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**Explaining Low Sulfur Dioxide Allowance Prices: The Effect
of Expectation Errors and Irreversibility**

by

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Abstract

The low price of allowances has been a frequently noted feature of the implementation of the sulfur dioxide emissions market of the U.S. Acid Rain Program. This paper presents theoretical and numerical analyses that explain the gap between expected and observed allowance prices. The main contributing factors appear to be expectation errors augmented by the presence of irreversible investments.

Keywords: emissions trading, allowance prices, irreversible investments

JEL Classification: D4, L1, Q2

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1. Introduction

One of the most noted features of emissions trading under the U.S. Acid Rain Program (Title IV of the 1990 Clean Air Act Amendments) has been the lower than expected price of sulfur dioxide (SO₂) allowances.² While seen initially as a sign of allowance market failure, the lower than expected price of SO₂ allowances is now touted as evidence that emissions trading can dramatically lower the cost of compliance with environmental policy. Allowance prices and costs are related but distinct concepts. The focus of this paper is allowance prices and particularly the disparity between projected and actual allowance prices in the early years of Phase 1. Costs have been lower than expected, but not as low as some of the more exaggerated claims, which rest on a poor understanding of past forecasts and a faulty analysis of the relation between allowance prices and abatement cost (Smith et al., 1998). After reviewing the various arguments that have been advanced to explain lower than expected allowance prices, we contribute some new ones and then conduct a numerical assessment of the relative importance of the principal causes.

In theory, the price of allowances should reflect the marginal cost of compliance,³ which early studies of compliance cost estimated at about \$300 per ton, although it was possible to find even higher estimates.⁴ The interest in low allowance prices began with EPA's first annual auction in March 1993. The auction clearing price was \$131, much below the few previous bilateral trades and contemporaneous estimates of experts concerning the value of allowances. The subsequent development of a relatively active private allowance market demonstrated that this early auction price was not "too low" and that, if anything, it provided an accurate, early signal of future allowance values. As is now well known, allowance prices sank thereafter to a low slightly below \$70 in early 1996, and it was only in April 1998 that prices again regained the level of the clearing price in the 1993 auction.

¹ An earlier version of the paper was presented at the 1998 World Congress of Environmental and Resource Economists in Venice. We have benefited from many discussions with Paul Joskow and Richard Schmalensee. Financial support from the MIT Center for Energy and Environmental Policy Research, the U.S. Environmental Protection Agency and the Chilean National Science Foundation (Fondecyt Grant No. 1971291) is gratefully acknowledged. Remaining errors are our own responsibility. Authors' e-mails are: <jpmonter@ing.puc.cl> and <ellerman@mit.edu> respectively.

² Details of program's design and performance are discussed by Joskow and Schmalensee (1998) and Schmalensee et al. (1998), respectively. A more general discussion on emissions trading can be found in Tietenberg (1985).

³ We make the distinction between long and short run marginal cost later in the paper.

⁴ For early estimates see EPRI (1993) and Hahn and May (1994).

A number of explanations for the lower than expected price for allowances have been advanced:

- (i) The design flaws of EPA auctions (Cason, 1993 and 1995; and Cason and Plot, 1996);
- (ii) Uncertainty regarding the rate-making treatment of allowances traded (Burtraw, 1996; Rose, 1994; and Bohi and Burtraw, 1992);
- (iii) Barriers to trading (Winebrake et al., 1995);
- (iv) Transaction costs (Doucet and Strauss, 1994);
- (v) Technology innovation (Burtraw, 1996);
- (vi) Proliferation of new allowances above the original distribution (Rico 1995; and Conrad and Kohn, 1996);
- (vii) Stringent local regulations (Coggins and Swinton, 1996);
- (viii) Political pressures and “perverse incentives” in the form of bonus allowances to install uneconomical high-cost irreversible technologies—scrubbers (Burtraw, 1996);⁵ and
- (ix) Unanticipated cost-based market penetration of western low sulfur coal, mainly from the Powder River Basin (PRB) in northeast Wyoming (Ellerman and Montero, 1998).

The first four reasons, which can be grouped as “market imperfection” explanations,⁶ do not seem to have much empirical support. All are plausible, and some were weakly consistent with empirical data when allowances first started trading. Still, they cannot explain the even lower prices that accompanied the large and increasing trading activity reported by Joskow et al. (1998), who note *inter alia* that the EPA auctions constitute a very small portion of the allowance market. In the same vein, Bailey (1998) finds little evidence that public utility commission rulings have discouraged trading. Even if transaction costs are present, it is not clear *a priori* whether the market price would be higher, lower, or unchanged (Stavins 1995; and Montero, 1998a). The last five reasons can be classified as “expectation error” explanations, with the possible exception of endogenous technological innovation. For example, expectations that fail to take into account bonus allowances awarded to utilities for installing scrubbers will certainly overestimate allowance prices. A similar result will occur if new SO₂ state regulations other than Title IV are not considered.

Any attempt to explain the difference between projected and observed prices requires defining an “expected price” and its underlying assumptions. For the purpose of this paper, we use the expected price provided by EPRI (1993) as the benchmark against which the importance of the different expectation errors can be assessed. EPRI (1993) stands out among the early studies of compliance with the U.S. Acid Rain Program for the detail of its forecast and its explicit assumptions, with which the later actual data can be compared. In particular, it included the Phase I extension allowances for scrubbers,

⁵ Scrubbers are flue gas desulfurization facilities that remove the SO₂ leaving the stack.

⁶ One could also include market power (Hahn, 1983) as another market failure explanation. Based on allowance allocations however, there is no indication of monopsony power that can drive prices down.

which account for most of the allowances above the original distribution.⁷ EPRI (1993) also predicted an expected equilibrium allowance price of \$273 under favourable trading conditions.⁸ This expectation was well above actual prices in early Phase 1, but it was a well-informed estimate that reflected expected prices at the time when electric utilities were defining their compliance strategies for Phase 1.⁹

Table 1. Reduction and compliance costs in 1995 (in 1995\$)

Method of Compliance	Emission reduction		Avg. Cost \$/ton	Min \$/ton	Max \$/ton	Total Cost million \$
	tons of SO ₂	percentage				
Title IV Scrubbers	1,733,743	45%	267	186	773	463.1
Non-Title IV Scrubbers	20,698	1%	65	65	65	1.3
Coal Switching	1,707,819	44%	153	60	297	261.3
Non-cost switching	425,242	11%	0	0	0	0.0
Total	3,887,502	100%	187	0	773	725.7

Source: Ellerman et al. (1997)

As we will explain below, forecast or expectation errors cannot fully explain the difference between the EPRI's figure and actual prices. The irreversibility of many compliance decisions has an augmenting effect upon prices. Capital investments, such as in scrubbers, are irreversible; and even decisions to switch to low-sulfur coals can have irreversible elements, when the coal is obtained by multi-year contract with fixed prices. As shown in **Table 1**, scrubbers played an important role in Phase 1 compliance, and these decisions were based, among other things, on expectations of allowance prices that existed in 1992-93, before there was "good" information about allowance prices. The importance of fixed price, multi-year contracts for low sulfur coal is not as easy to determine, but they were likely important in early Phase 1, although their influence will not be as lasting as scrubbers.¹⁰ Once made, these compliance decisions will be maintained even if the price expectation turns out to be wrong. The capital is sunk, and the contract committed to, and abatement will be performed so long as the current price does not fall below the variable abatement cost (zero for long-term contracts). Thus, to the extent that compliance decisions are irreversible, the effect on the current price will be greater than otherwise. Were the irreversible elements small in importance,

⁷ It did miss the early reduction credits in 1995 and some unanticipated extra allowances associated with substitution units.

⁸ The estimate in EPRI (1993) is \$250 in 1992\$. Unless otherwise noted, values are expressed in 1995\$ using a 3% inflation rate.

⁹ The price is within the range established by the earliest bilateral trades. Furthermore, a number of respondents to the MIT/CEEP questionnaires on Title IV compliance cited expectations of early Phase 1 allowance prices in this range (Ellerman et al., 1997).

¹⁰ For example, the *Guide to Coal Contracts* (by Pasha Publications) lists many low sulfur contracts for the duration of Phase 1. Others are only 2-3 year contracts.

expectation errors would not matter much. Similarly, if expectation errors were small or offsetting, irreversibility would not matter much. However, when irreversible elements loom large, as they do in Phase 1, and the errors in expectation are large or compounding, actual prices will be much lower (or higher) than they would otherwise be.

Results from numerical exercises indicate that after controlling for the expectation errors and irreversibility of some abatement investments, EPRI's 1995 equilibrium price of \$273 drops to \$106—almost equal to the actual 1995-96 average of \$105. Unanticipated cost-based expansion of PRB coal accounts for 60% of the drop, while irreversibility accounts for 27%. The remaining 13% is divided almost evenly between two other factors not included in EPRI (1993): voluntary participation from non-affected sources and the more intensive utilization of units retrofitted with scrubbers. Keeping in mind that this paper is not about price volatility (or how the market clears in the short run) but rather about long-term trends, we conclude that expectation errors and irreversibility explain reasonably well the observed gap between projected and observed prices.

The remainder of the paper is organized as follows. The next section explains the sources of expectation errors and their effect on prices. Section 3 illustrates the augmenting effect of irreversible investments on prices using a static model. Section 4 develops a dynamic model of the allowance market to simulate the effects of expectation error and irreversibility. This model is then used in section 5 to conduct a numerical experiment to illustrate the effects on allowance prices. Concluding remarks follow.

2. Sources of Expectation Errors

There were undoubtedly many sources of error in pre-Phase 1 forecasts of allowance prices, but three factors are particularly significant. First, for reasons largely unrelated to the Acid Rain Program, low-sulfur coal from the western U.S. became economically attractive to many mid-western plants that had been burning local high sulfur coal. As a result, the amount of abatement required to meet the cap in both Phases 1 and 2 was reduced considerably. Second, electric utilities made unexpectedly large use of the voluntary opt-in provisions of the Program, and this had the effect of reducing marginal costs (and allowance prices), as well as slightly loosening the emissions cap. Third, units with retrofitted scrubbers were dispatched far more intensively during Phase 1 than had been expected. The result was to produce more cheap (short-run) abatement than had been expected, with consequent effect on allowance prices. In this section, we explain each of these reasons for lower than expected counterfactual emissions and marginal costs.

Table 2. Statistics of Phase 1 and Phase 2 Units for Selected Years

Variables	Table A units	Substitution units in 1995 ^a	Eligible Phase 2 units that did not opt-in in 1995 ^b	Other Phase 2 units
No. of units	263	182	438	1370
Total capacity (MW)	88,007	41,643	97,812	286,677
No. of coal-fired units	257	154	299	472
No. units with NSPS scrubbers	1	25	31	139
No. units with Title IV scrubbers	26	0	0	0
Total Baseline 8587 (10 ¹² Btu)	4,363	1,740	3,223	9,228
Total Heat Input 90 (10 ¹² Btu)	4,391	1,847	3,574	9,853
Total Heat Input 93 (10 ¹² Btu)	4,395	1,718	3,890	10,137
Total Heat Input 95 (10 ¹² Btu)	4,708	1,931	4,579	10,552
Total SO ₂ Emissions 1985 (10 ³ ton)	9,302	1,377	2,104	3,309
Total SO ₂ Emissions 1990 (10 ³ ton)	8,683	1,272	2,386	3,382
Total SO ₂ Emissions 1993 (10 ³ ton)	7,579	973	2,505	3,715
Total SO ₂ Emissions 1995 (10 ³ ton)	4,445	853	2,884	3,644
Average SO ₂ Rate 1985 (#/mmBtu)	4.24	1.58	1.31	0.72
Average SO ₂ Rate 1990 (#/mmBtu)	3.76	1.38	1.34	0.69
Average SO ₂ Rate 1993 (#/mmBtu)	3.45	1.13	1.29	0.73
Average SO ₂ Rate 1995 (#/mmBtu)	1.89	.88	1.26	0.69
1995 Allowances (10 ³)	7,215	1,329	-	-
Basic	5,551	-	-	-
Extension	1,350	-	-	-
Substitution		1,329	-	-
Early reduction credits	314	-	-	-
1995 EPA auction ^c	150	-	-	-

a. It includes 7 compensating units.

b. These are eligible units that did not opt in.

c. Not necessarily all of them went to Table A unit.

2.1 Rail deregulation and PRB coal

As shown in **Table 2**, the pre-1995 reduction of SO₂ emissions at Table A units, those that were mandated to be subject to Phase 1, is substantial.¹¹ Between 1985 and 1993, heat input (generation) at these units was constant, but total emissions declined by 1.7 million tons, or by almost 20%. Furthermore, the trend started before 1990, when the

¹¹ The approximately 50% SO₂ emissions reduction goal of the Acid Rain Program is to be achieved in two phases. In Phase 1 (1995 through 1999), 263 electric utility generating units are subject to interim limits (Table A units), while in Phase 2 (2000 and beyond), virtually all electric generating units become affected.

legislation containing the Acid Rain Program was enacted. Earlier research (Ellerman and Montero, 1998) has addressed the reasons for this unanticipated decline in emissions and found that it was caused primarily by changes in the economics of coal choice. Specifically, the decline in transportation costs associated with the deregulation of rail rates in the 1980s made low sulfur coal from the western U.S., mostly from the Powder River Basin (PRB), economically competitive in the Midwest, where a large proportion of the Table A units were located.¹² Their econometric analyses indicate that 1993 SO₂ emissions from coal-fired units were 2.17 million tons below what emissions would have been if emission rates had not changed from 1985, and that 92% (2.0 million tons) of that reduction was due to changes related to the greater economic attractiveness of western coals.¹³ As can be seen in **Table 1**, this trend continued in 1995. Approximately 11% of the reduction effected in 1995 consisted of switching to lower sulfur fuels at no identifiable additional cost, of which amount 87% was accounted for by PRB coals.

Ellerman and Montero (1998) has been conducted within a static framework in which productivity improvements in rail transportation and the consequent lower rates are treated as exogenous to the Acid Rain Program. It is possible that the flexibility associated with emissions trading, and more particularly the lack of any technology mandate, has encouraged innovation and investment in a wide array of SO₂ compliance options, including the transportation of low sulfur coal from the West (Burtraw; 1996 and EPA, 1996). Whatever the extent of such stimulative effects, they were not incorporated in earlier forecasts of SO₂ emissions and prices. Therefore, failing to account for them should also be considered as “expectation errors.”

2.2 *Voluntary opt-in*

The Acid Rain Program includes two additional provisions, less noted during the legislative debate, under which Phase 2 units—those units that are not mandatorily affected until year 2000—can voluntarily opt-in into Phase 1.¹⁴ The Substitution Provision was created to reduce compliance costs by allowing the owner (or operator) of any of the 263 Table A units to substitute emission reductions by a designated non-affected unit, so-called *substitution* unit, under the owner’s control for reductions otherwise required of Table A units. The Reduced Utilization Provision was created to prevent owners of Table A units from meeting their emissions reduction obligations by switching generation to non-affected units. If generation at a Table A unit was reduced significantly for compliance reasons, one or more non-Table A units, so-called *compensating* units, had to be brought under Phase 1 to compensate. As explained by Montero (1998b), resort to the Reduced Utilization Provision has been slight; however, participation with the Substitution Provision has been significant. Among the more than

¹² These units were the “big, dirties” and hence high sulfur coal units by definition.

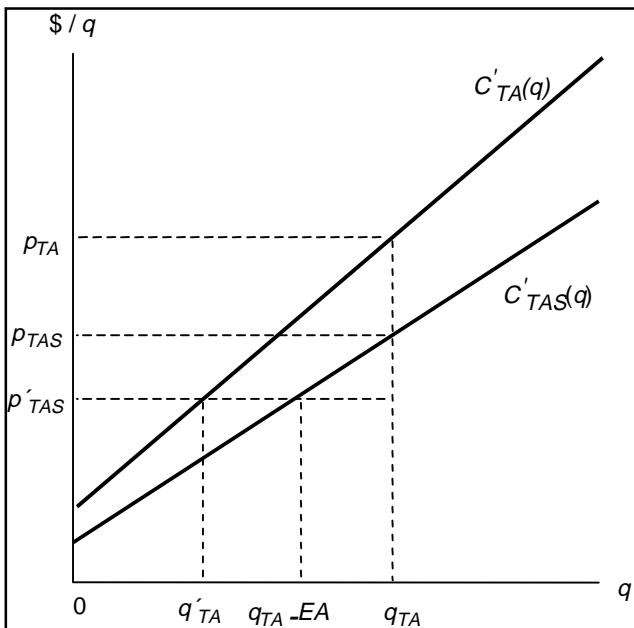
¹³ The other 8% is properly attributable to Title IV, chiefly state laws requiring early compliance and several clean coal projects partially funded by the U.S. Department of Energy (DOE).

¹⁴ See Montero (1998b) for a complete discussion of these provisions.

600 eligible substitution units, 182 did so in 1995. These units increased Phase 1 affected generating capacity by 47% (see **Table 2**).

Despite the presence of these provisions and the large response, none of the earlier studies of compliance cost included such units. The general view seems to have been that there would be few substitutions or that substitutions would have no effect on allowance prices. Yet, the entry of such units will reduce compliance costs and allowance prices for two reasons. First, the inclusion of units with lower marginal costs shifts the marginal abatement curve downward and with it, the equilibrium price. Second, the use of historic emissions as the basis for allocating allowances to volunteers inevitably creates adverse selection problems (Monero, 1998c). Units whose emissions decline subsequent to the baseline period for other reasons will opt-in and receive excess allowances (allowances above their true counterfactual), which raises the cap and reduces the total amount of abatement required. Units whose emissions do not decline, or increase, will have no such incentive, and typically they will not opt-in.

Figure 1. Effect of voluntary opt-in on prices



To illustrate, consider the one-period model of **Figure 1**. Let q be the aggregate quantity of emissions reductions and $C_{TA}(q)$ the aggregate control costs from affected sources (Table A units). As usual, we have that $C'(q) > 0$, $C''(q) > 0$. Let q_{TA} be the emissions reduction target chosen by the authority to be imposed on Table A units. Without the substitution provision, the equilibrium price is p_{TA} .

With the inclusion of substitution units having lower marginal control costs, the new marginal control cost curve shifts downward to $C'_{TAS}(q)$. If substitution unit emissions in the year of compliance would have been equal to or greater than the historic emissions baseline, the reduction target remains unchanged and the equilibrium price would be p_{TAS} . However, if some substitution units have reduced their counterfactual emissions levels below their historic emissions and in this case below the allowance allocation, the original reduction target q_{TA} reduces to $q_{TA} - EA$, where EA are the total excess allowances from opt-in sources.

Therefore, the equilibrium price drops from p_{TA} to p'_{TAS} , and reduction from Table A units is only q'_{TA} .¹⁵

As shown in **Table 2**, the number of excess allowances and emissions reductions are modest compared to the corresponding totals in 1995—247,000 allowances and 229,000 tons, respectively (Montero, 1998b). Nevertheless, the Substitution Provision remains active during the five years of Phase 1 and its cumulative effect on prices may not be negligible.¹⁶

2.3 Higher utilization of scrubbed units

It is evident from **Table 1** that scrubbing has been extensively used by electric utilities to comply with the Acid Rain Program. Fully half of the entire 4 million ton reduction of emissions in early Phase I has been achieved by units retrofitted with scrubbers. It has been less widely appreciated that these generally large units have been utilized more intensively after the retrofit than before. The utilization of the 27 units retrofitted with scrubbers for Phase 1 has increased from an average of 62% for the years 1988-94 to 79% for the years 1995-97, or by 27%. In contrast, the average utilization of non-scrubbed Table A units have increased from 56% to 60% over the same years.¹⁷ Obviously, with the onset of Title IV, generation has shifted to the units retrofitted with scrubbers. Since these units have considerably lower emissions than non-scrubbed Table A units, the effect of this shift in generation is to provide more abatement from the scrubbed units and to require less from the non-scrubbed units than had been expected.

The observed Phase 1 shifting of generation to scrubbed units has a plausible explanation. Consider a price-taker utility operator subject to SO₂ limits that maximizes the (short-run) profit function

$$\pi = p_E y - c(y, q) - p_A e(y, q) + p_A z \quad (1)$$

where y is electricity output, p_E is the exogenous market price of electricity; $c(\cdot)$ is the generation cost function that depends on the level of electricity output and emission abatement q and has the usual convexity properties such that $\partial c / \partial y$, $\partial^2 c / \partial y^2$, $\partial c / \partial q$, $\partial^2 c / \partial q^2 > 0$; $e(\cdot)$ are emissions that depend on output and abatement such that $\partial e / \partial y > 0$ and $\partial e / \partial q = -1$, p_A is the price of allowances, and z are grandfathered allowances. Both functional forms $c(\cdot)$ and $e(\cdot)$ will also depend on the abatement technology chosen by the operator that in our case can be either coal switching or scrubbing.

Solving for the first order conditions for y and q leads to

¹⁵ Note that aggregate emissions can be lower if the allocation rule to opt-in sources is very stringent (EA < 0). However, the new equilibrium price will always be lower than p_{TA} .

¹⁶ Similar numbers are obtained from preliminary analysis of 1996 data.

¹⁷ These calculations assume a heat rate of 10,000 Btu/kwh for all units and availability for all 8,760 hours in the year.

$$\frac{\partial c}{\partial y} = p_E + \frac{\partial c/\partial q}{\partial e/\partial q} \frac{\partial e}{\partial y} \quad (2)$$

The left-hand-side is the marginal cost of generation for an individual unit in a broader electricity market. In the absence of an abatement constraint, in this case Title IV, $\hat{\alpha}/\hat{\alpha}q = 0$, so that the second-term on the right-hand-side is not present, and $\hat{\alpha}/\hat{\alpha}y = p_E$. However, when the operator faces a binding constraint, the second term becomes negative, and it is an additional cost element to be considered in evaluating a particular unit's relative competitive position. If this additional cost element is uniform for all units, competitive positions will be unchanged, but typically this will not be the case. In particular, where some units are affected and others are not, the relative position of the affected units would be made worse and, for unchanged aggregate production, output from affected sources would be expected to drop. This effect is usually called output "leakage."

Although equation (2) assumes continuous and convex functions, it can be used to compare the relative *ex-post* dispatch position of two affected sources, one relying on scrubbing (scr) and the other on coal switching (sw), before and after compliance with Title IV. The variable costs of abatement for scrubbing and switching are different. The variable cost of abatement for scrubbing is relatively low and constant, depending on the cost of limestone, power, and disposal.¹⁸ With the possible exception of March 1996, allowance prices have been higher than the constant marginal abatement cost of scrubbing, and in general, the allowance price can be expected to rise over time. In contrast, the variable cost of abatement for switching depends on the cost of allowances and on the sulfur premium paid for the lower sulfur coal. When coal and allowance markets are integrated, that is, when the coal sulfur premium reflects the equivalent value of an allowance, the marginal abatement cost incurred by switched units will be equal to allowance prices. Thus, when coal and allowance markets are integrated, $[\hat{\alpha}/\hat{\alpha}q]_{scr} < [\hat{\alpha}/\hat{\alpha}q]_{sw} = p_A$. Furthermore, the characteristics of the two abatement technologies are such that the increase of emissions associated with increased generation is greater for switched units than for scrubbed units, so that $[\hat{e}/\hat{\alpha}y]_{scr} < [\hat{e}/\hat{\alpha}y]_{sw}$.¹⁹ Plugging these expressions into (2), these conditions imply that, *ex post* $[\hat{\alpha}/\hat{\alpha}y]_{scr} > [\hat{\alpha}/\hat{\alpha}y]_{sw}$, which suggests that $[y]_{scr} > [y]_{sw}$.

While the above model illustrates how differing marginal abatement costs will affect utilization among affected units, it does not capture the full story about the integration of electricity, coal and allowance markets. Units with retrofitted scrubbers will also have a strong incentive to move to cheaper, higher sulfur coals with consequent effect on unit dispatch. In addition, when coal and allowance markets are integrated, generation costs for non-affected sources change, and in ways that do not necessarily lead to output leakage.

¹⁸ For all practical purposes, the cost of allowances can be ignored since removal efficiencies are typically 95% or higher.

¹⁹ Removal efficiency of scrubbing is always much higher than that of switching.

Table 3. Phase 1 effect on dispatch cost

Units Type	Sulfur Content of Coal (lbs of SO ₂ /mmBtu)		
	2.0	4.0	6.0
Pre-Phase 1			
Coal Cost	\$24.00	\$24.00	\$24.00
Allowance Cost	0	0	0
Scrubber Cost	0	0	0
Total Cost	\$24.00	\$24.00	\$24.00
Kwh equivalent (¢/kwh)	1.00	1.00	1.00
Phase 1 Switched Unit			
Coal Cost	\$27.60	\$24.00	\$20.60
Allowance Cost	3.60	7.20	10.80
Scrubber Cost	0	0	0
Total Cost	\$31.20	\$31.20	\$31.20
Kwh equivalent (¢/kwh)	1.30	1.30	1.30
Phase 1 Scrubbed Unit			
Coal Cost	\$27.60	\$24.00	\$20.60
Allowance Cost	0.18	0.36	0.54
Scrubber Cost	1.48	2.96	4.45
Total Cost	\$29.26	\$27.32	\$25.59
Kwh equivalent (¢/kwh)	1.22	1.14	1.07
Non Phase 1 Unit			
Coal Cost	\$27.60	\$24.00	\$20.40
Allowance Cost	0	0	0
Scrubber Cost	0	0	0
Total Cost	\$27.60	\$24.00	\$20.40
Kwh equivalent (¢/kwh)	1.15	1.00	0.85

Table 3 presents an illustrative example of the complete phenomenon. Each panel represents the costs associated with the use of coals having a sulfur content of 2, 4 and 6 lbs. of SO₂ per million Btu (hereafter #), respectively. Consider that the respective coals, which are of equal Btu content (12,000 Btu/lbs.), sell for the same price, \$24.00 per ton of *coal* before Title IV becomes effective. In other words, there is no sulfur premium over this range.²⁰ The electricity equivalent cost of the coal is calculated at an assumed heat rate of 10,000 Btu/kwh, so that, for instance, a ton of coal generates 2,400 kilowatt-hours (kwh). Thus, prior to Phase 1, the fuel cost component of electricity generated from these coals would be 1.0¢ per kwh. The Phase 1 costs associated with allowances and

²⁰ A premium has been paid for “compliance” coal, that which can meet the pre-1978 NSPS requirement, but it applies only to coals of 1.2#/mmBtu or less. Title IV effectively extends an allowance-based premium over the entire sulfur range.

variable scrubber costs are calculated per ton of *coal*, based on a \$150 value for allowances and variable scrubbing costs of \$65 per ton of SO₂ removed.

The second and third panels show that for any given coal, scrubbed units will incur less of an increase in *variable* costs than non-scrubbed units.²¹ These two panels also show that the additional cost associated with Phase 1 for the non-scrubbed unit is constant with respect to sulfur content. Although allowance cost increases with sulfur content, the price of coal decreases commensurately in an integrated market. More importantly for explaining the shift of generation to scrubbed units, the additional cost can be reduced by scrubbed units if they can switch to higher sulfur coals. Whereas the scrubbed unit may have been indifferent between the 4# and the 6# coal pre-Phase 1, or prevented from using the 6# by State Implementation Plan emission limits, it would now make sense to purchase the higher sulfur coal. In effect, the unit would incur additional compliance cost of \$78.75 per additional ton of SO₂ input, but realize savings in fuel cost of \$150.

Finally, the dispatch of units that are not part of Phase 1 are also affected by the integration of coal and allowance markets. Very high sulfur coal units (6# in Table 3) would experience a fall in generation cost since fuel prices would be lower. There are relatively few of these units, and they are small, since all units with emissions greater than 2.5#/mmBtu and larger than 100 MW^e were included in Phase 1. The far more numerous set of units are those with emissions less than 2.5#/mmBtu. The dispatch cost of these units will be increased as a result of the higher prices for low sulfur coal relative to higher sulfur coal. The increase in cost will not be as great as for non-scrubbed Phase 1 units, but as shown it can be greater than for scrubbed units using the 6# coal. To the extent that any of these non-Phase I affected units can shift to higher sulfur coals, the effect on dispatch will be lessened, but that possibility will depend on the availability and cost of higher sulfur coals and local emission limits.

Although the explanation for the increased utilization of scrubbed units seems rather obvious in retrospect, this effect does not seem to have been anticipated. Rather, most studies of the cost of abatement SO₂ by scrubbing assumed that the retrofitted units would achieve the same utilization as before. In any case, the implications for allowance prices are clear. The aggregate marginal abatement cost curve shifts downward and so does the equilibrium price of allowances.

3. Augmenting Effect of Irreversible Commitments

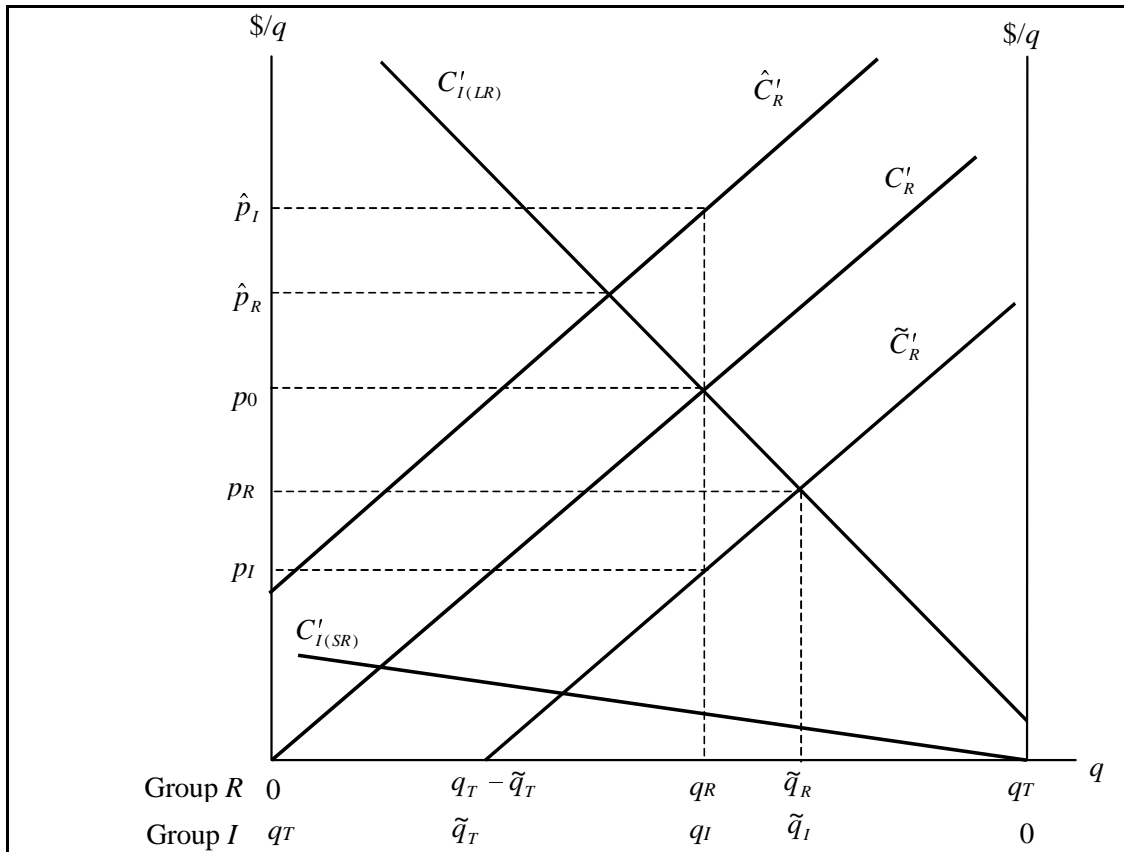
Many of the investments made to comply with the Acid Rain Program are irreversible. Scrubbing, for instance, is capital-intensive and the contracting and construction lead-time for placing a scrubber in service is two to three years. Consequently, decisions to comply with SO₂ limits by scrubbing required irreversible capital commitments in 1993 or before, when prices were expected to be around \$300.

²¹ In most cases, a comparison using total cost (including capital) would not favor scrubbing, but it is variable cost that determines dispatch.

With early Phase 1 allowance prices of around \$100-150, the *ex-ante* economics of building scrubbers would not have been as favorable; however, when those prices appeared, the capital had been sunk. With operating costs at about \$65 per ton (Ellerman et al., 1997), the *ex-post* economics of operating the scrubbers continued to be favorable. As a result, the supply of allowances from scrubbed units is relatively insensitive to changes in allowance prices, unless they fall below the \$65 mark.

Although fuel switching is generally a more flexible form of compliance, coal contracts can and do contain irreversible elements as well.²² Any utility planning to comply by switching to lower sulfur coal would have had to decide whether to sign a long-term contract for the low sulfur coal before 1995 or to procure the coal on the spot market, or some combination thereof. In either case, a premium would be paid for the lower sulfur product, and the choice would be whether to lock in a premium (and the Btu value of the coal) in 1993 or 1994 or to pay whatever the spot market required in 1995 and thereafter. To the extent that the utility contracts early for the lower sulfur coal, it is constrained from switching to a higher sulfur coal later, should allowance prices be lower. Thus, the abatement associated with long-term contracts for low sulfur coal is irreversible until the contract expires or is otherwise terminated.

Figure 2. Effect of irreversibility on prices



²² See Joskow (1987).

The implications of irreversibility for allowance prices can be better explained with the one-period model illustrated in **Figure 2**. Think of a system with two groups of emitting sources that are subject to an aggregate level of SO₂ emissions reduction q_T . We let the first group (R) be the units that are installing *reversible* abatement technologies (e.g. switching under no contracts) and the second group (I), the units that are installing *irreversible* technologies (e.g. scrubbers and switching under contracts). Note that for the first group short and long-run marginal control costs are the same, while for the second group short-run marginal costs are much lower.

The diagram in **Figure 2** is arbitrarily drawn such that the origin of the aggregate marginal control cost curve for the first group (C'_R) is the left-hand axis and the origin of the aggregate (short and long-run) marginal cost curve for the second group ($C'_{I(SR)}, C'_{I(LR)}$) is the right-hand axis. Also, the marginal control costs for either group need not be zero at $q = 0$. So drawn, the diagram gives all possible allocations of the total q_T units of emissions reductions between the two group of units.

Setting aside inefficient investments, those that would have been made regardless expected prices (*i.e.*, think of q_T as the reduction required after subtracting for the reduction from the inefficient investments),²³ the optimal reductions from each group are q_R and q_I , respectively, and the equilibrium price is p_0 . Under these circumstance all reductions from irreversible investments, scrubbers and switching under contracts, are cost-effective. No emissions are abated at a cost higher than p_0 . Now, if counterfactual emissions are lower or more allowances are distributed than had been initially expected, the emissions reduction obligation is reduced from q_T to \tilde{q}_T . This is the same as to say that C'_R shifts inwards to \tilde{C}'_R . If everything is reversible so that $C'_{I(SR)} \equiv C'_{I(LR)}$, the new optimal reduction allocation among groups would be \tilde{q}_R and \tilde{q}_I , respectively, and the equilibrium price would be p_R . Because of irreversibility however, reductions from irreversible investments remain at the q_I level, so that reductions from reversible investments are only $\tilde{q}_T - q_I$. The new equilibrium price is p_I , which is determined along \tilde{C}'_R , and it will be even lower than p_R . The augmenting effect of irreversible investments is simply the further drop in prices from p_R to p_I .

Similarly, if C'_R shifts outward to \hat{C}'_R as the result of unexpectedly higher electricity demand and some of the additional abatement capacity required can not be installed immediately (e.g., scrubbers), there can be also an augmenting effect that would last only until that capacity is installed. In this case, the price temporarily jumps to \hat{p}_I instead of \hat{p}_R .

²³ Those forced by political reasons aimed at protecting local high-sulfur coal miners.

4. Modeling Expectation Errors and Irreversibility in a Dynamic Context

The ability to bank allowances in Phase 1 means that the effect of an error in expectation is not limited to the current price of allowances. Without banking, the current price would reflect current demand and supply only, including the full consequences of any errors. With banking, expected demand and supply in future periods is also taken into account. For instance, if a very low price in the current period is below the present value of expected future marginal cost, a party might decide to hold the allowances (and even buy more) in order to defer expected Phase 2 abatement requirements.

In this section we set up a very simple model (Schennach, 1998) to understand the effect on market variables of the errors in expectation and irreversibility identified in the preceding section. Besides the effect on today's prices, we are also interested in the size of the bank at the end of Phase 1, the year when the bank expires, and the allowance price at that time (i.e. long-run equilibrium price). We start by setting the condition on total emissions during the banking period, which is

$$\int_0^T q_t dt = \int_0^{T_1} (u_t - z_t) dt + \int_{T_1}^T (u_t - z_t) dt \quad (3)$$

where q_t are aggregate emissions reduction at time t , u_t are aggregate unrestricted (or baseline) emissions in period t , z_t are total allowance allocated in period t , T_1 is the time when Phase 1 ends, and T is the time when the bank expires during Phase 2. Equation (3) simply establishes that the total reduction in emissions over the entire banking period $(0, T)$ must be equal to the sum of the annual differences between aggregate counterfactual emissions and allowance allocations during Phase 1 $(0, T_1)$ and Phase 2 (T_1, T) . Equivalently, total emissions during the banking period must be equal to total allowances distributed in those years. For simplicity we will assume a constant baseline throughout, and constant allowance allocations in each period such that $u_t - z_t = \gamma_1$ for Phase 1, and $u_t - z_t = \gamma_2$ for Phase 2. A necessary condition for banking is that less abatement is required in Phase 1 than in Phase 2, so that $\gamma_1 < \gamma_2$. With marginal cost rising as a function of abatement, total emissions in Phase 1 will be less than the allowance allocation, and for the years in Phase 2 when the bank is being drawn down, emissions will be higher than the allowance allocations in those years. At time T , the following terminal condition must also hold,

$$q_T = u_T - z_T = \gamma_2 \quad (4)$$

which indicates that after exhaustion of the bank, emissions will be equal to allowances. From then on, we assume this condition continues to hold.

We model the aggregate abatement cost curve in a very simple way

$$C(q_t) = \alpha_j q_t^2 \quad (5)$$

where α_j is a cost parameter for Phase j ($j=1,2$). Since the universe of units affected in Phase 1 is originally restricted to Table A units, we do not expect the Phase 1 cost curve to be identical to the Phase 2 cost curve. Just as the entry of substitution units shifts the Table A cost curve downwards, as illustrated in Figure 1, so will the entry of other low cost Phase 2 units.²⁴ The extent of the shift, that is, of the extent to which cheaper abatement becomes available in Phase 2, will be indicated by the horizontal distance between the two curves. Consequently, we expect that $\alpha_1 > \alpha_2$. If agents have perfect foresight and the market is always in long-term equilibrium, prices will be equal to (long-run) marginal costs in every period, and they will rise at some interest rate until the bank runs out. In a continuous time setting, this is

$$p_t = C'(q_t) = p_{t-\Delta t} e^{r\Delta t} \quad \forall t \in (0, T) \quad (6)$$

where p_t is the allowance price at time t , r is the interest rate, and Δt is an infinitesimal time increment.

From (5) and (6) we can establish that $q_t = q_T e^{-r(T-t)}$ if $0 < t \leq T_1$, and $q_t = (\alpha_1 / \alpha_2) q_T e^{-r(T-t)}$ if $T_1 < t \leq T$. Note that the discontinuity in the Phase 1 and Phase 2 cost curves ($\alpha_1 > \alpha_2$) will cause an increase in abatement at T_1 equal to the horizontal distance between the two cost curves. Plugging these expressions into (3) and using the terminal condition (4), we can solve for T

$$rT + e^{-rT} \left[\frac{\alpha_2}{\alpha_1} + e^{rT_1} \left(1 - \frac{\alpha_2}{\alpha_1} \right) \right] = \left(1 - \frac{\gamma_1}{\gamma_2} \right) rT_1 + 1, \quad (7)$$

which in turn permits us to solve for the size of the bank at the end of Phase 1 (B)

$$B = \frac{\gamma_2}{r} (r(T - T_1) + e^{-r(T-T_1)} - 1), \quad (8)$$

the long-run equilibrium price (p_T)

$$p_T = \alpha_2 \gamma_2, \quad (9)$$

and today's price (p_0)

$$p_0 = p_T e^{-rT}. \quad (10)$$

²⁴ Although many of these units would be represented in the Phase 1 cost curve through the substitution provision, not all Phase 2 units were eligible to become substitution units.

With the aid of the system of eqs. (7)-(10), we can explore how changes in cost (α) and required abatement (γ), affect T , B , p_T , and p_0 . The unanticipated intrusion of PRB coal in Midwestern high sulfur markets reduces the counterfactual in both Phase 1 and Phase 2, so that γ_1 and γ_2 are lower. Voluntary compliance by substitution units and early reduction credits affect only Phase 1 parameters, by lowering both α_1 (from cheaper reductions) and γ_1 (from excess allowances and extra allowances). The higher utilization of scrubbers has effect throughout by reducing both α_1 and α_2 . The effect of irreversibility can be represented through changes in the α parameters. *Ex post* inefficient choices reduce marginal costs; however, as time passes and the price rises, some of the initially *ex-post* inefficient irreversible investment becomes efficient. Therefore, irreversibility has the effect of lowering α_1 more than α_2 . It may be the case that α_2 does not change at all if prices rise high enough before the end of Phase 1.

5. Numerical Model

The effect of errors in expectation and the augmenting effect of irreversibility can be quantified by a simple numerical exercise that applies the theoretical framework for market dynamics to the benchmark provided by EPRI (1993).

5.1 The benchmark

In this section we define and estimate the different “market” conditions regarding allowance allocations, counterfactual emissions, discount rate, and marginal control costs that yield the equilibrium price of \$273 for 1995 in EPRI (1993). Emissions caps for Phase 1 and Phase 2 are obtained directly from EPRI (1993). In the case of Phase 1, it corresponds to aggregate allowances to affected units plus counterfactual emissions from non-affected units. Among the allowances of Phase 1, EPRI (1993) does not include any substitution allowances and early reduction credits. For Phase 2, the emission cap is equal to aggregate allowances, which remains the same for the period 2000-2010.²⁵ Counterfactual emissions are also obtained directly from EPRI (1993).

To estimate the (long-run) marginal control cost curves, we use an indirect approach by fitting an aggregate control cost curve C_j for Phase j ($j=1,2$) of the form

$$C_j(q) = \alpha_j q^2 \quad (11)$$

where q is the amount of reduction, and α is a cost parameter to be estimated econometrically with the following specification

$$p_t = \beta_1 \cdot q_t + \beta_2 \cdot P2_t \cdot q_t + \varepsilon_t \quad (12)$$

²⁵ If necessary to go beyond 2010 we will use the 2000-10 cap.

where p_t is equilibrium price in period t and equal to the (long-term) marginal cost C'_t , q_t is the amount of cost-effective reduction in year t , $P2_t$ is a dummy to control for Phase 2 and equals one if $t \geq 2000$, and ε is the usual error term.²⁶ We obtain 12 price/marginal-cost and quantity “observations” for the banking period posited in EPRI(1993), 1995 through 2006, by using EPRI’s emissions reduction profile for those years, and by applying a 6% real discount rate (as in EPRI, 1993) to the initial allowance price of \$273.²⁷ The resulting OLS regression results are given in the first column of **Table 4** and the parameter estimates yield $\alpha_1 = 0.1667$ and $\alpha_2 = 0.1621$.

Table 4. OLS estimates for EPRI’s abatement costs

	p	p	$\log(p)$
q	0.0834 (90.215)**	0.0740 (15.744)**	
$P2 \cdot q$	-0.0023 (2.153)*	0.0007 (0.401)	
$\log(q)$			0.7730 (7.994)**
$\log(P2 \cdot q)$			0.1791 (1.521)
$P2$			-1.4815 (1.510)
Intercept		34.7609 (2.016)*	-0.6177 (0.778)
Adj. R ²	0.9996	0.9931	0.9893
Observations	12	12	12

** significant at the 99% level, * significant at the 90% level

The first row of **Table 5** (step 0) presents our benchmark based on EPRI (1993). The four variables that will be affected by errors in expectation and irreversibility are shown, followed by the allowance allocations for various years and the counterfactual emissions assumed for Phases 1 and 2. In the EPRI benchmark, the equilibrium allowance price in 1995 ($p_{95} \equiv p_0$) is \$273; and it rises to \$519 (p_T) when the bank runs out in year 2006 (T). The accumulated Phase 1 bank (B) is 8.15 million allowances.

²⁶ We adopt the quadratic not only for simplicity, but also because it provides the best fit (see Table 4).

²⁷ We control for 579,000 tons of SO₂ reductions that were found to come from non-cost effective scrubbers. Large part of those were under the DOE’s Clean Coal Technology Program. We assume these reductions would have taken place regardless expectations of allowance prices and therefore are not part of the cost-effective reductions.

Table 5. Numerical data and results

STEPS	p_{95}	T	P_T	B	Cap (10^6 allowances)			Counterfactual (10^6 ton)	
	\$/ton		\$/ton	10^6 allow.	1995-96	1997-99	2000-15	1995-99	2000-15
(0)	273.2	2006	519.0	8.15	14.45	13.28	9.40	16.29-.50	16.56
(1)	172.9	2008	368.8	9.32	14.14	12.97	9.40	14.39-.60	14.65
(2)	163.0	2009	368.5	11.34	14.71-.39	13.22	9.40	14.39-.60	14.65
(3)	150.9	2009	341.3	11.67	14.71-.39	13.22	9.40	14.39-.60	14.65
(4)	106.3	2015	340.9	14.50	14.71-.39	13.22	9.40	14.39-.60	14.65

Note Numbers are in 1995 dollars. Steps correspond to: (0) EPRI (1993) or benchmark, (1) unanticipated PRB coal, (2) voluntary opt-in and early reduction credits, (3) higher utilization of scrubbed units, and (4) irreversibility of some investments.

5.2 Accounting for expectation errors and irreversibility

The remaining rows on **Table 5** show the effect of the different factors explained earlier on the variables, p_{95} , T , p_T , and B . Each new factor is added progressively so that (1) accounts for the lower counterfactual due to the PRB coal expansion, (2) adds the effect of voluntary opt-in and the early reduction credits distributed in 1995, (3) adds the more intensive utilization of scrubbed units, and finally (4) adds irreversibility.

Step (1) sets the new 1995 counterfactual based on data from Ellerman and Montero (1998) and Ellerman et al. (1997), and then maintains the difference from EPRI's (1993) counterfactual for 1995 in all subsequent years.²⁸ For step (2), recall that the entry of substitution units has two effects. The entry of the cheaper units shifts the marginal cost curve downwards, while the adverse selection effect results in a slight loosening of the cap. We account for these effects by increasing the annual allowance issuance in Phase 1 by 247,000 allowances, the number of excess allowances in 1995 (Montero, 1998b), and by shifting the Phase 1 curve to the right by an amount equal to the reduction of emissions effected by these units in 1995.²⁹ In addition, we add early reduction credit allowances, as indicated in **Table 2**, for 1995 only.

In step (3), we shift the Phase 1 and Phase 2 cost curves downward by the number of tons equal to the increased average heat input at scrubbed units times the difference in 1995 emission rates between these units and non-scrubbed units. Econometrics results based on 1995 data indicate an additional reduction of approximately 228,620 tons. We assume that higher utilization of scrubbers remain the same for all the subsequent years.³⁰

²⁸ We also run a simulation exercise using EPRI (1995) counterfactual, which is slightly higher (1.8%) than that ours, with similar results. In Table 5, the Phase I cap is also reduced to reflect the PRB effect on non-Phase I units.

²⁹ See Montero (1998b) for more details. Based on EPA (1997), a preliminary analysis of 1996 compliance indicates that this is a reasonable assumption and that may even be conservative.

³⁰ We also note that the expected amount of reduction from scrubbers was a little higher since Baldwin was never installed. All the other scrubbers were considered by EPRI (1993).

Finally in step (4), the cost curves are also shifted downward, but in a much more complicated way. We assume that all scrubbers and a portion of long-term contract are *ex-post* inefficient and irreversible, but that over time this amount diminishes as contracts expire or allowance prices rise to equal the long-run marginal cost associated with these commitments.³¹ Since the “new” p_T is greater than \$300, the approximate price expectation for most of the commitments, these investments will enter eventually, but much later during Phase 2. In the meantime, they remain *ex-post* inefficient for being made too early. These adjustments result in a series of annual short-run cost curves that approach the long-run curve over time.

5.3 Numerical results and discussion

The combined effect of all factors is a significantly lower allowance price for 1995 (p_{95}) and one close to the 1995 average of \$129, and almost equal to the 1995-96 average of \$105. The most important factors explaining the low allowance prices in early Phase 1 are lower counterfactual emissions (step 1) and the irreversibility of many compliance actions (step 4). In fact, unanticipated declining emissions and irreversible investments account for 60% and 27% of the p_{95} drop from \$273 to \$106, respectively. The other two factors (steps 2 and 3) account almost equally for the remaining 13%.

These factors also affect the other market variables, T , p_T and B , but in different ways. For instance, the unanticipated expansion of PRB coal (step 1) has significant effects on the eventual equilibrium price in Phase 2, dropping it from \$519 to \$369, but smaller effect on the size of the bank (B) or the end of the banking period (T). The reason for the small effect on T and B is that the roughly proportionate decrease in counterfactual emissions does not change the *relative* costs, that is, the advantage of Phase 1 over-compliance. This can be explained by looking at eqs. (7) and (8). If both γ_1 and γ_2 decrease by $\Delta\gamma$, the expression $(1 - \gamma_1/\gamma_2)$ in (10) increases slightly, as does T . Although a decrease in γ_2 leads to a lower B (see eq. [8]), this is more than offset by the increase in B due to a larger T ($\partial B/\partial T > 0$).

Similarly, the higher utilization of scrubbers (step 3) shifts the cost curves in both Phases 1 and 2 by lowering α_2 and α_1 in similar proportions.³² The consequent effect on prices in both phases and the slight effect on T and B can also be explained by looking at eqs. (7)-(10). While a decrease in α_2 lowers the terminal price p_T , a small increase in α_2/α_1 slightly increases T and hence B .³³ Since our numerical model is discrete, we do not observe this change in T in **Table 5**.

In contrast, voluntary compliance and early reduction credits (step 2) and irreversibility (step 4) have a large effect on B and T , but little effect on p_T . This result

³¹ Reductions from long-term contracts in 1995 are found to be 115,000 tons of in 1995 according to reported contracts in the *1995 Guide to Coal Contracts* (by Pasha Publications).

³² Because of the way we model the higher utilization of scrubbers and provided that $\alpha_1 > \alpha_2$, we will have a slightly larger drop in α_1 .

³³ It is not difficult to show that $\partial T/\partial(\alpha_2/\alpha_1) > 0$ in eq. (7).

occurs because both substitution and irreversibility are Phase 1 phenomena that shift the marginal cost curve downward and thereby change the relation between Phase 1 and Phase 2 compliance costs. While substitution takes place exclusively during Phase 1, irreversibility provides low cost supply mostly during Phase 1.

Our numerical analysis should not be taken as a prediction, much less as a replication of what would have been the “right” prices in early Phase 1. Anyone familiar with the allowance market knows that prices went much lower, to \$70, in 1996. Also, it is obvious that a 6% real rate of discount cannot explain the increase of prices since then, and particularly the near doubling of allowance prices between late 1997 and mid 1998. Instead, our purpose has been to evaluate the relative importance of the several factors that have caused Phase 1 allowance prices to be much lower than expected. The exercise should also persuade the reader that early Phase 1 allowance prices are very sensitive to assumptions about the counterfactual and the location of the marginal cost curves. As expectations about counterfactual emissions and Phase 1 costs change, so will current allowance prices, evidently with considerable swings in magnitude.

6. Conclusions

The low price of allowances has been one of the most noted aspects of the sulfur dioxide emissions market of the U.S. Acid Rain Program. This paper has presented theoretical and numerical analyses of the gap between expected and observed allowance prices. The principal explanations appear to be the unanticipated decline of emissions due to the cost-based market penetration of low sulfur western coal and the augmentation of the effect of that error by irreversible investments such as scrubbers and long-term contracts with low sulfur coal suppliers. Other minor factors are voluntary participation of non-affected sources and the higher than expected utilization of units retrofitted with scrubbers. The analysis presented here illustrates, as in any real market, the important role of expectation errors and irreversibility in the evolution of SO₂ allowance prices.

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