cost savings may be insufficient to offset the increased transactions and administrative costs associated with implementing the global ADP strategy.

The remainder of this paper proceeds as follows. The second part presents the design and mathematical formulation of the MPR systems, allowing derivation of a proposition that ranks the local costs and ambient degradation of local systems. The third part presents the data and algorithms used to model alternative control strategies. Finally, results and conclusions follow in the fourth and fifth parts.

THE DESIGN AND IMPLICATIONS OF ALTERNATIVE POLLUTION CONTROL STRATEGIES

In this section we examine the design and implications of the local and global SIP and MPR systems for controlling pollution. The local SIP strategy is a non-optimal allocation scheme based on individual source ambient degradation. However the local MPR systems may be described using the Kuhn-Tucker conditions derived from a constrained cost-minimization problem. Global solutions for all strategies are modelled by adding constraints on long-range acid deposition to local strategies.

The local SIP strategy examined in this paper assigns individual source control requirements necessary to meet the standards in proportion to each source's contribution to total local ambient degradation. Individual percentage contributions for source j are computed as

$$s_j = \sum_i (d_j^{\mathrm{SIP}} \cdot a_{ij}) / \sum_{ij}\sum d_j^{\mathrm{SIP}} \cdot a_{ij}, \quad j = 1, \ldots, n, \tag{1}$$

where

d_j^{SIP} = the emissions in grams/sec (g/s) from source j under the SIP strategy,

a_{ij} = the transfer coefficient relating emissions from source j to ambient degradation at receptor i.

Given an estimated level of total regional emission removal necessary to achieve the standard at each receptor, ERER, the estimated required control level for source j is computed as

$$ec_j = s_j \cdot \mathrm{ERER}. \tag{2}$$

Remaining source emissions are then run through an air quality diffusion model (described below) to determine if air quality at the receptor registering the greatest ambient concentration just meets the standard, g_i. That is,

$$\sum_j a_{ij} d_j^{\mathrm{SIP}} \leq g_i, \qquad i = 1, \ldots, m, \tag{3}$$

with equality at one receptor. If not, the procedure in equation (2) is repeated until (3) is satisfied. The global SIP strategy requires, in addition, that the following constraint on long-range SO_4 transport be satisfied:

$$\sum_v a_v \sum_j d_j^{SIP} \leq r, \tag{4}$$

where

a_v = the long-range transport coefficient mapping SO_2 emissions from Cuyahoga County into $\mu g/m^3$ of SO_4 in the vth neighbouring region, and

r = the 'optimal' SO_4 concentration ($\mu g/m^3$) allowed in all regions due to Cuyahoga County SO_2 emissions.

In simulating all MPR control strategies we assume that the cost functions for the sources under study are convex, smooth, and continuous and that each firm minimizes its cost of control, given the requirement that scrubbers be installed. Cost minimization under the local ADP strategy is equivalent to minimizing the cost of controlled emissions plus the expenditure on ADPs for the ambient degradation due to uncontrolled emissions. These permits are assumed to be traded in competitive markets. Following Montgomery (1972), we can write the cost-minimization problem to model the local ADP strategy for firm j, $j = 1, \ldots, n$, as a quadratic programming (QP) problem:

minimize

$$z^a = c_j d_j^a + b_j (d_j^a)^2 + \sum_i p_i^a \cdot l_{ij}^a \tag{5}$$

subject to

$$a_{ij} d_j^a \leq l_{ij}^a, \qquad i = 1, \ldots, m, \tag{6}$$

and

$$l_{ij}^a \geq 0, \qquad i = 1, \ldots, m, \tag{7}$$

$$d_j^a \geq 0, \tag{8}$$

subject to the market clearing condition

$$\sum_i p_i^a \sum_j l_{ij}^a = 0, \tag{9}$$

where

c_j, b_j = coefficients representing the cost of emission control in $\$/g/s$ for the jth source,

d_j^a = the emissions in g/s by source j under the ADP system,

p_i^a = the price of an ADP in $\$/\mu/m^3$ for receptor i,

l_{ij}^a = the volume of ADPs which source j must purchase for receptor i,

and a_{ij} is defined above. The product of a_{ij} and d_j^a yields $\mu g/m^3$ of air quality degradation at receptor i due to emissions by source j. For the local ADP strategy, form the Lagrangean for firm j:

$$L^a(d_j^a, l_{ij}^a, \mu_i) = f_j(d_j^a) + \sum_i p_i^a l_{ij}^a + \sum_i \mu_i[a_{ij}d_j^a - l_{ij}^a], \tag{10}$$

where

$$f_j(d_j^a) = c_j d_j^a + b_j(d_j^a)^2.$$

From Kuhn-Tucker theorem the following complementary slackness conditions are necessary and sufficient for the constrained minimum for firm j:

$$\partial L^a/\partial d_j^a\!: \quad f_j'(d_j^a) + \sum_i \mu_i a_{ij} \geqslant 0, \tag{11}$$

$$d_j^a \left[f_j'(d_j^a) + \sum_i \mu_i a_{ij} \right] = 0, \tag{12}$$

$$\partial L^a/\partial l_{ij}^a\!: \quad p_i^a - \mu_i \geqslant 0, \qquad i = 1, \dots, m, \tag{13}$$

$$\sum_i l_{ij}^a(p_i^a - \mu_i) = 0, \tag{14}$$

$$\partial L^a/\partial \mu_i\!: \quad a_{ij}d_j^a - l_{ij}^a \leqslant 0, \qquad i = 1, \dots, m, \tag{15}$$

$$\sum_i \mu_i(a_{ij}d_j^a - l_{ij}^a) = 0. \tag{16}$$

These conditions may be interpreted as follows. Equations (11–12) state that each source that emits will equate its marginal cost of incremental emission control to the marginal cost of the ADPs required to cover the ambient degradation due to uncontrolled emissions. The latter cost is based on the unique market-determined prices for ADPs. Equations (13–14) imply that the market price, p_i, for all ADPs purchased at the ith receptor by the jth source will equal the shadow value μ_i corresponding to the ith constraint in equation (6). Equations (15–16) state that each source must cover its ambient degradation at each receptor with the purchase of ambient permits at all receptors where the ambient constraint is binding. Potentially, this trading rule requires each source to purchase ambient permits for each receptor. Thus, at the ith receptor, where u_i is pre-control air quality and g_i is the air quality standard, $g_i - u_i = \Sigma_j l_{ij}^a$. Equation (9) guarantees that total permit expenditures exactly equal total permit revenues among all firms, which will be automaticlly satisfied as an accounting identity. Finally, the global ADP control method can be written as the QP problem in equations (5)–(9) plus the additional acid deposition constraint in equation (4), where d_j^a is substituted for d_j^{SIP}.

Cost minimization under the local EDP strategy is equivalent to minimizing the cost of controlled emissions plus the expenditure on EDPs for uncontrolled emissions. Again a competitive permit market is assumed. The local EDP strategy for firm j, $j = 1, \dots, n$, is modelled as the solution to the following QP program:

minimize

$$z^e = c_j d_j^e + b_j(d_j^e)^2 + p^e l_j^e \tag{17}$$

subject to

$$d_j^e \leqslant l_j^e, \tag{18}$$

and

$$d_j^e \geqslant 0, \tag{19}$$

$$l_j^e \geqslant 0, \tag{20}$$

subject to the market clearing condition

$$p^e \sum_j l_j^e = 0, \tag{21}$$

where

d_j^e = the emissions in g/s by source j under the EDP system,

p^e = the price of an EDP in $\$/g/s$, and

l_j^e = the volume of EDPs purchased by source j.

For the local EDP strategy, form the Lagrangean for firm j:

$$L^e(d_j^e, l_j^e, \lambda) = f_j(d_j^e) + p^e l_j^e + \lambda(d_j^e - l_j^e), \tag{22}$$

where $f_j(d_j^e) = c_j d_j^e + b_j(d_j^e)^2$. Again, the following conditions are necessary and sufficient for the constrained minimum for firm j:

$$\partial L^e/\partial d_j^e\colon\ f_j'(d_j^e) + \lambda \geqslant 0, \tag{23}$$

$$d_j^e[f_j'(d_j^e) + \lambda] = 0, \tag{24}$$

$$\partial L^e/\partial l_j^e\colon\ p^e - \lambda \geqslant 0, \tag{25}$$

$$l_j^e(p^e - \lambda) = 0, \tag{26}$$

$$\partial L^e/\partial \lambda\colon\ d_j^e - l_j^e \leqslant 0, \tag{27}$$

$$\lambda(d_j^e - l_j^e) = 0. \tag{28}$$

These conditions may be interpreted as follows. Equations (23–24) state that each source that emits will equate its marginal cost of control to the shadow value, λ, corresponding to the constraint in (18). Equations (25–26) imply that each EDP's price, p^e, will equal the shadow value, λ, for all EDPs purchased by source j. Equations (27–28) state that each source must cover its total emissions with the purchase of EDPs so long as their price is non-zero. However, since EDPs are unrelated to ambient degradation, ambient standards will not initially be satisfied by (18), except by chance. Thus, the control authority will have to adjust the total number of permits after observing actual air quality or running emissions through an air quality diffusion model. Equation (21) guarantees that total permit expenditures equal total permit revenues among all firms via an accounting identity. The EDP global strategy is defined as the solution to the QP problem in equations (17)–(21) plus constraint equation (4), where d_j^e is substituted for d_j^{SIP}.

We are now able to prove a proposition that has important implications for local control costs and long-range acid deposition.

PROPOSITION: *Measured at local receptors, the ambient degradation of the local ADP strategy will equal or exced that of the local EDP and SIP strategies and, consequently, the cost of the local ADP strategy will be less than or equal to that of the local EDP and SIP strategies.*

Proof: Under the EDP system, the pollution control agency monitors air quality at each receptor and iteratively adjusts the number of EDPs so that the standard is satisfied at each receptor. That is,

$$\sum_j a_{ij} d_j^e \leqslant g_i, \qquad i = 1, \ldots, m. \tag{29}$$

In addition, the constraint equation (27) is satisfied with equality for all j. Under the ADP strategy the pollution control agency issues ADPs for each receptor such that the standard is exactly met at each receptor:

$$\sum_j l_{ij}^a = g_i, \qquad i = 1, \ldots, m. \tag{30}$$

Summing equation (15) over all j and substituting from (30) yields

$$\sum_j a_{ij} d_j^a \leqslant \sum_j l_{ij}^a = g_i, \qquad i = 1, \ldots, m. \tag{31}$$

Since the EDP system is subject to one additional binding constraint, equation (27), it follows that

$$\sum_j a_{ij} d_j^a \geqslant \sum_j a_{ij} d_j^e, \qquad i = 1, \ldots, m. \tag{32}$$

Since the SIP system employs a method of assigning additional control responsibility in proportion to ambient degradation, independent of costs, it is not a cost-minimizing solution. Thus,

$$\sum_j a_{ij} d_j^a \geqslant \sum_j a_{ij} d_j^{\mathrm{SIP}}, \qquad i = 1, \ldots, m. \tag{33}$$

It follows directly from (32) and (33) that the total cost of control for the local ADP system must be less than or equal to that of the local EDP and SIP systems, since the latter reduce environmental degradation by at least as much as the former.

This proposition establishes an ordinal ranking of local ground-level environmental degradation and control costs for all local strategies. Thus, if the control costs for the local ADP system are lower than for the other local systems, its local ambient degradation must be greater. However, this proposition does not shed light on the magnitude of the differences between the SIP system and the marketable permit systems with regard to the following three properties: first, the magnitude of any cost savings under the local ADP strategy versus the local EDP and SIP strategies; secondly, the magnitude of any increased local degradation under the local ADP versus the local

EDP and SIP strategies; and finally, the increase in control costs when restrictions on long-run acid deposition are incorporated, that is, when global strategies are examined. The magnitude of differences in costs to achieve local ambient standards critically affects the political acceptability of local permit systems. The magnitude of increased local ambient degradation is a critical factor determining the extent of the resulting long-range acid deposition and the increase in control costs under global control systems.

Differences in costs and long-range acid deposition cannot be determined analytically, since they depend on the individual control costs, emissions, and emission dispersion characteristics of the sources comprising a particular region. Thus, we turn to a simulation of these strategies for the Cleveland area to measure these differences.

SIMULATION DATA AND ALGORITHMS

Simulating the local and global systems defined in the preceding section requires a source inventory for the Cleveland area, a local SO_2 air quality diffusion model, a long-range SO_4 transport model, control cost functions, and a quadratic programming algorithm.

Source inventory

The sources examined in this study comprise the twenty-five largest point-source emitters of SO_2 in the Cleveland area, defined by Cuyahoga County.[9] Together these point sources account for 95 per cent of total regional emissions from all major point sources and 60 per cent of total ambient degradation. The remaining ambient degradation from excluded point sources and all area sources is treated as background. The facility name, SO_2 process, and per cent SO_2 content of the fuel burned for each source are given in table 1. Fourteen of the twenty-five sources generate electricity, one is a steam-heat boiler, one is a waste-water treatment plant, and the remainder are industrial sources. As seen in table 2, electricity generating sources account for 95 per cent of SO_2 emissions and employ substantially taller stacks than the other sources. Thus, the potential for long-range acid deposition is greater for these emitters.

Although twenty-five sources are examined, only eight are independently owned. Assuming no decentralization of decision-making, the question arises whether a competitive equilibrium can be attained with a small number of buyers and sellers of MPRS. As indicated by Smith et al. (1982), the results of a large number of studies of experimental markets with at least four buyers and sellers indicates an extremely rapid convergence to a competitive equilibrium. In most permit markets we would expect many more buyers and sellers than are examined in this simulation.

Table 1 indicates that some additional switching to lower sulphur fuels may be

9 The author wishes to thank Robert Hodanbosi for supplying the source inventory and answering numerous questions about the compatibility of sources and scrubbers.

TABLE 1

Inventory of SO_2 sources, Cuyahoga County

Source	SO_2 process	Per cent SO_2
1 ALCOA	Industrial coal boiler	3.57 per cent coal
2 ALCOA	Industrial coal boiler	3.57 per cent coal
3 Cleveland Electric Illuminating Co. (CEIC)	Steam heat boilers	0.70 per cent coal
4 CEIC – Avon Lake Plant	Electrical generation	0.24 per cent oil
5 CEIC – Avon Lake Plant	Electrical generation	0.24 per cent oil
6 CEIC – Avon Lake Plant	Electrical generation	0.24 per cent oil
7 CEIC – Avon Lake Plant	Electrical generation	0.24 per cent oil
8 CEIC – Avon Lake Plant	Electrical generation	2.65 per cent coal
9 CEIC – Avon Lake Plant	Electrical generation	2.65 per cent coal
10 CEIC – Avon Lake Plant	Electrical generation	2.65 per cent coal
11 CEIC – Eastlake Plant	Electrical generation	3.14 per cent coal
12 CEIC – Eastlake Plant	Electrical generation	3.14 per cent coal
13 CEIC – Lakeshore Plant	Electrical generation	1.62 per cent oil
14 CEIC – Lakeshore Plant	Electrical generation	1.62 per cent oil
15 CEIC – Lakeshore Plant	Electrical generation	1.62 per cent oil
16 CEIC – Lakeshore Plant	Electrical generation	1.62 per cent oil
17 CEIC – Lakeshore Plant	Electrical generation	0.74 per cent coal
18 Division Pumping Station	Water treatment plant	2.24 per cent coal
19 Ford Engine Plant #2	Coal boilers	2.90 per cent coal
20 General Motors – Chevrolet	Coal boilers	2.26 per cent coal
21 Lincoln Electric	Coal boilers	2.90 per cent coal
22 Medical Center	Coal boilers	1.88 per cent coal
23 Republic Steel	Boiler	coke oven gas
24 Republic Steel	Slab R.F. #1	coke oven gas
25 Republic Steel	Slab R.F. #2	coke oven gas

possible. However, the greatest incremental improvements in ambient air quality through fuel switching have already been achieved. Further, as shown later, reduction of fuel sulphur content by 40–54 per cent is required to meet the primary ambient standard and by up to 90 per cent to meet this standard plus constraints on acid rain deposition. The availability of fuels clean enough to meet these requirements is highly unlikely. For both reasons we examine the mandatory retrofitting of all major point sources with scrubbers, assumed to have a maximum efficiency of 90 per cent, based on Mitre (1981).

Local diffusion model and long-range transport model

Local air quality diffusion modelling is performed using the RAM steady-state Gaussian dispersion model developed by the EPA (Turner and Novak, 1978). Principally, RAM determines urban air quality concentrations from one hour to one day, resulting from pollutants released by point and area sources. This algorithm is applicable for locations with level or gently rolling terrain, where a single wind vector, mixing height, and stability class are assumed representative of the entire area for each hour.

Source-receptor pollutant transfer coefficients are computed from the RAM-

TABLE 2

Potential long-range transport under existing controls

Source	Current emission rate (g/s)	Stack height (m)
1 ALCOA	106.80	60.96
2 ALCOA	72.20	45.72
3 CEIC – Steam	79.60	95.71
4 CEIC – Avon	148.90	84.40
5 CEIC – Avon	148.90	84.40
6 CEIC – Avon	148.90	84.40
7 CEIC – Avon	148.90	84.40
8 CEIC – Avon	1,578.90	152.40
9 CEIC – Avon	1,668.00	119.50
10 CEIC – Avon	4,501.30	182.90
11 CEIC – Eastlake	5,067.40	163.00
12 CEIC – Eastlake	4,986.00	182.80
13 CEIC – Lakeshore	453.81	81.69
14 CEIC – Lakeshore	453.81	81.69
15 CEIC – Lakeshore	521.88	81.69
16 CEIC – Lakeshore	521.88	81.69
17 CEIC – Lakeshore	1,055.16	81.69
18 Division Pump Station	40.80	69.49
19 Ford Engine	329.51	41.76
20 General Motors	35.44	27.43
21 Lincoln Electric	44.50	18.59
22 Medical Center	174.60	58.52
23 Republic Steel	145.50	68.60
24 Republic Steel	68.40	49.10
25 Republic Steel	68.40	49.10
Total	22,569.6	

calculated contributions of each source to the ambient concentrations at each receptor by dividing each ambient concentration in $\mu g/m^3$ by the emission rate of the contributing source in g/s. The RAM model was run to simulate a typical twenty-four-hour interval for July. The output of the diffusion model was examined to determine whether the maximum twenty-four-hour SO_2 standard of 365 $\mu g/m^3$ was violated during any of the twenty-four hours. The hour and receptor associated with each violation as well as the extent of each violation are given in table 3.

The long-range transport model utilized in this study[10] employs separate matrices computed for utility sources (assumed stack height of 175 metres) and industrial sources (assumed stack height of seventy-five metres) for July meteorology, which corresponds to the month of the RAM diffusion model run. The matrix coefficients map millions of metric tons of SO_2 emitted per day in one state into average concentrations in $\mu g/m^3$ of SO_4 in a receptor state. In constraint equation (4), employed by the global solutions, long-range transport coefficients are converted into

10 See the U.S. Department of Energy (1981).

TABLE 3

Receptors exceeding the maximum twenty-four-hour standard

(Receptor, hour)	Air quality ($\mu g/m^3$)	Required improvement to achieve standard ($\mu g/m^3$)
(1, 20)	600.12	235.12
(2, 16)	366.85	1.85
(6, 23)	366.44	1.44
(9, 16)	443.90	78.90
(14, 23)	439.54	74.54
(19, 2)	546.51	181.51
(22, 24)	662.45	297.45
(26, 23)	375.25	10.25

units of $\mu g/m^3/g/s$. The total contribution of the twenty-five Cuyahoga County sources to other regions' SO_4 concentrations is computed as 13.33 $\mu g/m^3$ for all utility sources and 0.79 $\mu g/m^3$ for all industrial sources.[11] In the following analysis of global strategies, the cost of reducing these contributions by 50 per cent is computed. Biologists have specified that reductions of this amount are necessary to restore acidified lakes to normal conditions.[12]

Control costs

The costs of SO_2 control are estimated using data reported by Mitre (1981) for industrial and utility sources. Based on discussions with Ohio EPA officials, all industrial sources are assumed to be retrofitted with dual alkali FGD equipment and all utility sources with limestone FGD equipment, both of which appear more likely to be adopted than spray dryer systems. Details on estimating control costs as a function of the percent of SO_2 removal are provided in the appendix.

SIMULATION RESULTS

The individual source control requirements, the annual variable, fixed, and total control costs, and the long-range acid degradation for each of the local and global strategies of pollution control are presented in table 4. The expectation was that the local ADP strategy would be substantially cheaper than the local EDP and SIP strategies but would contribute more heavily to long-range acid deposition. Further, it was expected that including constraints on long-range SO_4 deposition in all systems would substantially reduce the cost advantage of the local ADP strategy. These expectations are in fact borne out by the simulation results.

The local ADP strategy is clearly more cost-effective than the other systems in

11 It should be recognized, however, that the link between emissions and long-range acid deposition is subject to substantial error. Thus, the estimated absolute magnitudes of long-range deposition are to be considered suggestive rather than definitive.

12 See Committee on the Atmosphere and Biosphere (1981), 181.

TABLE 4

Control responsibilities, costs, and long-range deposition under alternative control strategies

	Control requirements (g/s)				
	SIP method		ADP method		EDP method
Source	local	global	local	global	local and global
1	72.50	101.58	–	96.12	96.12
2	51.98	71.20	–	–	64.08
3	1.88	2.63	–	–	71.64
4	80.76	113.15	–	–	9.01
5	80.76	113.15	–	–	9.01
6	78.01	109.30	–	–	8.49
7	78.01	109.30	–	–	8.49
8	731.95	1,025.48	687.61	572.04	1,421.01
9	815.95	1,143.17	706.03	483.34	1,501.20
10	1,859.57	2,605.31	2,451.90	2,845.30	4,051.17
11	1,386.57	1,942.63	3.37	3,152.98	4,560.66
12	1,325.51	1,857.07	–	2,887.89	4,487.40
13	453.81	453.81	169.80	169.39	168.27
14	453.81	453.81	169.80	169.39	168.27
15	521.88	521.88	215.54	215.95	215.90
16	521.88	521.88	215.54	215.95	215.90
17	–	–	–	–	504.68
18	22.83	31.99	–	–	36.72
19	0.01	0.01	–	296.56	296.56
20	–	–	–	–	–
21	44.60	44.60	21.97	21.97	40.14
22	0.05	0.06	–	157.14	157.14
23	42.22	59.16	–	–	–
24	–	–	–	–	–
25	–	–	–	–	–
Total g/s removed	8.624	11,281	4,642	11,284	18,092
Annual variable cost ($/year)	67,472,401	88,329,333	26,952,379	56,841,304	102,197,612
Annual fixed cost ($/year)	56,016,059	56,016,059	56,016,059	56,016,059	56,016,059
Total annual cost ($/year)	123,488,460	144,345,392	82,968,438	112,857,363	158,213,671
Total long-range acid deposition ($\mu g/m^3$)	8.36	7.06	11.25	7.06	2.91

meeting local ambient standards. The total annual cost of the local ADP strategy, $82,968,438, is approximately 1.5 times less than that of the local SIP strategy, $123,488,460, in order to satisfy the local twenty-four-hour maximum SO_2 standard. This is due to the ADP strategy's allocation of control responsibility according to the lowest marginal cost per unit of local air quality improvement. The SIP method simply increases all sources' control responsibility by the same percentage, regardless of individual source cost-effectiveness.

The local ADP and SIP strategies are substantially less expensive than the local EDP strategy. The total annual cost for the local SIP strategy is approximately 1.28 times less than that for the local EDP strategy, which is $158,213,671. This cost differential is a dramatic example of the Rose-Ackerman (1973) proposition and primarily results from the higher levels of overall control required by the local EDP strategy to attain the standard at receptor 1. Further, the total annual cost of the local ADP strategy is approximately 1.9 times less than that of the local EDP strategy.[13]

However, the local cost advantage of the ADP and SIP strategies is achieved through greater long-range acid deposition. The total amount of SO_4 degradation is 11.25, 8.36, and 2.91 $\mu g/m^3$ for the ADP, SIP, and EDP local strategies, respectively. As a basis of comparison, pre-control acid deposition is 13.33 $\mu g/m^3$. The greater degradation under the local ADP strategy is due to three factors. First, as shown above, since the ADP strategy is cost-effective locally, it leads to the greatest local environmental loading with SO_2. Under the local ADP strategy, air quality is degraded to the level of the ambient standard at four of eight receptors. However, under both the SIP and EDP strategies, this occurs at only one receptor. This is reflected in the permit prices for the local ADP and EDP strategies in table 5. Secondly, as seen in table 4, the local ADP strategy removes approximately one-half and one-fourth of the total SO_2 emissions controlled by the local SIP and EDP strategies, respectively, to achieve the local ambient standard. As a basis of comparison, total pre-control emissions are 22,570 g/s. Finally, emissions from the tallest stacks increase dramatically, moving from the EDP to the SIP and finally to the ADP strategies. From table 2, sources 10–12, power plants with the tallest stacks (from 163–183 m), have a combined control responsibility of 13,099, 4,572, and 2,455 g/s for the local EDP, SIP, and ADP strategies, respectively. These differences occur because the local ADP and SIP strategies partially base control requirements on ground-level ambient degradation, which is substantially reduced as stacks become taller, while the local EDP strategy bases control responsibility solely on marginal costs.

Once constraints on long-range transport are included, levels of total emission control are increased and equalized across strategies, while the least-cost advantage of the ADP strategy is substantially reduced. Global solutions for all strategies require a 50 per cent reduction of the precontrol contribution of the twenty-five Cuyahoga County sources to SO_4 concentrations in all regions. After imposing this constraint, total SO_2 emissions under the global SIP and ADP strategies are highly similar, with controlled emissions almost two and one-half times larger than under the local ADP

13 The smaller difference in relative costs among local strategies in this simulation versus the studies by Atkinson and Tietenberg (1982) and Anderson, et al. (1979) is partly due to differences in capital costs. In the present study all sources are required to install SO_2 scrubbers, whereas in the other studies a number of different pollution removal devices were allowed, including fuel switching. A second important factor is that the SIP strategy examined here employs the RAM diffusion model, thereby capturing some of the cost-savings of the ADP system, whereas the SIP system examined by Atkinson and Tietenberg (1982) employs source emission standards relating pollution output to heat input. However, even in the present study, substantial absolute differences are found among strategies.

TABLE 5

Annual permit prices for the ADP and EDP strategies

For local ambient SO_2 degradation ($\mu g/m^3$) at receptor	ADP strategy ($\$/\mu g/m^3$) local	ADP strategy ($\$/\mu g/m^3$) global
1	\$ 38,836.80	\$ 19,702.60
2	115,534.10	–
3	–	–
4	–	–
5	–	–
6	838.70	3,636.10
7	78,786.20	9,348.60
8	–	–
For long-range SO_4 degradation ($\mu g/m^3$)	–	\$8,469,372.80
	EDP strategy ($\$/g/s$) local	EDP strategy ($\$/g/s$) global
For local SO_2 emissions (g/s)	\$408,566.70	\$408,566.70
For long-range SO_4 degradation ($\mu g/m^3$)	–	–

solution. Under the global ADP strategy, sources 10–12 are required to undertake substantially higher levels of control than under the local ADP strategy; their combined control responsibility increases from 2,455 to 8,886 g/s. The local and global EDP strategies are equivalent, since the high levels of control under the former caused the acid rain constraint to be non-binding under the latter. The level of controlled emissions under the EDP system is now only 1.6 times that under the global ADP system.

The total annual costs of the ADP and SIP global strategies have risen substantially relative to their local counterparts, since one-half of previous externalities are now internalized. However, the total annual cost of the global ADP strategy, \$112,857,363, has increased about 1.4 times, while that of the global SIP strategy, \$144,345,392, has risen approximately 1.17 times. Thus, the global ADP strategy is only 1.28 times less expensive than the global SIP strategy. Further, the global ADP strategy is now only approximately 1.4 times less expensive than the global EDP strategy. Table 5 presents the permit prices corresponding to the global ADP and EDP solutions that reflect the cost-equalization of strategies. Because the cost advantage of the ADP system has been substantially reduced, further analysis is required to determine whether the cost savings of the global ADP system will be sufficient to offset any additional transaction and administration costs relative to a global SIP system. Unfortunately, these costs have not been reliably estimated but will depend, in part, on the efficiency of the flow of information among potential traders or permits.

CONCLUSIONS

Considerable discussion has recently focused on the appropriate strategy to achieve compliance with local ambient standards. The use of MPR systems has been suggested by EPA as a far more cost-effective method of achieving this goal than the current SIP strategy. We show that the cost of control for a local ADP system to achieve local ambient standards is less than or equal to that under any other system. Thus, local political pressure for adoption of a local ADP system may be great. However, any cost saving under this system implies greater local ambient degradation than under the other systems. This creates a high probability of greater long-range acid deposition from the local ADP system.

To estimate these magnitudes we perform a simulation which indicates that the cost savings of the local ADP strategy is substantial, although the local EDP system fares quite poorly relative to the current SIP system. However, the ADP cost advantage, achieved through greater local environmental degradation, results in significantly increased long-range transport of locally generated SO_2. The introduction of constraints on acid rain transport substantially reduces the cost-saving advantage of the ADP strategy relative to the SIP and EDP strategies. The question then becomes whether the remaining differential is sufficient to cover any additional transaction and administrative costs of the global ADP system relative to the global SIP system.

APPENDIX: ESTIMATION OF SO_2 CONTROL COSTS

Highly similar procedures are used to estimate source control costs as a function of percentage of SO_2 removal for n sources comprised of q utility sources and k industrial sources. Estimation of utility cost functions are based on data for thirty plants supplied by the Tennessee Valley Authority and reported in Mitre (1981). These data include the annualized costs of control (annualized capital costs plus annual operating and maintenance costs) in mills per kilowatt hour (MKWH), the SO_2 percentage content of fuel burned (SO_2), the megawatt capacity of the plant (MW), and the percent of SO_2 removal (PR). The assumed annualization factor for capital costs is 0.1494, based on a thirty-year plant life and 14.7 per cent discount rate, equal to the assumed regulated rate of utility financing. After converting MKWH to total annual cost (TAC), using a load factor of 62.8 per cent, as suggested in Mitre (1981), TAC was regressed on a quadratic function of SO_2, MW, and PR, using ordinary least squares (OLS):[14]

$$\mathrm{TAC} = \alpha + \beta_s \cdot \mathrm{SO_2}^2 + \beta_m \cdot \mathrm{MW} + \beta_p \cdot \mathrm{PR} + \beta_{ss} \cdot \mathrm{SO_2}^2 + \beta_{mm} \cdot \mathrm{MW}^2 + \beta_{pp} \cdot \mathrm{PR}^2 + \beta_{sm} \cdot \mathrm{SO_2} \cdot \mathrm{MW} + \beta_{sp} \cdot \mathrm{SO_2} \cdot \mathrm{PR} + \beta_{pm} \cdot \mathrm{PR} \cdot \mathrm{MW} + e. \quad \text{(A1)}$$

this functional form was justified, particularly since the marginal cost of additional PR

14 The estimated coefficients in equation (A1) should be sensitive to the assumed discount rate and load factors. However, since the expected life of all scrubbers is the same and load factors should be approximately equal, relative costs and hence control burdens should exhibit little sensitivity.

TABLE A1

Estimated coefficient values for equation (5) for significant point sources

Source j / Parameter	Fixed cost constant	Variable cost PR_j	Variable cost PR_j^2	Upper limit of emissions with 90 per cent control
1	2613870	4532.72		96.12
2	1952340	4516.74		64.08
3	2106740	4666.80		71.64
4	456905	12231.50	464.74	134.01
5	456905	12231.50	464.74	134.01
6	457596	12553.40	464.74	134.01
7	457596	12553.40	464.74	134.01
8	1896510	61801.20	464.74	1421.01
9	2201910	74676.40	464.74	1501.20
10	5393260	209223.00	464.74	4051.17
11	6319920	209545.00	464.74	4560.66
12	6310870	209223.00	464.74	4487.40
13	720003	19956.60	464.74	408.42
14	720003	19956.60	464.74	408.42
15	780678	24141.10	464.74	469.69
16	780678	24141.10	464.74	469.69
17	974285	82079.70	464.74	949.64
18	1387310	4513.96		36.72
19	6751950	4666.85		296.55
20	1287730	4509.90		31.89
21	1458000	4509.42		40.14
22	3872940	4633.57		157.14
23	3087900	25687.50		130.95
24	1785080	14452.20		61.56
25	1785080	14452.20		61.56

should differ across firms based on individual MW and SO_2 levels, and since marginal cost should increase with PR, all else constant.

Dropping insignificant terms in equation (A1) and re-estimating yielded the following regression:

$$\text{TAC} = \underset{(573482)}{430629} + \underset{(17.47)}{321.88}\cdot\text{PR}\cdot\text{MW} + \underset{(105.42)}{464.74}\cdot\text{PR}^2 + \underset{(260.80)}{2881.06}\cdot\text{SO}_2\cdot\text{MW}, \tag{A2}$$

with an $\bar{R}^2 = 0.98$. Standard errors are given in parentheses. The fixed cost (FC_q) component is computed for source q as

$$\text{FC}_q = \alpha_q + \beta_{sm}\cdot\text{SO}_{2q}\cdot\text{MW}_q = 430629 + 2881.06\cdot\text{SO}_{2q}\cdot\text{MW}_q, \tag{A3}$$

where the values of SO_{2q} and MW_q are substituted. The variable cost (VC_q) component is computed as a function of PR_q for source q as

$$\text{VC}_q = \beta_{pm}\cdot\text{PR}_q\cdot\text{MW}_q + \beta_{pp}\cdot\text{PR}_q^{\,2} = 321.88\cdot\text{PR}_q\cdot\text{MW}_q + 464.74\cdot\text{PR}_q^{\,2}, \tag{A4}$$

where the values of MW_q are substituted. For each source the FC_q component is reported in column two of table A1 and the components of VC_q corresponding to PR_q and $\text{PR}_q^{\,2}$ are reported in columns three and four, respectively, of this table.

A similar procedure was employed to estimate industrial cost functions. Total annualized costs were computed using a plant utilization rate of 60 per cent and a capital annualization factor of 0.1715, assuming a thirty-year plant life and a 17 per cent discount rate. Data in Mitre (1981) for eighty-nine industrial plants were employed to estimate equation (A1) by OLS. After dropping insignificant variables and re-estimating this equation, the following regression was obtained:

$$\underset{}{\text{TAC}} = \underset{(74491.3)}{629276} + \underset{(1216.51)}{4484.78}\cdot\text{PR} + \underset{(0.082487)}{0.599402}\cdot\text{PR}\cdot\text{MW} + \underset{(216.069)}{6950.57}\cdot SO_2\cdot\text{MW}, \quad \text{(A5)}$$

with an $\bar{R}^2 = 0.98$. Again, standard errors are given in parentheses. The fixed cost (FC_k) and variable cost (VC_k) components of equation (A5) are computed for source k as

$$FC_k = \alpha_k + \beta_{sm}\cdot SO_{2k}\cdot MW_k = 629276 + 6950.57\cdot SO_{2k}\cdot MW_k \quad \text{(A6)}$$

and

$$VC_k = \beta_p\cdot PR_k + \beta_{pm}\cdot PR_k\cdot MW_k,$$
$$= 4484.78\cdot PR_k + 0.599402\cdot PR_k\cdot MW_k, \quad \text{(A7)}$$

where the values of MW_k and SO_{2k} are substituted. For each source the FC_k and VC_k components are reported in columns two and three, respectively, of table A1. Finally, estimation of costs in terms of PR_j requires redefining c_j, b_j, and a_{ij} in terms of PR_j in equations (5)–(9) and (17)–(21) before the MPR quadratic programming algorithms for PR_j can be solved.[15]

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