Ancillary Benefits of Reduced Air Pollution in the U.S. from Moderate Greenhouse Gas Mitigation Policies in the Electricity Sector

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Abstract

This paper considers how actions to slow atmospheric accumulation of greenhouse gases from fossil fuel use could also reduce "criteria" air pollutants (as defined in the Clean Air Act) in the U.S. The benefits that result would be "ancillary" to greenhouse gas abatement. Moreover, these benefits would tend to accrue in the near term, while any benefits from reduced climate change mostly accrue over a time frame of several decades or longer. Primary emphasis is placed on reduced pollutants from the electricity sector. We present a preliminary analysis using a new model of the electricity market to predict changes in nitrogen oxides (NO_x) from moderate carbon policies. These changes are fed through an atmospheric transport and health model to predict changes in health status, and to characterize these changes in monetary terms. We find that ancillary benefits from a tax of \$10 per metric ton of carbon emissions would yield NO_x related health benefits of about \$3 per metric ton of carbon reduced (1996 dollars). Additional savings accrue from reduced investment in SO_2 abatement in order to comply with the SO_2 emission cap due to the shift away from coal for electricity generation under a carbon tax. At greater levels of a carbon tax, the value of ancillary benefits from NO_x reductions per ton of carbon reductions declines; however, more aggressive carbon reduction policies are also likely to lead to additional benefits from sulfur reductions if the SO_2 emission cap is no longer binding.

Key Words: climate change, greenhouse gas, ancillary benefits, air pollution, co-control benefits

JEL Classification Numbers: H23, I18, Q48

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ANCILLARY BENEFITS OF REDUCED AIR POLLUTION IN THE U.S. FROM MODERATE GREENHOUSE GAS MITIGATION POLICIES IN THE ELECTRICITY SECTOR

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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, 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 preliminary results from a new model of the electricity sector called HAIKU. The model calculates market equilibrium by season and time of day for three customer classes at the 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 NO_x that result from these carbon taxes. NO_x emission rates are assumed to comply with standards proposed by the EPA in 1998, affecting the Ozone Transport Rulemaking Region. This proposal goes beyond requirements of the 1990 Clean Air Act.

We find that ancillary benefits from further reductions in NO_x emissions to be about \$3 per metric ton of carbon reduced under a \$10 per ton carbon tax in the electricity sector

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(1996 dollars). The *average* cost per ton of carbon reduced will be less than $10 per ton and hence ancillary benefits may justify the moderate carbon tax.

The payoff function for ancillary benefits from NO_x reductions per ton of carbon reduced declines with greater carbon reductions. A carbon tax of $25 yields NO_x benefits of $2.50 per ton carbon reduced. However, ancillary benefits from sulfur dioxide (SO_2) reductions, which are effectively capped for small carbon reductions, may become relevant at higher levels of a carbon tax. The potential for SO_2 emission reductions will be the subject of subsequent analysis.

II. BACKGROUND

Three types of methodological issues are important to the consideration of how GHG mitigation could yield ancillary benefits. 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 environmental and public health effects of fuel and technology choices in electricity generation stem from air emissions. These effects typically total about 85 percent or more of the quantifiable environmental concerns, e.g. excluding climate change and species biodiversity (Lee et al., 1995; Rowe et al., 1995; EC, 1995). Hence in this analysis we focus on air emissions and their potential health effects as the environmental pathway of greatest interest.

Previous studies have investigated the reduction of "criteria" air pollutants (as defined in the Clean Air Act) from reduced fossil fuel use. The pollutants of interest include sulfur dioxide (SO_2), nitrogen oxides (NO_X), carbon monoxide (CO), particulates (PM), and tropospheric ozone (O_3).[1] Lead (Pb) also is an important criteria pollutant and is included in some previous ancillary benefits calculations, but given the stringency of existing control measures the additional lead reduction benefits from GHG policies probably are small. 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. Studies of the entire economy also identify potentially significant reductions in CO (Scheraga and Herrod 1993). 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. Reductions in VOCs or direct particulate emissions that are likely to result from CO_2 policies are significantly smaller than the NO_x and CO reductions.

[1] Ozone is not directly emitted into the air but is instead formed in a complex photochemical reaction of its precursor emissions, volatile organic hydrocarbons (VOCs) and NO_x. Lead (Pb) has been virtually phased out of motor fuels, but emissions still occur in small amounts from stationary sources and changes in emissions are valued in some of the models we evaluate.

Secondary pollutants (sulfates and nitrates as particulates, or ozone) are treated in an inconsistent manner across previous studies, and often are not mentioned at all.

In this study we focus on NO_x emission reductions that are ancillary to CO_2 emission reductions achieved in the electricity sector. While the electricity sector is responsible for one-third of carbon emissions presently, the EIA projects that this sector will be responsible for about three-quarters of CO_2 emission reductions in the U.S. under potential implementation of the Kyoto Protocol (EIA, 1998). This sector will be especially important as the least expensive and likely first source of reductions under moderate reduction scenarios.

Health Effects

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).

The damage function approach is more complex than the use of simple unit values and thus is less immediately practical for evaluating national policy. 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.[2] U.S. population is expected to grow by 45 percent 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.

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[2] 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.

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, technology investments, and emissions of GHGs and criteria pollutants with and without the GHG policy.

The issue is confounded 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, the ancillary benefit estimate will overstate environmental savings. Indeed, historical emission rates may be ten times the rates that apply for new facilities. In addition, 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.

In this paper we include in the baseline NO_x controls *beyond* Phase II of Title IV of the 1990 Clean Air Act Amendments. These controls are modeled as a uniform performance standard set to 0.15 lbs. per million Btu of heat input at all fossil-fired and wood-fired generation facilities in the five eastern NERC regions.

Another important example of a regulatory baseline is the cap on SO_2 emissions from electricity generation in the U.S. A consequence of the current emissions cap is that aggregate SO_2 emissions from electric utilities (the major source category in the U.S.) 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 away from coal in significant fashion and the long-run annual level of SO_2 emissions is less than the annual emissions cap would ancillary benefits from further reductions in SO_2 be achieved.

Many previous studies use historical SO_2 emission rates and do not incorporate the SO_2 emission cap, and hence they *overstate the ancillary benefits* that may be achieved, at least by moderate climate policies. By the same token, however, historically based CO_2 abatement cost estimates that do not incorporate the effects of the SO_2 cap *overstate the opportunity cost* of CO_2 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 CO_2 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 assume the SO_2 cap is binding and hence we do not anticipate ancillary benefits from changes in SO_2 emissions for the moderate policies we model. However, we do anticipate reduced costs of compliance with the SO_2 cap to result as a consequence of climate policies, and this estimate is discussed separately. Finally, if anticipated new standards regarding NO_x emissions from power plants that we model take the form a cap and trade program analogous to the SO_2 program, then further emissions in NO_x that we predict also may not be achieved due to a moderate climate policy. However, in this case we would expect an ancillary economic saving due the avoided abatement investment for NO_x controls, analogous to the avoided abatement investment for SO_2 controls under the SO_2 cap.

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 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.

Two components of the HAIKU model are the Intra-regional Electricity Market Component and the Inter-regional Power Trading Component. 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 three time periods (peak, middle and off-peak hours) in each of three seasons (summer, winter, and spring/fall) within each of 9 NERC regions.[3] The Inter-regional Power Trading Component solves for the level of inter-regional power trading necessary to equilibrate regional electricity prices (gross of 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.

The model can be used to simulate changes in electricity markets stemming from public policy associated with increased competition or environmental regulation. In this analysis we adopt a conservative 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. Two regions, the northeast (New England and New York State) and the west, are modeled to have marginal cost pricing.

[3] The current version of the HAIKU model includes the 9 NERC regions: NPCC, MAAC, ECAR, SERC, MAIN, MAPP, SPP, ERCOT and WSCC, as they were defined in 1997. Recently, Florida has split from SERC to form its own NERC region, FRCC, but this region is included in SERC for this analysis.

We model NO_x controls beyond Phase II of Title IV of the 1990 Clean Air Act Amendments as a uniform performance standard set to 0.15 lbs. per million Btu of heat input at all fossil-fired and wood-fired generation facilities in five NERC regions. These are the regions roughly corresponding to the Ozone Transport Rulemaking Region affected by the EPA's September 1998 proposed rule regarding NO_x emissions. Other regulations such as the SO2 cap and trade program are kept constant in the model.

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 model makes conservative assumptions regarding the role for renewable electricity technologies over this time frame, and for the future of co-generation and re-powering. Most new investment is in conventional technologies including integrated combined cycle natural gas units and gas turbines, and in the baseline scrubbed coal.

To the extent these assumptions impose a bias, we suspect they serve to understate the potential emission reductions that could be achieved in the near term. An offsetting bias is the lack of an explicit model of fuel supply in this version of the model. Increased demand for natural gas as a consequence of carbon policies is likely to exercise an upward pressure on price. However, for moderate policies that we model this effect is not likely to be dramatic, though the issue deserves further investigation.

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 $10 and $25 per metric ton of carbon. All values are reported in real (inflation adjusted) 1996 dollars. There is no discounting.

The changes in emissions of NO_x are fed into the Tracking and Analysis Framework (TAF). TAF is a nonproprietary and peer-reviewed model constructed with the *Analytica* modeling software (Bloyd et al., 1996).[4] 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 U.S. are not evaluated.

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

[4] 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.

statistical lives lost to premature death. The health 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, USEPA 1996b). The Health Effects Module contains C-R functions for PM_{10}, total suspended particulates (TSP), sulfur dioxide (SO_2), sulfates (SO_4), nitrogen dioxide (NO_2), and nitrates (NO_3). The change in the annual number of impacts of each health endpoint is the output that is valued. In this exercise inputs consist of changes in ambient concentrations of NO_x, and demographic information on the population of interest. The numbers used to value these effects are similar to those used in recent Regulatory Impact Analysis by the USEPA.

IV. RESULTS

The results of the analysis are presented in Table 1. In the first scenario reported in Table 1, identified as Low Cost of Capital, we find that a carbon tax of $10 per metric ton of carbon in the year 2010 would yield ancillary benefits from reductions in NO_x of $3.60 for each ton of carbon reduced (1996 dollars). The primary category of these benefits is mortality. Morbidity benefits are also significant. Previous analysis (Burtraw et al., 1998) using TAF indicates that the value of visibility improvements are about the same order of magnitude as morbidity benefits, but these results are not included here.

TABLE 1. Ancillary health benefits from reductions in NO_x emissions resulting for various carbon taxes in the electricity sector in 2010 using HAIKU/TAF (1996 dollars).

	Low Cost of Capital Scenario		**High Cost of Capital Scenario**	
Level of Carbon Tax ($/metric ton)	**10**	**25**	**10**	**25**
Emission Reductions (metric tons)				
Carbon (millions)	71	246	105	258
NOx (thousands)	337	952	422	955
NOx Related Health Benefits (million dollars)				
Morbidity	52	130	53	103
Mortality	203	489	210	439
Total	255	619	263	542
NOx Related Health Benefits per Ton Carbon (dollars)				
Morbidity	0.7	0.5	0.5	0.4
Mortality	2.9	2.0	2.0	1.7
Total	3.6	2.5	2.5	2.1

In the Low Cost of Capital case, the ancillary benefits for a $25 tax increase in the aggregate, but on a per ton of carbon basis they fall to $2.50. In addition, we have taken a rough look at the ancillary benefits for a $50 tax (not reported in Table 1) and find they fall further to $1.50 per ton. Hence, we observe that per ton benefits of ancillary reductions in NO_x to be a declining function of the level of carbon reductions.

The quantity of carbon emission reductions that are achieved by a $25 tax is proportionately greater than that achieved by a $10 tax, which illustrates that the marginal abatement cost curve for carbon reductions is not strictly convex over this range. This is an indication of the lumpy aspects to investment and retirement in the model. 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 coal in some parts of the nation. A $10 tax serves to make new combined cycle natural gas plants more competitive with new and existing coal plants.

A $25 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. The cost of capital additions, and constraints on how quickly investment and retirement can occur, constrain the role of combined cycle facilities in the model. However, the $25 tax also improves the situation for gas turbines and for wood biomass, relative to coal. Hence, the $25 tax imposes a difference in costs that surpasses a threshold with respect to the economics of these technologies, and this makes significant additional emission reductions possible in the model.

The change in generation that is induced by these carbon taxes is reported in Table 2. This table reports aggregate national electricity generation as a ratio to generation in the baseline by fuel type under the $10 and $25 taxes. In the Low Cost of Capital scenario, gas generation increases by 65 percent under the $10 tax and 250 percent under the $25 tax. Meanwhile, coal generation falls by 13 percent under the $10 tax and 47 percent under the $25 tax. Non-hydro renewables increase almost 10 percent under the $25 tax due to new wood biomass facilities.

TABLE 2. The ratio of generation under tax to generation under the baseline for each respective scenario.

	Low Cost of Capital Scenario		**High Cost of Capital Scenario**	
Level of Carbon Tax ($/metric ton)	**10**	**25**	**10**	**25**
Gas Generation	1.65	3.52	2.06	3.48
Coal Generation	0.87	0.53	0.79	0.49
Non-hydro Renewable Generation	1.00	1.10	1.04	0.94

The benefit estimates in Table 1 also 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, 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 in the Low Cost of Capital case. The following numbers are derived from Table 1. The benefits from a reduction in NO_x emissions fall from $757 per ton under a $10 carbon tax, to $650 per ton of NO_x at a $25 tax. A tax of $50 causes this to fall to $631 per ton of NO_x. This reduction in the benefit per ton of NO_x reduction is entirely due to locational differences. In essence, this means that 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.

We have conducted initial sensitivity analysis to examine the influence of some assumptions in the model. In an alternative scenario we increased the cost of capital by 50 percent and we used intermediate-run rather than short-run elasticities of demand for electricity. These results are labeled the High Cost of Capital scenario in Table 1.

Compared to the results for the previous case, the High Cost of Capital scenario yields a greater reduction in electricity demand, a greater quantity of carbon emission reductions, and a somewhat smaller measure of ancillary benefits per ton of carbon. In this scenario the ancillary benefits from reductions in NO_x emissions associated with a $10 carbon tax were found to be $2.50 per ton carbon reduced. The ancillary benefits associated with a $25 carbon tax were found to be $2.10 per ton carbon reduced.

Table 2 indicates that gas generation doubles under the $10 tax compared to the baseline in the High Cost of Capital scenario, and it increases by about 250 percent under the $25 tax. Meanwhile, coal generation falls by 22 percent under the $10 tax and 51 percent under the $25 tax.

A comparison between the two scenarios also indicates that about the same level of aggregate NO_x emissions in the latter scenario under the $25 tax leads to smaller health benefits than for the previous scenario. This comparison illustrates further the nonlinear relationship between NO_x emissions and health benefits, and the usefulness of a disaggregated model.

In our conclusion and in Table 3, which compares our results with those of previous studies, we report a midpoint of $3 in ancillary benefits from NO_x reductions per ton carbon reduced for a $10 carbon tax. For a $25 tax per ton of carbon, our midpoint estimate of ancillary benefits from NO_x reductions is $2.30. SO_2 emissions are presumed to be unchanged in these scenarios for the size of carbon taxes we consider. However, in reviewing previous estimates below, we calculate the ancillary savings associated with reduced investment in SO_2 abatement that results from decreased use of coal in electricity generation. This is estimated to represent an additional $3 per ton of carbon emission reductions.

TABLE 3. Estimates of air pollution reduction benefits in the U.S. from greenhouse gas limitations

Source	Model type	1990 Clean Air Act	Targeted sectors, pollutants and policy	Average ancillary benefit per ton carbon reduction (1996 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.	$3
Previous Regional Studies				
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	$3.22
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	$2.95
EXMOD	NY State electricity sector; atmospheric transport and valuation	Yes	Reduced utilization of existing (average emissions in 1992) coal steam plant at a suburban location in New York; only PM, NO_x and SO2 (under emission cap) changes valued, including secondary particulates and ozone effects; all health ,visibility and environmental effects that could be quantified are included	$23.79
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	$4.85

TABLE 3 (cont'd). Estimates of air pollution reduction benefits in the U.S. from greenhouse gas limitations

Source	Model type	1990 Clean Air Act	Targeted sectors, pollutants and policy	Average ancillary benefit per ton carbon reduction (1996 dollars)
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	\$23.74
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.	\$33.36
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	\$39.79
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	\$88.15

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 3, replicated in part from Burtraw and Toman (1997), compares our results with those of previous studies. Note that in every case there is a wide range of values around the mid-point estimate that appears in the table.

Two previous modeling efforts are based on frameworks that include considerable detail about the electricity industry. 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. Pollutants modeled include NO_x, SO_2, CO, TSP, VOCs, and PM_{10}. The study examines the change in emissions on a geographic basis, according to North American Electric Reliability Council (NERC) Regions. The study also is unique because it examines changes on a seasonal and time-of-day temporal basis, by modeling changes in the electricity load duration curve and facility operation. In addition, the study is the most comprehensive in the consideration of changes in emission rates already destined to occur due to provisions in Title IV of the 1990 Clean Air Act Amendments. The study suggests that SO_2 emissions will be approximately invariant to the actions that are studied, though the timing of emission reductions under Title IV may be affected by the policies that were evaluated. Baseline NO_x emissions are also projected to fall due to the requirements of Title IV.

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.[5] 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 $393 per ton of avoided NO_x emissions (54,120 tons), totaling $21.7 million (1996 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. Pollutants that were modeled in addition to CO_2 were SO_2, NO_x and TSP with changes reported by NERC region. 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 study highlights the possibility for double-counting benefits from technology policies. The emission changes for strategies considered collectively is 11 percent less than the sum of emission changes when the policies are considered separately in the short run scenario. Also, the potential perverse effects from technology policy are identified through increased emissions of NO_x from that gas offset somewhat the reductions from coal.[6]

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 $135 per ton of avoided NO_x emissions (1.04 million tons), totaling $141 million (1996 dollars). These benefits accrue with a 47 million tons reduction in carbon emissions. Note that the benefits per ton are about one-third of the benefits that result from Holmes et al./PREMIERE. This

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[5] PREMIERE is a derivative of the Tracking and Analysis Framework (TAF), a peer-reviewed integrated assessment model developed in support of the National Acid Precipitation Assessment Program (Bloyd et al., 1996). See Palmer and Burtraw (1997). Relevant aspects of TAF are described in greater detail in the next section.

[6] We ignore the Dowlatabadi et al. estimates for SO_2 because they do not model the allowance trading program, and we ignore the reduction in TSP because it is negligible.

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.[7] 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.[8] The estimate uses average emission rates from an existing coal steam plant in a relatively densely populated suburban area in New York State, with a reduced-form model of atmospheric dispersion, exposure and valuation. 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 percent of the damage from conventional pollutants through all environmental pathways.

The fourth of the previous estimates in Table 3, Coal/PREMIERE, is comparable to the third, except that it is applied on a weighted-average national basis. This example considers a one percent reduction in utilization of coal fired electricity generation and calculates changes in CO_2, SO_2 and NO_x emissions at the regional level for use in PREMIERE. 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 percent of the NO_x related benefits result from decreased mortality.[9]

The sensitivity of conclusions to the valuation of damages is illustrated by comparing the PREMIERE and EXMOD estimates to the fifth estimate in Table 3, which uses assumptions drawn from the recent Draft Regulatory Impact Analysis (RIA) for new particulate and ozone standards (USEPA, 1996b). 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 (USEPA, 1996b). On net this

[7] These are described in greater detail in Burtraw and Toman (1997).

[8] A product of the Rowe et al. (1995) study was a computer program that can predict impacts from a power plant at any location in New York State, for a variety of fuel choices and plant designs. To accomplish this the model includes a reduced form atmospheric transport model to characterize the dispersion portion of the damage function approach. This model, named EXMOD, would not be sufficient for a full-blown environmental impact assessment, but it is a useful and relatively sophisticated tool for planning and policy evaluation which we use in subsequent parts of the paper.

[9] 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.

approach yields a valuation of mortality impacts from NO_x changes (excluding ozone impacts) of three times that from PREMIERE.[10]

We use the EXMOD and Coal/PREMIERE models to calculate another type of economic savings associated with carbon reductions. This is the avoided investment in SO_2 abatement stemming from reduced utilization of coal that is not reflected in the estimates in the table.[11] We estimate this value to be about $3 per ton of carbon reduction from these facilities. This estimate is not included in the values reported in Table 3 because these values reflect ancillary environmental benefits. This value is likely to be considerably smaller than the health benefit that would be induced if total SO_2 emissions were reduced by a GHG policy, leading to a reduction in fine sulfate particles implicated in increased premature mortality (Burtraw et al., 1998).

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. Primary emissions of eight pollutants are modeled (TSP, SO_x, NO_x, VOCs, CO, Pb, PM_{10} and CO_2). 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 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 percent relative to the base case projection in the model.[12] When a carbon tax is used for this purpose, the emission reductions for conventional pollutants range from 1.4 percent (VOC) to 6.6 percent (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. Although the authors do not make this comparison, 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.

Jorgenson et al. (1995) provides another dynamic general equilibrium model that includes adjustments for projected technical change on an industry basis. Their results

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[10] 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 percent less than ASTRAP when considering sulfates, but no comparison of nitrates was made.

[11] This is calculated by applying the emission rates for SO_2 at the modeled facilities to estimate the SO_2 emission reductions that would result from decreased utilization of these facilities. These reductions were valued at 1996 SO_2 allowance prices.

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

conform with a "strong form" of the double-dividend hypothesis (Goulder, 1995). This means they find negative (gross) economic costs (that is, positive benefits) from the energy taxes, as measured by equivalent variation defined over goods, services and leisure, when the revenues are used to displace property taxes or capital taxes, even when environmental benefits are not considered. 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 3.

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, and the authors report the value per ton of secondary pollutant. 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 percent of total emissions). The authors report the optimal *ad valorem* tax on coal is about 45 percent, comparable to a $9/ton carbon charge (1996 dollars).[13]

The final estimate in Table 3 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.

Finally, though not reported in Table 3, Ekins (1996) reviews the European literature and suggests a benchmark of $273 in ancillary benefits per ton carbon reduction (1996 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 $188 (1996 dollars).[14] 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,[15] and the ecological effects resulting from on-shore atmospheric transport of sulfur, in contrast to off-shore transport in the eastern U.S.

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

[14] 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 $25 for SO_2 related benefits per short ton in the UK only if realized as additional emission reductions, or $42 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 percent total (European) secondary benefits applicable to changes in emissions from the UK. We infer the range of $33-$71 (in 1990 dollars) for SO_2 benefits if they are realized through additional emission reductions.

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

VI. 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.

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 $10 per metric ton carbon tax would yield ancillary benefits from NO_x reductions of over $3 per metric ton of carbon (1996 dollars). Although we have not calculated the average cost of these carbon emission reductions, we expect the average cost to be less than $10 per ton. Hence, for a carbon tax of this magnitude, ancillary benefits from reductions in NO_x emissions alone may justify the cost of carbon emission reductions.

With a larger carbon tax, the value per ton of ancillary benefits from NO_x reductions is less. We find that a $25 carbon tax would yield ancillary benefits from NO_x reductions of about $2.30 per ton carbon reduced. However, we also note that more aggressive carbon reduction policies are also likely to lead to additional benefits from sulfur reductions if the SO_2 emission cap is no longer binding.

Among previous estimates, we have greater confidence in the first four listed in Table 3, 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. Note that the national estimates suggest modest (about $4/ton) benefits for the United States as a whole, though benefits could be significantly higher in certain areas (EXMOD). Restriction 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 fifth 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. With the cap in place, SO_2 emissions are unlikely to change for moderate levels of carbon taxes.

An important corollary of this observation is that the marginal ancillary benefits from a small reduction in GHGs are likely to differ from the marginal benefit from the last unit of

GHG reduction in a more aggressive program of aggregate GHG control. Even if the underlying atmospheric transport and health effects models are essentially linear, 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 RIA for a new particulate standard, calculates a very large benefit from NO_X and SO_2 reduction.

Even for a moderate policy that leaves the SO_2 cap unaffected, climate policies that promote substitution away from coal for electricity generation would reduce the demand for SO_2 emission allowances and cause some additional investments in SO_2 abatement to be avoided. We estimate that this savings amounts to about $3 per ton of carbon emission reductions, in addition to the ancillary benefits identified with reduction in NO_x emissions.

Several biases may affect these results and will be the subject of further analysis. The HAIKU model has inadequate modeling of renewable resources, which could play an important role in reducing carbon emissions. Also, the model has an inadequate modeling of fuel markets. Changes in relative prices in fuel markets could affect the amount of carbon reductions that could be achieved for a given tax. However, we believe that this bias is muted for small carbon taxes.

A potentially larger source of bias is in the definition of the baseline. Our baseline was Old Source Performance Standards for NO_x (0.15 lb/mmBtu) in the five eastern NERC regions. To the extent that NO_x emission trading is adopted to meet an aggregate performance standard based on this emission limit, some of the low cost options for NO_x and carbon reductions that we capture in our carbon tax analysis--such as fuel switching from coal to gas--may not be available. This will tend to lower the carbon and NO_x reductions available at any tax rate. Finally, considerable weight in these estimates hinge on the numbers used to value changes in health status. This literature remains controversial, and changes in these values will directly affect our results.

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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