The Costs and Benefits of Reducing Acid Rain

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Abstract

Title IV of the 1990 Clean Air Act Amendments initiated a dramatic reduction in emissions of sulfur dioxide and nitrogen oxides by electric power plants. This paper presents the results of an integrated assessment of the benefits and costs of the program, using the Tracking and Analysis Framework (TAF) developed for the National Acid Precipitation Assessment Program (NAPAP). Although dramatic uncertainties characterize our estimates especially with respect to the benefits of the program, many of which we have modeled explicitly, we find that the benefits can be expected to substantially outweigh the costs of the emission reductions. The lion's share of benefits result from reduced risk of premature mortality, especially through reduced exposure to sulfates, and 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, each of which measures approximately equal to costs. In contrast, 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, at least with respect to "use values" for the environmental assets that are affected.

Key Words: acid rain, sulfur dioxide, nitrogen oxides, cost-benefit analysis, Clean Air Act, Title IV

JEL Classification Nos.: H43, Q2, Q4

Table of Contents

List of Tables and Figures

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I. INTRODUCTION

This paper presents the first contemporary analysis of the prospective benefits and the costs of Title IV's Allowance Trading System for reducing sulfur dioxide (SO_2) emissions and Title IV's mandated reductions in emissions of nitrogen oxides (NO_X).[1] This benefit-cost assessment is conducted using the Tracking Analysis Framework (TAF) that was developed to support the activities of the National Acid Precipitation Assessment Program (NAPAP).

Control of SO_2 emissions under the 1990 Clean Air Act Amendments instituted two important innovations in U.S. environmental policy. The more widely acknowledged of these is the SO_2 emissions trading program. Firms are allowed to transfer allowances among facilities, or to bank them for use in future years. Less widely acknowledged is the average annual cap on aggregate emissions by electric utilities, set at about one-half of the amount emitted in 1980. The emissions cap represents a guarantee that emissions will not increase with economic growth. Title IV also used a more traditional approach in setting NO_X emission rate limitations for coal-fired electric utility units, although this approach has been modified to allow emission rate averaging among commonly owned and operated facilities. Hence, there is no cap on NO_X emissions, but Title IV is expected to result in a 27 percent reduction from their 1990 emissions.

Below, we describe TAF and its components, and then turn to the development and description of baseline assumptions, and default and sensitivity case scenarios. Next we report the results for our default scenario. Then, three sets of sensitivity analyses are reported. One set uses assumptions other than our default assumptions. We explore the sensitivity of results to changes in baselines and compare levelized costs with expected health mortality benefits only. Confidence intervals are constructed out of the statistical uncertainties associated with the health effects and monetary values. Subsequently we compare the TAF mortality benefits with estimates developed by Hagler Bailly (HB, 1995) for EPA's Acid Rain Division, and the

[1] There exist analyses of benefits and analyses of the costs, some of which we describe below. This is the first analysis to compare benefits and costs under uniform assumptions.

EPA's Regulatory Impact Analysis (RIA) for the proposed new particulate standard (USEPA, 1996). Finally we compare cost estimates in TAF with other recent studies.

We find that expected health mortality benefits alone far exceed expected costs in all but one of the variations in assumptions we tried, and that even 5th percentile estimates of benefits do not dip below costs for any of these scenarios (but one) in any years after 2010. Our mortality benefits estimates are substantially lower than HB's, though we predict *larger* changes in sulfate concentrations for a given change in emissions. Our lower mortality benefit estimates can be attributed primarily to our estimates of smaller emission reductions (lower emissions in the baseline against which we compare the policy), and smaller reductions in mortality risks for a given change in sulfates and a smaller value of statistical life.

In addition, we find that mean values for three other modeled pathways--health morbidity, recreational visibility, and residential visibility--each approximately equal mean levelized costs of the program. Recreational lake fishing benefits appear to be of much lower magnitude. We compare these estimates in a qualitative and relative ranking with our informed conjecture about the likely magnitude and uncertainty of several other benefit categories that are not modeled quantitatively.

We compare the TAF default cost estimate with other scenarios and other recent estimates within TAF. The TAF default estimate is on the low end of other estimates with respect to SO_2. In part, this reflects a downward trend in the estimates and secular trends in the industries that affect compliance. The TAF estimate as well as these others assumes that a well-functioning SO_2 allowance market will allow the industry to achieve emission reductions at minimum feasible cost. This is not strictly evident in the first two years of compliance with the program, and so the short-run cost estimates may be low. However, we expect least cost compliance to be a reasonable characterization of the future, as the electricity industry becomes increasingly competitive. The estimates of NO_x control costs are proximate to those of other recent estimates; however, the estimates do not reflect the opportunity for emission rate averaging which are expected to lower costs. At the same time, the TAF default estimate and all other estimates are low because they fail to account for the costs of the regulation within a general equilibrium framework with pre-existing taxes and distortions away from efficiency. Nonetheless, with all the omissions, caveats and uncertainties taken into account, we find the benefits of Title IV exceed the costs by a significant margin.

II. DESCRIPTION OF TAF

The Tracking and Analysis Framework (TAF) is an integrated assessment model of acid precipitation damages and the effects of Title IV of the 1990 Clean Air Act Amendments.[2] TAF integrates models of electric utility emissions and costs, pollutant transport and deposition (including formation of secondary particulates but excluding ozone), visibility effects, effects on recreational lake fishing through changes in soil and aquatic

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[2] TAF is documented in Bloyd et al. 1996.

chemistry, human health effects, and valuation of benefits. The model also can be readily extended to include other benefit pathways as modeling capability is developed. To ensure that each component represented the state of the science in its respective modeling domain, each module was constructed and refined by a group of experts in that field, and draws primarily on peer reviewed literature to construct the integrated model. Thus, TAF is the work of a team of over 30 modelers and scientists from institutions all over the country. As the framework integrating these literatures, TAF itself was subject to an extensive peer review in December 1995, which concluded that "TAF represent(s) a major advancement in our ability to perform integrated assessments" and that the model was ready for use by NAPAP.[3]

Considerable uncertainty in parameter and model form exists in each of our modeled domains and in the underlying scientific and economic literature. We selected Analytica™ as the modeling platform for TAF in part because of its capability to propagate model uncertainties, and we adopted a process designed to identify and characterize those uncertainties. We chose an integrated assessment framework, as opposed to a suite of related but unlinked models, because it met the following needs of the TAF project:

- To provide comparable results across a variety of effects (visibility, recreational lake fishing, human health), for a common region (continental US), and over a single time horizon (1995-2030);
- To provide an integrated analysis of costs and benefits based on common assumptions, and to provide insight about model assumptions and components which contribute significantly to overall results;
- To suggest productive areas for future research and additional modeling based on an assessment of the current model's critical uncertainties and omissions.

TAF characterizes emissions, emission transport, atmospheric concentrations of pollutants and health effects at the state level. This level of aggregation introduces some uncertainty into the analysis, but it is not evident that a bias is introduced. The estimation of effects also is amenable to modeling at a less centralized level, and we use probabilistic methods to represent variations in sources of emissions, geography and population density within states. TAF omits benefits that occur in Canada and Mexico. Recreational lake effects are characterized for a distribution of lakes in the Adirondacks. Recreational visibility effects are characterized at two parks and valued nationally, and residential visibility effects are characterized and valued for five metropolitan areas. These results are most usefully considered on a per capita basis. In this paper we do not try to assess regional issues in a thorough way, but we do display the regional pattern of health benefits.

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[3] ORNL, 1995. TAF is being used to provide supplementary analysis to NAPAP in drafting their 1996 Integrated Assessment, but it is not a centerpiece.

The Benefits Valuation Module

Benefit valuation is essential for comparison of various physical effects with each other and with costs. From an economic perspective, values are measured by how much of one asset or service individuals in society are willing to sacrifice in order to obtain or preserve another. Economics refers to this as an "opportunity cost approach" to valuation. Values are expressed in monetary terms, although, in principle, they can be expressed in other metrics. The value or opportunity cost of goods and services that are readily traded in markets is reflected in their prices. For goods that are not traded in markets, the economics literature on monetizing benefits and costs is more developed in certain areas than in others, which is reflected in the characterization of uncertainty in the benefit models.

The Benefits Valuation Module provides an accounting of pathways and benefit endpoints considered in TAF. The module values effects on visibility (recreational and residential), Adirondack lake sport fish populations, and human health. These effects are valued only where physical effects have been modeled in TAF, so comprehensive geographic coverage is not provided. Other kinds of effects, such as forest, stream, and material damages, are not valued at this time, but they are represented in TAF in a qualitative manner.

Health Effects

The Health Effects Module is designed to estimate the health impacts of changes in air pollution concentrations. Impacts are expressed in terms of the number of days of acute morbidity effects of various types, the number of chronic disease cases, and the number of statistical lives lost to premature death. The change in the annual number of impacts of each health endpoint is the output of this module. Inputs consist of changes in ambient concentrations of SO_2 and NO_x, demographic information on the population of interest, and miscellaneous additional information such as background PM_{10} levels for analysis of thresholds.

The module is based on concentration-response (C-R) functions found in the peer-reviewed literature. The C-R functions are taken, for the most part, from articles reviewed in the U.S. Environmental Protection Agency (EPA) Criteria Documents (see, for example, USEPA 1995). These documents are outcomes of a recurring comprehensive process initiated by the Clean Air Act and its Amendments for reviewing what is known about the health effects of the so-called "criteria" air pollutants.[4] Such information, and judgments about its quality, eventually help the Administrator of the EPA make decisions about National Ambient Air Quality Standards (NAAQS) that would "protect the public against adverse health effects with a margin of safety." These Criteria Documents contain thousands of pages evaluating toxicological, clinical, and epidemiological studies that relate particular criteria pollutants to a variety of health endpoints, including primarily acute cardiopulmonary and respiratory effects, chronic effects and prevalence of chronic illness, and premature mortality. The TAF

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[4] The Criteria Pollutants include ozone [O_3], nitrogen dioxide [NO_2], sulfur dioxide [SO_2], particulate matter less than 10 microns in diameter [PM_{10}], lead [Pb], and carbon monoxide [CO].

Health Effects Module contains C-R functions for PM_{10}, total suspended particulates (TSP), SO_2, sulfates (SO_4), NO_2, and nitrates (NO_3).[5]

The Health Effects Module calculates morbidity impacts resulting from sulfates and nitrates, which are particulates created from emissions of SO_2 and NO_X, respectively, and SO_2 and NO_X as gases. Mortality impacts are only represented as resulting from the particulates. The C-R functions found in the literature for these endpoints are documented within the software model.

The top level of the Health Effects Module is structured according to an influence diagram that visually depicts the fact that, in a C-R function, concentration changes and demographic data determine the number of morbidity and mortality impacts experienced in a population. Within the morbidity and mortality submodules there is great flexibility to structure the model so as to test a range of assumptions about the relationship between pollutant concentrations and health effects.

For both the morbidity and mortality endpoints, the Health Effects Module contains a comprehensive library of C-R functions found in the peer reviewed literature, in total consisting of more than fifty studies linking air pollution to premature death, chronic disease, hospitalizations and other symptoms. The user may select from among any of the studies in the library available for a given health endpoint, or may decide to weight coefficients from a number of studies.

For the mortality endpoint, in addition to the choice of a C-R function, the user may decide to treat the various components of particulate matter separately. For example, some evidence suggests that the fine fraction of the mass may have more of an effect than the coarser components. Four plausible interpretations of the evidence on this subject are offered to the user as options (Table 1). Within each of these options, the user may choose from among the available studies in the library for each pollutant and endpoint, or use a combination of other C-R functions weighted to reflect the user's judgment. Options 1 and 2 assume that sulfates and nitrates have the equivalent potency in causing health effects as any other particle 10 microns or less in diameter (PM_{10}), but option 2 allows the user to look at the age-disaggregated effects of air pollution on mortality. These reflect the fact that the over 65 population is more likely to die as a result of high particulate levels than is the under 65 population. Option 3 treats sulfates as distinct and associates them with relatively greater potency than other constituents of PM10. Option 4 treats both sulfates and nitrates as relatively more potent than other components of PM_{10}. We focus on the third option as most plausibly representing the evidence at the time the work was completed.

The morbidity submodule allows the user a choice of either aggregating SO_2, PM_{10} and sulfate effects according to a scheme designed to avoid double-counting, such as symptom days and restricted activity days, or of using SO_4 effects as a proxy for particulate and SO_2 effects. NO_X is included for eye irritation and phlegm days. As with the mortality

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[5] Since nitrates are particulates, and no independent effect of nitrates on health has been established, they are treated as a component of PM_{10}.

submodule, default studies have been identified for each endpoint, but where other studies exist in the literature they may be substituted for the defaults.

Table 1. Options for Assessing Mortality Effects

Option 1	Sulfates and nitrates treated as PM10
Option 2	Sulfates and nitrates treated as PM10, disaggregated by age
Option 3 (default)	Nitrates treated as PM10, sulfates distinct and more potent
Option 4	Sulfates and nitrates treated as sulfates

The Health Valuation Submodule of the Benefits Valuation Module assigns monetary values taken from the environmental economics literature (e.g., Lee et al., 1994) to the health effects estimates produced by the Health Effects Module. The benefits are totaled to obtain annual health benefits for each year modeled. The Health Valuation Submodule also contains a comprehensive library, based on the environmental economics literature, of values associated with morbidity and mortality endpoints. As with the Morbidity and Mortality Submodules, defaults have been selected, but the user may test the effects of assigning alternative values to the various health endpoints, consistent with the valuation literature.

Visibility

The Visibility Effects module calculates changes in visual range for five cities (Albany, NY; Atlantic City, NJ; Charlottesville, VA; Knoxville, TN; and Washington, DC), and two national parks (the Grand Canyon, and Shenandoah). Seasonal distributions of mid-day visual range are based on estimated atmospheric sulfate and nitrate concentrations from the Atmospheric Pathways module -- a reduced-form model of the Advanced Statistical Trajectory Regional Air Pollution (ASTRAP) model. Calculation of change in visual range is based on the Visibility Assessment Scoping Model (VASM), which uses Monte Carlo techniques to produce short-term variations of visual impairment based on seasonal lognormal distribution parameters of the six important particulate species (sulfate, nitrate, elemental carbon, organic carbon, fine-particle dust, and coarse-particle dust), relative humidity distribution statistics from climatology, and modeled changes in the seasonal means of the sulfate and nitrate concentrations.

The Visibility Valuation submodules examine both recreational and residential benefits. Chestnut and Rowe (1990) proposed a functional form to value both recreational and residential visibility that takes into account the nonlinearity of willingness to pay (WTP) for a given change in visual range (i.e., the diminishing marginal utility for visibility enhancement). WTP for improvements in recreational visibility were drawn from contingent valuation (CV) studies and involve both use and nonuse values for residents living in either park's state or another state ("out-of-state" residents). To value residential visibility improvements we employ a range of WTP coefficients from the Brookshire et al. (1979) Los Angeles study, and the McClelland et al. (1991) study of Atlanta and Chicago. We assume residential WTP is

positive only for local residents (e.g. only use values matter), so we adjust values for "in-state" recreational visibility to avoid double counting with improvements in residential visibility.

Recreational Lake Fishing

The Recreational Lake Fishing module predicts changes in lake chemistry and soil chemistry caused by acid deposition. Using a set of "acid stress indexes" (ASIs) that describe the responses of specific species of fish to varying levels of acidity (pH) in the water, the module estimates economic benefits resulting from improvements in recreational fishing due to decreased acidification. Future surface-water and soil chemistry conditions in the watersheds are projected by reduced-form models based on the Model of Acidification of Groundwater in Catchments (MAGIC). MAGIC is a lumped-parameter model that uses chemical equilibrium and mass balance equations to predict changes in lake and soil chemistry. The reduced-form models have been applied to lakes in New York's Adirondack region, using a set of 33 lakes chosen to be representative of the target population of lakes in the region.

The Recreational Lake Fishing Benefits module allows the user to specify whether benefits are to be estimated on the basis of benefits to recreational anglers, or alternatively as avoided lake liming costs. The Recreational Lake Fishing submodule estimates changes in the catch rates (catch per unit effort, or CPUE) of anglers fishing for three species of fish in Adirondack Park. Values are assigned to these changes through the use of a "random utility" travel cost model. Benefits are calculated for the change in value of a single-day fishing trip (as opposed to an overnight or multi-day outing) as a result of changes in CPUE. The submodule also estimates the change in the annual number of single-day fishing trips the average Adirondack Park angler will take in the park, as a function of changes in CPUEs and other factors.[6]

The submodule does not attempt to account for benefits enjoyed by new anglers attracted by improved conditions, or for angler benefits other than improvements in catch rates.[7] There are two reasons for this simplification. First, no more than 10 percent of the population fishes for recreation, and the use benefits enjoyed by non-anglers are probably of second order to the anglers' values for improved catch rates. Second, there are no reliable estimates on which to base valuations of non-fishing uses--in part because relative aesthetic effects are much smaller than the effects on fish populations. TAF does not include estimates of the nonuse or existence benefits that may be enjoyed by persons not visiting the affected lakes. Other parts of the country are not modeled currently. However, we use the effects in

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[6] The aquatics valuation literature focuses on single-day trips because it is thought that valuations for multi-day trips, of which there are far fewer, are intrinsically different. For instance, it would be necessary to better control for lake amenities such as lodging and camping facilities, which would presumably be important determinants of lake choice. These "use values", for multi-day trips, are not represented in the TAF analysis.

[7] Changes in fish populations could be correlated with changes in lake amenities such as the health of the lakeside flora and fauna.

the Adirondack region to illustrate the potential magnitude of benefits on a broader scale by presenting benefits in per capita terms for the affected population.

Costs and Emissions

Embedded in TAF are estimates of costs and an algorithm for determining compliance activities at different facilities, developed by Argonne National Laboratory, and based on their unit inventory called GECOT. Compliance options for SO_2 reductions include scrubbing, fuel switching (including plant modifications), retirement and replacement of plants. Decisions by utilities to install retrofit desulfurization equipment (scrubbers) at 21 units for compliance in Phase I of the SO_2 trading program are taken as given. The module ranks further compliance options on a unit cost ($/ton reduction) basis, with the most-cost-effective units being implemented first, until the emission reduction requirements are satisfied.

Many units are found to achieve cost savings through fuel switching and/or blending, consistent with other studies (Burtraw, 1996; Ellerman and Montero, 1996). In these cases the emission reductions are not included in the analysis of benefits because we assume the baseline (without Title IV) scenario also should reflect these emission reductions. However, we observe that the flexibility of the emission allowance trading program has allowed firms to take advantage of advantageous trends in fuel markets and to realize cost savings, while conventional regulatory approaches such as technology standards may have prohibited firms from doing so. Emission allowance trading is modeled implicitly by allocating compliance in a cost-effective way. NO_X compliance is modeled to achieve emission rate reductions sufficient to meet the emission reduction goals of the program. Emission rates and costs are equivalent to low NO_X burners absent further flexibility for compliance that characterizes the SO_2 program. This description differs somewhat from actual implementation which has allowed firms to average emission rates among commonly owned and operated facilities, and hence our estimate of costs can be viewed as conservative (high). The total cost of compliance is calculated as the present value of revenue requirements to cover compliance costs summed over all units, and this quantity is levelized (equal annual costs spread over the lesser of 35 years or the remaining life of the facility) for comparison with benefits.

For SO_2 reductions, the module predicts the industry will rely on fuel switching and blending as the primary means of compliance, and that much of this switching will be implemented at low cost or cost savings to the affected firms. Scrubbing is also implemented, to a limited degree. This scenario appears robust to recent developments in the coal industry, and hence we use these estimates as a benchmark for compliance costs over the long-run. We explore the robustness of the module through scenario analysis about plant lifetimes and future electricity demand, and through comparison with other recent studies.

Other Effects Not Modeled

There are numerous other effects of Title IV that TAF does not model quantitatively because of a lack of proper scientific and/or economic data and models. These include effects

to material and cultural resources, nonuse of ecosystem health, recreational forests, agriculture and commercial forestry, and radiative forcing. Material and cultural resource valuation lacks a complete inventory of affected assets, data about the economic lives of affected assets, and information on behavioral responses. While nonuse values of ecosystem health are expected to be large, there is no characterization of ecosystem changes associated with Title IV or of a valuation framework for assessing benefits from improvements in ecological indicators, especially given the temporal aspects of ecological dynamics. Similarly, the link between primary pollutants and forest recreation effects that people care most about is not established. Exposure to ambient ozone is likely to be the most significant air pollutant causing significant effects on crops, but the studies examining these effects fail to account for behavioral responses in an adequate way, and the data on changes in ozone as a result of Title IV are not currently available. Lastly, atmospheric models predict changes in particulates and their effect on radiative forcing, but the economic methods for modeling damages of climate change are very uncertain, and data for valuation of local effects are not available.

III. BASELINES AND SCENARIOS

The analysis requires an estimate of the time path of emissions of SO_2 and NO_x (plus associated abatement costs) from 1995 to 2030 in the absence of Title IV--termed the baseline--and estimates of the emissions (and costs) associated with Title IV. Subtracting the emissions for the scenario from the baseline emissions provides emissions changes (which are fed into the atmospheric transport module) to estimate benefits of Title IV. These benefit estimates are compared with costs under a consistent set of assumptions, as well as "off-line" comparisons with alternative cost estimates.

We developed three baselines and picked one as the default. The baselines differ according to an estimate of plant lifetimes (60 versus 70 years) and the growth in electricity demand over the period (3 percent, termed "high growth", and 1 percent, termed "low growth"). Growth rates in electricity demand are weighted by state population growth. We think that the 70 year-low growth baseline is the most likely, but also examine the effects of a 60 year-low growth and 70 year-high growth baseline.

The scenarios all involve Title IV with SO_2 trading and NO_x reductions mandates. Specifically, the first phase of SO_2 reductions implemented in 1995 require average emission rates to be about 2.5 lb. sulfur per million Btu heat input. This rate applies to 431 units, including nearly 200 so-called "substitution and compensation" units that were voluntarily brought into Phase I to ease the cost of compliance on average. The second phase, taking effect in 2000, will lower the average emission rates to about 1.2, and will affect over 2,000 units. The first phase of NO_X controls took effect in 1996 and reduced emission rates to .45 or .50 lb. per million Btu, affecting 239 units, all but 16 of which were also affected by Phase I SO_2 rules. The second phase of NO_X controls expand the set of affected facilities and go into effect in 2000 and are not yet final, but are expected to take effect in 2000.

Since health benefits emerge as by far the most important of the benefits we quantify, we focus several analyses toward an exploration of the sensitivity of those benefits to various

sets of assumptions. First we test the sensitivity of health benefits to two alternative baseline scenarios involving different life expectancies for power plants and different projections for growth in electricity demand.

Next, under our default baseline for power plant life expectancy and growth in electricity demand, we explore four scenarios involving different assumptions involved in estimating health benefits, which we compare with our default assumptions for the health benefits case.

The default case health benefits estimates resulted from our best judgment about the epidemiological and valuation literature at the time the work was completed. Our most important choice concerns the C-R functions for the mortality effects of reductions in sulfates and nitrates. For sulfates we use a weighted mean of the coefficient estimate of two benefit studies, giving both studies equal weight. This coefficient predicts the change in the number of incidents of mortality annually resulting from changes in total PM_{10} (sulfate and nitrate) concentrations. The low estimate (0.1 percent), based on Plagiannakos and Parker (1988), assumes that sulfates are equally as potent as any PM_{10} particle class, and estimates only daily mortality. The high estimate (0.7 percent), based on Pope et al. (1995), addresses the effects of cumulative exposure to fine particles, and probably captures much of the daily mortality risk. The high estimate implies that sulfates, which fall into the fine fraction of the particulate mass, are a relatively potent constituent of PM_{10}.

We depart from some of the benefit literature (Hagler Bailly, 1995) by ignoring the higher estimates of the particulate mortality coefficient (1.4 percent) found in the Dockery et al. (1993) study because it only examines mortality effects in 6 cities and a sample of 8,111 people versus the 151 cities and 552,000 people covered by the Pope et al. (1995) study.[8]

For nitrates, we assume that they are no different in potency from any constituent of PM_{10} based on Schwartz and Dockery (1992). Taken together, these choices imply that nitrates are, overall, less potent than sulfates, an assumption that reasonably reflects the state of the literature. For both functions we assume that there are no thresholds, meaning health benefits from emissions reductions can be expected to occur irrespective of the baseline concentration of particulates.

The other key choice is the estimate of WTP for mortality risk reductions. In the base case, we use a lognormal distribution with mean of $3.1 million per statistical life (in $1990), and a 90 percent confidence interval of $1.6 and $6 million. This distribution generally accords with the valuation literature, but is somewhat on the low side because we give less weight to the labor market studies relative to the contingent valuation studies, the latter being marginally more appropriate for valuing mortality risks in the environmental health context and also capture age effects, based on Jones-Lee et al. (1985). The Jones-Lee study finds that

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[8] A fourth study, Evans *et al.* (1984), with a mid-range particulate mortality coefficient (0.3 percent) was also considered by Hagler Bailly (1995). We implicitly endorse use of this study as it falls within the range of low and high estimates we use in the TAF default case.

the value of a statistical life for the 65 years and older group is about 75 percent of that of the average (40 year old) participant in their study.

As seen below, for the default case, benefits of reduced risk of health mortality alone far exceed the costs of emission reductions. For this reason, we only explore downside sensitivities of the health benefits estimates which are designed to test whether there are plausible assumptions under which benefits no longer exceed costs. We explore three options and compare them each individually to the default assumptions. Then we explore a combined case.

- Impose threshold for PM_{10}. In this case we assume that there is a threshold in effects at a 24-hour average concentration of 30 $\mu g/m^3$ PM_{10} (Lee, et al., 1995). Days in which the baseline concentration of PM_{10} in a county is below this amount will not register benefits of sulfate or nitrate reductions.

- Treat sulfates as PM_{10}. In this case we assume that nitrates have *no* effect on mortality rates, in line with the lack of any direct epidemiological evidence linking nitrates with such effects. We assume that sulfates are no more potent than any other PM_{10} constituent and use the daily mortality studies only (equivalent to applying the base case mortality assumptions for nitrates to sulfates).

- Mortality Risk Valuation. Even using the Jones-Lee et al. study to adjust the value of a statistical life (VSL) estimates for age probably overestimates benefits of mortality risk reductions from PM_{10} because this study (and the rest of the VSL literature) provides estimates for reducing risks of accidental and immediate death, such as in a car accident. Particulate matter exposure, on the other hand, may lead to higher probabilities of death for individuals only when they are already quite old. For most of the population, then, the mortality benefits of *today's* PM_{10} reduction may be zero or very small. It may contribute to a higher probability of developing chronic respiratory disease which, in turn, may reduce life expectancy. Said another way, the WTP for a risk reduction realized in the future is likely to be much lower if one has to pay today versus in the future. Unfortunately, we cannot take this effect into account directly in the sensitivity analysis. Instead we use an approach to adjust the VSL downwards, based on life-years remaining, that probably provides a lower bound to the VSL.[9,10]

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[9] This age disaggregated estimate, which is based on a procedure that assumes each year of life is worth the default VSL divided by the life expectancy of a 40 year old, and that those over 65 are willing only to pay by the year for the number of years they can be expected to live, results in the assignment of a VSL to the over 65 population of $0.9 million, about 1/3 that of the under 65 population, for which the VSL is assumed to be the default.

[10] It is worth noting that there are additional reasons why WTP estimates in the "auto-death"-type context may over or underestimate risks in the PM-mortality context. The former may overestimate the latter if the older people at risk from PM have compromised health. The former may underestimate the latter if air pollution is thought to be an involuntary risk and auto-death risk is thought to be voluntary.

- Combined Case. In this case we assume that there is a 30 μg/m³ PM$_{10}$ threshold *and* that sulfates only have the potency of the average PM$_{10}$ particle.

The Hagler Bailly Study of Health Benefits from Sulfate Reductions

EPA commissioned a study by Hagler Bailly (HB, 1995) of the health benefits of reductions in emissions associated with Title IV reductions in SO$_2$ emissions. This study began with estimates of emissions changes made by ICF Resources using their Coal and Electric Utilities Model (CEUM) on behalf of the EPA's Acid Rain Division. The EPA tied those changes in emissions to their Regional Acid Deposition Model (RADM) to obtain changes in sulfate (fine particle) concentrations in the Eastern U.S., and used a particular set of health concentration-response and valuation functions to estimate the monetized health benefits of the emissions changes. The HB study places an expected value of a statistical life at $3.2 million (1990$) compared to an expected value of $3.1 in TAF. Expected benefits are higher from the HB study than under our default health benefit estimates.

To reconcile the differences between these results, we incorporated the HB study into TAF to compare results for 2010. Since EPA population estimates could not be easily obtained, TAF population projections were used in all scenarios.[11] We calculated mortality benefits per ton for SO$_2$ emission reduction. We did not have access to RADM for direct comparison with ASTRAP in TAF. However, by explicitly comparing the state-aggregated emission reductions forecast by TAF and HB, and the predicted health effects and valuation functions, we were able to impute the influence that the different atmospheric models had on benefit estimates.

The EPA's Regulatory Impact Assessment for Particulates

As part of the Regulatory Impact Assessment (RIA) for the new proposed standards for particulates, the EPA has developed new health effect and valuation functions. The RIA examines mortality effects from PM$_{2.5}$ (which includes both sulfates and nitrates), using a value of a statistical life of $4.8 million. We incorporate these new functions as an option in TAF and compare them with our default assumptions.

Alternative Cost and Emission Estimates

To examine the sensitivity of our findings to changes in costs, we compare our default cost estimates for SO$_2$ reductions with several others from the literature including White et al. (1995), compiled for the Electric Power Research Institute, ICF (1995), compiled for the EPA, and GAO (1994). Burtraw et al. (1997) provides econometric estimates of short-run

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[11] HB used different population estimates than are modeled in TAF. The estimates for 2010 differ from TAF both by state and nationally, with average difference leaving HB estimate about 3.6 percent above that of TAF, though most of the difference is in areas without a large change in SO$_4$ in the benefits module. Hence, their benefits estimate increase only 1.5 percent as a result of population differences. We adjust HB's population estimates to fit ours; i.e., all results presented in this paper for HB reflect a small downward population adjustment.

and long-run costs. We compare TAF default estimates of the cost of NO_X control with an ICF (1996) and E.H. Pechan (1996).

With respect to emissions, our default estimates lead to emission estimates that are proximate to empirical measures based on the first two years of the program. In reporting our results, we focus primarily on long-term estimates for the year 2010 and beyond, when the program will be in full swing. To consider an alternative emission scenario and its effects on benefits, we compare the Argonne model with emissions and forecast by HB.

IV. RESULTS

Figure 1 and Table 2 summarize the mean expected costs and benefits in per capita terms for the included benefit pathways, for our main run of 50 realizations of the Monte Carlo simulation model. We emphasize that the exact same results will not obtain in running the model two different times because of random aspects of the sampling procedure, and because we may vary the choice of sampling procedure. The virtue of this approach is that it avoids a false sense of precision in the estimates, and allows us to focus on the likely distribution of outcomes and identify qualitative results.

Table 2: Per Capita Benefits in 2010 for Affected Population.

Effect	Benefits per Capita (1990$)
Morbidity	3.50
Mortality	59.29
Aquatic	0.62
Rec. Visibility	3.34
Resid. Visibility	5.81
Costs	5.30

Estimates in Table 2 are projected for the year 2010, when the second phase of the SO_2 program and the NO_X programs are expected to be in full effect. (Note the vertical axis in Figure 1 is a log scale.) The dominant source of benefits is reduced human mortality risk, and taken singularly it results in a mean benefit estimate in 2010 that is nearly an order of magnitude greater than costs. Expected benefits from human morbidity, recreational visibility and residential visibility each individually are approximately equal to the annualized expected cost per capita in 2010.

Health and recreational visibility benefits are presented as the average per capita benefits for all U.S. residents. Recreational visibility represents an estimate of average willingness-to-pay for modeled visibility improvements at just two parks--Grand Canyon and Shenandoah. Although there would be improvements at other park locations, problems of embedding benefit endpoints in the application of contingent valuation techniques to estimation of nonuse benefits suggest that measures of WTP at other locations would not be additive to these, and indeed we

may capture most of the WTP for improvements across the entire nation with these locations (Chestnut and Rowe, 1990).
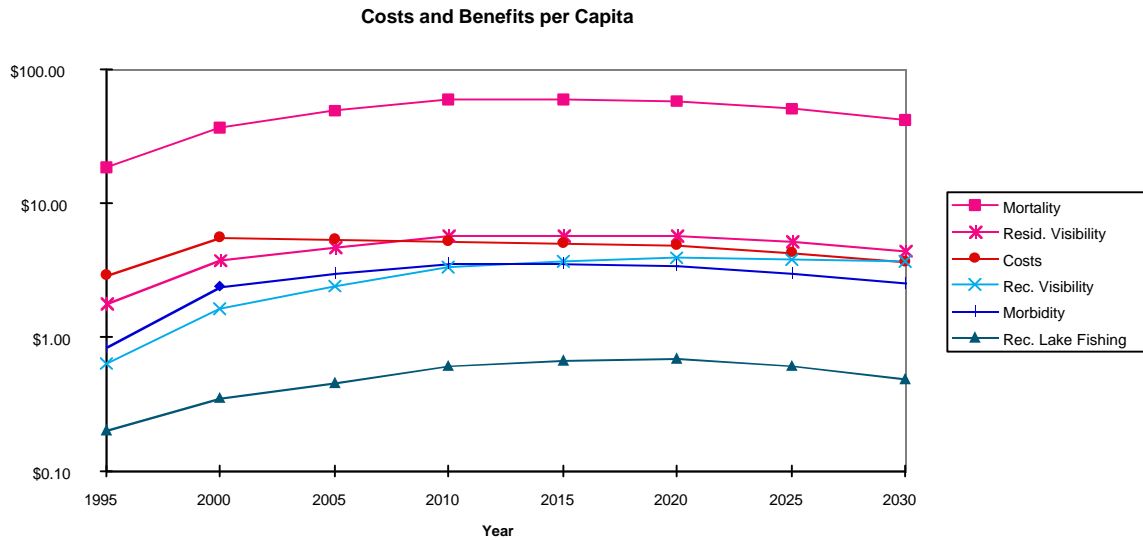
Costs and Benefits per Capita

Figure 1: Costs and Benefits for Modeled Pathways for Affected Populations (Log-scale)

A virtue of a per capita comparison is that we can include benefit pathways that are not modeled for the entire U.S. The residential visibility benefits are those benefits that obtain for all residents in the five modeled cities of Washington, Atlantic City, Knoxville, Charlottesville, and Albany. The aquatic benefits are those that obtain for the portion of the population that is engaged in recreational fishing in Adirondack lakes. We express these benefits in per capita terms for each affected population in order to obtain a measure of the potential magnitude of such benefits at a national level. In the case of residential visibility, an extrapolation to the national level would likely overstate benefits because changes in sulfate and nitrate concentrations would be less in other parts of the country. In the case of aquatic effects, an extrapolation to the national level also would likely overstate benefits because a large portion of the population does not pursue recreational fishing, and again because the changes in lake chemistry would be less in most, if not all other parts of the country.

A potential point of confusion is the measure of tons reduced under the program, which depends importantly on the characterization of what would have happened to emissions in the absence of the program. To avoid confusion over the baseline emissions (we discuss the issue again below), we draw attention to benefits calculated per ton of emission reductions. The location of emission reductions still matters importantly to the calculation of benefits per ton, and this is modeled explicitly in TAF. Measured in this way, health still plays a dominant role in the assessment of benefits. Median mortality benefits for the entire U.S. per ton SO_2 reduction under TAF's default scenario are \$3,102. We find the 90 percent confidence interval around TAF's reference case estimate for SO_2 mortality benefits to range from \$1743 to \$9,649. The median value of human morbidity effects for TAF are \$193 per ton of SO_2

reduction. The median estimate of benefits resulting from changes in NO_X emissions in 2010 are $463 per ton for mortality (through the change in nitrate concentrations) and $137 for morbidity. These do not include the effects from changes in ozone concentrations. In contrast, annualized costs in 2010 are estimated to average $271 per ton of SO_2 emission reduction, and $382 per ton for NO_X emission reduction.

Figure 2 displays the benefit-cost ratio, using health benefits only, under alternative baseline assumptions about plant lifetimes and growth in electricity demand. In the year 2020, when the benefit-cost ratio is greatest, annual costs (1990$) are $1.56 billion in the default case (low growth-70 year retirements), while benefits are $19.9 billion. Costs drop to $1.19 billion in the low growth-60 year retirements case, while benefits drop to $13.2 billion. Costs are $1.63 billion in the high growth-70 year retirements case, while benefits are $21 billion. For the high growth-70 year retirement case, the benefit-cost ratio of Title IV is even larger than for the default case. The reasons are that changes in assumptions affect both benefits and costs in the same direction but to differing degrees. For instance, lower growth in electricity demand implies that there is a lower opportunity cost to retiring older plants. It also suggests that emissions in the baseline would be lower, and hence emission reductions and program benefits would be lower. It is also interesting that benefits in the low growth-60 year retirement case are less than or equal to the default case in every year. The benefit-cost ratios are not much different among the cases.

Perhaps the most interesting aspect of this figure is that the benefit-cost ratio does not vary by a huge amount under the different assumptions, even though the measure of benefits or the measure of costs taken separately does vary significantly. This points out a virtue of TAF in that it allows us to explore benefits and costs under a consistent set of assumptions and sensitivity cases.

Because of the dominant role of health, we devote a considerable part of our sensitivity analysis to whether the mortality and morbidity benefit estimates are robust. Figure 3 displays the annual health benefits alone for the default scenario, with associated uncertainty bars, in comparison with our default annualized expected cost estimates, in millions of dollars. Annualized costs for SO_2 and NO_X reductions are about $761 million per year in 1995, increasing to $1.51 billion in 2000 and $1.56 billion in 2020. Expected benefits in the default scenario rise from $5.1 billion in 1995 to $19.9 billion in 2020, dropping back to $15.5 billion by 2030. The ramp up of benefits is attributable to meeting Title IV year 2000 goals as well as to population and income growth, while the drop after 2020 is attributable to plant retirements that occur in the baseline.

Our main observation in Figure 3 is that the uncertainty bounds around the benefit estimates show that there is no year in which benefits (at the 5 percent confidence level) are less than expected annualized costs. Uncertainty in the cost estimates is explored through the three scenarios involving alternative assumptions about plant lifetimes and electricity demand growth described in Figure 2. However, these alternatives generate such a small range in costs, compared to uncertainty in benefits, that it does not display in Figure 3. About 94 percent of total health benefits result from mortality benefits in 2010. Only about 11 percent of total

**Benefit (Health only): Cost Ratio Under
Alternative Assumptions about Electricity Industry**

Legend:
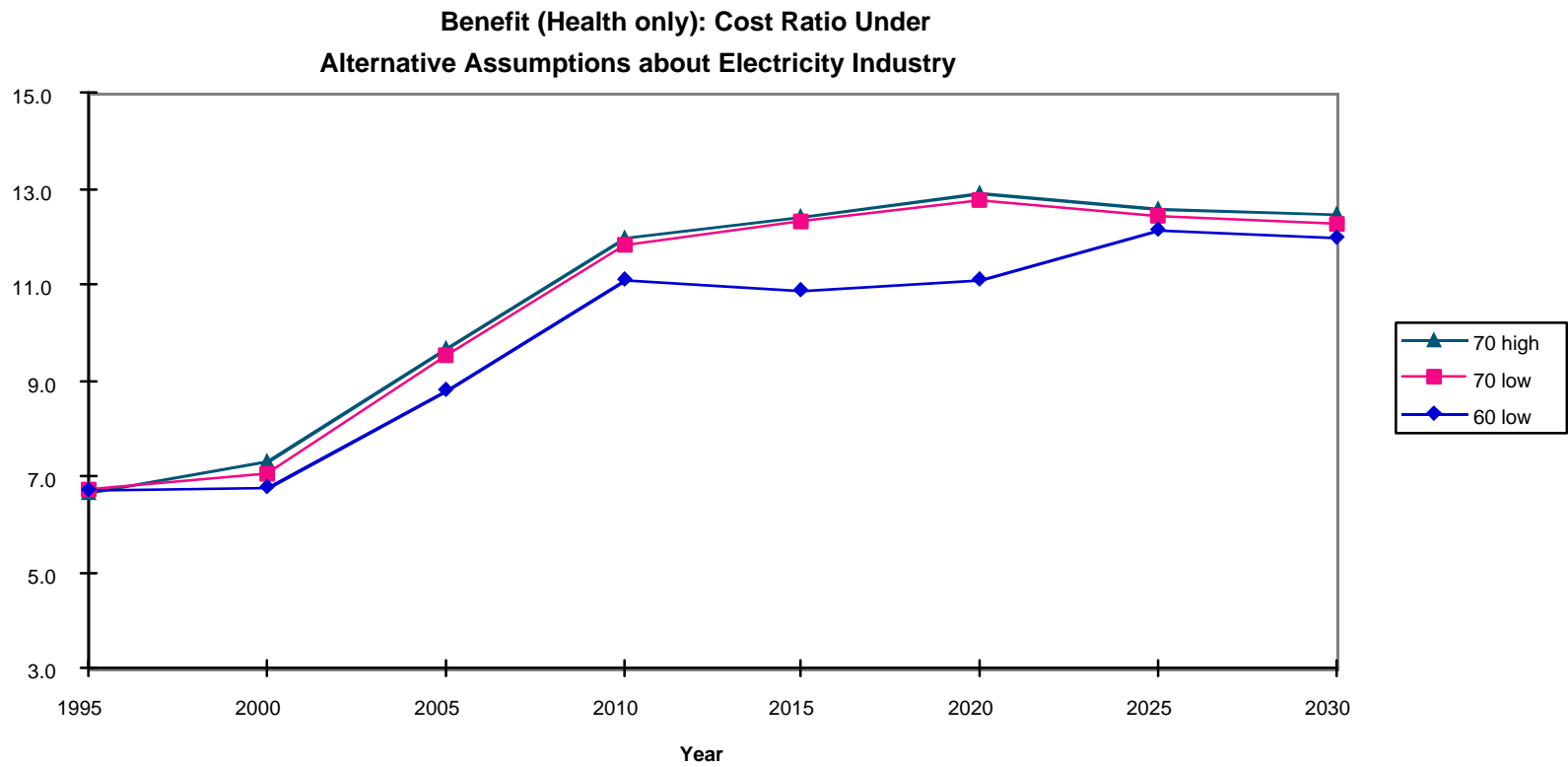- 70 high
- 70 low
- 60 low

X-axis: Year

Figure 2: Benefit-cost ratio for health benefits under alternative assumptions about electricity industry
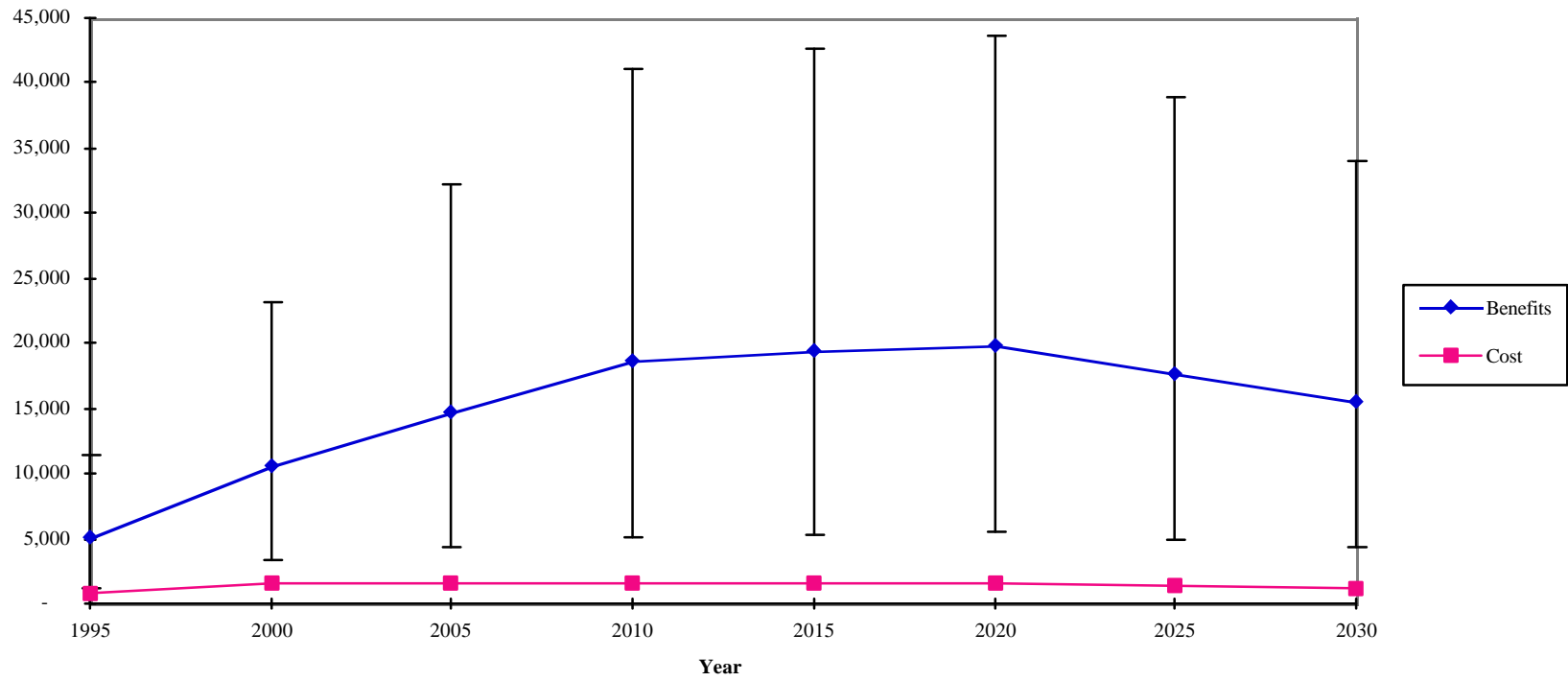
16

Figure 3: Annual mean total health benefits with 90% confidence intervals compared with expected annualized costs

benefits are attributable to NO_x reductions (the rest are attributable to sulfate reductions). Of morbidity benefits, NO_x reductions account for closer to 27 percent of the benefits, according to our analysis.

Figure 4 reports the annual mean total health benefits and annualized costs for the TAF default case, the HB case for sulfates only, each of the three separate sensitivity analyses which are *designed* to reduce benefits, and for the combination case. The three separate analyses do not eliminate the gap between expected benefits and levelized costs in any year when taken separately. The most dramatic reduction in benefits occurs when we use very conservative assumptions to value statistical life. For instance, in 2020, expected total health benefits are $19.9 billion in the default scenario, but only $5.4 billion in this sensitivity case. Uncertainty analysis on the three sensitivity cases reveals that 5th percentile benefits are less than annualized costs up to, but not beyond, either 2000 or 2005, depending on the case, but that in no case do total costs exceed total health benefits. Only when we do a *combined* sensitivity analysis--where we assume that sulfates affect mortality with the potency of the average component of PM_{10} and that there is an effects threshold of 30 µg/m^3 PM_{10}--do we find total expected costs proximate to total expected benefits, though it is still less than benefits.

Annual Mean Total Health Benefits and Annualized Costs by Scenario
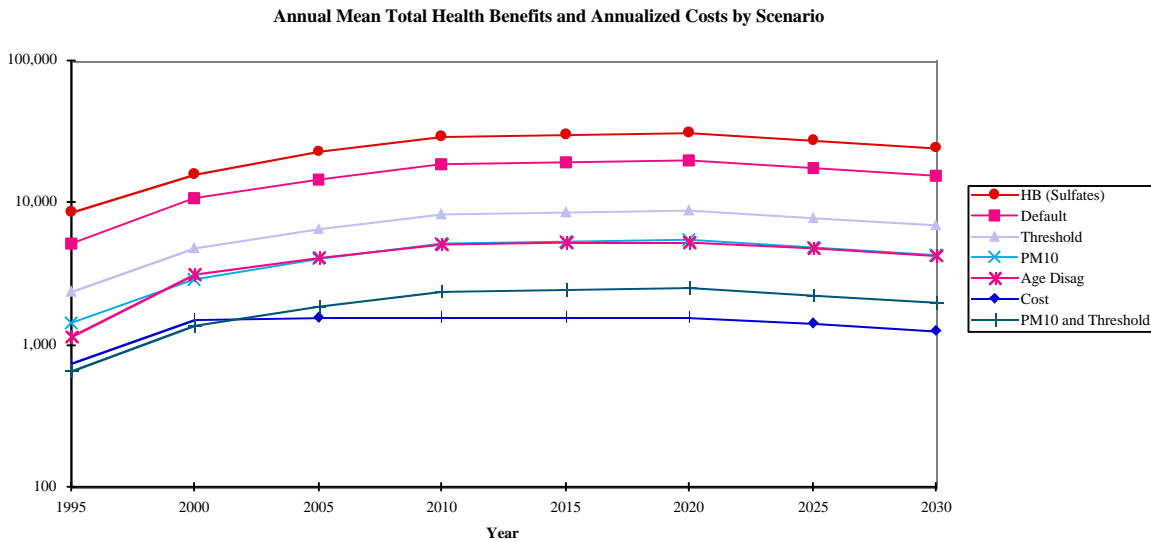
Figure 4: Annual mean total health benefits and levelized costs (log scale) by scenario

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 were largely concentrated in the Ohio Valley, many observers claimed that emissions from these power plants were contributing to environmental degradation in the Northeast. The regional decomposition of health benefits from reduced emissions is less parochial because atmospheric concentrations are

affected closer to the source of emissions. Table 3 illustrates that, expressed in per capita terms, the greatest health benefits accrue to the regions with the greatest changes in emissions.

Table 3: Expected total health benefits for 2010 and percent of national SO_2 emission reductions by state

State	Per Capita Health Benefits (1990$)	Percent of National Health Benefits	Percent of National SO_2 Emission Reductions
WV	$171.38	1.8%	12.0%
OH	$159.85	10.2%	23.3%
DC	$158.81	0.5%	0.0%
PA	$157.84	11.0%	9.8%
KY	$148.29	3.3%	11.0%
VA	$135.41	5.5%	0.4%
MD	$131.77	4.1%	0.4%
IN	$131.46	4.4%	16.0%
DE	$131.21	0.6%	0.0%
NJ	$130.70	6.2%	0.4%
NY	$115.42	11.6%	2.2%
Other	$36.93	40.8%	24.5%

Comparison with HB study

Table 4 provides sulfate mortality benefit estimates comparing the HB model and our default values in TAF. This comparison was obtained through a different run of the model than the results reported previously and consequently the results for our default assumptions vary due to use of a different sample drawn with a different sampling procedure. A common sample was drawn for all examples in this comparison, however.

Because we use identical census population projections for both estimates, there are three margins along which TAF and HB estimates may differ: (i) the quantities and locations of emissions changes differ; (ii) the "source-receptor matrices" linking emissions to concentrations over space differ; and (iii) the concentration-mortality risk estimates and the estimates of the value of a statistical life differ. Each scenario in Table 4 is identified by the source for emission changes (EPA for the HB study, or TAF's default values), the atmospheric model (RADM for HB, or ASTRAP for TAF) and the health effects and valuation functions (HB or TAF).

Table 4: Comparison of HB and TAF Mortality Sulfate Benefits (billions $1990) for Eastern U.S. with percent changes over previous scenario, Year 2010

Scenario:	EPA/HB	*New Transport*	*New Emissions*	*New Health* TAF
Emissions	EPA	EPA	TAF	TAF
Transport Model	RADM	ASTRAP-TAF	ASTRAP-TAF	ASTRAP-TAF
Health/ Valuation	HB	HB	HB	TAF
Mean				
Benefits (billion $)	30.3	56.9	25.1	15.4
Percent Change		+87.8%	-55.9%	-38.6%
Benefits ($) per ton	3,289	6,179	6,296	3,852
Median Benefits (billion $)	19.0	34.5	15.3	12.64
Percent Change		+81.6%	-55.7%	-17.4%
Benefits ($) per ton	2,061	3,749	3,828	3,153

Expected (mean) mortality benefits are higher from HB than TAF. Before any adjustments, HB found sulfate mortality health benefits of $31 billion in 2010 (1990$) in the Eastern U.S. while TAF estimates benefits of $15.4 billion in this region.[12] We reconcile differences in population estimates by using TAF's estimates in both scenarios. Under these assumptions, adjusted HB estimates are $30.3 billion as reported in Table 4.

Although we do not focus on uncertainty in this reconciliation, we note that the adjusted HB estimates range from $5 to $67 billion for the 20th and 80th percentiles around the mean. TAF has tighter uncertainty bands, at $7.6 to $24 billion for the same confidence interval. This uncertainty difference is driven primarily by our use of a narrower range of PM-mortality studies than those used by Hagler Bailly.

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[12] When including morbidity, total health benefits for HB are $35.5 billion, and for TAF they are $17.8 billion. Benefits in the Eastern U.S. make up the 98% of the benefits in TAF for the entire U.S. Also note that in using RADM for atmospheric modeling, HB is using the median of several runs of the model rather than the mean.

To reveal the effect of each of these differences in underlying assumptions, we begin with the HB analysis, and gradually replace HB assumptions with default assumptions in TAF. We begin by substituting the ASTRAP source-receptor coefficients used in the TAF analysis for RADM, which results in a large (87.8 percent) *increase* in the benefit estimates (from $30.3 billion to $56.9 billion). Viewing the results state-by-state explains what is happening. The HB version with RADM shows a highly variable pattern of benefits, ranging from $360 per capita in Tennessee to $13 per capita in Minnesota. The highest benefits are in the south (particularly the southeast and southern Appalachians); Mid-Atlantic and New England states have very low benefits per capita. In contrast, the TAF-ASTRAP version yields larger benefits that are also less variable. Further, ASTRAP shows much larger effects in the northeast, followed by the Mid-Atlantic states, and then some southern states, with smaller benefits in several others. These differences translate to per capita benefits with ASTRAP that are highest in the Mid-Atlantic, about equal in the Midwest and Northeast, and smallest in the South.

What could account for such differences between ASTRAP and RADM? Shannon, et al. (1997) found the two models' predictions reasonably in agreement for predicting atmospheric sulfate concentrations in the eastern U.S., though RADM actually predicts greater sulfate reductions in the more populated regions including the mid-Atlantic. Weather patterns appear to be handled differently by RADM and ASTRAP in a way that could account for much of the difference in benefits. In the HB application, the *median* episode taken over 30 episodes is used rather than a weighted average of episodes. In contrast, ASTRAP uses 11 years of daily meteorology to develop its source-receptor (S-R) matrices, which are constructed to represent average meteorology for each season. Given the lognormal distribution of meteorology, the median could be far below the mean.

Substituting EPA emissions forecasts with the TAF emissions forecasts *decreases* mortality benefits (which drop 56 percent from $56.9 billion to $25.1 billion). Although approximately equal average annual emissions should obtain in the long run, the EPA forecast suggests a higher baseline level of emissions and hence greater emission reductions under the program. EPA's higher baseline projects fewer units switching to coals with lower sulfur content than does the TAF model.

We complete the reconciliation by substituting TAF mortality coefficients and values of a statistical life for those in HB (recall that we are only considering mortality effects). This switch decreases our mean benefit estimate by 38.6 percent (from $25.1 to $15.4 billion). This change is primarily a consequence of the inclusion by HB of the Dockery et al. (1993) "six city" study relating annual PM2.5 concentrations to the probability an individual in the cities will die during the study period. While HB assigns this study a weight of 25 percent, we give it no weight because it is dominated, in our opinion, by the Pope et al. (1995) study, which uses a similar approach but is applied to 552,000 individuals over 151 cities. HB also uses somewhat higher values of a statistical life than we do (they use an estimate with a expected value of $3.2 million, the expected value of the TAF estimate is $3.1 million).

Comparison with the RIA

For further analysis of heath effects we substitute coefficients from the EPA's draft Regulatory Impact Assessment (RIA) for particulates into the health effects and health valuation modules. Compared with the EPA/HB analysis in Table 4, which reported mean annual mortality benefits from sulfate reductions in 2010 of $30.3 billion in the Eastern U.S., the RIA (using EPA emissions and RADM for atmospheric modeling) approach yields $25.6 billion. The RIA uses a higher value of a statistical life ($4.8 million) than HB, but predicts a smaller change in mortality for the same change in sulfate concentrations, despite including long-term mortality effects. The EPA/RADM/RIA analysis estimates are still larger than the mean estimates for TAF of $15.4 billion. When we substitute the RIA for TAF in measuring health effects and valuation (TAF/ASTRAP/RIA), the expected benefits fall to $21.3 billion.

Cost Comparisons

The costs of SO_2 reductions under Title IV have attracted considerable attention because of the innovative allowance trading program. Cost projections from the middle 1980s based on command and control approaches, and projections of *marginal costs* under a market with an inadequate level of trading, ranged as high as $1500 per ton (Bohi and Burtraw, 1997). At the time of Title IV's enactment the EPA projected costs in 2010 of $450-$620 per ton (ICF, 1990). Cost estimates have continued to decline, in large part because the program gives utilities the flexibility to exploit advantageous trends in coal markets and the cost of rail transport that have led to a drop in the cost of switching to lower sulfur coal.

Table 5 reports a series of estimates for *average costs* (which are expected to be lower than marginal costs in Phase II), illustrating that various projections have continued to decrease as allowance trading has taken hold. Nonetheless, the TAF default costs are on the low end of this range. The ICF (1995) estimates are the final in a series of declining estimates provided for the EPA by ICF since 1989. ICF (1995) estimates were reported in the EPA's Regulatory Impact Assessment for Title IV. These estimates describe a considerably greater emissions reduction because of higher projected emissions in the baseline than assumed in TAF. The greater annual costs spread over greater emission reductions yield comparable average costs. It makes sense that the average costs per ton are greater in the TAF estimates since it assumes more switching to low sulfur coal for economic reasons in the baseline; a greater portion of this switching is accounted for as part of Title IV by ICF and this brings down the average cost per ton in that study. Based on recent econometric estimates (Burtraw et al., 1997) and the recent trend in fuel markets, and also due to current trends toward increasing competition in the electric utility industry, we believe the TAF estimates can be taken as central estimates. ICF (1995) suggests annual costs about 2.5 times those included in the TAF default case; however, the estimated cost per ton reduction is just about equal to that for TAF.

Table 5: Long run (Phase II, year 2010) cost estimates for SO2 reduction

Study	Annual Cost (billion 1990 dollars)	Average Cost per Ton SO2 (1990 dollars)
TAF Default	0.8	205
ICF (1995)	2.0	216
White, *et al.* (1995)	1.2-2.5	245-286
GAO (1994)	1.8-2.9	197-320
Van Horn Consulting *et al.* (1993)	2.0-3.2	289-373

Other reported estimates include White et al. (1995) and Van Horn Consulting et al. (1993) which were compiled for the Electric Power Research Institute. The range of estimates in White et al. is associated with the level of plant utilization, comparable to TAF's low and high electricity demand cases. Van Horn Consulting was also the contractor for the GAO (1994) estimates. The range of estimates for GAO pertain to variations in the liquidity of the allowance market, and the range in the Van Horn Consulting estimates cover a mix of scenarios.

Another aspect of regulatory costs that has only recently been investigated and estimated is the hidden social cost of imposing additional regulations in a second-best setting characterized by pre-existing regulations and taxes that already distort the economy away from economic efficiency. This issue has ignited colorful debate with respect to policies to address climate change. Goulder et al. (1997) addressed this issue in an analytical and computable general equilibrium model of the SO_2 program to estimate hidden social costs due to the second-best setting for Title IV. They estimated that the social costs stemming from interactions between the trading program and pre-existing taxes in the economy were $533 million per year. This social cost stems from the fact that the SO_2 program, like any regulation, imposes a cost that reduces the real wage of workers. This cost can be viewed as a virtual tax, and when imposed on top of pre-existing taxes, has large consequences for economic efficiency. Unfortunately, as far as this issue is concerned, the SO_2 trading program imposes particularly large costs because it encourages firms to internalize not only their abatement costs, but also the cost of residual emissions through the opportunity cost of SO_2 allowances. Were the program to raise revenues through the auction of permits, it could use these revenues to offset this tax-interaction effect by reducing other distortionary taxes. However, the SO_2 allowances are allocated without charge, so there is no revenue available for this purpose, and consequently the tax-interaction effect and resulting social cost is substantial.

Table 6 reports alternative cost estimates for the NO_X portion of Title IV. The E.H. Pechan (1996) estimate may be high because it reflects average costs for 3.7 million tons per year in NO_X emission reductions. This is greater than the other estimates, and reflect reductions as a result of Title IV requirements coupled with requirements on electric utilities

23

stemming from other parts of the Clean Air Act Amendments. Also, like the TAF estimates, E.H. Pechan does not allow for averaging of emission rates among commonly owned and operated facilities, which is a feature in the actual implementation of the regulation. In contrast, the TAF emission reductions are 1.97 million tons per year and the ICF (1996) reductions are forecast to be 2.06 million tons per year, both reflecting only the specific requirements of Title IV. Among these three sets of estimates, only ICF reflects the reduction in costs that can be expected through emissions averaging, which helps explain why it is lower than the others.

Table 6: Long run (Phase II, year 2010) cost estimates for NO_X reduction

Study	Annual Cost (billion 1990 dollars)	Average Cost per Ton NO_X (1990 dollars)
TAF Default	0.8	382
ICF (1996)	0.5	229
E.H. Pechan (1996)	1.6	438

Considering the alternative cost estimates, and also recognizing that costs stemming from the second-best setting of environmental regulation are excluded, we argue that TAF's more conservative default estimate is a reasonable midpoint. We feel especially justified in this view because of the apparent magnitude of benefits compared to costs. If one were to double TAF's estimate, this difference would have an important effect on the benefit-cost comparisons illustrated in our previous examples; however, it would not by itself change the qualitative finding that benefits appear to outweigh costs by a significant margin.

Unmodeled Pathways and Research Priorities

To varying degrees, members of the team of scientists and economists that contributed to construction of TAF initiated review and modeling of environmental pathways that were not part of our quantitative analysis. Based in part on these efforts, we have constructed a qualitative review of pathways that are not modeled, including a relative ranking of their expected magnitude, and a prioritization for further research according to our assessment of the value of additional information for each. This evaluation is reported in Table 7.

Short run and long run research needs vary among the modeled and unmodeled pathways. Estimates of health and visibility benefits remain uncertain; however, the cost of reducing uncertainty appears to be relatively less than many other areas. To evaluate Title IV on the basis of a comparison of benefits and costs, it may be sufficient to focus efforts at assessing benefits from health and visibility, because these benefits alone appear to outweigh the costs. Environmental areas including aquatics and forests stand to benefit in addition.

Table 7: Qualitative evaluation of expected benefits and value of additional information for modeled and nonmodeled pathways

Categories ● high ◐ high-mid ◖ mid ◉ low-mid ○ low	Expected Benefit: Are expected benefits large?	Value of Additional Information: With the goal of improving benefit estimates, what is the relative short-term return on investment?
Health: Mortality	●	●
Health: Morbidity	◐	◐
Visibility	◐	◐
Materials and Cultural Resources	◐	◐
Nonuse Values: Ecosystem Health	●	◖
Aquatics: Recreation	◉	◖
Forests: Recreation	◉	◖
Agriculture and Commercial Forestry	◖	◉
Radiative Forcing	◉	○

While there are many issues facing the health scientists and epidemiologists, economists should work to improve the basis for the valuation of small risks to mortality health due to environmental changes. Also, economists need to develop estimates for WTP to avoid these risks that depend on the age and health status of the affected individual. For visibility, valuation needs to be more precise with respect to the endpoints that are important for assessment of benefits, and particular attention should be paid to the nature of preferences for changes in visibility, such as the trade-off between changes in the mean and extreme values of visual range. Benefits to materials and cultural resources is another area where benefits may be sizable. Rapid progress could be made through further work on the valuation of cultural resources, which should concentrate on the identification of the resources and the attributes of those resources that are meaningful endpoints to individuals. Assessment of benefits to commercial materials requires an improved inventory of affected materials, and improved estimates of their economically useful lives.

Over the longer time frame, we suggest assessment of nonuse values for ecosystem health should be afforded high priority. However, a research emphasis in this area would require sustained levels of funding over several years to yield results that would be reliable.

Also, agriculture and commercial forestry would receive a somewhat higher ranking in Table 7 were a sustained level of funding to be committed. One reason sustained funding over time would be necessary is that agriculture is undergoing structural change due to reforms passed by Congress in 1996 that may not be fully attained until the next decade. In addition, estimating rural ozone effects may be costly and time consuming, though such modeling would also contribute to an understanding of human health benefits and forest recreation.

The most important of the uncertainties and omissions in this analysis are summarized in Table 8 which appears as an appendix to this paper. In this table we indicate our qualitative assessment of the direction of the bias for each of these shortcomings. A plus sign (+) indicates the uncertainty or omission imposes an upward bias in our benefit or cost estimate; a negative sign (-) indicates otherwise. Additional information about the uncertainties and limitations at each step in the TAF model is provided in the documentation for TAF (Bloyd et al., 1996).

V. CONCLUSIONS

Although important limitations, caveats, and major uncertainties inhibit the comprehensiveness of this benefit-cost analysis, the clear conclusion that emerges from the array of scenarios we explore is that the benefits of Title IV exceed the costs by a substantial margin. This assessment differs from the information that was available to policy makers at the time the program was enacted in 1990. At that time, Portney (1990) ventured to offer a comprehensive assessment of the Clean Air Act Amendments. Portney wrote that the expected benefits and costs appeared to be about equal for Title IV, in part because of the cost savings that were expected to result from the innovative allowance trading program. Since that time it appears that costs have fallen significantly compared to prior expectations, and benefits are now thought to be greater than expected.

Expected benefits tend to be high in some areas that were not a primary focus of benefits assessment in the 1980s, particularly health and visibility. The dominant category of benefits is mortality, which we expect to be several times the costs of the program. We find mortality values that are less than previous estimates for the EPA. Still, in our analysis there is no year in which health benefits alone at the 5 percent confidence level are less than the levelized expected costs. About 89 percent of the total health benefits are attributable to changes in SO_2 and 11 percent attributable to changes in NO_X emissions.

We emphasize that there are tremendous uncertainties in measuring and valuing 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. In the future we expect these critiques to gain in credibility as more is learned about how to measure benefits. On the other hand, we note that because environmental exposures are involuntary, compared with studies of labor market behavior, the latter may underestimate willingness to pay to avoid environmental exposures.

Morbidity, recreational visibility, and residential visibility benefits each separately appear to measure at comparable magnitude with costs. About 73 percent of morbidity effects are attributable to SO_2, and 27 percent are attributable to NO_X. (We do not model the contribution of NO_X to ozone.) The visibility estimates illustrate their potential magnitude, but we note that the literature is narrow and should be subject to closer scrutiny.

Public attention in the 1980s to air pollution from SO_2 and NO_X emissions largely centered on the problem of acidification ("acid rain"), with particular concern for its affect on water and soil chemistry and ultimately ecological systems. It is surprising to many that relatively low benefits are estimated by economists for effects on aquatics (in this study) or are expected to result from effects on forests and agriculture. 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 values for aquatics stem from an assessment of *use* values, or *commodity* values in the case of agriculture. Environmental changes may also yield *nonuse* values, and estimates for nonuse values are not available. Nonetheless, the evidence, based on a small number of relatively narrow studies, suggests these values may be significant.

The costs of compliance under Title IV have attracted attention because of the innovative allowance trading program. Many recent estimates find costs to be lower than anticipated for SO_2 emission reductions, in large part because of the flexibility the program gives firms to find least-cost ways to reduce emissions and to take advantage of advantageous trends in fuel and factor markets. Nonetheless, the TAF default costs are on the low end of previous estimates for SO_2 and somewhat high for NO_X control, and they do not take into account hidden social costs stemming from the second-best setting for environmental policy. These factors impart uncertainty around estimates of costs in this study.

The strength of this analysis using TAF is the flexibility it gives us to explore uncertainties in the measurement of benefits and costs, and to employ consistent assumptions in the comparison of benefits and costs. We acknowledge important gaps and uncertainties in this analysis. Nonetheless, in spite of, and in some cases because of these important caveats, our exploration of the relevant uncertainties leads us to find compelling evidence that benefits of Title IV substantially exceed costs.

Table 8:   Major uncertainties and omissions and direction of bias in TAF

Uncertainties and Omissions	Bias	Description
BENEFITS		
AGGREGATION TO STATE LEVEL	**?**	Emissions, atmospheric transport and effects are modeled at state level. Probability distributions are used to represent variability within states in the simulations.
ATMOSPHERIC MODEL DOES NOT CAPTURE ROLE OF AMMONIA	**+**	Ammonia may be a limiting factor in formation of secondary particulates. Reductions in one (e.g. sulfates) may allow increases in the other (e.g. nitrates).
AQUATIC EFFECTS CAPTURE ONLY LIMITED RECREATIONAL USE, ONLY AT LAKES	**-**	The measure does not capture effects on other recreational uses.
AQUATIC EFFECTS LIMITED TO ADIRONDACKS	**+/?**	The Adirondack region has high participation rates compared to nation. Calculation of effects on "per affected capita" basis yields inflated values when extrapolated to nation.
RECREATIONAL VISIBILITY	**+/?**	Only two parks included, but this may capture majority of benefits. Contingent valuation methods uncertain. Valuation is not precise with respect to the distribution of visibility improvements over time.
RESIDENTIAL VISIBILITY	**?**	Only five cities evaluated; benefits represented on "affected per capita" basis.
MORBIDITY MEASURES	**-**	Reduced workplace productivity for small effects not captured.
MORTALITY COEFFICIENT	**+**	Use of mortality coefficients treats all mortality effects equally. A preferable approach would be life-years lost.
VALUE OF STATISTICAL LIFE	**+/?**	The VOSL approach does not value appropriately small changes in life expectancy realized late in life (+). Health status is not included. (+) However, VOSL ignores involuntary nature of exposure (-).
OMITTED ENVIRONMENTAL ENDPOINTS AND NONUSE VALUES LISTED IN TABLE 6	**-**	Magnitude of use values for omitted pathways may be small as indicated by included aquatic endpoint. However, nonuse measures are not explored and may be significant.
BENEFITS OUTSIDE U.S. EXCLUDED	**-**	The analysis is limited to the continental U.S.
COSTS		
SO₂ PROGRAM MODELED AS PERFECT TRADING	**-**	Regulatory incentives may hamper allowance trading.

Table 8: Major uncertainties and omissions and direction of bias in TAF   (continued)

Uncertainties and Omissions	Bias	Description
NO$_X$ ABATEMENT MODEL DOES NOT REFLECT EMISSIONS AVERAGING	+	Implementation of NO$_x$ rules allows emission rate averaging among commonly owned and operated units which lowers costs.
ELECTRICITY DEMAND GROWTH	-	Previous analysis has indicated electricity demand growth and plant lifetime to be the most important variables in costs. Both variables explored in sensitivity analysis. Our analysis is conservative (low) on projected demand growth.
PLANT LIFETIME	?	Plant lifetime is treated parametrically.
PARTIAL EQUILIBRIUM ANALYSIS	-	General equilibrium effects indicate hidden efficiency costs from regulations that raise product costs. Also, failure of program to raise revenue.

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