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Innovation Under the Tradable Sulfur Dioxide Emission Permits Program in the U.S. Electricity Sector

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Abstract

The 1990 U.S. Clean Air Act Amendments (CAAA) instituted a national program in tradable sulfur dioxide (SO₂) emission permits, referred to as “emission allowances,” in the U.S. electricity sector. This paper provides a survey and assessment of the SO₂ allowance trading program with a focus on the role of innovation. Over the last decade the cost of compliance has fallen dramatically compared with most expectations, and today the total cost of the program is 40– 140% lower than projections (depending on the timing of those projections and the counter-factual baseline considered). Marginal costs of reductions are less than one-half the cost considered in most analyses at the time the program was introduced.

Innovation accounts for a large portion of these cost savings, but not as typically formulated in economic models of research and development (R&D) efforts to obtain patent discoveries. Innovation under the SO₂ allowance trading program involves organizational innovation at the firm, market and regulatory level and process innovation by electricity generators and upstream fuel suppliers. An important portion of the cost reductions that are evident was already in the works prior to and independent of the program. Nonetheless, the allowance trading program deserves significant credit for providing the incentive and flexibility to accelerate and to fully realize exogenous technical changes that were occurring in the industry. This marks a significant departure from conventional approaches to environmental regulation, which would not be expected to capture these savings. The ongoing transition to restructuring of electricity markets and expanding competition in electricity generation complements the design of the SO₂ allowance trading program by providing firms with full incentives to reduce costs of pollution control.

Key Words: innovation, incentive-based regulation, SO₂ trading, Clean Air Act Amendments

JEL Classification Numbers: O31, Q25

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Dallas Burtraw*

1. Introduction

Title IV of the 1990 U.S. Clean Air Act Amendments (CAAA) instituted an emission allowance trading program to regulate emissions of sulfur dioxide (SO_2) from electricity-generating facilities. The industry is allocated a fixed number of total allowances, and firms are required to hold one allowance for each ton of sulfur dioxide they emit. Firms are allowed to transfer allowances among facilities or to other firms or to bank them for use in future years.

A less widely acknowledged but equally important feature of Title IV is the annual cap on average aggregate emissions by electricity generators, which is set at about one-half of the amount emitted in 1980. The cap accommodates an allowance bank, so that in any one year, aggregate industry emissions must be equal to or less than the number of allowances allocated for the year plus the surplus that has accrued from previous years.

For years economists have urged that policy makers use incentive-based approaches (taxes or tradable permits) to control pollution to encourage industry to minimize the cost of reducing emissions. A conventional approach to environmental regulation might force firms to emit SO_2 at a uniform rate or to install specific control technology. The trading program is designed to enable firms operating at high marginal pollution abatement costs to purchase SO_2 emission allowances from firms operating at lower marginal abatement costs, thereby limiting SO_2 emissions at a lower overall cost than traditional command-and-control approaches.

Incentive-based approaches to regulation also are believed to encourage industry to minimize costs over time, promoting so-called “dynamic efficiency.” This dynamic efficiency is achieved by providing firms with an incentive to innovate, because firms can expect to keep some or all of the gains from innovation through reduced abatement costs plus reduced payments

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for taxes or permits. Such incentives to innovate are typically weak or absent with conventional regulatory approaches, especially those that use technology standards, which provide little reward to the development of alternative technologies or processes.¹

A significant literature has investigated the expected performance of different environmental policy instruments in promoting research and development (R&D). Most of the literature has argued that incentive-based approaches provide greater incentives for innovation than conventional approaches (e.g., Downing and White 1986). Milliman and Prince (1989) and Jung, Krutilla and Boyd (1996) find that among incentive-based instruments, the incentives for innovation are greatest under auctioned emission permits, less with an emissions tax, and least under free (grandfathered) emissions permits. These three policies are all found to be more effective than direct controls or performance standards. Fischer, Parry and Pizer (1999) analyze the incentive-based instruments and find that depending on the circumstances, each one of the three policies may induce a significantly higher welfare gain (including environmental benefits) than the other two. The relative ranking depends on the ability of adopting firms to imitate the innovation, as well as the cost of research and development and the nature of environmental benefits. In general, the literature offers the following broad consensus: while not as important as the environmental benefits that are achieved (Parry, Pizer, and Fischer 2000) or even as important as achieving cost-effectiveness in the short run, incentive-based approaches offer important advantages over conventional approaches in reducing the long-term cost of pollution control.

The SO₂ allowance market presents the first real test of the wisdom of economists' advice and therefore merits careful evaluation. How has trading affected the distribution of benefits and costs in the program? Has the allowance market significantly lowered the costs of abating SO₂? And most central to this paper: compared to other conventional regulatory approaches for controlling pollution, how has the program affected the nature and pace of innovation?

¹ Another type of dynamic efficiency promoted by incentive-based regulation is so-called "allocative efficiency." Allocative efficiency occurs because these approaches internalize some portion of the social cost of economic activity. For example, environmental taxes invoke costs associated with abatement activity (as do command-and-control approaches) and also invoke costs associated with the tax payments, thereby having a greater effect on product prices than just the cost of abatement. Similarly, tradable permits invoke abatement activity and also invoke costs associated with the opportunity cost of using a permit that could otherwise be sold to another firm. In a competitive market, this opportunity cost would be added to the cost of abatement in determining marginal costs of production. The consequence is to provide a more accurate signal of resource use in product prices both to consumers and to potential entrants in the market (Spulber 1985).

This paper addresses these issues by surveying the recent literature to assess the actual performance and success of the allowance trading program and then by attributing this success to various sources, including innovation. First, the paper provides a basic description of the program and the historical setting in which it emerged. Second, the paper addresses the environmental performance and the cost of the program, especially compared with the expected cost of the allowance trading program and the cost of conventional regulatory approaches. Subsequently, the paper turns to a survey of innovations that can be attributed to the program.

The conclusion offered, in brief, is that the SO₂ allowance trading program has been a noteworthy success from the standpoint of comparing benefits and costs. Emission allowance trading has not lessened, and may have contributed to, the environmental benefits of SO₂ reduction. Meanwhile, trading has contributed to significant cost reductions, compared to original forecasts of cost.

Innovation also accounts for a large portion of these cost reductions, but not simply in the way typically formulated in economic models of the research and development of patentable discoveries. This observation is consistent with the sparse empirical literature on the economic incentives for innovation created by environmental and energy regulation. Jaffe and Palmer (1997) found a positive relationship between regulatory stringency and R&D expenditures but no statistically significant relationship between compliance costs and patenting activity at the industry level.

In the SO₂ allowance trading program, flexibility in compliance has provided the lion's share of cost savings to date—a greater share than the exchange of emission allowances through trading. Similarly, Kerr and Newell (1997) investigated lead-reducing technology adoption decisions by petroleum refineries during the phase-down of lead in gasoline and found that changes in regulatory flexibility led to noticeable differences in technology responses across firms.

Also in the SO₂ program, input markets for electricity generation redirected investment dollars to take advantage of new opportunities for low-sulfur coal that were created by the SO₂ emission allowance trading program. Similarly, Newell, Jaffe, and Stavins (1997) explored the effect of economic incentives and direct regulation on energy-saving innovation, finding that manufacturers significantly redirected product-level innovation in an energy-efficiency enhancing direction during periods of energy price increases.

Generally, rather than patentable discoveries, innovation under the SO₂ allowance trading program has involved organizational innovation at the firm, market, and regulatory level and

process innovation by electricity generators and upstream fuel suppliers. An important portion of the cost reductions was already in the works, independent of the trading program. Nonetheless, a conventional regulatory approach would have failed to capitalize on many of these advantageous trends, and arguably would have discouraged them. The SO₂ allowance trading program deserves significant credit for providing the incentive and flexibility to accelerate and fully realize exogenous technical changes that were occurring in the industry.

2. Institutional Background

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

During the 1980s, more than 70 bills were introduced in Congress to reduce SO₂ emissions from power plants, especially those existing before the NSPS took effect. Some bills would have forced the scrubbing of emissions from all electricity-generating units, while others, to give firms some opportunity to choose a compliance strategy, would have provided limited flexibility by imposing uniform emission rate standards.

The 1990 Clean Air Act Amendments for regulating SO₂ move away from these types of uniformly applied regulations. Instead, reductions are to be achieved by setting a cap on emissions while allowing the trading of marketable pollution permits or allowances. The eventual goal is to cap average annual SO₂ emissions of electric utilities at 8.95 million tons—about half of the 1980 level. This is to be achieved in two phases. In Phase I, which began in 1995, each of the 110 dirtiest power plants (which have 263 generating units) were allocated allowances sufficient for an emission rate of 2.5 pounds SO₂ per million Btus of heat input. Firms can voluntarily enroll additional generating units (“Compensation and Substitution” units) in Phase I, subject to the constraint that the average emission rate of all units does not increase. In Phase II, which began in the year 2000, all fossil-fueled power plants larger than 25 megawatts are annually allocated allowances sufficient for an emission rate of 1.2 pounds of SO₂

per million Btus heat input. In both phases, heat input is based on the 1985–1987 reference period.

The key features of the SO₂ allowance trading program are themselves innovative. The primary focus is concern for the environment that is addressed through significant reductions in aggregate emissions. The firm national cap on emissions ensures these reductions will be maintained even as the economy and electricity demand grow in the future. Measurement of emissions ensures the cap will be met.

Additional key features are flexibility and simplicity. While I discuss the importance of flexibility at length, suffice it to say that simplicity in the program's design makes the program transparent to industry and environmental advocates alike, while also building trust in its performance. Automatic penalties remove the role of negotiation and uncertainty in the case of noncompliance. Finally, the program is national, but it does not supercede local standards that are set to protect human health and guard against potential local hot spots of pollution.

Allowance trading takes advantage of the fact that emission control costs vary across generating units and encourages firms with the cheapest control costs to undertake the greatest emission reductions. Unfortunately, firms may not have adequate incentives to minimize SO₂ compliance costs because of decisions made by some state public utility commissions (Rose 1997; Bohi 1994; Bohi and Burtraw 1992). For instance, to protect the jobs of miners in high-sulfur coal states, some regulators pre-approved the recovery of investment in scrubbers, while leaving it uncertain whether the cost of other possible compliance measures would be similarly recoverable. The allowance trading program itself encouraged scrubbing, for the explicit purpose of protecting jobs in regions with high-sulfur coal, by allocating 3.5 million bonus allowances to firms that installed scrubbers as the means of compliance. In addition, investments in scrubbers can be depreciated and in some cases expensed (deducted against taxable income) as soon as the scrubber is installed. In contrast, in many states the cost of purchased allowances cannot be recovered until they are used for compliance (Lile and Burtraw 1998). These facts suggest that—through no fault of its own—the allowance market might not succeed in capturing all the potential gains from emission trading

3. Environmental Performance

Facilities affected by the allowance trading program have been 100% in compliance. The opportunity to bank emission allowances for use in later years, especially those of Phase II for which the annual allocation of allowances is decreased significantly, led to significant over-

compliance during Phase I. Of course, this means the postponement of emissions, rather than their elimination. This section describes what is known about the environmental benefits of the program from an economic perspective, including the environmental effects of trading and banking.

Comparing benefits and costs

The primary measure of success of the SO₂ allowance trading program, from the perspective of economics, should be the comparison of benefits and costs. Burtraw et al. (1998) report the results of an integrated assessment of the benefits and costs through the year 2030, with benefits quantified for health, visibility, and lake recreation. Midpoint estimates of the benefits and costs per affected capita for the year 2010 are summarized in Table 1. The costs and benefits estimates are not additive, because they do not describe consistent geographic areas. Costs and health benefits are calculated for the entire nation. Visibility benefits are calculated at selected cities or states. Lake recreation benefits are calculated for the Adirondacks only. Hence, the values are expressed per affected capita to illustrate the potential relative magnitude of these benefits.

The study finds that benefits of the SO₂ allowance trading program are an order of magnitude greater than costs, a result that contrasts sharply with estimates in 1990 that pegged benefits about equal to costs (Portney 1990). What explains the difference between the earlier and recent estimates?

On the cost side, compliance has and will cost in the future one-half or less of what was anticipated in 1990, a point I subsequently consider in detail.

Meanwhile, the lion's share of benefits results from reduced risk of premature mortality, especially through reduced exposure to sulfates. These expected benefits measure several times the expected costs of the program. Significant benefits are also estimated for improvements in health morbidity, recreational visibility, and residential visibility, and benefits for each of these measures are approximately equal to costs. These areas, namely human health and visibility, were not the focus of acid rain research in the 1980s, and new information about health epidemiology suggests these benefits are greater than were previously anticipated (Burtraw et al. 1998).

In contrast, benefit areas that were the focus of attention in the 1980s, including effects to soils, forests and aquatic systems, still have not been modeled comprehensively, but evidence suggests benefits in these areas to be relatively small. It is surprising to many that relatively low

benefits are expected to result from effects of acid rain reduction on forests and agriculture or are estimated by economists for improvements in lake recreation (see Burtraw et al. 1998). One reason is that willingness to pay for environmental improvement depends on the availability of substitute assets. Economists would not expect changes in quality at one site to elicit large benefits if there are many sites available for comparable recreational opportunities. In contrast, individuals do not have the same kind of substitution possibilities with respect to health and visibility, which may help explain the relatively larger benefit estimates for these endpoints. Furthermore, one should note that the low benefit estimates stem from an assessment of use values, or commodity values in the case of agriculture. Environmental changes may also yield nonuse values, but estimates for nonuse values are not yet available. The evidence, based on a small number of relatively narrow studies, suggests these values may be significant.

Table 1. Benefits and Costs per Affected Capita in 2010

Effect	Benefits and costs per affected capita of expected emission reductions in 2010 (1995 dollars)
Benefits	
Morbidity	4
Mortality	69
Lake Recreation	1
Recreational Visibility	4
Residential Visibility	7
Costs	6

Note: Benefits are not additive because affected populations differ. However, morbidity and mortality benefits and costs are calculated for the entire nation. *Source:* Burtraw et al. (1998).

There are huge uncertainties, especially on the benefits side of the ledger and especially in valuation of mortality. Recent economic critiques have argued that the use of the value of a statistical life as the basis for valuing health risks from air pollution, instead of a more appropriate measure of quality-adjusted life years lost, could grossly overestimate mortality benefits. In addition, economists have questioned the appropriateness of using labor studies of prime-age men to value changes in life expectancy that occur among an older population (Johannesson and Johannesson, 1996; Krupnick et al. 2000). On the other hand, because environmental exposures are involuntary while labor market risks are assumed to be voluntary in

nature, the labor market studies may underestimate willingness to pay to avoid environmental exposures.

Burtraw, Harrison and Turner (1998) used Monte Carlo analysis and a parametric one-sided sensitivity analysis to investigate some of these sources of uncertainties. Their analysis finds that there is no year in which health benefits of the SO₂ emission reduction program at the 5% confidence interval are less than the annualized (levelized) expected costs. As noted, significant benefits are also estimated for improvements in health morbidity, recreational visibility, and residential visibility, each of which yields benefits approximately equal to costs. Despite tremendous uncertainties about benefits and costs, the main conclusion that benefits soundly outweigh costs appears to be robust.

The effects of banking

The banking provision of the SO₂ allowance trading program resulted in an accumulated surplus of allowances of more than 11 million tons by the year 2000, when Phase II of the program began. Beginning in 2000, allowance allocations to Phase I facilities were decreased, and additional facilities were covered by the program; it is expected that the allowance bank will be diminished over a period of several years.

The opportunity to bank allowances plays a significant role in reducing compliance cost, because it affords firms the flexibility to plan their investment activities. However, it has an ambiguous effect on benefits. To build up a bank, firms are expected to take advantage of relatively low-cost compliance options in the early years of the program, resulting in lower emissions than would occur were firms not able to bank allowances. This leads to greater environmental benefits in the early years. However, after 2000 when the bank is drawn down, emissions are expected to be greater than would occur absent the opportunity to bank, and hence environmental benefits are expected to be less.

The evaluation of the environmental consequences of banking is potentially complicated, depending on whether there are threshold effects in environmental or public health response and at what level of exposure those are achieved. The dominant view in health epidemiology regarding exposure to particulates is that the concentration-response function is linear over the range in which changes will occur. Hence, at least with respect to public health, the trade-off of exposure and response in the later years for less exposure and response in the near term is neutral with respect to the effect on health. From an economic perspective, benefits achieved sooner are

viewed as superior to benefits achieved later, owing to discounting. However, population growth implies that greater numbers of people potentially will be exposed in the future.

Burtraw and Mansur (1999) explored this issue with a benefit-cost model (Burtraw et al. 1998; Bloyd et al. 1996) to compare two scenarios. One is a default scenario intended to represent compliance with Title IV as it is taking shape. For comparison, they constructed a scenario that was identical except that allowances could not be banked, so emissions in each period must be less than or equal to allowance allocations in that period. Also, they assumed that no scrubbers were built in Phase I, based on estimates from Carlson et al. (2000) suggesting that, absent the bonus allowances, scrubbers were uneconomic, even with the opportunity to bank allowances at those facilities.

The result of this comparison indicated emissions should fall or stay constant in 1995 compared to the default. However, in 2005 emissions will increase in most states and in the total United States. The associated change in total health benefits (mortality and morbidity) that result from the opportunity to bank were valued for 1995 and 2005. All numbers are in 1995 dollars, but they were not present valued. The analysis indicated about \$4 billion more in health benefits in 1995; however, in 2005 there should be about \$2.1 billion in decreased benefits. The harm is less in 2005 than the improvement in 1995, but one should not be misled by this comparison, because draw-down of the allowance bank is expected to occur over a longer horizon than did its buildup. However, what one can conclude is that there is a fairly transparent trade-off between near-term and longer-term emissions when banking is allowed. In general, the effect is to shift emission reductions toward the present. Absent other scientific or social considerations, this would seem to be a good thing, especially when it allows the emission reductions to be achieved at significantly less cost.

Regional effects of trading

Legislative debates about acid rain in the 1980s had a sharp regional character. Since acid deposition typically occurs far from the source of emissions, which are somewhat concentrated in the Ohio Valley, many observers claimed that SO₂ emissions from these Ohio Valley power plants were contributing to environmental degradation in the Northeast. Long range transport of emissions from the Ohio Valley does have an important effect outside the region. However, the regional decomposition of health benefits from reduced emissions is less provincially divisive, because atmospheric concentrations of SO₂ and particulates that form from SO₂ are affected closer to the source of emissions than is acid deposition. Burtraw et al. (1998) found that,

expressed in per capita terms, those states providing 75% of the emission reductions accrue about 60% of total health benefits.

To explore the regional effects of trading, Burtraw and Mansur (1999) employed the benefit-cost model to compare trading and no-trading scenarios in order to calculate the distribution of benefits in the years 1995 and 2005 while holding the aggregate level of emissions approximately constant.

To model this, Burtraw and Mansur (1999) chose to constrain aggregate emissions in the no-trading scenario to equal those in the modeled baseline scenario (with trading). Figure 1 presents the results in a qualitative manner by illustrating that the effect of trading is to increase emissions in the Ohio Valley, but not in a uniform way. In 2005, the effect of trading will be to increase emissions from Illinois in percentage terms. For most states outside the Ohio Valley, the effect of trading is to reduce emissions.

The more important measure is the effect of trading on health benefits. Figure 2 illustrates that trading undermines the health benefits of the program in areas closest to where emissions increase. There has been significant concern that trading might serve to contribute to the transboundary effects of pollution, with the result that citizens in New England and along the Eastern Seaboard may suffer effects from emission increases in the Ohio Valley. However, those increases in the Ohio Valley imply decreases in other states that have an equal or greater impact on citizens in the East. As a consequence, it appears that trading actually leads to improvements in air quality in the East. The conclusion is that trading has not led to a deterioration of air quality or environmental assets in the Northeast, as some critics feared. Moreover, the slight changes are not significant compared to the 50% reduction in aggregate emissions that are being achieved (Swift 2000). In other applications of an emissions trading program, such as trading of SO_2 in Europe (Burtraw, Harrison and Turner, 1998) or NO_x in the eastern United States, the geographic effects of trading may be an issue that would have to be tackled directly in designing a trading program. It does not appear to be important in the U.S. allowance trading program for SO_2 .

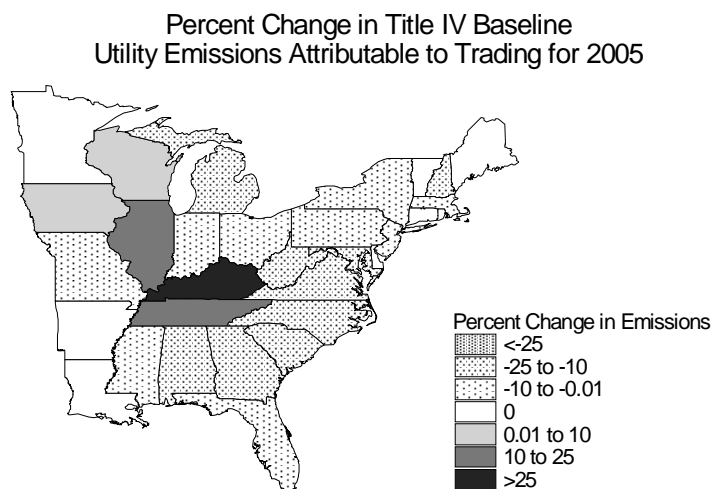


Figure 1. Percent change in Title IV baseline utility emissions attributable to trading for 2005

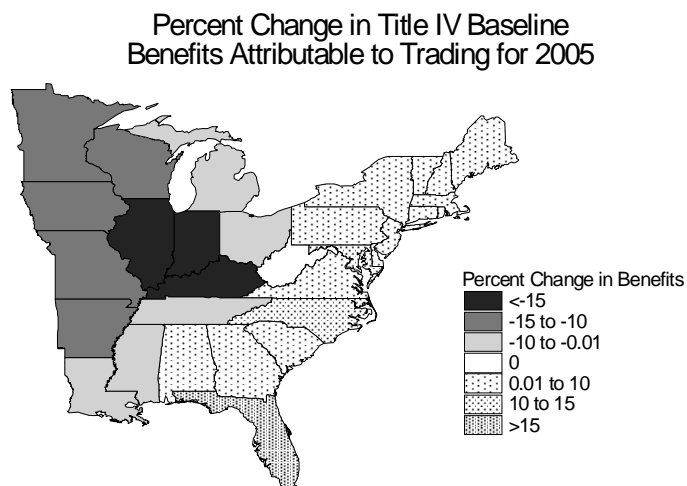


Figure 2. Percent change in Title IV baseline benefits attributable to trading for 2005

4. Cost Savings

Though they are substantial by any accounting, cost savings sometimes have been exaggerated. Advocates of ambitious climate change policies have suggested that SO₂ allowance prices are “so low” and that economists and engineers got it “so wrong” that policy makers should virtually ignore cost projections when developing new regulations such as a carbon or NO_x permit trading program. Some have claimed cost savings of nearly fifteen fold are attributable to the trading program, based on a comparison of recent allowance prices of just above \$100 with projections of long-run marginal costs near \$1500 per ton of abatement (see, for example, Karmarck 1997).²

This argument is flawed for several reasons (Bohi and Burtraw 1997; Smith, Platt, and Ellerman 1998). First, analyses that took into account the ultimate design of the program suggested that long-run marginal costs would be about \$700. Second, historical estimates of marginal costs were generally for Phase II of the program, and therefore cannot be compared with Phase I allowance prices unless the Phase II allowance price forecasts are discounted to the present. The present discounted value in 2000 is roughly 40% of the value of costs incurred around 2010, when Phase II is in full effect, and the allowance bank is expected to be depleted. Third, marginal costs are likely to be a poor proxy for total costs (or cost savings). Even if allowance price were equal to marginal abatement cost in the least-cost solution, it would not follow that all trading gains were realized. Price can equal marginal abatement cost even if many firms fail to participate in the market.

Together, these factors suggest that Phase I allowance prices in 1997 of about \$125 should be compared to a figure of about \$235, which is what U.S. EPA (1990) predicted would obtain as Phase I marginal abatement costs in 1997.³ This comparison suggests that marginal costs have fallen by more than half compared to the vantage point in 1990. Indeed, the performance of the program is very good: there is no need to exaggerate.

² See for example, ‘Economists’ Cold Forecast; Assumptions: Expect their dire predictions about the impact of the global warming treaty on the United States. Ignore all of them,’ by Elaine Karmarck, *Baltimore Sun*, December 28, 1997.

³ U.S. EPA (1990) predicted \$210 in \$1995 for the year 1995. Inflated at a 6% rate of interest, this is equivalent to \$235 for the year 1997.

A critical question is: to what extent can this decline in cost be credited to the allowance trading program? Subsequently, I ask the main question of interest: to what extent can this decline be credited to innovation?

Marginal and annual costs

Carlson et al. (2000) offered an econometric model to explore the role of allowance trading in achieving cost savings. To predict the cost of emissions reductions at fuel-switching generators, the model used marginal abatement cost functions derived from an estimated long-run cost function for electricity generation for more than 800 generating units for the years 1985–1994.⁴

To estimate potential gains from allowance trading in the long run, Carlson et al. computed the least-cost solution to achieving the 8.95-million-ton SO₂ cap in the year 2010. Several assumptions are critical to the calculation, and they are explored in the sensitivity analysis. Real prices of high- and low-sulfur coal are assumed to remain at 1995 levels while the rate of technical change experienced between 1985 and 1994 continues through 2010. Baseline emissions—those that would have prevailed absent Title IV—are calculated using 1993 emissions rates applied to 2010 levels of electricity production.

Under the above assumptions, the total annual cost of achieving the SO₂ cap of 8.95 million tons in 2010 is estimated to be \$1.01 billion (1995 dollars). Of this total, \$380 million represents the cost incurred by plants that fuel-switch, which account for about 60% of reductions from baseline emissions, with the remainder incurred by plants that installed post-combustion control. The marginal cost of emissions reduction, which should approximate the long run permit price, is \$291 per ton of SO₂.

Annual compliance costs of \$1 billion per year are less than half of the estimates of compliance costs originally predicted when the 1990 Clean Air Act Amendments were drafted (U.S. EPA 1989, 1990). This is reported in the first row of Table 2.

⁴ The cost function treats fuel type (high-sulfur and low-sulfur coal), labor, and generating capital as fully variable inputs. The econometric model consists of the cost function plus two share equations that specify the share of total costs attributed to capital and labor and an equation for the firm's mean annual emission rate. The study uses a translog form for the cost function, adding dummy variables for each plant in the database to measure fixed effects that vary among the plants. Costs for units with scrubbers are taken directly from reported data.

Rows 2 and 3 report on the sensitivity analysis. Holding technology constant at 1995 levels, compared with the preferred assumption of continuing trends in technology improvements, increases marginal abatement cost by about 50%. The assumption is that setting fuel prices at 1989 levels, compared with the preferred assumption of 1995 levels, further increases marginal abatement costs by nearly 20%.

These estimates can be compared with the U.S. EPA estimates from 1989 and 1990, at the time the Clean Air Act Amendments were being discussed. The comparison illustrates that the failure to anticipate changes in fuel prices, and the change in technology at the power plant explains the difference between the Carlson et al. estimates and those that formed the basis of expectations for the program. Under the maintained assumption that fuel switching determines marginal abatement cost, the assumption of stable 1989 fuel prices and technology (the third row of the table) produces marginal cost estimates approximately as large as those predicted when Title IV was written (the fourth and fifth rows of the table).

Table 2. Long-run (Phase II, year 2010) Cost Estimates from Carlson et al. 2000 Compared with Previous Studies

Scenario	Annual Cost (billion \$1995)	Marginal Cost per Ton SO ₂ (\$1995)	Average Cost per Ton SO ₂ (\$1995)
<i>Preferred Estimate *</i>	1.0	291	174
w/ 1995 Technology	1.6	436	198
w/ 1989 Prices and 1989 Technology	1.9	560	236
U.S. EPA (1990)	2.3–5.9	579–760	299–457
U.S. EPA (1989)	2.7–6.2		377–511

Annual costs continue to differ significantly among these rows. A major factor explaining the difference in annual cost is the assumption by the U.S. EPA in 1990 that a greater number of scrubbers (37) would be built than were actually constructed in Phase I (28) or than are likely to be built under the preferred estimate. Also, U.S. EPA (1990) failed to anticipate improvement in performance of scrubbers, increased utilization of these units, and greater utilization of nuclear units to meet baseload capacity. Since fuel switching is a marginal compliance option, the

estimates of marginal cost remain close in the comparison, but differences in scrubber estimates help explain differences in infra-marginal costs and total cost.

Also important to total (annual) cost are differences in the baseline from which emissions reductions are measured. In all of these calculations, the authors assume that the emission rates (lb. of SO₂/million Btus) that would have prevailed absent the 1990 Clean Air Act Amendments are those that prevailed in 1993. These are much lower than 1989 emission rates. Hence the reductions in emissions necessary to achieve the 8.95-million-ton cap, by the authors' calculations, are much lower than imagined in 1989 (specifically, about 2 million tons lower). Holding marginal abatement cost curves constant, lowering the necessary reduction in emissions will lower total compliance costs.

From these experiments, the characterization of technological change emerges as the most important assumption in explaining the difference between the econometric estimates and previous studies. Changing assumptions about other factors, such as fuel prices, retirement, and monitoring each weigh in as significant but of much less importance. The important caveat is to recognize that, to a large degree, these changes were exogenous to the SO₂ allowance trading program.

Potential Cost Savings from Allowance Trading

To calculate the cost savings from trading emission allowances, Carlson et al. (2000) compare the cost of meeting the SO₂ cap using a command-and-control approach with the least-cost (preferred) solution identified above. The command-and-control approach is modeled as an average emissions rate of 1.2 pounds of SO₂ per million Btus of heat input.⁵ The estimated potential gains from trading are \$784 million, or about 44% of the cost of command-and-control.

While these potential gains are significant, they are not as large in absolute terms as were originally predicted. The U.S. GAO (1994) estimated greater gains in both absolute and relative terms, suggesting that a per-unit cap on emissions would cost approximately \$5.3 billion annually—140% more than their least-cost solution (\$2.2 billion).

⁵ This approach already encompasses many of the beneficial incentives of the SO₂ emissions allowance trading program, compared to a technology-forcing approach, by providing individual facilities with flexibility in achieving the standard. Other command-and-control approaches that were seriously considered in the US, such as forced scrubbing at larger facilities, could have cost substantially more.

The explanation for relatively modest estimates of trading gains found by Carlson et al. (2000) is that many of the factors that have caused marginal abatement costs to fall also would have lowered the costs of achieving the SO₂ emissions cap via some forms of command-and-control policies. These factors include the fall in the price of low-sulfur coal and technical improvements that have facilitated fuel switching. Burtraw (1996) suggests that incentives under the allowance trading program have accelerated the pace at which these changes have occurred. However, to the extent that these innovations would have emerged under a command-and-control approach, they lower the potential cost savings from allowance trading as compared to a command-and-control baseline.

In addition to lowering marginal abatement cost curves, the fall in low-sulfur coal prices has made marginal abatement cost curves more homogeneous. This is because costs of transporting low-sulfur coal to more distant locations, for example, the East and Southeast, has fallen, rendering differences in transportation cost a less important component of the overall cost of fuel switching. Because a major source of gains from allowance trading is differences in marginal abatement cost curves among units in the market, this increased homogeneity is also responsible for lowering gains from trading.

In summary, estimates of costs for both a command-and-control approach and allowance trading have fallen over time owing to a number of factors. Allowance trading is resulting in cost savings relative to a command-and-control approach, but the absolute magnitude of these savings is expected to be somewhat less than previously envisioned owing to changes in fuel markets and technology. These changes made the trading of allowances somewhat less important in reducing costs, but the changes made the aspect of flexibility in a firm's compliance decisions even more important. Finally, note that Carlson et al. (2000) model a flexible type of command-and-control policy (performance standards). A more rigid approach that forced firms to adopt specified technologies would have precluded firms from taking advantage of the full range of options that have emerged in compliance with the program. Compared to a more rigid command-and-control policy, Carlson et al. (2000) conclude allowance trading could be argued to provide even greater savings.

5. Innovation

Heretofore, we find the SO₂ allowance trading program has realized tremendous cost savings compared to a conventional approach and even compared to expectations at the time the program was initiated. A portion of these savings is due to trading emission allowances, but a

large share of cost savings has been achieved outside the formal allowance market. The present question of interest is: to what extent can the cost savings be attributed to innovation?

We find evidence of several forms of innovation, but one common feature in this evidence is that the innovation generally is not patentable. Most of the innovations can be catalogued as changes in production processes, organizational behavior, regulation, markets, etc.

An individual facility has a variety of mechanisms for compliance under Title IV in addition to allowance trading, including intra-firm reallocation of emission allowances, fuel switching and/or blending, installing scrubbers, retiring plants, repowering plants, energy conservation, reduced utilization and substitution among facilities, and increased utilization of lower-emitting facilities. To survey the role of innovation, I consider these compliance options, including post-combustion control (scrubbing), as input supply. Subsequently I consider innovations at the organizational level.

Technological Change at Input Supply Level

The most important development in the implementation of Title IV has been the fall of prices in coal markets and of the operating cost of scrubbers. One explanation for this is the unanticipated degree to which input markets have been brought into direct competition. SO₂ allowance trading provides utilities with the flexibility to choose among several options for compliance in addition to the purchase of allowances. This flexibility provides the opportunity for vendors of various technologies to compete with emission reduction strategies at the power plant, and this additional competition can ignite a wider search for ways to reduce costs among suppliers of competing technologies. The result has been cost-reducing investments, resulting in a decline in allowance prices below forecast in every potential option for compliance (Burtraw 1996).

The most visible changes have occurred in the delivered cost of low-sulfur coal. Under the 1977 Clean Air Act Amendments, there was little value to the sulfur differentiation in coal, because the NSPS (Section 111 of the Clean Air Act) effectively forced adoption of specific technologies. Rules written in 1979 to implement the 1977 amendments imposed a minimum SO₂ reduction standard of 90% on high-sulfur coal and 70% on low-sulfur coal at all new facilities, effectively requiring the use of scrubbers and thereby eliminating the incentive for the use of low-sulfur coal. So-called “compliance coal” (low-sulfur coal) with an emission rate below 1.2 lb. SO₂ per million Btus remained in demand by facilities built between 1970 and

1977. But for facilities built before 1970 or after 1977, there was no economic incentive or requirement to use lower-sulfur coal for compliance with environmental goals.

About half of the reductions in sulfur during Phase I of the program have been achieved by changing to coal with lower sulfur content. A primary explanation, hinging on market fundamentals, is the low cost of this strategy. Another compelling explanation, hinging on institutional issues, is that this strategy is relatively non-capital intensive. In a period of uncertainty regarding the emissions allowance market, cost recovery, and, especially, competitive pressures facing the entire electricity industry, fuel switching and fuel blending are low-fixed-cost strategies that allowed affected utilities to comply with little risk.

The market for low-sulfur coal has grown and is expected to continue growing. Low-sulfur western coal has penetrated midwestern and eastern markets in record quantities, and eastern low-sulfur coal is being supplied at lower prices than anticipated as a result of increased mining productivity, lower rail rates, and competition from western mines.

Changes in Rail Transport of Coal

Many analysts have suggested that a large share of SO₂ emission reductions achieved in Phase I were predestined by actions taken before the 1995 start of the allowance trading program (Ellerman and Montero 1998; Burtraw 1996; Carlson et al. 2000). Emissions from facilities affected by Phase I totaled 9.3 million tons in 1985, and allowance allocations to these facilities for Phase I (beginning in 1995) total 6.9 million tons. But by 1993, emissions had already fallen to 7.5 million tons. This decline was due to demographic shifts in electricity demand toward areas more proximate to low-sulfur coal, coupled with increased availability of low-sulfur coal not only as a low-cost compliance option for the SO₂ program, but also as a cheaper fuel for power production at many facilities. Hence the decline in price of low-sulfur coal may well have stimulated a decline in emissions even in the absence of the SO₂ allowance trading program.

However, Carlson et al. (2000) find that an important portion of potential cost savings through fuel substitution and trading were unrealized in Phase I. This was due to historical forces and the traditional regulation of electric utilities, which has been changing rapidly. Because an important portion of savings was left unrealized, it is difficult to establish what portion of cost savings that were realized would have occurred absent the program. Given that the incentive to switch to lower-sulfur coal is greater with the program in place than if the program had not existed, it is reasonable to assume that the program contributes importantly to the switching to low-sulfur coal. This is the finding of Carlson et al. (2000), who control for “economic

switching” and find additional switching achieved for compliance with the SO₂ allowance trading program to be much more important.

In any event, it is clear the deregulation of the railroads in the 1980s led to greater competition among railroads for coal transportation business that emerged just at the time of the Clean Air Act Amendments. This competition led to a significant decline in coal transport costs, which is a major component of the delivered price of coal (Carter 1996; Heller and Kaplan 1996). Coal transport is the leading source of revenue for rail freight. The enthusiasm with which rail has competed for coal transport results from the Staggers Act of 1980 that largely deregulated railroads. In the 1980s rail rates fell 35%, yet profits went up owing to increased flexibility in tariffs and increased incentives to reduce costs.

Many observers in the Clean Air Act debates conjectured that bottlenecks would occur in rail transport that would preclude western coal from playing a big role in compliance plans of eastern utilities. Hence price forecasts hinged on prices for low-sulfur Appalachian coal that was locally available to eastern utilities. However, these potential bottlenecks failed to materialize. Burtraw (1996) reported that investment plans by railroads were realigned after passage of the CAAA in 1990, and the railroads were anxious to capture a share of the expected rapid growth in coal transport given the incentive to switch to low-sulfur fuel. Realignment of investment plans took advantage of new technologies such as increased size of car fleets and unit trains, AC motors, the laying of double and triple tracks, increased numbers of locomotives, use of aluminum cars, and increased car dump speed. This is not the usual form of innovation imagined as part of technical change. However, it does represent a diffusion of new technology and an organizational adaptation to market opportunity. When investments are realigned, then cost reductions in one arena are associated with delayed investments and foregone opportunities in other arenas. It is important to recognize these opportunity costs in order to characterize properly the costs of regulation. However, the costs are inevitably lower given the incentive and opportunity to realign investments in this manner.

The primary question, then, is whether opportunities for rail transport of low-sulfur coal would have existed under a counter-factual environmental regulation using conventional approaches. A technology standard that took the form of forced scrubbing at major electricity generating facilities was a leading proposal in the 1980s and characterized new performance standards after 1979. Clearly this approach would have precluded any advantage to low-sulfur fuel because scrubbers remove 95% of emissions, rendering the additional cost of low-sulfur fuel unnecessary.

A performance standard that established emission rates at plants would have promoted a large amount of switching to low-sulfur coal, as illustrated by Carlson et al. (2000). However, it would not have provided an incentive for over-compliance at facilities relatively close to supplies of low-sulfur coal in order to reduce costs at facilities further away. Hence it would not have complemented the allowance market or granted as much flexibility to firms as has the SO₂ trading program. In summary, the SO₂ allowance trading program deserves substantial credit for not precluding, and arguably for accelerating, environmentally beneficial trends that were occurring in fuel markets. This outcome would have been unlikely under alternative approaches.

Innovations in Fuel Blending

Blending coals is not as important as switching coals, but blending has provided significant cost savings. Fuel blending involves mixing high- with low-sulfur coals to reduce average SO₂ emissions. Like fuel switching, fuel blending has lower capital costs than scrubbing. Generally, electricity-generating facilities are designed for a particular type of coal.

In the late 1980s, it was widely believed that fuel blending was not practical in cyclone boilers because of the anticipated impact on the operation of the existing plants and boilers. Deviations in any of several important properties may impair plant performance or harm equipment. Low-sulfur subbituminous western coal would be most troublesome in this regard, because it does not share the characteristics of commonly used bituminous coal, including moisture content, heat content, and ash properties. (Equipment likely to be affected by blending coals include the coal-handling system, the fuel preparation and firing system, the primary air system, the steam generator, and the particulate removal system.)

Fuel blending falls soundly into the category of an unanticipated innovation that resulted from the allowance trading program. Experimentation prompted by the program has led to an improved understanding of the ability to blend fuels, and the detrimental effects of blending have been found to be less than originally supposed. While in the late 1980s the rate at which it was thought low-sulfur subbituminous coals could be blended with high sulfur coal was less than 5%, today coals are blended at rates of 30-40%. This process innovation was simple to achieve, but it was unanticipated and resulted from the incentives provided by the allowance trading program.

Innovations in the Scrubber Market

Scrubbers are a capital-intensive post-combustion compliance strategy with a larger initial cost and lower operating costs than most other strategies. The electric utility industry had relatively more experience with scrubbers prior to 1990 than with fuel switching and/or blending

Keohane (2000) finds that capital costs per installed kW of capacity have remained fairly constant for many years. Taylor (forthcoming) finds that capital costs have declined significantly over time. In any event, this experience did not foreshadow the fact that under SO₂ allowance trading program, less capacity was needed to achieve roughly equivalent reductions. Previous to the CAAA, scrubber systems usually included a spare module to maintain low emission rates when any one module was inoperative. One estimate of capital costs indicates they would increase by one-third with a spare module (U.S. EIA, 1994, 92). An important innovation in the scrubber market is the reduced need for spare absorber modules. As long as emission allowances are a sufficient compliance strategy, utilities can save considerable capital costs by eliminating the spare module and using allowances during periods of maintenance or unplanned outage. In addition, new scrubbers exhibit increased efficiency and reliability. Improvements in scrubber design and use of materials have reduced maintenance costs and increased utilization rates, also reducing the need for spare modules.

Another significant technical implication of the CAAA is the incentive for improved efficiency in scrubbing. Increasing SO₂ removal from, say, 90–95% can be cost effective compared to the overall cost of SO₂ removal and the opportunity cost of allowances. The incentives are such that upgrading of existing scrubbers through improvements, including larger modules and elimination of reheat, is likely to occur (Torrens, Cichanowicz, and Platt 1992, 221–222). These incentives did not exist under previous regulations affecting only new sources.

Keohane (2000) and Taylor (forthcoming) both find that abatement costs per ton of removal have gone way down, especially in retrofit scrubbers installed for compliance in the SO₂ allowance trading program. The retrofit scrubbers burn higher-sulfur coal, which leads to higher abatement rates and thus lower per-ton costs (assuming some abatement costs are insensitive to the amount of abatement—i.e., fixed costs of labor and maintenance are tied to the hours of operation rather than the tons of SO₂ removed.)

In addition there is significantly increased utilization of scrubbed units (Ellerman and Montero 1998; Carlson et al. 2000). Increased utilization is important to reducing the average cost of scrubbing, because it spreads capital costs over more tons reduced. Previous to the SO₂ allowance trading program, scrubbers did not exhibit reliability rates sufficient to achieve the current level of utilization. The increase in reliability is at least, in part, a response to incentives provided under the trading program, because of the permit cost savings associated with incremental reductions in emissions.

Organizational Innovations

Process changes and realignment of investment priorities are a subtle manifestation of innovation. An even more subtle, but also significant, type of change has occurred in organizational behavior—in firms, markets and regulators.

Firms and Markets

In 1990, in many firms, the response to the “revolutionary” (and sometimes deemed bureaucratically inspired and foolish) SO₂ allowance trading program was a conservative one. The responsibility for compliance with the unprecedented program was given to engineers or chemists typically charged with environmental responsibilities.⁶ Unfamiliarity with the new program led many to pursue a policy of autarky—no trade—and self-sufficiency in compliance (Bohi, 1994; Bohi and Burtraw 1997; Ellerman 2000; Hart 2000).

Several years later, one can observe responsibility for compliance resting more often with financial vice presidents, who have learned to treat SO₂ emissions allowances as financial assets. Decisions about how to manage allowance portfolios are treated analogously to decisions about how to handle fuel purchases; indeed, allowances are often bundled with fuel purchases. Several companies have developed software to manage their portfolio of emission allowances and to help make decisions about compliance (U.S. EPA 1996). The result is a much smoother and administratively less costly mechanism for planning and decision-making within the firm.

Meanwhile, the market for SO₂ allowances has matured considerably since the early 1990s. In previous small-scale permit trading experiments in local air quality districts, transaction costs often approached 30–40% of the value of the permits. Today, the transaction cost associated with SO₂ allowances is about 1% of the value of an allowance. And, the number of allowances traded virtually doubled each year between 1994 and 1998 (Kruger and Dean 1997).

⁶ Stavins and Whitehead (1996) describe the organizational barriers to taking advantage of incentive-based environmental policies that exist in many firms that are used to conventional approaches to regulation.

Convenience Value of Allowances

Although allowance trading is not the major form of compliance, the opportunity to trade allowances has an influence beyond the exchanges that actually occur. Furthermore, even in the absence of extensive trading, allowances potentially can play a constructive role in facilitating the optimal timing of investments. Firms considering capital investments in scrubbers may benefit from the option to delay investments if delay leads to the resolution of uncertainties pertaining to the planning process (Kaslow and Pindyck 1994). In Phase I, many firms expressed reluctance to engage in new capital investments, especially given the direction that restructuring of the electricity industry was likely to take. Chao and Wilson (1993) illustrated a plausible option value of \$85 on allowances valued at the marginal cost of scrubbing (which they assumed to be a relatively high \$400). Allowances also provide insurance against unanticipated events such as unplanned equipment failures. The insurance value stems from the possibility of stiff penalties were the utility to be in noncompliance. Hence, allowances provide sources of value that were not widely appreciated in the design of the program and that do not hinge on actual trading.

Regulatory Reform

The reach of innovation extends right into the regulatory administration of the SO₂ allowance trading program (Kruger, McLean, and Chen 2000). The U.S. EPA has taken advantage of exogenous technological change, especially the information revolution, to reduce administrative costs incurred by the agency and by firms. Monitoring of emissions is achieved through continuous emission monitors installed on every stack. Data streams into the U.S. EPA in electronic form and is organized by personal computers and involves a staff that is just a small fraction the size of staff managing other regulatory programs. The U.S. EPA's Allowance Tracking System (ATS) is an electronic system that facilitates enforcement and monitoring by the agency, industry, and the public. And, industry has learned to use the ATS as a way to confirm and record the transfer of allowances.

The SO₂ allowance trading program is part of a fleet of regulatory changes including deregulation of the railroads, energy markets, and the electricity industry, and the program has benefited from these other changes. In particular, ongoing deregulation of the electricity-generating sector was set in motion by the Energy Policy Act of 1992 and accelerated by the issuance of Federal Energy Regulatory Commission Order 888 in April of 1996 and related state-level deregulatory activities. This reform is creating greater competition among electricity

generators and associated pressures to reduce compliance costs, providing greater incentives to take advantage of the flexibility embodied in the SO₂ allowance trading program.

6. Conclusion

This assessment concludes that the SO₂ emissions allowance trading program has been an environmental success. It has achieved 100% environmental compliance and over-compliance in Phase I. The effect of trading and banking are roughly neutral with respect to the environmental benefits. An economic assessment of the benefits is that they are substantially greater than the costs of the program.

Particular interest is focused on the costs of the program because of the innovative design of the SO₂ trading program. Detailed analyses have found that the costs are one-half to one-quarter of projections. The cost savings are substantial and contribute to the tremendous success of the program.

Most of the cost savings have been achieved outside the formal allowance market. But after all, the point of allowance trading is not to trade allowances. The point is to give firms the flexibility to achieve emission reductions in the least costly manner. The SO₂ allowance trading program gives utilities the incentive and flexibility to capitalize on advantageous trends in fuel markets. Also, the program has placed numerous options for environmental compliance into direct competition with each other. This has helped to reduce the cost of compliance.

Innovation in a variety of forms is evident in the SO₂ allowance trading program. Econometric estimates of the magnitude of innovation are difficult to achieve, because they are not easily separable from other forces that have decreased the cost of compliance. Indeed, to an important extent the innovation stems from the unprecedented incentive and ability of firms to take advantage of these other forces of technological change. Further, the innovation that is in evidence has not been in the nature of patentable discoveries, but rather it is in the form of subtle process changes and changes in markets and organizational behavior that were seized upon to reduce costs once the incentive to do so was present.

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