Ancillary Benefits of Reduced Air Pollution in the United States from Moderate Greenhouse Gas Mitigation Policies in the Electricity Sector

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December 2001 • Discussion Paper 01–61

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Resources for the Future
1616 P Street, NW
Washington, D.C. 20036
Telephone: 202–328–5000
Fax: 202–939–3460
Internet: http://www.rff.org

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Abstract

This paper considers how moderate actions to slow atmospheric accumulation of greenhouse gases from fossil fuel use also could reduce conventional air pollutants in the United States. The benefits that result would be "ancillary" to greenhouse gas abatement. Moreover, the benefits would tend to accrue locally and in the near term, while benefits from reduced climate change mostly accrue globally and over a time frame of several decades or longer. The previous literature suggests that changes in nitrogen oxides (NO_X) would be the most important consequence of moderate carbon policies. We calculate these changes in a detailed electricity model linked to an integrated assessment framework to value changes in human health. A tax of $25 per metric ton of carbon emissions would yield NO_X related health benefits of about $8 per metric ton of carbon reduced in the year 2010 (1997 dollars). Additional savings accrue from reduced investment in NO_X and SO_2 abatement in order to comply with emission caps. These savings sum to $4-$7 per ton of carbon reduced. Total ancillary benefits of a $25 carbon tax are estimated to be $12-$14, which appear to justify the costs of a $25 tax, although marginal benefits are less than marginal costs. At a tax of $75 per ton carbon, greater health benefits and abatement cost savings are achieved but the value of ancillary benefits per ton of carbon reductions remains roughly constant at about $12.

Key Words: climate change, greenhouse gas, ancillary benefits, air pollution, co-control benefits, nitrogen oxides, sulfur dioxide, carbon dioxide, particulates, health

JEL Classification Numbers: H23, I18, Q48

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I. Introduction

A number of actions to slow atmospheric greenhouse gas (GHG) accumulation from fossil fuel use would also tend to reduce various "criteria" air pollutants (as defined in the Clean Air Act). The benefits that result would be "ancillary" to GHG abatement. Moreover, these benefits would tend to accrue in the near-term as does the cost of abatement, while any benefits from reduced climate change mostly accrue over a time frame of several decades or longer. In addition, ancillary benefits accrue largely to those countries undertaking mitigation action, in contrast to the benefits of reduced climate change risks that accrue at a global level.

A failure to adequately consider ancillary benefits could lead to an incorrect assessment of the "net costs" of mitigation policies--that is, the direct cost of climate policy less ancillary benefits that accrue from those policies--and an incorrect identification of "no regrets" levels of GHG mitigation. It also could lead to the choice of a policy that was unnecessarily expensive because of its failure to fully exploit potential ancillary benefits.

This paper presents results from a model of the electricity sector called Haiku. The model calculates market equilibrium by season and time of day for three customer classes at the

* Burtraw, Krupnick, Palmer, Paul, and Toman, Resources for the Future; Bloyd, Argonne National Laboratory.
The authors are grateful to Lawrence Goulder, Anne Grambsch, Peter Nagelhout and Joel Scheraga who shared co-authorship on an early draft of this paper and contributed significantly to its development. The authors are also grateful to Roger Dower and John Firor for comments on previous drafts, and to Ranjit Bharvirkar, Matt Cannon, Martin Heintzelman, Erin Mansur and Meghan McGuinness for outstanding assistance. This work was funded by the U.S. Environmental Protection Agency and by the U.S. Department of Energy. All errors and opinions remain the responsibility of the authors. Address correspondence to Burtraw, Resources for the Future, 1616 P Street NW, Washington DC 20036 (email: burtraw@rff.org).

regional level, with power trading between regions. The model is used to simulate the effects of various moderate carbon taxes on investment, retirement and system dispatch for the year 2010, and on changes in emissions of nitrogen oxides (NO_x) that result from these carbon taxes. We model alternative baselines in the absence the GHG policy, all of which go beyond requirements of the 1990 Clean Air Act. In one case, we model full implementation of Title IV of the 1990 Clean Air Act in the electricity sector, coupled with Phase II of NO_X reductions in the northeastern 11 state Ozone Transport Commission region. In another case, we include further reductions in the baseline by applying NO_x emission rates in an eastern 19 state region to comply with standards expected to take effect in 2004, affecting the so-called "SIP Call" region associated the requirement that states revise their State Implementation Plans. In a sensitivity analysis, we vary the representation of the regulatory structure in the electricity industry.

We find health-related ancillary benefits from further reductions in NO_x emissions under a \$25 carbon tax to be about \$8 per metric ton of carbon reduced (1997 dollars). Aggregate reductions in sulfur dioxide (SO_2) are not affected by the moderate carbon policies we model, but additional savings accrue from reduced investment in NO_X and SO_2 abatement in order to comply with emission caps. These savings sum to \$4-\$7 per ton of carbon reduced. Total ancillary benefits of a \$25 carbon tax are estimated to be \$12-\$14. These compare to expected average cost of carbon reductions of about \$12 for a \$25 tax. Hence ancillary benefits contribute significantly to a justification for the moderate carbon tax of this magnitude, though the marginal ancillary benefits are less than marginal costs of a \$25 tax.

At a tax of \$75 per ton carbon, greater health benefits and abatement cost savings are achieved but the value of ancillary benefits per ton of carbon reductions remains at about \$12. These compare to expected average cost of carbon reductions of less than \$37.5 for a \$75 tax. In this case ancillary benefits are expected to be about one-third of the average cost per ton. These findings compare favorably with the most detailed models that have been used in the previous literature, reviewed in Section V, after accounting for the omissions in those models that have been explicitly captured in this analysis.

Numerous uncertainties surround the estimates and the choice of assumptions in the parameterization of the models. Some of the previous literature has obtained relatively large estimates of ancillary benefits under assumptions that have been criticized. Therefore in this study we have tried to buttress the conclusions with assumptions that are well within the mainstream but may be likely to achieve smaller estimates than would defensible alternative assumptions. The main result survives this cautious approach. We find that ancillary benefits weigh importantly in the consideration of climate policy and provide near-term and local benefits that offset an important portion of the costs of the policies.

II. Background

Three types of methodological issues are important to the consideration of how GHG mitigation could yield ancillary benefits (Krupnick, Burtraw and Markandya, 2000). These include the characterization of changes in emissions, the characterization of health benefits, and the baseline against which these changes are measured.

Emissions

Recent comprehensive studies of electricity fuel cycles indicate that the lion's share of the quantifiable environmental and public health effects of fuel and technology choices in electricity generation stem from air emissions (Lee et al., 1995; Rowe et al., 1995; EC, 1995). In reviewing these studies, Krupnick and Burtraw (1996) find that 82% to 93% of all quantifiable damages (e.g. excluding climate change and species biodiversity) stem from the air-health environmental pathway. Other effects may exist but are not quantifiable at this time (Burtraw et al., 1998). The major component of quantifiable damage is attributable to the change in particulate concentrations.

Previous studies that address only the electricity sector identify potentially significant reductions in NO_x that may result from policies aimed primarily at reducing CO_2 emissions. The studies vary in their predictions about reductions in SO_2 depending on their treatment of the emission cap under the 1990 Clean Air Act Amendments, an important baseline issue we discuss below. Secondary pollutants (sulfates, nitrates and ozone) are treated in an inconsistent manner across previous studies, and often are not mentioned at all.

In this study we focus on the reduction in emissions of NO_x that are ancillary to CO_2 emission reductions achieved in the electricity sector, and which is the pollutant of greatest interest in previous studies. We focus on the effect of NO_x directly and through particulate (nitrate) formation (but excluding ozone formation) on health effects. These limitations contribute to the view that our estimates may be a lower bound of the estimates that would be achieved if a complete analysis was possible. The focus on the electricity sector in not especially limiting. The sector is responsible for one-third of CO_2 emissions presently, and the EIA projects that this sector will be responsible for about three-quarters of CO_2 emission reductions in the United States under economy wide and cost-effective climate policies (USEIA, 1998). This sector will be especially important as the least expensive and likely first source of reductions under moderate reduction scenarios.

Health Effects

Many previous studies have attempted to calculate health benefits based on aggregated "unit values," i.e., uniform estimates of benefits expressed as "dollars per ton of pollutant reduced." These estimates do not incorporate information about geography and demography in valuing benefits. An alternative method, the "damage function approach," focuses on estimating the social cost of electricity generation from facilities examined on an individual basis. This approach has been used in recent analyses of environmental impacts of electric power plant siting and operation in specific geographic locations (Lee et al., 1995; EC, 1995; Rowe et al., 1995; Banzhaf et al., 1996).

The damage function approach is more complex than the use of simple unit values. However, the results of detailed studies may be generalizable. Krupnick and Burtraw (1996) survey three major social cost studies and largely reconcile the differences in quantified damages from conventional pollutants based on measurable differences in technical parameters at the power plants and in the size of exposed populations, although atmospheric modeling remains an important source of unpredictable variation.

It also is important to account for changes in population, especially since population trends have greatly outstripped energy prices over the last century.[1] The United States' population is expected to grow by 45% over just the next fifty years, which coupled with expected income growth, suggests that there will be greater exposure to a given level of pollution and consequently greater benefits from reducing that pollution (Krutilla, 1967). This demographic consideration suggests that the reported values for conventional pollutants in previous studies underestimate damage in future years, if all other things are equal.

In this study we use a damage function approach that involves an atmospheric transport model linking changes in emissions at a specific geographic location with changes in exposure at another location. Concentration-response functions are used to predict changes in mortality and a number of morbidity endpoints. The model accounts for expected changes in population, and for expected changes in income that affect estimates of willingness to pay for improvements in health status.

The Baseline

An analysis of benefits requires a clear definition of a baseline against which the prospective scenario can be measured. In a static analysis the baseline can be treated as the status quo, but since climate policy inherently is a longer-term effort, questions arise about projecting energy use, energy regulation, technology investments, and emissions of GHGs and criteria pollutants with and without the GHG policy (Morgenstern, 2000).

One potentially important aspect of the baseline is the regulation of the electricity sector. In this analysis we adopt a cautious assumption regarding the future regulation of the industry by assuming that traditional average cost pricing continues in effect for most of the nation over the study period. Seven subregions of the North American Electric Reliability Council (NERC) located in the northeast (New England and New York State), the west (California and the

[1] In real terms, energy prices have been about constant for the last century. The price of oil in the U.S. has fluctuated between $15 and $20/bbl for about a 100 years, except for the period 1974-1985. The mean jumped slightly for the period after 1986 as compared to that before 1973.

mountain states) and Texas, are modeled to have marginal cost pricing. The year in which restructuring is assumed to occur is reported in Table 1. In sensitivity analysis we explore an alternative scenario and describe the effect of electricity restructuring and marginal cost pricing at the national level.

The issue of the baseline is confounded further because of ongoing changes in the standards for criteria air pollutants. If one proceeds on the basis of historical standards and ignores expected changes in the standards, one would fail to anticipate that there may be less NO_X emitted per ton of CO_2 than there is today and the ancillary benefit estimate will overstate environmental savings. Historical emission rates may be ten times the rates that apply for new facilities. The recent tightening of standards for ozone and particulates and associated improvements in environmental performance over time imply that benefits from reductions in criteria air pollutants resulting from climate policies will be smaller in the future than in the present. The benefits of NOX reductions from current levels would have already been achieved, but the credit for the improvement could not be given to the climate policies. This underscores the general point that focusing on the ancillary benefits of climate policies is a partial view.

Furthermore, the nature of the ancillary benefits varies directly with the structure of the environmental policy that is in place (Lutter and Shogren, 2001). For example, regulation that establishes uniform emission rates such as a performance standard for new or all sources would enable reductions in conventional pollutants at those sources as a facility is utilized less. On the other hand, a cap and trade program will prevent aggregate emissions from changing as long as the cap continues to bind under the carbon policy. A climate policy is likely to yield savings in avoided investments in abatement under each type of policy, though the magnitude of those savings will differ greatly. Hence, absent the promulgation of a specific policy or identification of a specific proposal for implementing future emission reductions, one cannot estimate the ancillary benefits of concomitant climate change policy. In this study we look as far as possible into the future with respect to regulation of conventional pollutants as far as specific proposals regarding the shape of the regulation have taken shape.

Finally, it is also challenging to establish a baseline for technological change.[2] The rapid introduction of new technologies such as fuel cells could change both the overall efficiency of energy use but also the fuel type, but the rate of penetration is difficult to anticipate. Since the end point of this study is 2010, the technology baseline uncertainties should be small.

Table 1. Listing of NERC subregions, the year marginal cost pricing begins, and subregions covered by cap and trade NOX policies under modeled scenarios.

NERC Subregion	Geographic Area	Year Marginal Cost Pricing Regime Begins	OTC NO_X Trading Region	SIP NO_X Trading Region
ECAR	MI, IN, OH, WV; part of KY	-		ECAR
ERCOT	Most of TX	2002		
MAAC	MD, DC, DE, NJ; most of PA	2000	MAAC	MAAC
MAIN	Most of IL, WI; part of MO	2001		MAIN
MAPP	MN, IA, NE, SD, ND; part of WI	-		
NY	NY	1999	NY	NY
NE	VT, NH, ME, MA, CT, RI	2000	NE	NE
FRCC	Most of FL	-		
STV	TN, AL, GA, SC, NC; part of VA, MS, KY	-		STV
SPP	KS, MO, OK, AR, LA	-		
NWP	WA, OR, ID, UT, MT	-		
RA	AZ, NM, CO, WY	2001		
CNV	CA, NV	1998		

In this paper, baseline controls include restrictions on NO_x emissions beyond Phase II of Title IV of the 1990 Clean Air Act Amendments. These controls are modeled as cap and trade programs set to achieve an average emission rate of 0.15 lbs. per million Btu of heat input at all fossil-fired and wood-fired generation facilities. In one baseline, we model further reductions

[2] For example, SO_2 emissions in 2020 that were forecast in 1990 varied by a factor of two on the basis of expectations of clean coal technology and plant life (USNAPAP 1991, p. 222).

beyond Title IV in the Ozone Transport Region (OTR), which comprises 11 northeastern and mid-Atlantic states stretching from Maryland to Maine, plus the District of Columbia and the northern counties of Virginia, as indicated in Table 1. The OTR established NO_X emission "budgets" for each state for the five-month summer season, when ground-level ozone is commonly a problem, and enabled emissions trading among sources and states, beginning in summer 1999. The total NO_X budget for the region is 219,000 tons per summer (USEPA 1997a), a substantial reduction from the 490,000 tons of emissions in the region in the baseline year, 1990.

In a second baseline, indicated in Table 1, we model an expanded NO_x cap and trade program encompassing 19 states and the District of Columbia, resembling the EPA's proposed regional program to achieve NO_x emissions that initiated a redrafting of State Implementation Plans (SIPs) in the region. The EPA has promoted a trading program under an emission cap for the five-month summer ozone season affecting primarily fossil and wood-fired electricity generators. At the national level, the program would lead to reductions of 22% from an annual baseline level of 5.4 million tons in 2007 to a new annual level of 4.25 million tons, according to EPA estimates. Summer-season emissions in 2007 would fall by 40% from 2.4 million tons to 1.45 million tons.[3] In the affected region, the program is expected to reduce summer-season emissions by 62%, from 1.5 million tons to 0.56 million tons.[4]

Another important example of a regulatory baseline is the cap on SO_2 emissions from electricity generation in the United States. A consequence of the current emissions cap is that aggregate SO_2 emissions from electric utilities (the major source category in the United States) are not likely to change much as a result of moderate GHG emissions reductions such as we describe in this paper. Only if climate policies are sufficiently stringent that utilities substitute

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[3] USEPA 1998a, Table 2; USEPA 1998b, Table 2-1.

[4] USEPA 1998b, Table 2-1. The reductions pertain to EPA's original program that targeted 22 states and the District of Columbia.

significantly away from coal and the long-run annual level of SO_2 emissions is less than the annual emissions cap, would further reductions in SO_2 be achieved.[5]

Many previous studies use historical emission rates and do not incorporate the SO_2 emission cap, and therefore they do not recognize that aggregate SO_2 emissions will remain roughly constant. Hence they *overstate the ancillary benefits* that may be achieved, at least by moderate climate policies. By the same token, however, historically based carbon abatement cost estimates that do not incorporate the effects of the SO_2 cap *overstate the opportunity cost* of carbon reductions. For instance, the imposition of controls on a conventional pollutant such as SO_2 may reduce the cost advantage that coal has over gas for electricity generation. Layered on top of a control on SO_2, the reduction of carbon emissions (achieved by substitution from coal to gas) would be less expensive than it would appear were the model to ignore the SO_2 controls.

Further, there is an ancillary economic saving associated with CO_2 reductions, even with a binding SO_2 emissions cap. Under the cap, a facility that reduces its SO_2 emissions makes emission allowances available for another facility, displacing the need for abatement investment at that facility. In this paper we find the SO_2 cap remains binding under the moderate policies we model, and hence we do not anticipate ancillary health-related benefits from changes in SO_2 emissions. However, we do anticipate reduced costs of compliance with the SO_2 cap to result as a consequence of climate policies.

We also model existing and anticipated new standards concerning NO_x emissions from power plants that take the form of a cap and trade program analogous to the SO_2 program. In this framework, changes in NO_x emission in response to carbon policies are not expected in the region of the country covered by the NO_X cap, except for the subtle effects of changes in the location of emissions, which are captured in the model.[6] However, potentially important

[5] Direct emissions of PM are likely to be affected to only a small degree because current control technology already removes over 98% of PM at the stack.

[6] Changes in the location of SO_2 emissions under the aggregate emissions cap are not reflected in the estimates. Burtraw and Mansur (2000) examine the health effects of changes in the location of SO_2 emissions under the aggregate emission cap under the SO_2 emission trading program.

ancillary economic savings can result from the avoided abatement investment for NO_x controls, analogous to the avoided abatement investment for SO_2 controls under the SO_2 cap. In the event that the EPA's proposed cap is implemented but the trading program is not implemented, because the EPA lacks the authority to compel states to participate in trading, the level of emissions would be approximately the same as we model in our baselines but the cost of compliance with the NO_X rules would be greater. Therefore, our estimate of the compliance cost savings resulting form a carbon tax would be likely to underestimate the savings, in this case.

III. The Models

This study employs an electricity market equilibrium model called Haiku to simulate electricity generation and consumption between 2000 and 2010. Changes in emissions that result from policy experiments are fed into an integrated assessment model of atmospheric transport and environmental effects called the Tracking and Analysis Framework (TAF).

Haiku models market equilibrium in regional electricity markets and inter-regional electricity trade with a fully integrated algorithm for NO_X emission control technology choice. Haiku is constructed with the *Analytica* modeling software. The model simulates electricity demand, electricity prices, the composition of electricity supply, inter-regional electricity trading activity among NERC regions, and emissions of key pollutants such as NO_x, SO_2 and CO_2 from electricity generation. Investment in new generation capacity and retirement of existing facilities are determined endogenously in the model, based on capacity-related "going forward costs." Generator dispatch in the model is based on minimization of short run variable costs of generation.

Haiku employs a convergence algorithm to search for equilibria in multiple linked markets. The Intra-regional Electricity Market Component solves for a market equilibrium identified by the intersection of electricity demand for three customer classes (residential, industrial and commercial) and supply curves for each of four time periods (super-peak, peak, shoulder, and baseload hours) in each of three seasons (summer, winter, and spring/fall) within each of 13 NERC subregions. The Inter-regional Power Trading Component solves for the level of inter-regional power 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 NERC. Factor prices such as the cost of capital and labor are held constant. Fuel price forecasts are calibrated to match EIA price forecasts for 2000 (USEIA 1999). The model includes fuel market modules for coal and natural gas that calculate prices that are responsive to factor demand. Coal is differentiated along several dimensions including fuel quality and location of supply, and both are differentiated with respect to point of delivery. All other fuel prices are specified exogenously, with most changing over time.

The model can be used to simulate changes in electricity markets stemming from public policy associated with increased competition or environmental regulation. Technical parameters are set to reflect midpoint assumptions by the EIA and other organizations regarding technological change, growth in transmission capacity, and a number of other factors. The economic and technical parameters in the model yield relatively modest forecasts regarding increases in renewable electricity technologies over this time frame.[7] Most new investment in the baseline and in the policy cases we examine is in conventional technologies including integrated combined cycle natural gas units and gas turbines.

To estimate the potential for carbon emission reductions, we impose a tax on all emissions in the industry. This tax is collected through the price of electricity and affects dispatch and investment decisions. We explore three levels for the tax, all of which are far below the EIA's estimated tax of $348 per metric ton carbon required to achieve Kyoto budgets in 2010 in the absence of international trading. In the experiments the tax is set at $0, $25 and $75 per metric ton of carbon. All values are reported in real (inflation adjusted) 1997 dollars. There are minor reductions in carbon emissions that are achieved through fuel switching from coal to natural gas. In practice, there is a parasitic loss from running post-combustion controls at the power plant that may amount to 2% of power at the plant, and thereby lead to increased carbon emissions, but this is not represented in the model. There are slight reductions in carbon achieved in switching from less efficient to more efficient coal-fired generation, and due to reductions in consumption, that are represented.

The changes in emissions of NO_x are fed into the Tracking and Analysis Framework (TAF). TAF is a nonproprietary and peer-reviewed integrated assessment model constructed with the *Analytica* modeling software (Bloyd et al., 1996).[8] TAF integrates 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 chemistry, human health effects, and valuation of benefits. All effects are evaluated at the state level and changes outside the United States are not evaluated. We report only health-related impacts, which are the lion's share of impacts according to previous papers (Krupnick and Burtraw, 1996; Burtraw et al. 1998).

Health effects are characterized as changes in health status predicted to result from changes in air pollution concentrations. Impacts 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 to premature death. The health module is based on concentration-response (C-R) functions found in the peer-reviewed literature.[9] The C-R functions are taken, for the most part, from epidemiological articles reviewed in EPA's Criteria Documents that, in turn appear in key EPA cost-benefit analyses, such as the EPA Section 812 prospective and retrospective studies (USEPA, 1997a; USEPA, 1999).[10] The health effects module contains C-R functions for particulate matter smaller than ten microns in diameter (PM_{10}), total suspended particulates (TSP), sulfur dioxide (SO_2), sulfates (SO_4), nitrogen dioxide (NO_2), and nitrates (NO_3).

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[7] In this analysis we do not allow for cofiring of biomass with coal as a means of carbon reduction.

[8] TAF was developed in support of 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 is the work of a team of over 30 modelers and scientists from institutions around 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 (ORNL, 1995). The entire model is available at www.lumina.com\taflist.

[9] See Bloyd et al. (1996) and documentation at www.lumina.com\taflist.

[10] USEPA (1997b) provides health benefit estimates using the so-called acute studies, of which we use one of the best in Schwartz and Dockery (1992), and for the so-called chronic studies, which we use in our sensitivity analysis in Section V.

The PM_{10} mortality concentration-response function that is used for nitrates in this analysis is drawn from the daily time series study by Schwartz and Dockery (1992). In this exercise inputs consist of changes in ambient concentrations of NO_x, and demographic information on the population of interest. The potency of nitrates for mortality effects is treated as distinct from the potency of sulfates. Sulfates are considered relatively more potent than other constituents of PM_{10}, and nitrates are treated as comparable to other components of PM_{10} for both mortality and morbidity effects based on significant epidemiological linkages found between sulfates and various health endpoints (e.g., Pope et al, 1995) and the lack of such linkages found for nitrates when measured as distinct from PM. However, in this analysis we ignore changes in concentrations of emissions of SO_2 due to the cap on aggregate emissions.

For morbidity, changes in NO_2 and NO_3 are modeled according to a scheme designed to avoid double counting of effects such as symptom days and restricted activity days, using a variety of studies from the literature.[11] NO_X is included for respiratory symptom days, eye irritation days, and phlegm days. There is little if any evidence of a threshold in the concentration-response functions for any of the pollutants treated in this study so improvement in health status is assumed to result from reductions at any level of concentration. The change in the annual number of impacts of each health endpoint is the output that is valued.

The health valuation submodule of 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. The numbers used to value these effects are similar to those used in recent regulatory impact analysis by EPA (USEPA, 1997b) and the EPA Retrospective and Prospective studies (USEPA, 1997; USEPA, 1999). However, compared with EPA’s preferred estimate ($5.9 million in 1997 dollars), the value of a statistical life (VSL) in our model is adjusted downward ($3.8 mil in 1997$). The EPA choice is based on a curve-fitting analysis of 26 mostly labor market studies.

[11] For nitrates, which are modeled as PM_{10}, morbidity endpoints include asthma attacks, adult and childhood chronic bronchitis, chronic cough, emergency room visits, restricted activity days, hospital admissions, and respiratory symptom days. For NO_2, morbidity endpoints include eye irritation impacts and phlegm-day impacts.

The lower estimate that we use is more consistent with the VSL ($3.35 million in 1997 dollars) used by the Canadian government (DeCivita et al, 1999). In contrast, a new analysis by Mrozek and Taylor (2002) has performed a more sophisticated meta-analysis of 38 studies contributing 203 VSL estimates. They find that EPA's best estimate is three times too large (i.e., the best estimate of Mrozek and Taylor is $2 million), owing to a number of factors. The most important is a false attribution of wage rate differentials to mortality rate differences, when in fact, much of this variation is due to inter-industry differences in wage rates that occur for other reasons.

It has become increasingly recognized that the labor market approach relies on 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 an additional literature to estimate VSL through stated preference approaches in contexts more appropriate to that of mortality risks from particulate exposure. First results (Krupnick et al, 2002 and Alberini et al, 2001) show lower estimates of the VSL than being used by EPA, although the reasons for this may have more to do with futurity of the effect and better understanding of probability than health and age differences. Also, effects of dread and lack of controllability have not yet been factored into these new analyses. The sensitivity of the estimates with respect to the assumed VSL and other assumptions are explored in Section VI.

IV. Results

The first scenario reported in Table 2 is identified as OTC Baseline indicating that in this baseline a NO_X cap and trade program is in place in the northeast Ozone Transport Commission region. We find that a carbon tax of $25 per metric ton of carbon would yield ancillary benefits from reductions in NO_x of approximately $8 for each ton of carbon reduced in the year 2010 (1997 dollars). The primary category of these benefits is mortality, though morbidity benefits are also significant. In the OTC Baseline case, the ancillary benefits for a $75 tax increase in the aggregate, and when measured per ton of carbon basis they increase to nearly $10.

Table 2. Ancillary health benefits from reductions in NOx emissions resulting for various carbon taxes in the electricity sector in 2010 using Haiku/TAF (1997 dollars).

	OTC Baseline		SIP Call Baseline		SIP Call – MC Pricing Baseline	
Level of Carbon Tax ($/metric ton)	**25**	**75**	**25**	**75**	**25**	**75**
Baseline Emissions						
(metric tons)						
Carbon (millions)	682		664		687	
NOx (thousands)	5720		4543		4785	
Emission Reductions Under Carbon Policies						
Carbon (millions)	49	117	41	128	40	145
NOx (thousands)	502	1369	400	1203	380	2174
NOx Related Health Benefits						
(million dollars)						
Morbidity	86	246	66	205	66	400
Mortality	322	879	251	755	248	1,515
Total	408	1,125	317	961	315	1,916
NOx Related Health Benefits per Ton Carbon						
(dollars)						
Morbidity	1.7	2.1	1.6	1.6	1.6	2.7
Mortality	6.5	7.5	6.0	5.9	6.2	10.5
Total	8.4	9.6	7.6	7.5	7.9	13.2

The quantity of carbon emission reductions that are achieved by a $75 tax is less than proportional to that achieved by a $25 tax, which illustrates that the marginal abatement cost curve for carbon reductions is convex over this range. In the reference case, we find that the cost of new scrubbed coal and of new combined cycle natural gas generation are about equal, with a slight advantage to gas in most parts of the nation. The $25 tax serves to make new combined cycle natural gas plants more competitive with both new and existing coal plants. A $75 tax improves the situation for natural gas combined cycle plants further, making their operating costs less expensive than existing coal in almost the entire nation. However, the cost of capital additions, and constraints on how quickly investment and retirement can occur, constrain the role of combined cycle facilities. The carbon tax also improves the situation for gas turbines.

The national average delivered cost of natural gas in the OTC Baseline rose by about 9%, from $3.25 / mmBtu under the baseline to $3.55 under the $75 tax. The national average delivered price of coal fell by almost the same percentage from $0.96 / mmBtu to $0.88 over this range of policies. In the scenarios with NO_X controls in the SIP region, gas prices start out slightly higher and coal prices slightly lower than in the OTC Baseline, and the relative changes from the baselines are slightly less than in the OTC case. When the SIP region NO_X controls are overlain with marginal cost pricing, the baseline fuel prices and the change from baseline under the carbon taxes are very similar to the OTC scenarios.

In the OTC Baseline scenario with a zero carbon tax, the OTC region has about 15% of national generation in 2010 while the larger SIP Call region includes over 55% of national generation. In addition, the OTC region has less than 7% of national NO_X emissions while the larger SIP region has nearly 65%. In the second baseline, we model the NO_X cap and trade program in effect within the larger SIP region. In this baseline, NO_X emissions are reduced by over 16% at the national level and by 32% within the SIP region, compared to the OTC Baseline. The extension of NO_X controls to the SIP region could dramatically reduce the opportunity for ancillary benefits, especially since the form of regulation in the baseline is an emission cap, which implies that aggregate NO_X emissions are likely to remain unchanged. However, since the NO_X cap applies only during the five summer months, there remains an opportunity for reductions in the spring, fall and winter that would have health effects.

Table 2 reports that, measured against a SIP Baseline, a carbon tax of $25 per metric ton of carbon would yield ancillary health-related benefits from reductions in NO_x of almost $8 for each ton of carbon reduced in the year 2010 (1997 dollars). In the SIP Baseline case, the ancillary health benefits for a $75 tax are significantly greater in the aggregate, but they are nearly equivalent to those under the $25 tax when measured per ton of carbon reduction.

The third scenario reported in Table 2, labeled SIP Call with Marginal Cost Pricing, represents the possibility that restructuring of the electricity industry is implemented nationwide. We place somewhat less stock in this scenario because it is more speculative than the characterization of changes in NO_X policies that distinguish the first two scenarios. Consequently, we consider it a sensitivity analysis, in contrast to the first two scenarios that represent our preferred assumptions.

In the sensitivity analysis - SIP Call with Marginal Cost Pricing - we find ancillary health benefits of a $25 carbon tax are $8 per ton carbon reduced, about midpoint between the first two scenarios. However, for a $75 carbon tax the ancillary health benefits rise up to nearly $13 per ton carbon reduced, the highest value we observe in the cases we examine.

The benefit estimates in Table 2 indicate that benefits are not strictly linear with respect to NO_x reductions. This reflects the geographic differences in the national electricity industry, the geographically specific sources of emissions, atmospheric transport of pollutants and the different population densities exposed to those pollutant concentrations in the air.

We can examine how much of the increase in NO_x benefits is related to locational differences in generation by comparing the benefits per ton of NO_x reduction. The following numbers are derived from Table 2. The benefits from a reduction in NO_x emissions vary from $793 per ton of NO_x under a $25 tax in the SIP Baseline to $800 per ton at a $25 tax in the OTC Baseline. A $75 tax produces a similar pattern ranging from $798 to $822 in benefits per ton of NO_X reduced, with a greater measure in the case of the OTC Baseline scenario. In the sensitivity analysis labeled SIP Call with MC Pricing, the value per ton of NO_X reduced ranges up to $881. The differences in the benefit per ton of NO_x reduction are entirely due to locational differences. In essence, lower values result when the additional sources reacting to the higher carbon tax are located in areas where the conversion of NO_x to nitrates is less efficient, or where fewer people are being exposed to the nitrate concentrations, or both. Taken together, the nonlinearity in emission reductions and in the benefits of those reductions provides an indication of the importance of using a regionally disaggregated model to investigate this issue, unlike some of the previous studies that are discussed below.

The electricity generation in each baseline and the change from the relevant baseline under each carbon policy is reported in Table 3. In the OTC Baseline scenario, coal generation represents about 45% of total generation, and gas generation represents just over one-quarter in 2010. Under a $25 carbon tax, coal generation falls by over 11% and gas increases by about 10%

relative to their levels in the baseline. Total generation falls by about 2.5% in response to the increase in price, which increases by almost 5% on a national average basis. Non-hydroelectric renewables also decrease by a small amount in absolute terms, but by almost a quarter relative to the level in the baseline. This decrease may appear counter-intuitive, because the price of renewables does not increase under a carbon tax. However, the result is consistent in Haiku and some other models absent a policy that specifically promotes renewables. The reason is that the dispatch of technologies is scheduled according to short run variable cost. When new gas units are built in response to a policy, they have relatively low variable cost and very high potential utilization rates. Their relatively low cost allows them to crowd out some opportunity for renewable generation. The prospect for gas-fired generation is linked to the price path of natural gas, which has been volatile in recent years and is uncertain in the long run, but is expected to be relatively favorable toward the addition new gas-fired capacity over the next decade.

Table 3: National generation by fuel and electricity price in baseline, and change from baseline, under alternative scenarios, for 2010.

	Generation (million MWh)				Price (1997$/MWh)
Baseline/Policy Scenario	**Coal**	**Gas**	**Non-Hydro Renewables**	**Total**	
OTC Baseline	1877	1174	85	4147	60.7
$25 Carbon Tax	-213	+122	-20	-108	+2.9
$75 Carbon Tax	-536	+379	-15	-171	+11.8
SIP Call Baseline	1809	1182	90	4087	61.0
$25 Carbon Tax	-203	+159	-31	-68	+3.4
$75 Carbon Tax	-589	+408	-17	-192	+10.8
SIP Call Baseline with MC Pricing	1902	1147	87	4147	62.4
$25 Carbon Tax	-184	+126	-22	-80	+3.1
$75 Carbon Tax	-681	+507	-24	-199	+11.8

When expanding the carbon policy to a \$75 tax, the decrease in coal generation is nearly proportional to the \$25 case. Again, this decrease is made up primarily by an increase in gas-fired generation and also, to a lesser extent, by further decreases in generation in total. Under the \$75 tax, total generation falls by over 4% from the baseline, in response to an average electricity price increase of over 19%.

The change in generation under a SIP Baseline is similar to the OTC Baseline scenario. Perhaps the biggest difference between these scenarios is evident in the initial baselines, in the absence of a carbon tax. In the OTC Baseline total generation is greater, coal generation is greater and electricity price is lower than in the SIP Baseline because the SIP Call NO_X program initiates a switch from coal to gas within the region. Consequently, as indicated in Table 2, NO_X emissions are substantially less under the SIP Baseline. Also, carbon emissions are lowest in the SIP Call Baseline both inside and outside the SIP Call region.

The sensitivity analysis with marginal cost pricing also indicates the greatest difference in generation among the scenarios in the absence of a carbon tax. The introduction of marginal cost pricing leads to a significant decrease in new capacity and a greater reliance on existing capacity, including use of existing coal facilities. However, under marginal cost pricing, the choice of generation is more responsive to the carbon tax. The difference between the marginal cost pricing sensitivity case and the other scenarios is largely erased with a \$25 carbon tax and it is reversed with a \$75 carbon tax. In the absence of a carbon tax, the marginal cost pricing scenario has the most coal and the least gas generation of the scenarios we modeled. However, under the \$75 carbon tax this is reversed; the marginal cost pricing scenario has the least coal and the most gas generation. The reversal is evident as well in the reduction in NO_X emissions and the calculation of ancillary benefits per ton of carbon reduction reported in Table 2.

Table 4: Change in compliance cost for NOX and SO2 control, and cost savings per ton of carbon reduction, for 2010 (1997 $).

	OTC Baseline		SIP Call Baseline		SIP Call – MC Pricing Baseline	
Level of Carbon Tax ($/metric ton)	**25**	**75**	**25**	**75**	**25**	**75**
Baseline NO_X Compliance Costs (million dollars)	104		2199		2285	
Change from Baseline in NO_X Compliance Cost (million dollars)	-76	-100	-130	-414	-104	-904
NOx Compliance Cost Savings per Ton Carbon (dollars)	1.6	0.9	3.2	3.3	2.6	6.2
Change in SO_2 Compliance Cost (million dollars)	-136	-178	-139	-202	-120	-223
SO_2 Compliance Cost Savings per Ton Carbon (dollars)	2.8	1.5	3.4	1.6	3.0	1.5
SUM of Compliance Cost Savings per Ton Carbon (dollars)	4.4	2.4	6.6	4.9	5.6	7.7

Heretofore we have focused only on emission changes and their health effects. We noted the emission changes under an emission cap are zero as long as the cap is binding; however, the cost of achieving the cap on a conventional pollutant is affected by the carbon policy. There exist potential ancillary cost savings from the regulation of NO_X and SO_2 emissions under their respective caps.

To estimate the cost savings from avoided abatement of NO_X we rely on a direct estimate of compliance cost associated with post-combustion controls that are obtained in the model. The compliance cost estimates include annual capital and operating costs. These estimates are divided by the projected carbon emission reductions reported in Table 3 to obtain an estimate of NO_X related compliance cost savings per ton of carbon reduced. Table 4 indicates that these estimates range from around $1-2 per ton carbon, in the OTC Baseline scenario where NO_X regulation is the least stringent, to around $3 in the SIP Call Baseline scenarios. In the sensitivity analysis that simulates marginal cost pricing, the compliance cost savings reach as high as $6 per ton carbon reduced.

We cannot rely on investments in post-combustion controls for SO_2 abatement because no additional investments of this nature are expected in the baseline, so none could be avoided under a carbon tax. Marginal compliance in the baseline is expected to occur through substitution among types of coal that vary by sulfur content. Fuel costs savings associated with avoiding the expense of using low-sulfur coal is commingled with the additional cost of switching from coal to gas to comply with the carbon tax. Consequently, to evaluate the cost savings associated with SO_2 abatement we calculate the reduction in SO_2 emissions from each baseline that would result from reduced coal-fired generation under each carbon tax, were the average SO_2 emission rate to remain unchanged. The allowance price in any year represents the present discounted value of marginal compliance costs in 2010 (Carlson, et al. 2000). The implied reduction in demand for SO_2 emission allowances is valued at the average allowance price in 2000, which is equal to $138 in 1997 dollars. This approach is used to estimate compliance cost savings in 2010 under a $25 tax for each scenario as reported in Table 4.

Using the average allowance price as a proxy for the savings from avoided SO_2 abatement may yield an estimate that is too great in the case of a $75 carbon tax because the greater the reduction in demand for SO_2 allowances, the lower will be the allowance price. Under a large carbon tax the scarcity value of SO_2 allowances may trend toward zero. However, as long as the SO_2 cap is binding the allowance price has a floor at about $70 per ton of SO_2, which is roughly the operating cost of installed post-combustion control (flue gas desulfurization) for SO_2 removal. Therefore, for the $75 carbon tax we base our calculations on $70 as the value of an SO_2 allowance.

The estimated compliance cost savings for SO_2 are divided by the carbon reduction under each policy to obtain an estimate of the ancillary compliance cost savings per ton carbon reduced. We have relatively more confidence in the OTC Baseline scenario estimates, because current allowance prices reflect this baseline, though to some degree current allowance prices may reflect the expectation of a SIP Call NO_X policy. The difference across scenarios is not great in any case and is centered at about $3 per ton of carbon reduction for a $25 carbon tax, and about $1.5 per ton of carbon for a $75 carbon tax.

Table 5: Sum of ancillary benefits by scenario for 2010 (1997 $).

Dollars per ton of carbon reduced (1997 dollars)	OTC Baseline		SIP Call Baseline		SIP Call – MC Pricing Baseline	
Level of Carbon Tax ($/metric ton)	**25**	**75**	**25**	**75**	**25**	**75**
Health benefits	8.4	9.6	7.6	7.5	7.9	13.2
Sum of Compliance Cost Savings	4.4	2.4	6.6	4.9	5.6	7.7
TOTAL	**12.8**	**12.0**	**14.2**	**12.4**	**13.5**	**20.9**

The last row of Table 4 provides the sum of compliance cost savings for NO_X and SO_2 control. This information is reproduced in Table 5, along with the estimate of health-related ancillary benefits reported in Table 2. In every case health benefits are greater than compliance cost savings, but the latter matter importantly to the total measure of ancillary benefits reported in the bottom row of the table. These benefits range from $12-$14 per ton of carbon for our preferred scenarios, and increase to $20 in the sensitivity analysis with marginal cost pricing.

V. Previous Estimates

Most previous efforts have relied on average estimates of the benefits of reduced emissions without consideration of atmospheric transport of emissions or representation of the exposed population. Table 6 compares our results with those of previous studies.[12] In every case there is a wide range of values around the mid-point estimate that appears in the table. One pattern that emerges from the array of estimates in the table and others we discuss is that greater

[12] Cifuentes, Davis and Krupnick (2000) provide additional comparison and analysis of these studies.

level of detail in the modeling and in the characterization of the baseline has led to lower (and to many eyes more credible) estimates of ancillary benefits from reduced air pollution. However, there also emerges a category of savings associated with avoided investments in abatement of conventional pollutants that contributes importantly to total benefits.

Three previous modeling efforts are based on frameworks that include considerable detail about the electricity industry. McCubbin et al. (1999) (Abt/Pechan) is a detailed analysis similar to the Haiku/TAF that estimates changes in energy consumption by region and sector of the economy. These changes are translated into changes in emissions and concentrations of particulates, and mapped into changes in health status and valued in monetary terms. McCubbin et al. paid careful attention to revisions in the U.S. air quality standards in constructing their baselines. The study accounted for reductions in compliance costs for achieving ambient air quality standards in regions of the country that are in attainment of air quality standards, as well as improvements in air quality and health status in regions that are in nonattainment.

A limitation of the study is that the total carbon reductions that are achieved under the tax is not reported, makes estimation of ancillary benefits per ton of carbon reduced difficult. The high-end estimates result when the carbon policy causes SO_2 reductions to fall below the cap established in the 1990 Clean Air Act. The proportion of SO_2 reductions that are achieved relative to carbon reductions is greater than that in Haiku/TAF; and, for a comparable carbon tax we find the SO_2 cap continues to bind and SO_2 benefits are not achieved.

Holmes et al. (1995) used the DEGREES model to examine four out of approximately 50 actions identified in the Climate Change Action Plan announced by the Clinton Administration in 1993, and the impact these actions would have on electricity demand, generation, and associated emissions. The study examines the change in emissions on a geographic basis, according to North American Electric Reliability Council (NERC) Regions. The study also examines changes on a seasonal and time-of-day temporal basis, by modeling changes in the electricity load duration curve and facility operation.

To supplement this analysis, we fed the predicted emission changes into PREMIERE, a model that employs a reduced-form atmospheric transport model linked to monetary valuation of health impacts at a NERC region level.[13] Emission reductions for NO_x that would result from the most influential action studied, Motor Challenge, yields benefits from changes in direct emissions and secondary nitrate concentrations of $401 per ton of avoided NO_x emissions (54,120 tons), totaling $22.1 million (1997 dollars). These benefits accrue with a 6.2 million tons reduction in carbon emissions.

Dowlatabadi et al. (1993) employ another detailed model of the electric utility system called the Energy Policy Assessment model to assess emission changes at the regional level. This modeling effort was based on a 1987 plant inventory, and it did not include changes resulting from the 1990 Clean Air Act Amendments. The model was used to consider technology including seasonal gas burning; use of externality adders in dispatch of facilities; extension of the life of nuclear facilities; elimination of federal subsidies; and improvement of the efficiency of electricity distribution transformers. The emission changes for strategies considered collectively is 11% less than the sum of emission changes when the policies are considered separately in the short run scenario, highlighting the possibility for double-counting benefits from technology policies.[14]

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[13] PREMIERE is a derivative of the TAF model, described previously. See Palmer and Burtraw (1997).

[14] We ignore the Dowlatabadi et al. estimates for SO_2 because they do not model the allowance trading program.

Table 6. Estimates of air pollution reduction benefits in the United States from greenhouse gas limitations

Source	Model type	1990 Clean Air Act	Targeted sectors, pollutants and policy	Average ancillary benefit per ton carbon reduction (1997 dollars)
Haiku / TAF	Regional electricity sector; atmospheric transport and valuation	Beyond 1990 CAAA	Moderate electricity sector carbon tax in 2010 with population adjustment; NO_x health benefit valuation. No ozone or visibility benefits. Includes compliance cost savings for NO_X and SO_2.	$7-10 (health) $2-7 (compliance cost) **$12-14 (total)**
Previous Regional Studies				
McCubbin et al. (Abt/Pechan)	Regional multi-sector model, atmospheric transport and valuation	Beyond 1990 CAAA	Carbon taxes of $30 and $68; modeled changes in particulates (no ozone) and health, visibility and materials. Only health monetized. Includes avoided abatement costs for NO_X and SO_2. High tax leads to net SO_2 reductions.	$8-69
Holmes et al./ PREMIERE	Regional electricity sector; atmospheric transport and valuation	Yes	Nationwide Motor Challenge voluntary program (industry), analyzed at regional level; health effects from NO_x changes valued using PREMIERE, including secondary nitrates, excluding ozone effects	$3
Dowlatabadi et al. /PREMIERE	Regional electricity sector; atmospheric transport and valuation	No	Nationwide seasonal gas burn in place of coal, analyzed at regional level; health effects from NO_x changes valued using PREMIERE, including secondary nitrates, excluding ozone effects	$3
EXMOD	NY State electricity sector; atmospheric transport and valuation	Yes	Reduced utilization of existing (1992) coal steam plant at suburban location in NY; only PM, NO_x and SO2 (under emission cap) changes valued, secondary particulates and ozone effects; health ,visibility and other effects included	$24

Table 6 (cont'd). Estimates of air pollution reduction benefits in the United States from greenhouse gas limitations

Source	Model type	1990 Clean Air Act	Targeted sectors, pollutants and policy	Average ancillary benefit per ton carbon reduction (1997 dollars)
Coal/PREMIERE	Regional electricity sector, atmospheric transport and valuation	Yes	Equal percentage reduction in utilization of existing (1994) coal plants analyzed at state level; only health effects from NO_x changes valued using PREMIERE, including secondary particulates and excluding ozone	$5
Coal/ PREMIERE/RIA	Same	Same	Same, except only NO_x related mortality changes valued using PREMIERE, and using 1997 EPA RIA estimates of impacts and valuations	$24
General Equilibrium Studies				
Goulder/ Scheraga and Leary	Dynamic general equilibrium; unit valuation	No	Economy-wide carbon tax with stabilization at 1990 levels in 2000; human health effects from all criteria pollutants, no secondary particulates or ozone.	$34
Boyd et al.	Static general equilibrium; unit valuation	No	Economy-wide carbon tax; human health and visibility effects calculated from reduced total emissions of all criteria pollutants	$41
Viscusi et al.	Valuation only, average for nation	No	Equal percentage reduction in utilization of existing (1980 average) coal steam plants; human health and visibility effects from reduced total emissions of all criteria pollutants	$90

We supplement that analysis by feeding predicted emission changes for NO_x that would result from the seasonal gas burn policy into PREMIERE. The health benefits that result from direct emissions and secondary nitrate concentrations are estimated to be $138 per ton of avoided NO_x emissions (1.04 million tons), totaling $144 million (1997 dollars). Note that the benefits per ton are about one-third of those from Holmes et al./PREMIERE. This reflects the difference in the locations of emission changes in the two models, which produces a difference in the atmospheric transport of pollutants and the size of the exposed populations.

We provide two additional analyses that look at uniform decreases in coal utilization without accounting for how the shortfall in supply is replaced.[15] Hence, both estimates are greater than the two preceding ones because they do not account for the bounceback effect that may result from increased utilization of another technology such as natural gas to replace coal utilization. The third description in the list of previous studies is an estimate using a model developed for New York State called EXMOD. The estimate uses average emission rates from an existing coal steam plant in a relatively densely populated suburban area. This estimate includes health damages from airborne exposure to particulates, NO_x (including ozone) and changes in the location of SO_2 emissions under the cap, holding total emissions constant. Collectively these are calculated to be 90-96% of the damage from conventional pollutants through all environmental pathways.

The fifth of the previous estimates in Table 6, Coal/PREMIERE, is comparable to the third, except that it is applied on a weighted-average national basis. This example considers a 1% reduction in utilization of coal fired electricity generation. The benefits per ton carbon reflect only changes in NO_x, excluding both ozone impacts and SO_2 changes (due to the cap). About 65% of the NO_x related benefits result from decreased mortality.[16]

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[15] These are described in greater detail in Burtraw and Toman (2000).

[16] SO_x changes are not included due to the SO_2 cap, but they would amount to several times that for NO_x per ton carbon were emissions not made up through the trading program.

The sensitivity of conclusions to the valuation of damages is illustrated by comparing the EXMOD and PREMIERE estimates to the sixth estimate in Table 6, which uses assumptions drawn from the Regulatory Impact Analysis (RIA) for new particulate and ozone standards (USEPA, 1997). The Coal/PREMIERE/RIA example considers the same change in emissions, with atmospheric transport calculated with PREMIERE, but with an assumption that the mortality coefficient used in the RIA for $PM_{2.5}$ applies to nitrates. The RIA also places greater weight on one study, Pope et al. (1995), leading to greater estimates of long-term mortality than does PREMIERE, which treats this as a high estimates in a distribution of possible estimates. Finally, the valuation of mortality effects in the RIA is about 1.5 times that in PREMIERE. On net this approach yields a valuation of mortality impacts from NO_x changes (excluding ozone impacts) of three times that from PREMIERE.[17]

Lutter and Shogren (1999) provide estimates specific to California that we do not include in the table because the modeling is less detailed. A significant portion of benefits is due to savings in complying with strict new ambient standards for particulates specified in the EPA's 1997 air quality standards. Benefits are based on Pope, et al. (1995). Total ancillary benefits of $320 per ton are estimated. The study offers an analytical description of how changes in carbon emissions affect the emissions of other pollutants and include an accounting of the reduction in compliance costs in achieving air quality standards for conventional pollutants.

Three previous studies employed general equilibrium analyses. Goulder (1993) incorporates the intertemporal investment and savings decisions of firms and households, and also accounts for household labor supply decisions. The model uses fuel-based industry-specific average emission rates, including emissions from mobile sources. Emissions over and above those that can be attributed to fuel use are attributed to output for each industry. Emission

[17] One can also ask how the use of a reduced form version of the Advanced Statistical Trajectory Regional Air Pollution (ASTRAP) for modeling atmospheric transport in PREMIERE compares with the use of Regional Acid Deposition Model (RADM), which is the model used in the Draft RIA. Burtraw et al. (1998) compared the two directly and find RADM yields valuation numbers about 50% less than ASTRAP when considering sulfates, but no comparison of nitrates was made.

factors are held constant at 1990 levels in the base case, ignoring the SO_2 cap and other aspects of the 1990 Clean Air Act Amendments.

This case is extended by Scheraga and Leary (1993) to estimate a level of CO_2 emission reductions sufficient to return to 1990-level emissions in the year 2000, about 8.6 % relative to the base case projection in the model.[18] When a carbon tax is used for this purpose, the emission reductions for conventional pollutants range from 1.4% (VOC) to 6.6% (NO_x). They append estimates of the monetary value of avoided health damage culled from a variety of sources, including EPA Regulatory Impact Assessments from the 1980s to estimate reductions in VOCs, SO_x, particulates and NO_x. Ancillary benefits are found to lie in the range of $300 million to $3 billion. A rough estimate of the cost of this level of taxation suggests that about one quarter of the cost of the policy is offset by the value of criteria air pollutant reductions.[19]

Boyd, Krutilla and Viscusi (1995) use a simpler general equilibrium model, with land treated as a separate factor of production, to consider *ad valorem* taxes on fuels. Environmental benefit estimates are drawn directly from Viscusi et al. (1992). The Viscusi et al. value reflects a reduction in secondary pollutants absent geographic resolution. The "optimal" tax levels in the analysis Boyd et al. model are defined as those that maximize the sum of benefits from reducing conventional environmental externalities (excluding any benefits from reducing carbon emissions) less the economic costs of the tax. In the base case the optimal carbon emission reductions are 0.19 billion tons (about 12% of total emissions). The authors report the optimal *ad valorem* tax on coal is about 45%, comparable to a $9/ton carbon charge (1997 dollars).[20]

The final estimate in Table 6 is a utilization of the benefit estimates from Viscusi et al. (1992) applied to an equal percentage reduction of coal steam plants at the national level with vintage 1980 without accounting for changes in other types of generation.

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[18] However, after year 2000 emissions are allowed to increase, which has an implication for the type of abatement measures employed.

[19] Jorgenson et al. (1995) provides another dynamic general equilibrium model that includes adjustments for projected technical change on an industry basis. The Jorgenson et al. estimate is expressed as a percentage of carbon tax revenue, and GHG reductions are not reported, so it is not shown in Table 6.

[20] We have difficulty replicating their calculations regarding the carbon charges.

Finally, though not reported in Table 6, Ekins (1996) reviews the European literature and suggests a benchmark of $278 in ancillary benefits per ton carbon reduction (1997 dollars), about half of which is from reduced sulfur emissions. This estimate does not take into account reductions in emissions that are anticipated, especially resulting from the 1994 European Second Sulfur Protocol. We take this and other issues into account in adjusting the estimate to be about $192 (1997 dollars).[21] This value is relatively high, which may reflect the aggregate level of modeling in these studies, different assumptions about health epidemiology, greater population density in Europe,[22] and the ecological effects resulting from on-shore atmospheric transport of sulfur, in contrast to off-shore transport in the eastern United States.

VI. Uncertainty

A central purpose of this analysis is to show that a detailed characterization of many of the assumptions embodied in the previous literature leads to a revision in estimates. The estimates we obtain in many cases are smaller, in terms of ancillary benefits per ton of carbon reduced, but we feel they inspire a greater level of confidence than the previous literature in the main finding that ancillary benefits should weigh importantly in the consideration of climate policy.

Nonetheless, there are numerous uncertainties that surround the calculation of ancillary benefits. The nature of uncertainty in this analysis might be categorized as two types: model uncertainty and parameter uncertainty. Section V highlights model uncertainty and also identifies a number of uncertain parameters. In this analysis we identify six questions that appear most important to the main finding.

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[21] Ekins adjusts his point estimate to account for planned reductions in sulfur emissions stemming from the Second Sulfur Protocol signed in 1994 but not yet implemented, to arrive at an estimate of $31 for SO_2 related benefits per short ton in the UK only if realized as additional emission reductions, or $52 if realized as avoided investments in abatement. Note that the latter figure is far larger than the $3/ton for the U.S. that we estimate. Ekins also notes benefits in the UK from reduced SO_2 emissions range from 35-81% total (European) secondary benefits applicable to changes in emissions from the UK. We infer the range of $41-$87 (in 1997 dollars) for SO_2 benefits if they are realized through additional emission reductions.

[22] See Krupnick and Burtraw (1996) for a related discussion.

One of these is the characterization of market structure in the electricity industry. This is fundamentally an uncertainty about the model because significantly different institutions are relevant to simulating behavior in the electricity sector under different scenarios. Our preferred case is limited restructuring, but we examine the alternative of nationwide restructuring. Under restructuring, the movement to marginal cost pricing at the wholesale or retail level is expected to lead to a reduction in the cost of generation and the price faced by consumers. This should lead to an increase in electricity generation, much of which is expected to come from existing coal-fired power plants. It will lead to higher emissions of carbon and NO_X in the baseline, even when combined with a NO_X policy in the SIP Call region, and it leads to greater quantities of emission reductions of both pollutants in general. The value of ancillary benefits per ton of carbon reduction is the greatest under this market structure from among those we considered.

A related source of uncertainty about parameters is the assumption about future fuel prices. In the months since publication of the estimates that we use in this analysis, natural gas price prices have risen and then fallen precipitously. Most analyses view these changes as short run variability in price and they continue to adhere to long-run forecasts similar to those we use. However, if natural gas supplies become limited, either due to natural availability or regulatory decision making, then we would expect to see more coal-fired generation in both the baseline and in the policy cases we model. The result would be somewhat closer to the scenario involving the effects of marginal cost pricing in the electricity sector.

A third question that also can be characterized as model uncertainty is the form of the institution for environmental regulations in the future. We assume the cap on SO_2 emissions precludes important changes in emissions from modest carbon mitigation policies, but that NO_X is not capped on a national or annual basis. If future reauthorization of the Clean Air Act was to retain a strong flavor of performance standards, which many advocate, then emissions would vary with carbon policies. If both pollutants are capped in the aggregate, then ancillary benefits from health effects under a carbon policy would tend toward zero although benefits from avoided investment in abatement may be significant.

A fourth parametric uncertainty is the level of control and the timing of regulations governing conventional pollutants in the future. Currently, implementation plans for achieving new fine particulate matter standards are due in 2007 and compliance with the new standards is scheduled for a decade later. It would be unprecedented if this schedule was close to being achieved. Nonetheless, implementation of tighter standards would reduce emissions in the baseline, but the effect on ancillary benefits of carbon policy would depend on the institution used to achieve the lower emissions, as mentioned previously.

A fifth important question stems from the health epidemiology, that in our integrated assessment model boils down to the value of parameter. We characterize the potency of nitrates as comparable to other components of PM_{10} and not as potent as sulfates in affecting human health. If instead we characterized nitrates as comparable to fine particulates ($PM_{2.5}$) as measured by Pope (1995), their potency would increase three-fold, and the mortality benefits of emission reductions would increase commensurately.

The valuation of economic benefits of improvement in human health is affected most strongly by the choice of an estimate of the value of a statistical life. The estimates that can be found in recent reviews of the economics literature range from about $2 million to about $6 million, with the EPA's preferred choice at the high end of this range. The value we use of $3.8 million is about mid-point in this range.

VII. Conclusion

Early analyses of ancillary benefits of carbon policies yielded unrealistically high estimates of ancillary benefits because of incomplete modeling of emissions, health effect valuation, and policy baselines. More recent analysis has suggested potential benefits are still significant, but of a lower magnitude.

This study adds to the previous literature by offering results from a more detailed examination of changes in NO_x emissions in the electricity sector. We exercise an electricity market model to calculate ancillary benefits for modest carbon taxes. We consider changes that would occur in addition to those resulting from NO_x controls that go beyond the requirements of the 1990 Clean Air Act Amendments. Our study also demonstrates the need to view greenhouse gas mitigation strategies in an integrated fashion including such factors as population shifts which influence both the production of greenhouse gases as well as the value of their impacts.

With the goal in mind to identify the ancillary benefits per ton of carbon reductions for a *modest* carbon abatement program, we find that a \$25 per metric ton carbon tax would yield ancillary health-related benefits from NO_x reductions of about \$8 per metric ton of carbon (1997 dollars). Avoided abatement costs for NO_X and SO_2 controls under existing or anticipated emission caps are estimated to yield another \$4-\$7 in benefits. The total benefits are estimated to sum to \$13-14 per ton carbon reduced in the scenarios we think most likely.

We expect the average cost to be less than the marginal cost, which would equal the carbon tax. By varying the size of the carbon tax in this and other exercises (Burtraw et al., 2001), we find the schedule of opportunities for carbon reduction to begin at a marginal cost of about zero and to be almost linear and slightly convex, so that the average cost per ton of carbon reduced would be less than or equal to one-half of the marginal cost. Hence, we expect, the average cost of carbon reductions under a \$25 carbon tax would be around \$12 per ton reduced. Thus, total costs would be about equal to the estimated ancillary benefits of the policy, though marginal costs would exceed marginal ancillary benefits. For a carbon tax of this magnitude, ancillary benefits from reductions in NO_x emissions contribute significantly to justifying the cost of carbon emission reductions.

With a larger carbon tax, aggregate ancillary benefits increase, but the value per ton of carbon reduced is roughly unchanged. We find that a \$75 carbon tax would yield ancillary benefits of health and compliance cost savings combined of about \$12 per ton of carbon reduced. The average cost of a \$75 carbon tax would be considerably less than its marginal cost. At a value one-half of the marginal value, the average cost would be around \$37 per ton reduced. In this case ancillary benefits per ton are expected to be about one-third of the average cost per ton. Finally, we find in a sensitivity analysis, which embodied restructuring of the electricity industry on a nationwide basis, ancillary benefits could rise to over \$20 per ton of carbon reduced under a \$75 carbon tax.

Among previous estimates, we have greater confidence in the first five listed in Table 6, all of which reflect the impact of GHG reductions in the electricity sector. These estimates reflect the most detailed methodologies, including locational differences in emissions and exposures, and take into account the role of the SO_2 cap in limiting ancillary benefits. The first study includes the possibility of decreases in the SO_2 cap which leads to its high-end estimate, a result we do not find for comparable parameter values. Only the first of these studies account for the ancillary compliance cost savings that we calculate. Note also that the national estimates suggest modest health-related benefits (about $3-8 per ton) for the United States as a whole, though benefits could be significantly higher in certain areas (EXMOD). Restriction of most of these estimates to the electricity sector is not too troublesome in evaluation of a modest policy because this sector is the likely target of modest emission reductions. The sixth of the previous estimates listed in the Table is higher and reflects alternative assumptions about the scale of health impacts, the role of nitrates, and the economic valuation of impacts. The difference illustrates that ancillary benefits are sensitive to such assumptions, but given the controversy surrounding these specific assumptions, we put less stock in this estimate.

One way that previous analyses were flawed was inaccurate modeling of the 1990 Clean Air Act Amendments, and in particular inaccurate modeling of the SO_2 cap. As we have discussed, with the cap in place, SO_2 emissions are unlikely to change for moderate levels of carbon taxes. As the studies presented here implicitly or explicitly assume, there will be a threshold at the point where GHG control has made the SO_2 cap no longer binding. Beyond this point, health benefits from additional net reductions in SO_2 will accrue. For example, Batelle's Second Generation Model cited in Scheraga and Herrod (1993) estimates that a policy to stabilize CO_2 emissions by the year 2000 will yield reductions in annual SO_2 emissions of 1 million tons beyond reductions that will be achieved by the SO_2 cap. The Clinton Administration's unpublished analysis of the impacts of stabilizing GHG emissions at 1990 levels in 2010 calculates even larger SO_2 emissions reductions (on the order of 4 million tons) and, using analysis derived from the same sources as EPA's Regulatory Impact Analysis for a new particulate standard, calculates a very large benefit from NO_X and SO_2 reduction.

Several biases may affect these results and will be the subject of further analysis. One of the most important is the considerable weight in these estimates placed on the value of changes in health status. This literature remains controversial, and changes in these values will directly affect our results. In addition, we have not modeled all potential health effects of changes in conventional pollutants, and health effects do not exhaust all the environmental benefits of emission reductions. Furthermore, we have looked only at modest carbon policies. Considerable uncertainty surrounds the estimates of ancillary benefits that exist. Nonetheless, our analysis indicates that ancillary benefits from modest reductions in greenhouse gases appear significant relative to the costs of those reductions and should play an important role in the debate regarding near-term policies to address the threat of climate change.

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