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October 2002 • Discussion Paper 02–45

RESOURCES
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Abstract

This paper provides new estimates of efficient emission fees for sulfur dioxide (SO_2) and nitrogen oxides (NO_X) emissions in the U.S. electricity sector. The estimates are obtained by coupling a detailed simulation model of the U.S. electricity markets with an integrated assessment model that links changes in emissions with atmospheric transport, environmental endpoints, and valuation of impacts. Efficient fees are found by comparing incremental benefits with emission fee levels. National quantity caps that are equivalent to these fees also are computed, and found to approximate caps under consideration in the current multi-pollutant debate in the U.S. Congress and the recent proposals from the Bush administration for the electricity industry. We also explore whether regional differentiation of caps on different pollutants is likely to enhance efficiency.

Key Words: emissions trading, emission fees, air pollution, cost-benefit analysis, electricity, particulates, nitrogen oxides, NO_X, sulfur dioxide, SO_2, health benefits

JEL Classification Numbers: Q2, Q4, D61

Contents

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1. Introduction

The electricity sector is a major contributor to emissions of NO_x, SO_2, mercury, and CO_2 in the United States. This sector faces the prospect of having to make substantial reductions in the emissions of the first three of these pollutants over the next 10 to 15 years in order to comply with anticipated new U.S. Environmental Protection Agency (EPA) regulations related to fine particulates, regional haze, and hazardous air pollutants. As an alternative to this expected cavalcade of regulations, some members of congress and the Bush administration have proposed plans for capping emissions of these three pollutants from the electricity sector at levels substantially below current emissions. This multi-pollutant cap-and-trade approach is intended to provide some regulatory certainty to the industry by creating a timetable now for future reductions. By regulating multiple pollutants simultaneously, this approach would allow firms to efficiently allocate their emission reduction activities across different pollutants and to take advantage of synergies in pollution reduction. Also, this approach would provide firms with the flexibility to achieve aggregate emission reduction goals at low cost.

A central question that arises when designing a multi-pollutant cap-and-trade policy is at what levels the emission caps should be set. Principles of economic efficiency suggest that the cap on emissions of each pollutant should be set at the level where the marginal benefit of further emission reductions is equal to the marginal cost of obtaining those reductions. An alternative approach is an emission fee that is set to equal marginal emission damages at that point. This strategy has the same efficiency implications as the cap-and-trade strategy in which emission allowances are auctioned to firms, but different implications for efficiency and the allocation of rents relative to a trading program that distributes emission allowances for free (Burtraw et al. 2001a).

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* Dallas Burtraw and Karen Palmer are Senior Fellows and Spencer Banzhaf is a Fellow at Resources for the Future. The authors are grateful to Ranjit Bharvirkar, David Lankton, Meghan McGuinness, and Anthony Paul for excellent assistance with this research.

In this paper, we seek to identify second-best efficient emission fees for NO_x and SO_2 in the electricity sector. The estimates are second-best because we take as given many aspects of regulatory and fiscal policy that preclude ideal solutions, and search for the efficient fees within this institutional setting. The estimates are obtained by coupling a detailed simulation model of the U.S. electricity markets with an integrated assessment model that links changes in emissions with atmospheric transport, environmental endpoints, and valuation of impacts. Efficient fees are found by solving the electricity model under different values for the emission fees and finding the associated value of the marginal damages associated with the resulting level of emissions for each pollutant. This methodology allows us to estimate the marginal damages and marginal abatement costs for different emission levels and then to approximate the optimal fee or range of fees where the marginal cost (emission fee) is equal to the marginal emission damages. It also allows us to estimate emissions at these tax levels. Because of the duality of the price and quantity instruments, the resulting emissions levels can be interpreted as the efficient permit caps, and can be compared to current legislative proposals.

We find that the efficient emission fee for SO_2 is between \$4,700 and \$1,800 per ton, which will yield between 0.9 and 3.1 million tons of emissions in the year 2010. (All values are in 1999 dollars.) For NO_x, the best estimate of the efficient emission tax lies between \$1,200 and \$700 per ton, which yields emissions between 1.0 and 2.8 million tons. These results suggest that the emission caps included in the Bush administration and congressional proposals are within the range of emissions that can be supported by current knowledge. We also find there is substantial regional variation in the benefits achieved by reducing pollution, suggesting that a regionally differentiated policy could yield greater net benefits than a uniform national policy.

2. Policy Context and Prior Research

Twelve years after the passage of Title IV of the Clean Air Act Amendments of 1990 and the first federal cap-and-trade program for a major air pollutant, policymakers in Washington are considering another round of cap-and-trade regulations for the electricity sector that would dramatically reduce its emissions of several pollutants. Two proposals are currently in play.

Senate Bill 556, which was introduced into the Senate in March of 2001 by Senator Jeffords (I-VT), proposes to cap annual emissions of NO_x and SO_2 from the electricity sector at 25% of their 1997 levels; annual emissions of mercury would be capped at 10% of 1999 levels by 2007. This is equivalent to annual caps of about 1.5 million tons for NO_x, 2.25 million tons for SO_2, and 5 tons for mercury. The bill also caps annual electricity sector emissions of CO_2 at 1990 levels beginning in 2008. The bill allows for emissions trading for all gases except mercury.

The second plan is the Bush administration's "Clear Skies" proposal, which was introduced in the House by Rep. Barton (R-TX) (HR5266) and in the Senate by Sen. Smith (R-NH) (SB 2815) in July 2002. The proposal caps annual emissions of SO_2 at 4.5 million tons in 2010 and at 3.0 million tons in 2018; annual emissions of NO_x at 2.1 million tons in 2008 and 1.7 million tons in 2018; and annual emissions of mercury at 26 tons in 2010 and 15 tons in 2018.[1] This proposal permits the trading of emission allowances for all three pollutants.

In addition to the emission caps, the bills differ on other important issues. For example, S556 requires that all plants, when more than 40 years old, must come into compliance with new source performance standards by installing "best available control technologies." Over time, this technology-based standard would likely become more binding than the emissions caps. In contrast, the Bush administration proposal has been linked by many in the administration with a phase-out of the technology-based standards already present in the Clean Air Act ("New Source Review"). Thus, in addition to the targets and timetables, there are important institutional differences that affect the bills' cost-effectiveness for any given target. We address only the question of the efficient target and not other issues associated with timing or implementation.

Several states also have passed or are considering laws limiting emissions of some or all of the same pollutants from electricity generators. Most of these laws or proposals, such as new regulations in Connecticut and Massachusetts that limit non-ozone season emissions of NO_x, are formulated as limits on emission rates. The largest state action is in North Carolina, which has recently placed emissions caps on its largest coal-fired plants. A similar plan has been adopted in New Hampshire for all existing fossil fuel generators.

Relative to the status quo, the S556 and the Bush administration proposals envision similarly restrictive caps on national annual emissions of NO_x and SO_2 once the proposals are fully implemented, although the timing for achieving the reductions varies. Nonetheless, the similarity in the level of emission reductions suggests a degree of political consensus on how

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[1] The Clear Skies initiative does not include a cap on CO_2 emissions, but instead proposes to cut greenhouse gas intensity on an economy-wide basis by 18% over the next 10 years using mostly voluntary initiatives and providing a formal mechanism for recognizing cuts that are made voluntarily.

tightly to set the caps. However, the appropriate level for caps is a fundamental empirical question that economists have not studied closely.

In the past decade, economists have conducted a number of studies of the benefits of additional controls as well as the costs of controlling different pollutants. Most policy research has used a transfer methodology to estimate benefits, in which existing estimates of health effects and values are applied to a new context.[2] In one example, the recent benefit-cost analyses of the Clean Air Act (U.S. EPA 1997a, 1999) estimates benefits on a national scale, but reports only total benefits from the improvements induced by the act, rather than the schedule of estimated benefits, making it impossible to know the efficient level of emission reduction. Others have estimated only regional damages from specific power plants (Desvousges et al.1998, Rowe et al. 1995, Harrison et al. 1993, and Thayer et al. 1994). Thus, there is room for improving our understanding of the national picture of the benefits of large changes in pollution.

With respect to costs, Carlson et al. (2000) econometrically estimate the cost of SO_2 emission reductions and the cost savings from allowance trading under the 1990 Clean Air Act Amendments, and Ellerman et al. (2000) provide similar estimates based on a survey of industry costs. Burtraw et al. (2001) and U.S. EPA (1998a) estimate the costs of achieving the summertime reductions in NO_x emissions that would be required in the so-called "NO_x SIP Call Program" scheduled to take effect in 2004 in 19 eastern states. U.S. Energy Information Administration (EIA) (2001a, 2001b) and EPA (2001) provide detailed analysis of the cost of proposals that resemble S556, but do not assess benefits.

Despite the tremendous importance of such information, few studies have attempted to actually compare benefits and costs of pollution reduction. Boyd et al. (1995) analyzed benefits and costs together in a general equilibrium model, with a single, constant value for the per-ton benefits of pollution abatement based on EPA regulatory analyses that are now more than 15 years old. Burtraw et al. (1998) used an integrated assessment, partial equilibrium model to estimate the benefits and costs of Title IV of the 1990 Clean Air Act Amendments that imposed reductions on SO_2 and NO_x and initiated emissions trading for SO_2. In contrast, we use a much

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[2] Other research has used revealed preference methods to infer household willingness to pay from housing markets using hedonic price regressions, discrete choice models, and equilibrium sorting models. See Smith and Huang (1995), Chattopadhay (2000), and Sieg et al. (2001) for respective examples and summaries.

more detailed model of the electricity sector to calculate emission changes and costs, and an update of the same integrated assessment method to estimate household benefits. EPA (1997a, 1999) provides a benefit-cost analysis of the Clean Air Act, and a recent analysis of the benefits and costs of the Bush administration proposals (2002). But again, the EPA studies report only total net benefits from the improvements induced by the act, rather than the schedule of estimated benefits costs, making it impossible to evaluate the improvements from policy changes.

In addition to estimating the efficient level of emissions nationally, this research also can identify the regions of the country whose emissions contribute the highest marginal damages, and where benefits would be experienced. Geographic differences speak to two aspects of the current policy debate. First, they are relevant to the problem of "hot spots," in which the flexibility of permit trading could allow pollution to concentrate in a densely populated area.[3] Second, the geographic differences raise the question of whether the caps should be national or regional in scope. The current proposals differ in their treatment of this issue. Under the Clear Skies Initiative there would be separate eastern and western regional trading zones for NO_x, but a single national cap for SO_2. The justification for the distinction is that large reductions in NO_x emissions are necessary in the eastern states to protect human health, while the overall level of emissions and possible reductions are smaller in the west. The regional cap will prevent migration of emissions to the west and protect health and visibility improvements. Inter-regional trading would not be allowed. In S556, emissions of NO_x face a uniform national cap, but SO_2 emissions are subject to different caps in the east and west. This difference arises largely from efforts to honor a recent agreement reached among states in the Western Regional Air Partnership to reduce emissions of SO_2 to combat visibility problems in the west. Our analysis focuses on the range of human health benefits resulting from reduced emissions and considers if moving from a uniform national policy to one with multiple trading regions is likely to increase net benefits.

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[3] Previous research about trading under the SO_2 program has found no hot spot problem (Burtraw and Mansur, 1999; Swift, 2000).

3. The Models

The study employs two distinct modeling components. First, the "Haiku" electricity model simulates electricity consumption, generation, and associated emissions of NO_x, SO_2, and CO_2. The resulting emissions of NO_x and SO_2 feed into an integrated assessment model of atmospheric transport and environmental effects called the Tracking and Analysis Framework (TAF). This model computes the health benefits attributable to the different emissions profiles associated with each Pigouvian tax.

3.1 Haiku Model Description

The Haiku model simulates equilibrium in regional electricity markets and inter-regional electricity trade with an integrated algorithm for SO_2 and NO_X emission control technology choice.[4] The model calculates electricity demand, electricity prices, the composition of electricity supply, inter-regional electricity trading activity, and emissions of key pollutants such as NO_X, SO_2, CO_2, and mercury from electricity generation. The model solves for the quantity and price of electricity delivered in 13 regions, for four time periods (super-peak, peak, shoulder, and baseload hours) in each of three seasons (summer, winter, and spring/fall). For each of these 156 segments, demand is aggregated from three customer classes: residential, industrial, and commercial. Supply is aggregated from the complete set of electricity plants in the United States, which for modeling purposes are aggregated into 48 representative plants in each region. Investment in new generation capacity and retirement of existing facilities are determined endogenously in a dynamic framework, based on capacity-related costs of providing service in the future ("going forward costs"). Generator dispatch in the model is based on the minimization of short run variable costs of generation.

Inter-regional power trading is identified as the level of trading necessary to equilibrate regional electricity prices (accounting for transmission costs and power losses). These inter-regional transactions are constrained by the assumed level of available inter-regional transmission capability as reported by the North American Electric Reliability Council (NERC).

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[4] Haiku was developed by RFF and has been used for a number of reports and articles that appear in the peer-reviewed literature. The model has been compared with other simulation models as part of two series of meetings of Stanford University's Energy Modeling Forum (Energy Modeling Forum 1998, 2001).

Factor prices, such as the cost of capital and labor, are held constant. Fuel price forecasts are calibrated to match EIA price forecasts for 2002 (U.S. EIA 2002). Fuel market modules for coal and natural gas calculate prices that are responsive to factor demand. Coal is differentiated along several dimensions, including fuel quality and location of supply, and both coal and natural gas prices are differentiated by point of delivery. All other fuel prices are specified exogenously.

For control of SO_2, coal burning model plants are distinguished by the presence or absence of flue gas desulfurization (scrubbers). Unscrubbed coal plants have the option to add a retrofit SO_2 scrubber, and all plants select from a series of coal types that vary by sulfur content and price as a strategy to reduce SO_2 emissions. For control of NO_x, each plant solves for the least costly post-combustion investment from the options of selective catalytic reduction (SCR) and selective noncatalytic reduction and reburn. The variable costs of emission controls plus the opportunity cost of emission allowances under cap-and-trade programs are added to the variable cost of generation when establishing the operation of different types of generation capacity. Utilization of each plant is flexible and demand also may respond to changes in price in order to help achieve emission reductions.

3.2 TAF Description

The output of the Haiku model is emissions of each pollutant by a representative plant within each of 13 NERC subregions. The emissions are allocated to actual plant locations (latitude and longitude) based on an algorithm that reflects historic utilization and the expected location of new investment. Changes in emissions of SO_2 and NO_X that result from the policies are aggregated to the state level and fed into TAF, a nonproprietary and peer-reviewed integrated assessment model (Bloyd et al., 1996).[5] TAF integrates pollutant transport and deposition (including formation of secondary particulates but excluding ozone), human health effects, and valuation of these effects at the state level. Although our version of the model limits benefits only to particulate-related health impacts, these impacts account for the vast majority of all benefits according to the major integrated assessment studies of the impacts of electricity

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[5] TAF was developed to support the National Acid Precipitation Assessment Program (NAPAP). Each module of TAF was constructed and refined by a group of experts in that field, and draws primarily on peer-reviewed literature to construct the integrated model. TAF was subject to an extensive peer review in December 1995, which concluded "TAF represent[s] a major advancement in our ability to perform integrated assessments." (ORNL, 1995.) The entire model is available at www.lumina.com\taflist.

generation (Krupnick and Burtraw, 1996) and according to the other models cited in the previous section.

Pollution transport is estimated from seasonal source-receptor matrices that are a reduced-form version of the Advanced Source Trajectory Regional Air Pollution model, which uses 11 years of wind and precipitation data to estimate the variability of model results on the basis of climatological variability. In aggregating to the state level, the source-receptor matrix is calibrated to represent average effects observed in more disaggregate models. The model captures atmospheric chemistry as NO_x and SO_2 react to form nitrates and sulfates, which are constituents of particulate matter less than 10 microns in diameter (PM_{10}). It estimates concentrations of these separate constituents of PM_{10} plus residual NO_2 and SO_2.

Health effects are characterized as changes in health status predicted to result from changes in air pollution concentrations. Effects are expressed as the number of days of acute morbidity effects of various types, the number of chronic disease cases, and the number of statistical lives lost. The health module is based on concentration-response functions found in the peer-reviewed literature, including epidemiological articles reviewed in EPA's Criteria Documents that, in turn, appear in key EPA cost-benefit analyses (U.S. EPA, 1997a; U.S. EPA, 1999). The health effects modeled include, for particulates, premature mortality, chronic bronchitis, chronic cough, acute bronchitis cases, upper respiratory symptoms, cough episodes, and croup; for SO_2, they include chest discomfort and cough episodes; and for NO_2, they include eye irritation and upper respiratory symptoms.

Of these effects, mortality effects are the most important. To characterize these effects we use a cross sectional study by Pope et al. (1995). While this study and others have documented the separate effects of PM_{10}, $PM_{2.5}$ and sulfates (a constituent of $PM_{2.5)}$ on mortality, none have documented the specific effect of nitrates. Accordingly, we use the separate Pope et al. estimates for the potency of sulfates, but assume that nitrates have the potency of the average PM_{10} particle.

TAF assigns monetary values (taken from the environmental economics literature) to the health-effects estimates produced by the health-effects module. The benefits are totaled to obtain annual health benefits for each year modeled. For the most important aspect, the valuation of a statistical life, we have used an estimate of $2.25 million (1999 dollars) from a recent meta-analysis by Mrozek and Taylor (2002) of 203 hedonic labor-market estimates. This estimate is somewhat lower than that used in most previous work and less than half of the $6.1 million estimate used by EPA (1997a, 1999). The most important reason for this discrepancy is the attribution of wage rate differentials to mortality rate differences in previous studies cited by EPA, while Mrozek and Taylor attribute a larger portion of the wage rate differentials to inter-industry differences that occur for other reasons.[6]

As with past research, values for chronic morbidity effects (e.g., emphysema) are transferred from individual studies, often using a conservative cost-of-illness approach. Values for acute effects are predicted from the meta-analysis of Johnson et al. (1997), which synthesized contingent valuation studies of morbidity effects based on their severity according to a health-status index and other variables.

3.3 Iterative Algorithm

Using these models, we apply successive emission fees for SO_2 and NO_x to the U.S. electricity sector.[7] For each level of the fee, we use the Haiku model to estimate the response in electricity markets and the emission levels of each pollutant. Since profit-maximizing firms set their marginal cost of abatement equal to the emission fees, the resulting schedule is the marginal cost of abatement. We approximate the marginal cost curve by linearly interpolating the abatement levels between each successive pair of marginal costs.

The TAF model estimates the total damages from pollution at each fee level. As the fee is increased by one increment, emissions and damages decrease, giving the incremental benefits

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[6] There may be other reasons to suspect that the traditional values are too high. Labor market studies rely on the preferences of prime-age, healthy working males facing immediate and accidental risks of workplace mortality. In contrast, particulate pollution primarily affects seniors and people with impaired health status, and may occur years after initial exposure. This recognition has led to attempts to estimate values for life extensions (Johnson et al., 1998) and future risks (Alberini et al., 2002). New surveys that use contingent valuation to describe mortality risk reductions in a more realistic health context and that are applied to people of different ages and health status, find that the implied VSLs are far smaller than EPA's estimates, particularly for future risk reductions (Alberini et al, 2002). However, the effects do not appear to be strongly related to age and, although many conjecture that poor health status would reduce willingness to pay, the study finds people in ill health tend to be willing to pay more for mortality risk reductions than people in good health. On the other hand, effects of dread and lack of controllability have not yet been factored into these new analyses.

[7] Specifically, for the case of NO_x, we set marginal costs at \$0; \$700-\$1,500 in increments of \$100; \$1,700; \$1,900; \$2,200; and \$2,500, with the SO_2 tax held at \$3,000. For the case of SO_2, we set marginal costs at \$0; \$500-\$2,000 in increments of \$500; \$2,400; \$2,600-\$4,100 in increments of \$1,000; and \$4,500-\$6,500 in increments of \$500, with the NO_x tax held at \$900. The points were chosen to provide the most precision around the likely intersection of the marginal benefits curve, with less data in the tails.

of the emission reductions. Thus, we similarly trace a marginal benefit curve, estimated as a step function with marginal benefits averaged over each incremental change in emissions.

The intersection of these two curves is a static estimate of the second-best efficient level of pollution taxes or caps. This interpretation requires two important caveats. Although the electricity model provides a multi-year simulation, we estimate the efficient level of pollution in a single year (2010). The cost curve is derived dynamically under the assumption that pollution levels are constant over time. This level may not be consistent with the optimal path of pollution over time, since achieving it may require high costs relative to benefits in other years. While the ideal information would be the optimal dynamic path of pollution levels over time, such information is beyond the scope of this research. Second, the level of pollution estimated is second-best in the sense of being conditional on a single, national policy instrument. However, it also ignores consideration of market structure that would adjust the Pigouvian estimate to account for differences between price and marginal cost (Burtraw et al. 1997, Burtraw and Krupnick 1997).

3.4 Description of Uncertainty Analysis

All of the parameters used in these models are subject to uncertainty. On the benefits side, we quantify this uncertainty by using not only the point estimates of the concentration-response functions and valuation functions, but also the estimated standard errors. We use Monte Carlo methods to simulate a 90% confidence interval for benefits at each level of emissions, drawing repeatedly from distribution of parameters. In addition, we perform sensitivity analyses of the most important subjective judgments, such as the concentration-response function for mortality effects and the choice of the value of a statistical life; these results are given below. Unfortunately, the Haiku model of the electricity sector is too computationally intensive to allow a similar assessment of uncertainty on the production side. Thus, we report only the most-likely estimate of the marginal cost of abatement function.

4. Results

Figure 1 illustrates our approach. It shows the estimated marginal cost and marginal benefit curves for SO_2 over a small range of abatement (7.75 million tons to 8.25 million tons), when NO_x taxes are held at $900. For each level of the emissions tax, emissions are directly observed and presented in terms of abatement relative to an assumed baseline.[8]

The most striking feature of the figure is that, while marginal costs are relatively smooth and upward sloping (as expected), the marginal benefits are erratic. The behavior of the marginal benefits curve follows from the fact that, as the tax on emissions increases, the contribution to abatement at the margin comes from different plants in different geographic locations. For example, over some range of taxes, a southern plant may be at the margin, over another range, an eastern plant may be at the margin. These differences, in turn, have implications for benefits estimation because the exposed population differs.

In principle, the nonconvexity of benefits creates some difficulty in finding the efficient point since, rather than comparing marginal benefits and marginal costs, one must compare total benefits and total costs to find an optimum. However, while we have no doubt that such jumps exist in the schedule of benefits from national pollution abatement, the precise locations of the jumps are almost certainly an artifact of the model. Accordingly, it is more appropriate to focus on the trend in benefits as emissions are decreased. Consequently, we smooth the marginal benefit and marginal cost curves using a nonparametric, locally linear regression technique.

Figures 2a and 2b show the smooth estimated marginal benefits and marginal cost curves, with the 90% confidence intervals on the benefits curve, for SO_2 and NO_x reductions, respectively.[9] In each of these figures, the horizontal axis ends at a point equal to the total amount of emissions of the relevant pollutant in the baseline in 2010. These figures form the

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[8] As a baseline, we assume implementation of the summertime NO_x SIP Call trading program in 2004 in 19 eastern states and the continuation of the Title IV SO_2 cap-and-trade program. We assume no additional regulations affecting mercury or CO_2 and no additional enforcement of new source review beyond settlements already announced. We assume limited restructuring of the electricity sector with retail competition in about half of the country.

[9] In Figure 2a, the NO_x fee is held constant at $900. In Figure 2b, the SO_2 fee is held constant at $3,000. The basic pattern in these figures, and the conclusions below about optimal emissions caps, are not susceptible to the choice of fee for the other pollutant nor to the bandwidth in the smoothing function.

core of the analysis. We use them to discuss, in turn, the efficient level of abatement, regional differences and other patterns in benefits, and the factors contributing to the costs of abatement.

4.1 Efficient Tax Levels

The central issue of the analysis is the efficient level of pollution abatement. In the case of SO_2 (Figure 2a), the central estimate of marginal benefits equal marginal costs at $3500, or about 1.1 million tons of national SO_2 emissions in the year 2010 (8 million tons of abatement). The uncertainty introduced on the benefits side would suggest a range from about $1800 to $4700, or 0.9 million tons to 3.1 million tons of SO_2 emissions. By comparison, the Jeffords and Bush administration proposals ultimately would limit emissions to about 2.25 million and 3 million tons respectively. Thus, the aggressive targets in these proposals appear to be well justified from the perspective of economic efficiency. Indeed, the proposed emission levels are at the higher end of the range estimated by our research, and the most-likely estimate suggests that an efficient target would be even more stringent than these proposals.

Figure 2b illustrates the marginal benefits and marginal costs of reducing NO_x emissions. Uncertainty in the benefits measures induces an estimated range of efficient emission fees between $700 and $1200, or emission levels between 1.0 million tons and 2.8 million tons. Thus, at 1.5 and 2.1 million tons respectively, both the Jeffords and Bush proposals are within the range of emissions that can be supported by current knowledge. However, the figure shows that both the marginal benefit and cost curves are fairly flat and move together over a range of data, making the precise placement uncertain. Marginal costs intersect our most-likely estimate of marginal benefits at $800 and 2.6 million tons of emissions, in a trough in the marginal benefits curve. Discounting this trough and using the right-hand side of the overlapping range would yield an efficient point of $1100 and 1.3 million tons of emissions. In the discussions that follow, such as the abatement technologies utilized under these policies, we use this latter point as the most likely efficient tax level for NO_x. While an argument could be made for any point in this range, the potential importance of other effects from NO_x pollution such as ozone formation, acid deposition, and impacts on agriculture and silviculture, which were omitted from our formal analysis, suggest leaning toward the more stringent side of the range.[10]

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[10] U.S. EPA (1998b) estimates benefits to agriculture and silviculture from reduced NO_x emissions to be $325 and from reduced acid deposition to be $300 per ton.

4.2 Benefits

As shown in the figures, after smoothing, the marginal benefits curves are fairly flat for both pollutants. This pattern should be interpreted with caution, however, since, for any given improvement in local air pollution, the model uses linear approximations for the reduction in health effects and constant per-health-effect economic values. Thus, by construction, any given source of pollution must have near-constant marginal benefits of abatement (although seasonal variation in the timing of emissions is more relevant in the model due to differences in atmospheric transport of pollution over seasons). However, the pattern suggests that, while there may be abrupt shifts in the source of pollution over small ranges of the data (Figure 1), there is no long-term trend across regions of the country that affects aggregate benefits.

4.2.1 Regional Differences

On a disaggregated basis, however, differences in benefits within and between regions bear further scrutiny. Figure 3 illustrates the sum of benefits that accrue everywhere in the nation for a reduction in 1 ton of SO_2 emissions from each state measured against the baseline. Changes in emissions in California, the Carolinas, Tennessee, and Kentucky are the most potent with respect to economic benefits because they lead to changes in exposure for a large population. In contrast, emissions in the western states (save California) have the lowest impacts. These differences in the geographic location of the marginal source of emission reductions at each level of emission fee account for the large shifts in marginal benefits illustrated in Figure 1 prior to smoothing the benefits function.

Figure 3 also illustrates the potential usefulness of segregating the emission allowance trading market into separate regions (Kolstad 1987). The natural divide separating the relative harm to public health from emissions in the east and west due to differences in population density suggest that one would want to design a policy that incurred appropriately scaled marginal costs. On efficiency grounds, a region with large marginal benefits from emission reductions would justify high marginal costs associated with a strict target, while other regions might be assigned a more relaxed emission target. To a small degree, the Jeffords and Bush administration proposals both make an effort to accommodate these differences in idiosyncratic ways by imposing regionally specific caps (albeit each does so for only one of the pollutants). The welfare improvement that results from relaxing the restriction of a national standard to two or more standards remains an open empirical question.

In addition to geographical differences in the source of emissions, the geographical differences in the recipient of damages/benefits remain an important political issue. One criticism of cap-and-trade approaches to pollution abatement is that, without additional constraints, a cluster of pollution sources may become net purchasers of pollution permits, thereby increasing pollution concentrations in some areas and creating pollution "hot spots," as discussed previously. Figure 4 shows the reduction in SO_2 emissions in each state as a result of adopting the efficient SO_2 cap of 1.1 million tons. All states would reduce emissions, with the largest reductions occurring in the industrial Midwest, North Carolina, and Texas. More to the point, Figure 5 shows the change in predicted PM_{10} concentrations in each state resulting from these reduced emissions. (For both figures, the pattern is virtually identical for the NO_x cap.) The figure shows there are no predicted increases in concentrations in any state, and the mid-Atlantic states would enjoy the greatest improvement in air quality, with the northeast, midwest, and southeast states also enjoying large changes. The figure also can be thought of as approximating per-capita health benefits since (for a constant mix of demographic groups) such benefits are proportionate to air quality improvements.

4.2.2 Uncertainty

The results presented above quantify the uncertainty from sampling error in the transferred parameter estimates. However, there also is a broader form of uncertainty in the choice of model used in these studies, such as the relationship between particulate concentrations and health status. To assess this uncertainty, we perform additional sensitivity analyses. First we consider the consequences of transferring alternative concentration-response relationships between particulates and mortality. For example, if instead of using a separate estimate for sulfates we had used the same concentration-response for all particulates (still from the cross-sectional Pope et al. 1995 study), average per-ton SO_2 benefits would have been 9% lower (NO_x benefits being unchanged). On the other hand, if we had used one of the many time-series studies, per ton benefits of abatement would have been much lower. For example, using the concentration-response function from a meta analysis of 13 studies reported in Desvousges et al. (1998, Ch. 4), per ton benefits would have been 57% lower for SO_2 and 30% lower for NO_x. This adjustment would lead to optimal SO_2 emissions of 5.5 million tons, much higher than the central estimates, and NO_x emissions of 2.8 million tons, still within the 90% confidence interval.

Second, we consider the consequences of transferring alternative values of a statistical life from other studies. As noted above, the Mrozak and Taylor meta analysis of labor market studies estimates a fairly low value of about \$2.25 million. In contrast, using EPA's value of \$6.1 million would have more than doubled the per-ton benefits for both SO_2 and NO_x. For both pollutants, the higher value for a statistical life would put the best estimate of the efficient level of emissions at approximately the low end of the 90% confidence interval discussed above (more precisely, at 0.7 million tons SO_2 emissions and 1.0 million tons NO_x emissions). Thus—with the exception of the SO_2 emissions consistent with the time-series mortality estimates—the respective 90% confidence intervals approximately bracket the ranges induced by any of these subjective judgments.

4.3 Costs

There are three ways to imagine that emission reductions can be achieved. One is the installation of post-combustion controls, or through process changes at the power plant (abatement). The second is a change in the choice of fuel for electricity generation (input substitution). The third is a reduction in total generation and electricity consumption (output substitution).

SO_2 emissions are reduced using all three methods. Table 1 reports values for several variables under the efficient policy, including the efficient SO_2 and NO_x emission fees, and the percentage change in these variables from the baseline. The efficient fee of \$3,500 per ton SO_2 causes the installation of more than 160,000 MW of additional retrofit scrubbers. Most of this capacity comes in at fee prices above \$1,000 per ton and basically all of this capacity is already installed with a fee of \$2,600 per ton in the model. Note that in Figure 2a, after the fee reaches \$2,600, the marginal cost curve becomes markedly steeper, suggesting additional controls are not economically feasible and tax payments increase more rapidly instead. Under the efficient policy, the annual cost of the controls is about \$7.5 billion.

There also is a significant amount of shifting from high- to low-sulfur coal, which plays an especially important role for fees less than \$1,000 per ton. Figure 6 illustrates the quantity of delivered coal for electricity generation at each level of the SO_2 fee. Between 0 and \$1,000 fees, the amount of low-sulfur coal used almost doubles to substitute for high-sulfur coal. Also, there is a small increase in the total tonnage of delivered coal because low-sulfur coal has a lower heat content per ton. The baseline quantity of low sulfur coal (not shown in the figure) is one-third of the way from the level observed at \$0 and the level observed at \$1,000, reflecting the incentives of the existing SO_2 emissions cap under Title IV.

At an emission fee greater than \$1,000, where there is significant investment in retrofit scrubbers, there also is an incentive to revert to using higher-sulfur coal. Scrubbers remove about 95% of the SO_2 emissions and, given this removal efficiency, it is less worthwhile to pay the higher price for low-sulfur coal. However, by the time the fee reaches \$3,000, the opportunities for installing scrubbers is exhausted (Figure 2a) and further reductions must be achieved by switching again to low sulfur coal, even at units with SO_2 scrubbers. The efficient fee policy with a SO_2 fee of \$3,500 would lead to consumption of about 1 billion tons of low-sulfur coal.

The switching between coal and natural gas begins to be potent at \$1,000 per ton, which is the point where switching among coal types (from high to low sulfur coal) becomes insufficient for compliance. Figure 7 illustrates the percent change in generation from coal, natural gas, and the change in total generation for a wide range of SO_2 fees compared to the baseline.[11] At the efficient fee, coal-fired generation is at 93% of its level in the baseline, while gas-fired generation is at 115% of its baseline level (see also Table 1). The elasticity of coal's share of total generation with respect to the SO_2 fee is –0.04.[12] The sensitivity of the relative factor intensity of coal and natural gas with respect to a change in the SO_2 fee is –0.11. Even under the efficient policy, coal-fired generation accounts for roughly half of total generation.

The third way to achieve emission reductions is through a reduction in total generation, which results from an increase in electricity price. The change in electricity price due to the change in the SO_2 emission fee is illustrated in Figure 8, with an elasticity of –0.04. Although a response in electricity price is clear, the change in price is small, and thus total generation declines by only a small amount, as illustrated previously in Figure 7. The elasticity of total generation with respect to electricity price averages –0.28. At the efficient fee, total generation

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[11] As noted previously, the NO_x fee is assumed to be \$900 per ton for most of the simulations. With a low SO_2 fee, the generation from coal actually increases relative to the baseline, which includes the SO_2 trading program with an allowance price of \$102/ton in 2010 and the seasonal, regional NO_x trading program in the SIP region with allowance prices of \$1,730 per ton.

[12] All reported elasticity values are average (arc) elasticity estimates over the range from a zero SO_2 fee to the efficient fee. The coefficient estimates on a constant elasticity function over the same range are very similar.

is reduced by just over 1% from the baseline level (Table 1), with an elasticity with respect to the SO_2 fee of –0.01.

Reductions in NO_x emissions are primarily due to the increased utilization of existing post-combustion controls and the installation of additional controls, with less of a role for fuel switching or demand reduction than occurs with the SO_2 fee. The baseline policy already has a substantial amount of post-combustion control in place due to the requirements of the NO_x SIP Call, but those controls are only run on a seasonal basis.[13] The fees we model apply during the entire year, leading to year-round utilization of existing controls. About 108 GW of additional post-combustion controls are installed under the efficient policy compared to the baseline. The vast majority of post-combustion NO_x controls—roughly 90%—is SCR, and this holds for a wide range of fees up to the efficient level of $1,100. For NO_x fees above $1,100, the share of NO_x controls that is SCR grows to be as high as 95%. Note again that, after this point, the marginal cost of abatement becomes almost vertical in Figure 2b.

There is very little switching from coal to natural gas as a form of compliance for achieving NO_x reductions. Holding the SO_2 fee constant, the amount of switching is noisy at different levels of the NO_x fee but it hovers around 1% of gas-fired generation in the baseline. There is little fuel switching to gas because, although gas-fired generation has no SO_2 emissions, it has only slightly fewer NO_x emissions than the controlled rate for coal-fired generation. Also, electricity prices are less responsive to the NO_x fee than to the SO_2 fee, so there is little change in total generation in response to the NO_x fee.

Electricity price includes transmission and distribution costs, which are affected by the emission fees in only a small way. Almost all of the change in electricity price is due to the change in generation cost. While average electricity price increases by 4%, the average contribution of generation cost to electricity price increases by 12%. The SO_2 emission fees contribute 2.3% to generation cost, and the SO_2 emission controls contribute 4.6% to generation cost.[14] The NO_x emission fees contribute just less than 1% of generation cost, and the NO_x

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[13] The utilization, on an annual basis, of NO_x controls that exist in the baseline would yield increased net benefits compared to the seasonal program (Burtraw et al., 2001b; Burtraw et al., 2002).

[14] The manner in which these items contribute to costs depends on the way prices are set. In regions with regulated prices, these items contribute to total costs that are averaged over electricity sales. In regions with competitive prices, the electricity price is affected to the degree these costs are incurred by the marginal generator or reserve unit.

emission controls contribute 2.7% of generation cost. Not all of these costs are new under the efficient fee policy because of pre-existing permit trading programs in the baseline and pre-existing controls for SO_2 and NO_x. Roughly speaking, the efficient fees would lead to a doubling of the costs of pollution and pollution control in electricity generation.[15]

4.3.1 Ancillary Reductions in CO_2

The efficient fees for SO_2 and NO_x emissions lead to changes in technology and fuel for electricity generation, as well as a reduction in demand, that yields ancillary reductions in CO_2 emissions. We describe these reductions as ancillary because there is no regulation of CO_2 in this analysis.

Compared to the baseline, CO_2 emissions fall by 4.9% or 152 million short tons in 2010 (Table 1). The SO_2 emission fee leads to the larger share of emission reductions. Figure 9 illustrates the change in CO_2 emissions as the SO_2 emission fee is increased, holding the NO_x emission fee constant. The elasticity of CO_2 emissions with respect to the SO_2 fee is about -0.04. The reductions in CO_2 are due to the substitution of natural gas for coal in electricity generation and, secondarily, to the reduction in overall electricity demand. The relationship between CO_2 emissions and the NO_x emission fee is noisier, as was the relationship between electricity price and the NO_x fee. There is, on average, only a modest reduction in CO_2, because there is little change in electricity price and overall demand, and little change in the choice of fuel as a consequence of the NO_x fee.

5. Summary and Conclusion

The ongoing policy debate surrounding recent congressional proposals to cap emissions of multiple pollutants, including SO_2 and NO_x, from the electricity sector begs the question of the level at which these emissions should be capped. From the perspective of economic efficiency,

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[15] The cost of existing controls is commingled with capital costs in our model. Extrapolating the capital and operating costs of the new controls to existing controls implies pollution controls for SO_2 and NO_x of \$1.47/MWh in the baseline, compared to \$2.96/MWh with the efficient fees. In fact, the cost of controls has fallen and the capital cost of previous controls was greater than those shown for the choice of compliance in the model. Furthermore, other costs—such as fuel washing, low NO_x burners, and controls on direct particulates—are already widely used but not included in these estimates. The opportunity cost of emissions is reflected in permit costs of \$0.5/MWh in the baseline, and they are reflected in emission fees of \$1.3/MWh under the efficient fee policy. The cost of fuel switching is not included in these estimates.

the answer is that level at which the marginal benefits of further emission reductions are offset by the marginal costs.

We use the Haiku electricity model and the TAF integrated assessment model to identify these levels. We find that the efficient emission fee for SO_2 is between \$4,700 and \$1,800 per ton, which will yield between 0.9 and 3.1 million tons of emissions in the year 2010. For NO_x, the best estimate of the efficient emission tax lies between \$1,200 and \$700 per ton, which yields emissions of between 1.0 and 2.8 million tons. In comparison, the emission targets of the Bush administration and Jeffords proposals are in the higher end of the range estimated by our research for SO_2, and closer to the middle of the range for NO_x. In general, our results suggest the emission caps included in the congressional and administration proposals are within the range of emissions that can be supported by current knowledge.

Reductions in SO_2 emissions are achieved through a mix of responses to the emissions fee, including fuel switching among types of coal and from coal to natural gas, increased retrofitting of existing coal-fired capacity with SO_2 scrubbers, and a small reduction in electricity demand. Most of the emission reductions for complying with the efficient NO_x cap come from installing post combustion controls, the majority of which is SCR. Considered individually, there is little fuel switching that results from the NO_x fees. When considered in tandem, the efficient policies lead to an increase in average electricity price of 4% and total electricity demand decreases by about 1%. The fuel switching to natural gas and the small reduction in electricity demand, most of which is attributable to the SO_2 fee, produces ancillary reductions in CO_2 emissions of almost 5% of baseline levels in 2010 under the efficient policy.

Our findings are subject to three important caveats. First, as noted previously, we estimate only the static efficiency for a single point in time (2010), rather than an optimal path over time. Second, we do not include restrictions on mercury emissions in the analysis and these restrictions are included in both legislative proposals. Imposing caps on mercury will change the opportunity costs of reducing emissions of both pollutants. For SO_2, the costs will tend to shift down and this suggests that the optimal level of the SO_2 cap could be even lower than suggested here when mercury restrictions are taken into account. Third, we also do not consider the effects of a constraint on CO_2 emissions, which is a feature of the Jeffords bill. Because there are no post-combustion control options for reducing CO_2, a constraint on CO_2 emissions would lead to more fuel switching from coal to natural gas. For SO_2, we suspect that introducing a CO_2 cap would lower the opportunity costs of control and, consequently, the level of the optimal cap below that indicated in this analysis.

Our results suggest two potential modifications of basic national cap-and-trade programs, modifications that are, to some extent, present in the two main proposals. The first is a finer geographic resolution to the trading program. We find there is substantial regional variation in the benefits per ton that are achieved by reducing pollution, suggesting that a regionally differentiated policy could yield greater net benefits than a uniform national policy. In a national policy, pollution permits trade at a one-to-one ratio; in a regionally differentiated policy, region-specific permits would trade within the region at a three-to-two ratio, but across regions at a ratio set to the estimated ratio of marginal benefits (damages from pollution). For example, as shown in Figure 3, western sulfur permits might trade in a two-for-one ratio with eastern permits. In contrast, the Bush and Jeffords proposals each have separate regions for one or another of the pollutants, but do not include trading across regions.[16] Nonetheless, our analysis suggests that the efficient national emissions cap produces significant decreases in both nitrate and sulfate particulate concentrations in every state compared to the baseline.

The second potential modification is a hybrid tax and permit policy. As shown in Figure 2a, the marginal costs of sulfur abatement around the efficient point are very steep. In such a setting, taxes are more efficient than cap-and-trade mechanisms when there is some uncertainty in the marginal cost of abatement (Weitzman 1974), which is very likely over the large range of abatement contemplated. However, cap-and-trade policies are generally more realistic measures politically. A hybrid mechanism that allocates permits and then allows additional taxed emissions beyond the permit level (Roberts and Spence, 1976), would achieve both advantages.[17] It would also prevent ruinously high costs to industry in the event that the marginal cost curve is understated. Such a hybrid mechanism is included in the Bush proposal.

Even without such embellishments, the tradable permits for SO_2 introduced in the 1990 Clean Air Act Amendments have brought air pollution policy closer to an efficient, least-cost way to achieve a given pollution target. Our research suggests that tightening those targets and introducing a national aggregate cap for NO_x, along the magnitudes suggested in the current debate, would come close to achieving an efficient level of pollution as well.

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[16] The Jeffords proposal also allows for the possibility of nonuniform trading ratios when upwind sources are found to affect areas that fail to attain national ambient air quality standards.

[17] Pizer (2001) has looked at a hybrid policy, often called a "safety valve," in the context of a stock externality.

Figure 1. Example of Marginal Benefits and Marginal Costs of SO_2 Abatement
(NO_x Fee = \$900)

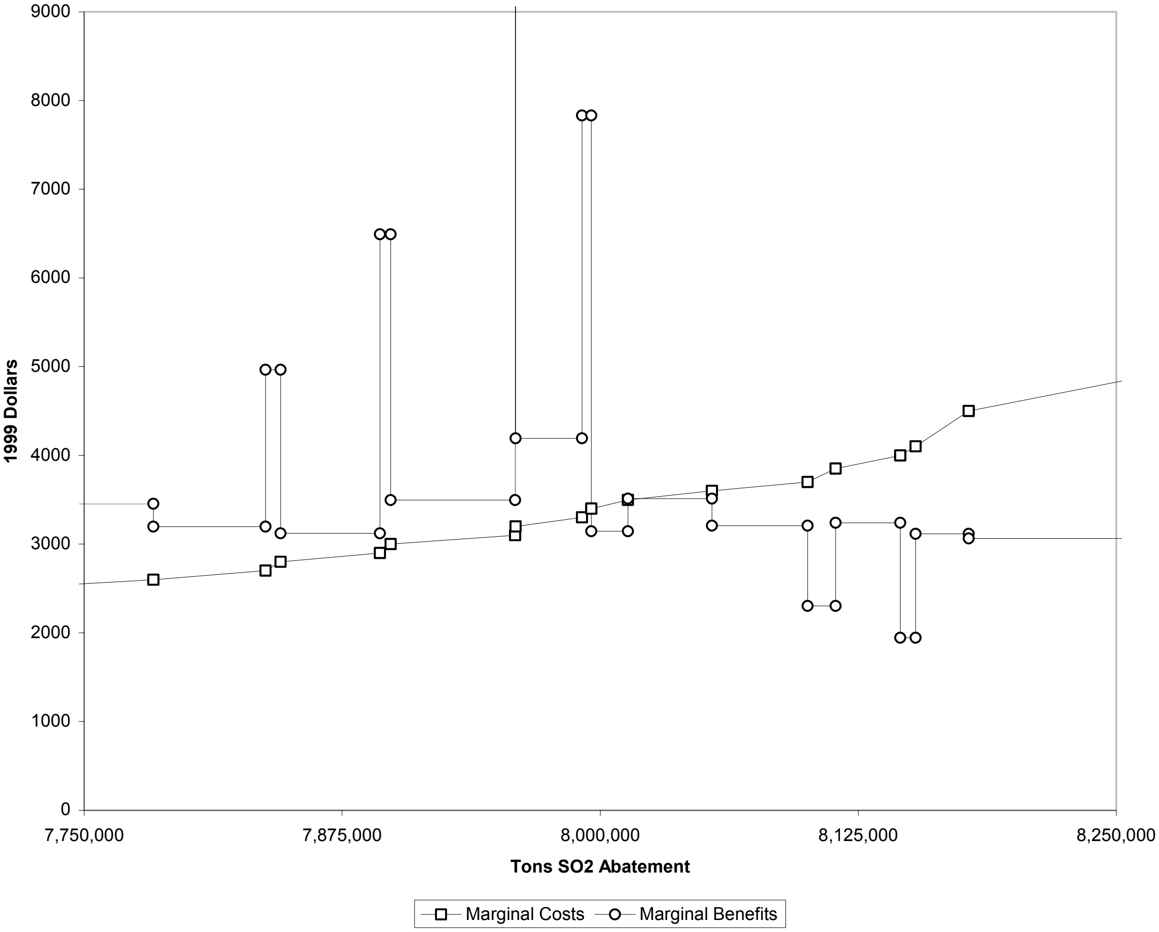
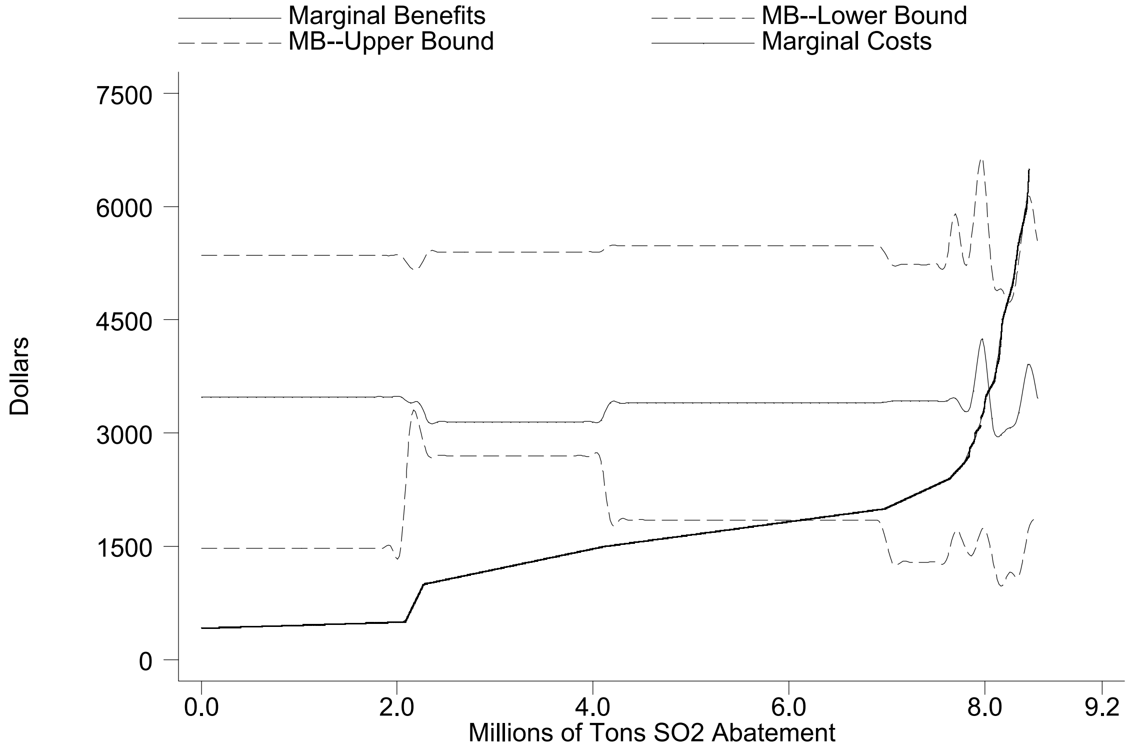


Figure 2a. Smoothed Marginal Benefits and Marginal Costs of SO_2 Abatement



(NO_x Fee = $900)

Figure 2b. Smoothed Marginal Benefits and Marginal Costs of NO_x Abatement (SO_2 Fee = $3,000)

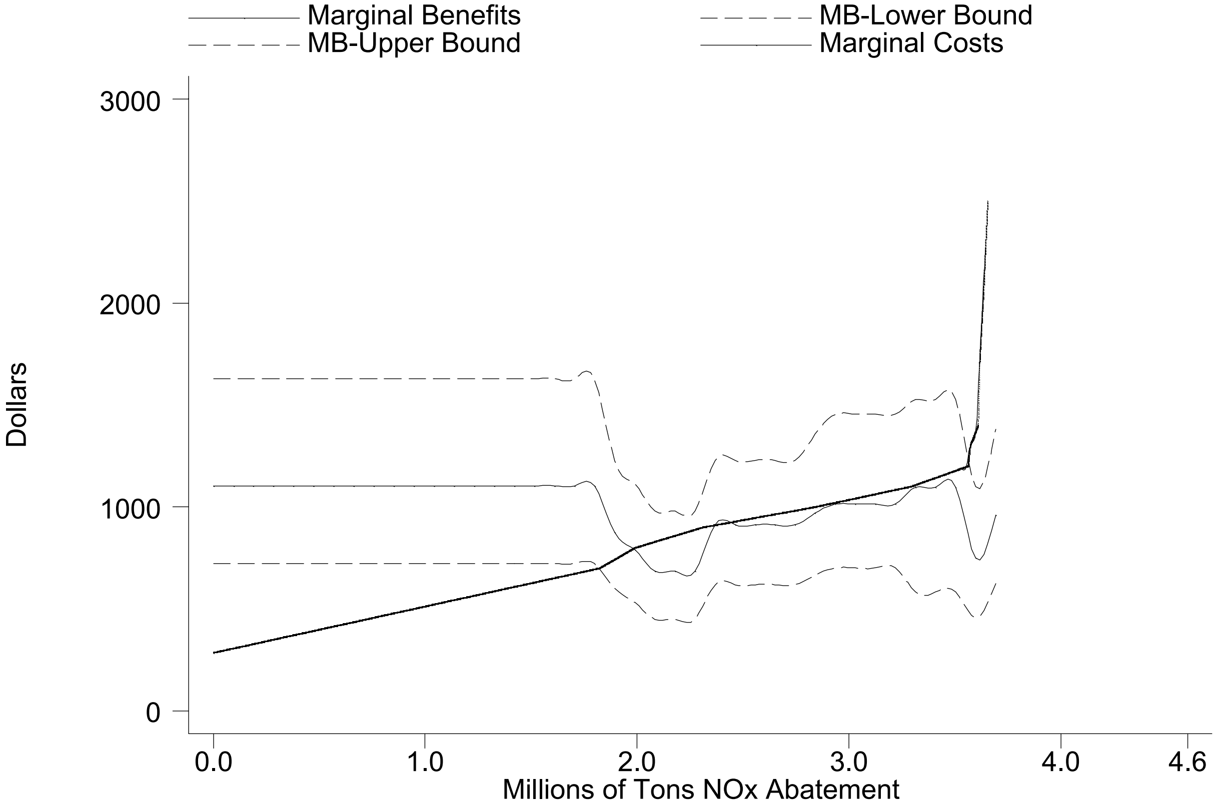


Figure 3. Average Benefits to the Nation Per Ton of Emission Reduction in Each State.

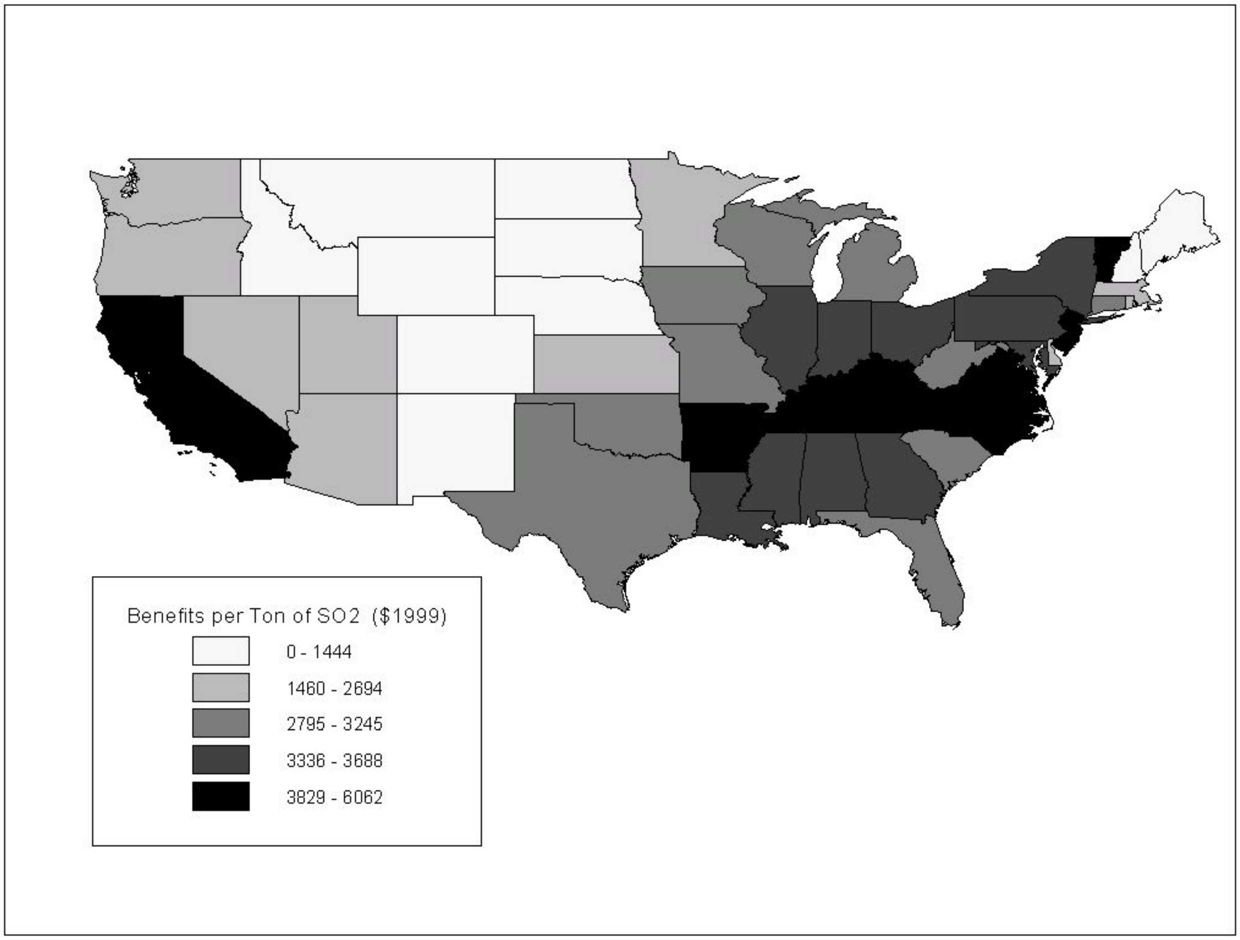


Figure 4. Reduction in SO_2 Emissions by State from SO_2 Cap of 1.2 Million Tons

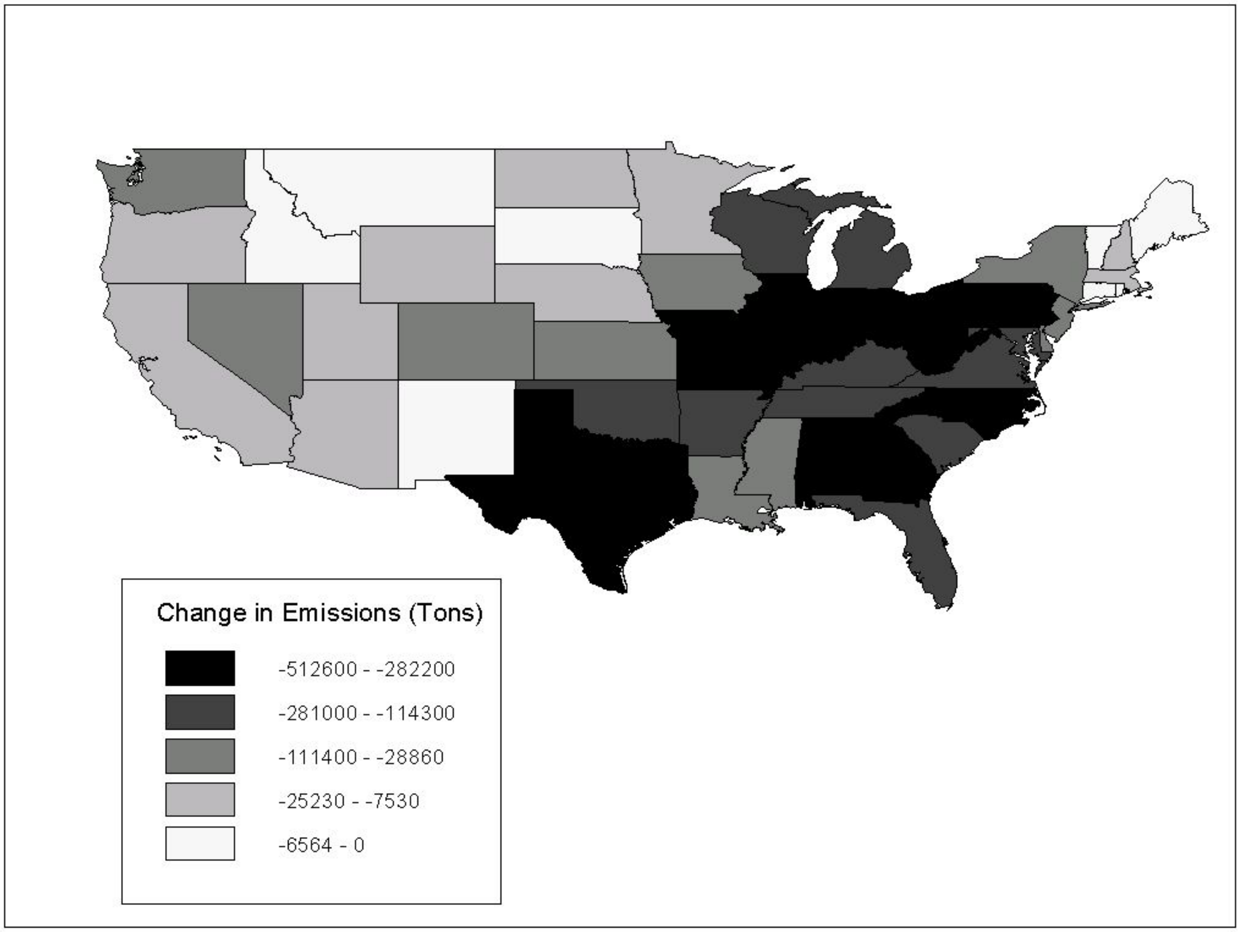


Figure 5. Reductions in PM_{10} Concentrations by State from SO_2 Cap of 1.1 Million Tons

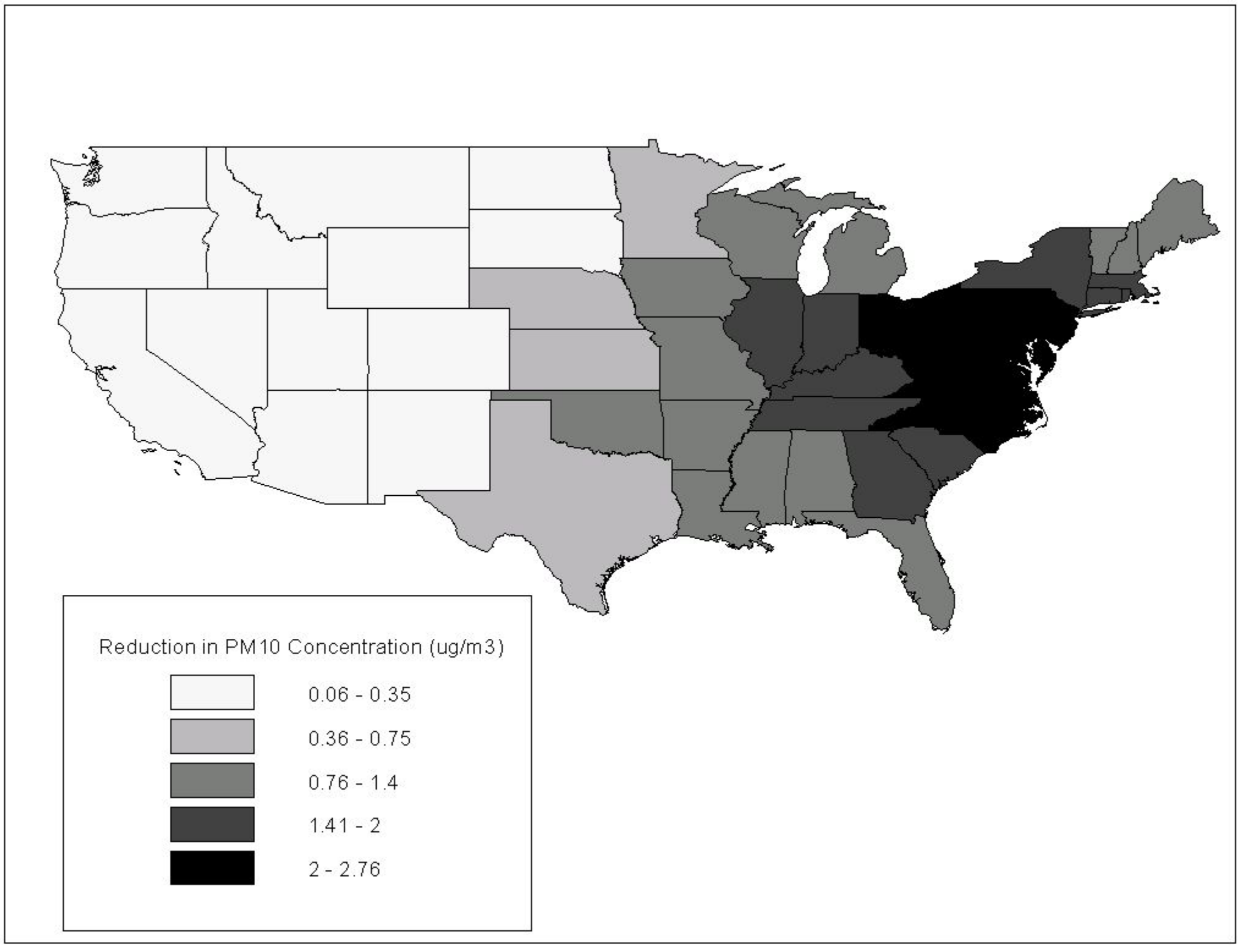


Figure 6. Coal Demand

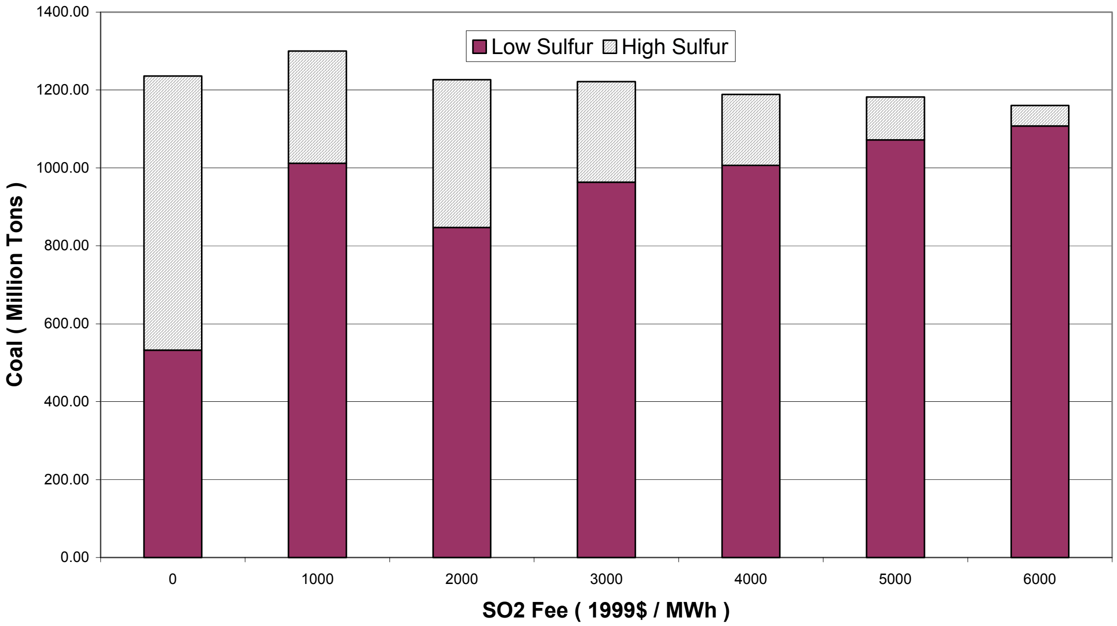


Figure 7. Percent Change from Baseline Generation.

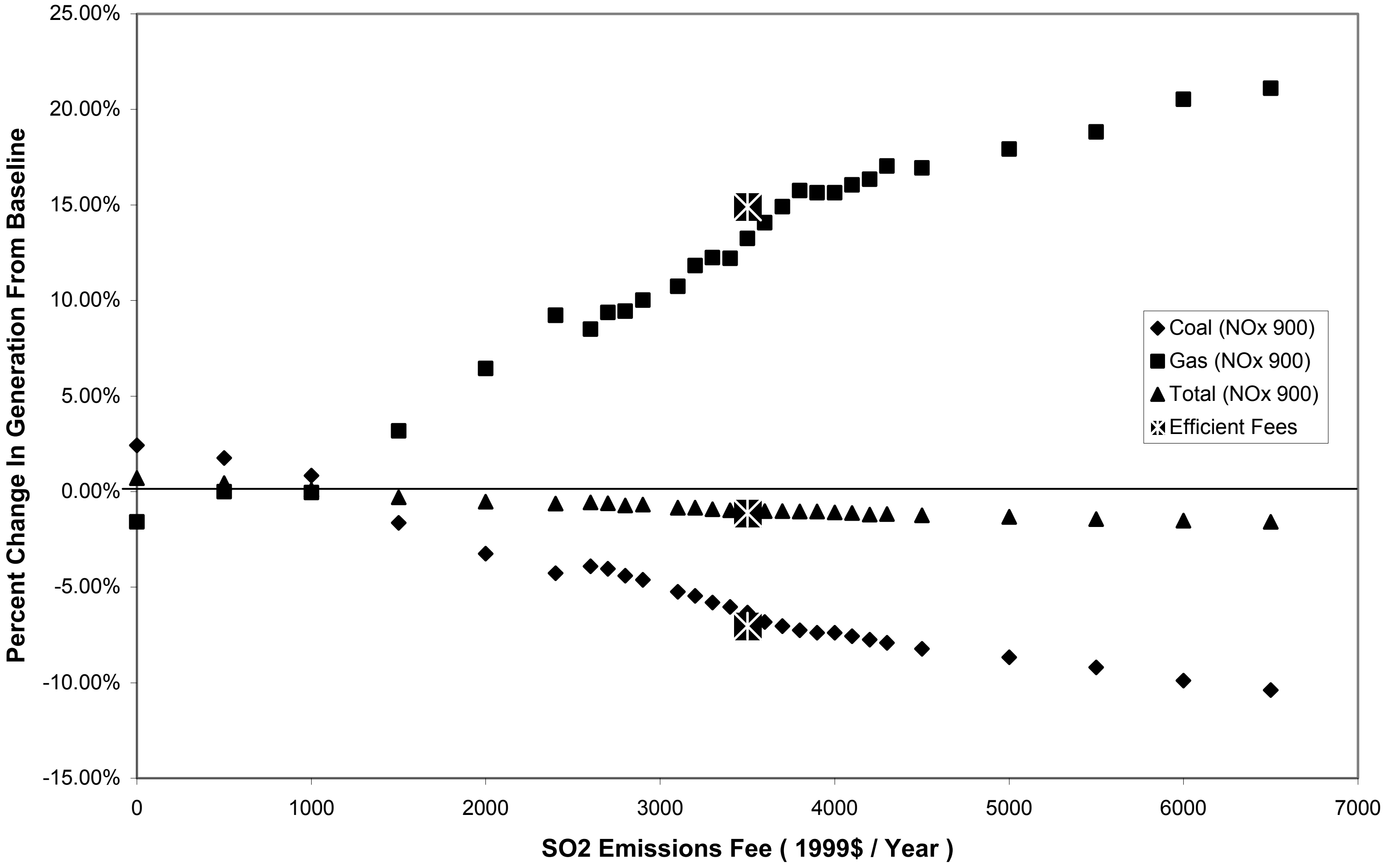


Figure 8. Change in Electricity Price Due to Change in SO_2 Emission Fee.

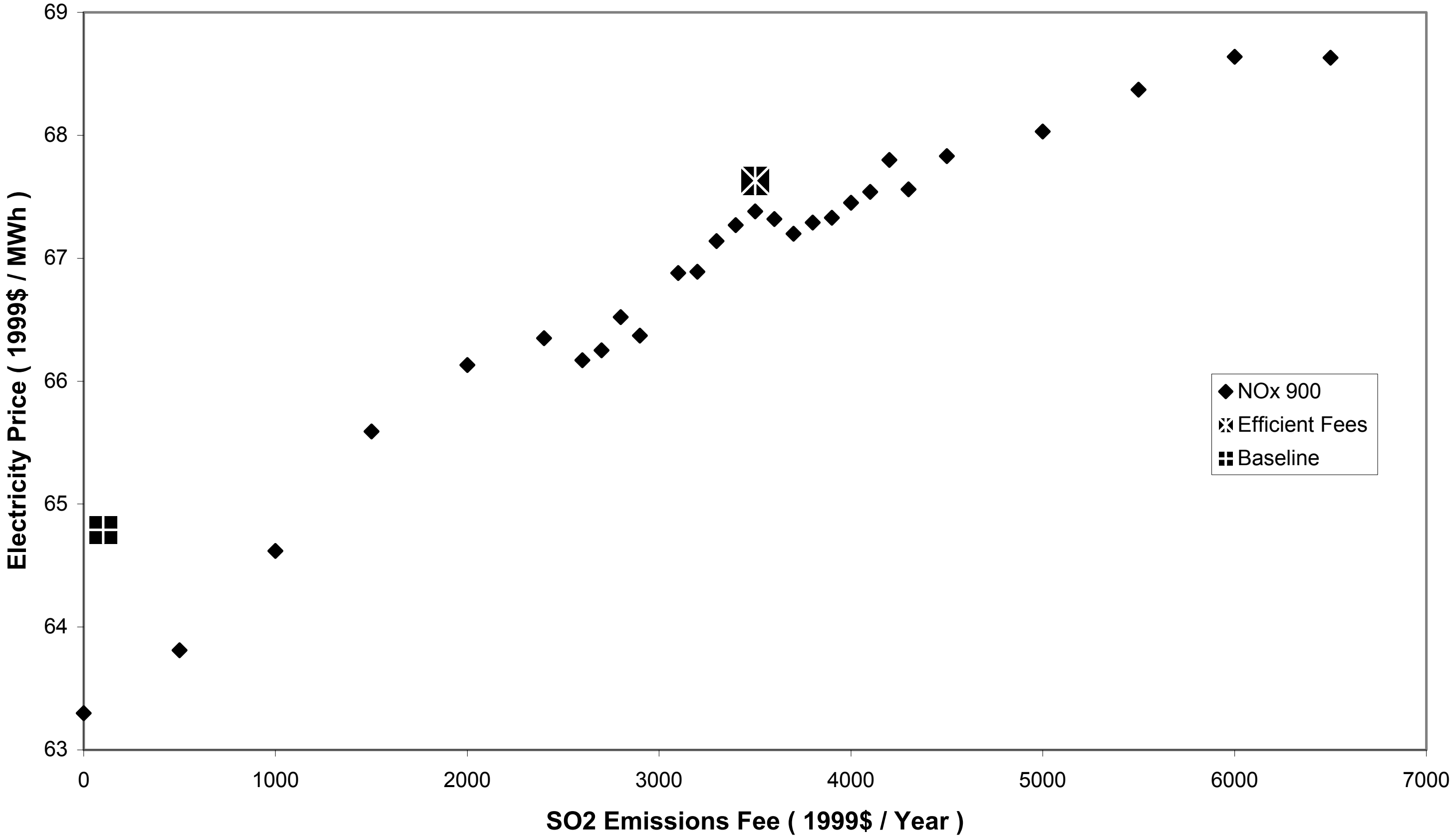


Figure 9. Change in CO_2 Emissions Due to Change in the SO_2 Fee.

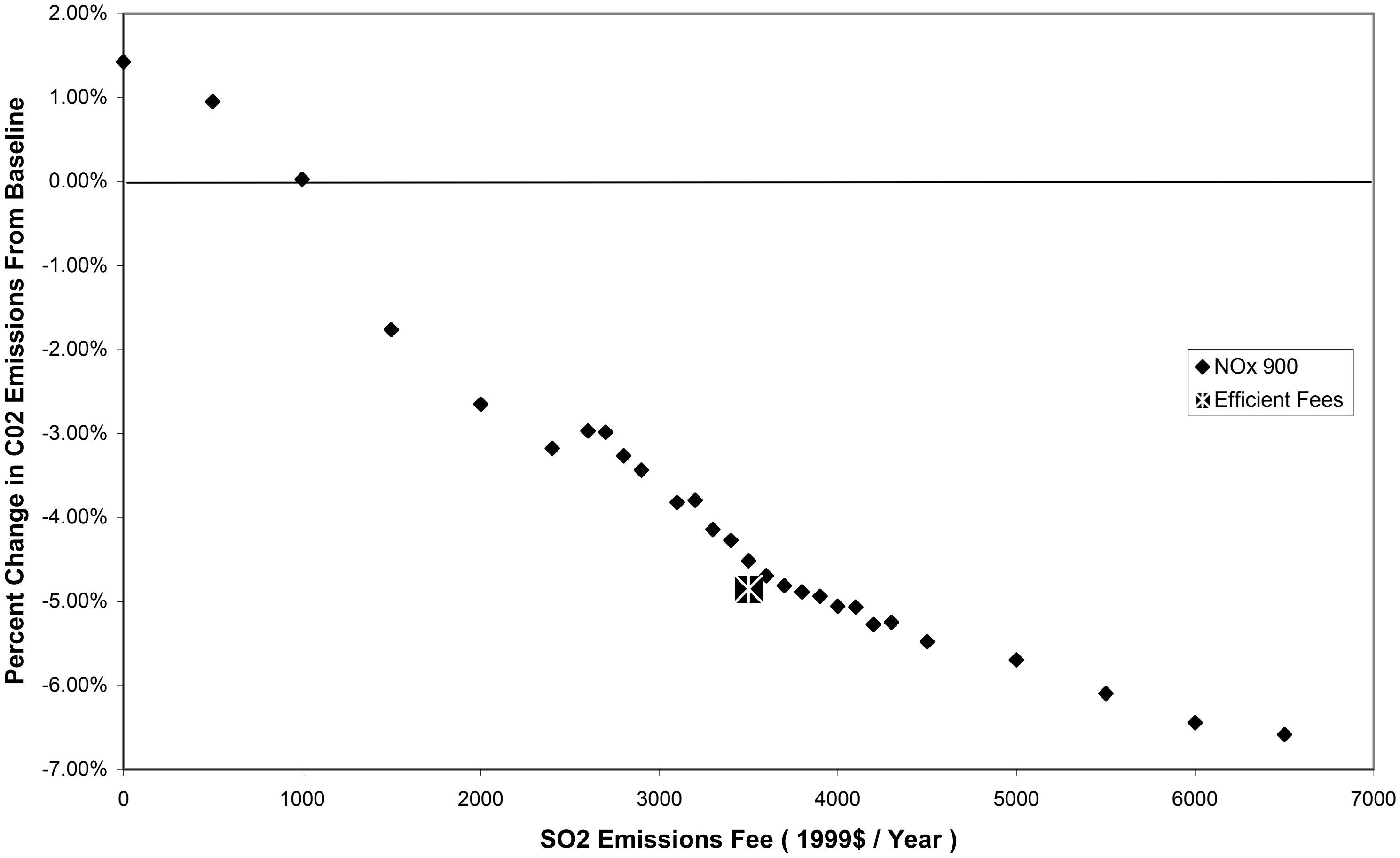


Table 1. Compliance Strategies and Costs

1999 dollars in 2010	Efficient Policy	Percent of Baseline
SO_2 Tax ($/ton)	3,500	N/A[φ]
NOx Tax ($/ton)	1,100	N/A[ψ]
Emission Controls on Steam Coal (thousand MW)		
SO_2	278	244%
NO_x	302	156%
Annualized Pollution Control Cost[π] (billion dollars)		
SO_2	7.48	N/A[π]
NO_x	4.36	N/A[π]
Generation (million MWh)		
Total	4,247	98.9%
Coal	2,113	93%
Gas	886	115%
Nuclear	768	104%
Electricity Price ($/MWh)		
Total	67.6	104%
Opportunity Cost[ξ] SO_2	0.92	307%
Opportunity Cost[ξ] NO_x	0.39	193%
Control Cost[π] SO_2	1.87	N/A[ρ]
Control Cost[π] NO_x	1.09	N/A[ρ]
Gas Price ($/mmBtu)	3.33	109%
Emissions (million short tons)		
NO_x	1.410	30.4%
SO_2	1.051	11.4%
CO_2	2,982	95.1%

[φ] SO_2 permit costs in the baseline for Title IV compliance are $102/ton.

[ψ] NO_x permit costs in the baseline for a seasonal policy in the SIP Call region are $1,730/ton.

[τ] Includes cost of reserve.

[ξ] Cost of emission fees embedded in electricity price.

[π] Includes annual capital and O&M cost.

[ρ] Values are not reported as changes from baseline because cost of pollution controls are embedded in capital costs of generation in the baseline.

References

Alberini, Anna, Maureen Cropper, Alan Krupnick, Nathalie Simon and Joseph Cook. 2001. "The Willingness to Pay for Mortality Risk Reductions: A Comparison of the U.S. and Canada." Paper presented at the Workshop on Economic Valuation of Mortality Risk Reduction: Assessing the State of the Art for Policy Applications. , November 2001, Silver Spring, MD.

Bloyd, Cary, et al. 1996. *Tracking and Analysis Framework (TAF) Model Documentation and User's Guide*, ANL/DIS/TM-36, Argonne National Laboratory, December.

Boyd, Roy, Kerry Krutilla, and W. Kip Viscusi. 1995. "Energy Taxation as a Policy Instrument to Reduce CO_2 Emissions: A Net Benefit Analysis." *Journal of Environmental Economics and Management* 29: 1-24.

Burtraw, Dallas, Ranjit Bharvirkar, and Meghan McGuinness. 2002. "Uncertainty and the Cost-Effectiveness of NO_X Emission Reductions Electricity Generation.," Discussion paper 02-01. Washington, DC: Resources for the Future.

Burtraw, Dallas, Karen Palmer, Ranjit Bharvirkar and Anthony Paul. 2001a. "The Effect of Allowance Allocation on the Cost of Carbon Emission Trading," Discussion paper 01-30. Washington, DC: Resources for the Future.

Burtraw, Dallas, Karen Palmer, Ranjit Bharvirkar, and Anthony Paul. 2001b. "Cost Effective Reductions of NOx Emissions from Electricity Generation." *Journal of the Air and Waste Management Association* 51: 1476 – 1489.

Burtraw, Dallas, Alan Krupnick, Erin Mansur, David Austin, and Deirdre Farrell. 1998. "The Costs and Benefits of Reducing Acid Rain." *Contemporary Economic Policy* 16: 379-400.

Burtraw, Dallas, Karen L. Palmer, and Alan J. Krupnick. 1997. "'Second-Best' Adjustments to Externality Estimates in Electricity Planning with Competition," *Land Economics*, vol. 73 (2) (May): 224-239.

Burtraw, Dallas and Alan J. Krupnick. 1997. "The Second-Best Use of Social Cost Estimates." *Resource and Energy Economics* 18: 467-490.

Burtraw, Dallas and Erin Mansur, 1999. "The Environmental Effects of SO_2 Trading and Banking." *Environmental Science and Technology* vol. 33: 3489-3494.

Carlson, Curtis, Dallas Burtraw, Maureen Cropper and Karen Palmer. 2000. "SO_2 Control by Electric Utilities: What are the Gains from Trade?" *Journal of Political Economy* 108: 1292-1326.

Chattopadhyay, Sudip. 2000. "The Effectiveness of McFaddens's [*sic*] Nested Logit Model in Valuing Amenity Improvements." *Regional Science and Urban Economics* 30: 23-43.

Desvousges, William H., F., Reed Johnson, and H. Spencer Banzhaf. 1998. *Environmental Policy Analysis with Limited Information: Principles and Applications of the Transfer Method*. Cheltenham, UK: Edward Elgar.

De Civita, Paul, et al. 1999. *Human Health and Environmental Benefits of Achieving Alternative Canadian-Wide Standards for Inhalable Particulates and Ground Level Ozone*. Final Report. (July 25), in Compendium of Benefits 99-08-17.

Ellerman, A. Denny, Paul L. Joskow, Richard Schmalensee, Juan-Pablo Montero and Elizabeth M. Bailey. 2000. *Markets for Clean Air: The U.S. Acid Rain Program.* Cambridge University Press.

Energy Modeling Forum. 1998. *A Competitive Electricity Industry* (final report of EMF Working Group 15). Stanford, CA: Stanford University.

Energy Modeling Forum. 2001. *Prices and Emissions in a Restructured Electricity Market* (final report of EMF Working Group 17). Stanford, CA: Stanford University.

European Commission. 1995. *Externalities of Energy: ExternE Project*. For the Directorate General XII. Prepared by Metroeconomica, CEPN, IER, Eyre Energy-Environment, ETSU, Ecole des Mines.

Harrison, D., A.L. Nichols, S.L. Bittenbender, and M.L. Berkman. 1993. *External Cost of Electric Utility Resource Selection in Nevada* (report prepared for Nevada Power Company). Cambridge, MA: National Economic Research Associates.

Johnson, F. Reed, William H. Desvousges, Melissa C. Ruby, David Stieb, and Paul de Civita. 1998. "Eliciting Stated Health Preferences: An Application to Willingness to Pay for Longevity." *Medical Decision Making* 18: S57-S67.

Johnson, F. Reed, Erin E. Fries, and H. Spencer Banzhaf. 1997. "Valuing Morbidity: An Integration of the Willingness to Pay and Health Status Index Literatures." *Journal of Health Economics* 16: 641-665.

Kolstad, Charles D. 1987. "Uniformity Versus Differentiation in Regulating Externalities." *Journal of Environmental Economics and Management* 14: 386-399.

Krupnick, Alan, Anna Alberini, Maureen Cropper, Nathalie Simon, Bernie O'Brien, Ron Goeree, and Martin Heintzelman. 2002. "Age, Health, and the Willingness to Pay for Mortality Risk Reductions: A Contingent Valuation Survey of Ontario Residents," *Journal of Risk and Uncertainty* (forthcoming). Also available as RFF discussion paper 00–37. Washington, DC: Resources for the Future (September).

Krupnick, Alan, and Dallas Burtraw. 1996. "The Social Costs of Electricity: Do the Numbers Add Up?" *Resource and Energy Economics* 18: 423-466.

Lee, R., A. J. Krupnick, D. Burtraw, et al. 1995. *Estimating Externalities of Electric Fuel Cycles: Analytical Methods and Issues, and Estimating Externalities of Coal Fuel Cycles*. Washington, DC: McGraw-Hill/Utility Data Institute.

Mrozek, Janusz R. and Laura O. Taylor 2002. "What Determines the Value of a Life? A Meta-Analysis." *Journal of Policy Analysis and Management,* forthcoming.

Oak Ridge National Laboratory. 1995. *Peer Review Of The Tracking And Analysis Framework (TAF) For Use in the 1996 NAPAP Integrated Assessment* (ORNL/M-4994). Oak Ridge, Tn: ORNL.

Pizer, William, 2002. "Combining Price and Quantity Controls to Mitigate Global Climate Change," *Journal of Public Economics* 85(3): 409-434.

Pope, C. A. III, M. J. Thun, M. M. Namboodiri, D. W. Dockery, J. S. Evans, F. E. Speizer, and C. W. Heath, Jr. 1995. "Particulate Air Pollution as a Predictor of Mortality in a Prospective Study of U.S. Adults." *American Journal of Respiratory and Critical Care Medicine* vol. 151: 669-674.

Rowe, Robert D., Carolyn M. Lang, Lauraine G. Chestnut, Douglas A. Latimer, Douglas A. Rae, Steven M. Bernow, and David E. White. 1995. *The New York State Externalities Cost Study*. Dobbs Ferry, NY: Oceana Publications.

Sieg, Holger, V. Kerry Smith, H. Spencer Banzhaf, and Randy Walsh. 2002. "Estimating the General Equilibrium Benefits of Large Changes in Spatially Delineated Public Goods." Mimeo. Pittsburgh, PA: Carnegie Mellon University.

Smith, V. Kerry, and Ju-Chin Huang. 1995. Can Markets Value Air Quality? A Meta-Analysis of Hedonic Property Value Models. *Journal of Political Economy* 103: 209-227.

Thayer, M.A., F.D. Sebold, J.C. Murdock, T.A. Mayer, D.R. Murray, S.R. Tracy, and J. Zapert. 1994. *The Air Quality Valuation Model* (report prepared for California Energy Commission). San Diego, CA: Regional Economic Research.

U.S. EIA (Energy Information Administration). 1999. *Annual Energy Outlook 2000.* DOE/EIA-0383 (2000). Washington, DC: Department of Energy.

U.S. EPA (Environmental Protection Agency. 1995. *Ozone Staff Paper.* Washington, DC: Environmental Protection Agency.

U.S. EPA (Environmental Protection Agency). 1997a. *The Benefits and Costs of the Clean Air Act: 1970 to 1990.* Washington, DC: Office of Air and Radiation/Office of Policy.

U.S. EPA (Environmental Protection Agency). 1997b. *Regulatory Impact Analysis for the Particulate Matter and Ozone National Ambient Air Quality Standards and Proposed Regional Haze Rule* (report prepared by Innovative Strategies and Economics Group, Office of Air Quality Planning and Standards, U.S. EPA). Research Triangle Park, NC: Environmental Protection Agency.

U.S. EPA (Environmental Protection Agency). 1998a. *Supplemental Ozone Transport Rulemaking Regulatory Analysis.* Washington, DC: EPA Office of Air and Radiation.

U.S. EPA. (Environmental Protection Agency). 1998b. *Regulatory Impact Analysis for the NOX SIP Call, FIP, and Section 126 Petition, Volume 2: Health and Welfare Benefits.* Washington, DC: EPA Office of Air and Radiation.

U.S. EPA (Environmental Protection Agency). 1999. *The Benefits and Costs of the Clean Air Act, 1990 to 2010.* Washington, DC: Office of Air and Radiation/Office of Policy,

U.S. EPA (Environmental Protection Agency). 2002. *Clear Skies Initiative Summary*. Briefing material available at http://www.epa.gov/clearskies/clearskiessummary04-11.pdf.

U.S. NAPAP (National Acid Precipitation Assessment Program). 1991. *1990 Integrated Assessment Report.* Washington, DC: U.S. NAPAP.