The Benefits of Reduced Air Pollutants in the U.S. from Greenhouse Gas Mitigation Policies

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Discussion Paper 98-01-REV

November 1997

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Abstract

Policies that reduce emissions of greenhouse gases can simultaneously alter emissions of conventional pollutants that have deleterious effects on human health and the environment. This paper first describes how these "ancillary" benefits--benefits in addition to reduced risks of climate change--can result from greenhouse gas (GHG) mitigation efforts. It then discusses methodologies for assessing ancillary benefits and provides a critical review of estimates associated with reductions of criteria air pollutants. We find that these benefits in the U.S. may be significant, indicating a higher level of "no regrets" greenhouse gas abatement than might be expected based on simple economic calculations of abatement cost. However, the magnitude of ancillary benefits realized by any program of GHG mitigation is highly dependent on the location, pollutant, degree of exposure, and the economic behavior of individuals in response to the program. It is also highly dependent on the interaction of GHG abatement policies with the policies used for regulating conventional pollutants. We identify a rule of thumb to suggest ancillary benefits could be on the order of 30 percent of the incremental cost of GHG mitigation. For modest carbon reduction that do not result in changes in emissions of sulfur dioxide by electric utilities, ancillary benefits may be as high as $7 per ton. Greater benefits could be obtained with larger GHG reductions, although the costs of abatement would also be much greater.

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

JEL Classification Nos.: H23, I18, Q48

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THE BENEFITS OF REDUCED AIR POLLUTANTS IN THE U.S. FROM GREENHOUSE GAS MITIGATION POLICIES

Dallas Burtraw and Michael Toman*

I. INTRODUCTION

Fossil fuel combustion, agricultural activity and changes in land use are increasing atmospheric concentrations of greenhouse gases (GHGs). Theses changes in the atmosphere are widely held to cause changes in the earth's climate, changes that could have adverse effects on natural systems and human interests (IPCC, 1995). Policy makers worldwide have been exploring options to prevent dangerous human interference in the climate system by slowing the growth in emissions of GHGs. To a large extent, the analysis of policies for GHG abatement has focused on their potential for reducing the rate of increase in atmospheric concentrations of greenhouse gases, and the economic costs of the emissions abatement measures.

A number of actions to slow atmospheric GHG accumulation would also tend to reduce "conventional" environmental pollutants. The benefits that result would be "ancillary" to GHG abatement and could be manifested in several ways. 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 these 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. To illustrate these issues, we consider how GHG reductions from reduced fossil fuel use could reduce various "criteria" air pollutants (as defined in the Clean Air Act), which we argue are likely to constitute the lion's share of ancillary benefits in the US.

The analysis indicates that average ancillary benefits from modest GHG emissions limits themselves are likely to be modest, when measured in terms of benefits per ton of

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carbon reduction, but they are still worth taking into account. A modest policy with an average cost per ton of carbon abated in the range of $10-20 could yield benefits that average $3-7 per ton, when measured in terms of benefits per ton of carbon reduction. Larger than average benefits would occur in locations with greater population density and higher levels of exposure to damages from criteria air pollutants.

Larger ancillary benefits on average for the nation could be obtained with more aggressive GHG controls, though these benefits themselves are not enough to offset the costs of abatement. These benefits could average $12-18 per ton of carbon reduced ($20-$30 at the margin) for a policy in which the average costs of each ton of carbon reduced may be on the order of $40-50 ($100 at the margin). Effectively, the ancillary benefits function is increasing with the level of GHG control over relevant values, due to the interaction of GHG policies with pre-existing regulations governing conventional pollutants.

We identify a rough rule of thumb that applies across the range of climate policies being considered that suggests ancillary benefits could be about 30 percent of the cost per ton of carbon reduced. In any case, there is considerable uncertainty about the size of ancillary benefits that precludes the identification of a single "best estimate" of their magnitude. The size of ancillary benefits also varies with the choice of policy for obtaining a given level of GHG control.

Section II of the paper provides further background on ancillary environmental benefits from GHG abatement. Section III provides an introduction to methodological issues arising in the estimation of ancillary benefits. Section IV is a critical review of previous estimates of ancillary benefits from reduced criteria air pollutants in the U.S. and provides references to studies in other contexts. Section V contains some new estimates that illustrate the importance of locational issues. Section VI draws together and compares the estimates. Section VII concludes the paper.

II. BACKGROUND

Our empirical focus is on 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 ancillary benefits calculations, but given the stringency of existing control measures the additional lead reduction benefits from GHG policies probably are small.

There is an extensive scientific literature on the adverse human health effects caused by exposure to criteria air pollutants.[2] Human health effects are widely seen as significant,

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[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.

[2] See USEPA (1996a & 1996b) for a review by the Environmental Protection Agency; for other reviews and perspectives see Portney (1990) and the literature discussed in Freeman (1993) and Cropper and Freeman (1991).

though the size of these effects depends on the magnitude and duration of exposure to specific pollutants, and the nature of the exposed population, among other factors. These effects include, among other things, the initiation or aggravation of various pulmonary disorders, as well as cardiovascular problems; the effects result in premature mortality as well as illness.

Reductions in premature mortality from reduced exposure to various forms of particulates typically account for about 75-85 percent of all estimated benefits in economic assessments of improved air quality (Lee et al., 1995; EC, 1995; Rowe et al., 1995; Krupnick and Burtraw, 1997; Burtraw et al., 1997). The pollutants described as particulates take a number of forms and arise from a number of sources. Particulates include soot emitted directly from the combustion process, soil dust (often mobilized in the air due to human activities), and secondary pollutants such as sulfate and nitrate aerosols that form chemically in the atmosphere from SO_2 and NO_X. The various particulate substances are found in different proportions in different areas, and they have different degrees of impact on human health. Of the various types of particulates, there is particular concern about the potency of sulfate and nitrate aerosols.

Another secondary pollutant that impairs human respiration is O_3, which is formed from the mixing of NO_X and volatile hydrocarbons (VOCs) in sunlight. While there are some short-term health effects from increases in O_3 concentrations, there is little evidence that ozone is associated with long-term illness or premature mortality for most of the population, and consequently O_3 receives much less weight than particulates in economic analysis. CO, while obviously fatal at high concentrations, has much more limited health effects (primarily related to cardiovascular systems) at ambient exposure levels normally encountered. Moreover, CO emissions are decreasing over time as new vehicles with low emissions replace older vehicles.

At high enough concentrations, criteria air pollutants can also damage ecosystems. NO_X and SO_2 are precursors to acidic deposition (commonly referred to as "acid rain") that has adverse effects on some forest aquatic ecosystems. Atmospheric deposition of nitrogen also is a potentially significant contributor to damaging algae blooms in certain estuaries (e.g., the Chesapeake Bay). Both SO_2 and O_3 can produce foliar damage in a number of crops and trees; O_3 is responsible for agricultural yield losses in the U.S. valued at several billion dollars each year, while the damages to forests and other ecosystems is still being assessed.

Criteria air pollutants also impair visibility and damage materials, affecting both aesthetic and property values. Airborne sulfates, for example, tend to impair visibility. Particulate matter causes soiling and acid rain accelerates the decay of buildings, statues, and monuments.

To understand the potential for GHG policies to reduce such damages, we note first that the vast majority of the U.S. economy's GHG emissions stem from fossil fuel combustion. The U.S. economy satisfies the lion's share of its energy needs with coal, petroleum and natural gas. U.S. energy consumption amounted to nearly 91 quadrillion Btu (quads) in 1995 (having risen from about 66 quads in 1970), of which 85 percent was provided by fossil fuels. Energy consumption was split not quite equally across transportation (27 percent), industrial (37 percent) and residential/commercial users (35 percent). Petroleum is the dominant energy source for transportation; coal and natural gas are the primary energy sources for industrial and residential/commercial energy needs. Hydroelectric and nuclear power accounted for one-third of electric power generation.[3]

Natural gas (methane) is the least carbon-intensive fossil fuel per unit of energy content, and it is also a relatively "clean" fuel in the sense of conventional pollutants. The main pollutant resulting from its combustion are relatively small amounts of NO_X. Petroleum products have intermediate carbon intensity and can generate significant emissions of PM, SO_2, NO_X, VOCs, and (in older cars) CO, again in the absence of effective emissions controls. Coal is the most carbon intensive of the fossil fuels, and its combustion also generates relatively high criteria pollutant emissions (especially SO_2, NO_x, and PM) in the absence of effective emissions controls (which, if used, can reduce these pollutants considerably). However, current regulatory standards require very stringent controls on dust and soot (PM) from stationary sources like power plants, and these controls reduce emissions substantially.

The most likely sources of reductions in particulate concentrations and large ancillary benefits from GHG policies that reduce energy use would be reduced sulfate aerosols formed by emissions of SO_2 from fuels that contain sulfur (coal and petroleum), reduced nitrate aerosols from NO_X created by all types of fuel burning, and reduced fine particulates from diesel engine emissions.

III. METHODOLOGICAL ISSUES IN ASSESSING ANCILLARY BENEFITS

The studies of air pollution impacts from GHG control we review below can be divided into two categories. One group combines computable general equilibrium models of the U.S. economy with estimates of emissions rates in various industries to relate changes in price from energy taxes to changes in investment, changes in efficiency, changes in CO_2 emissions, and commensurate changes in emissions of criteria air pollutants. A second group of studies has employed disaggregated models of the U.S. electric utility industry to examine changes in investment and facility operations (dispatch) and ultimately changes in emissions that result from more narrow policy initiatives or reforms. Examples of such narrower initiatives include reform of electricity transmission pricing, improvements in the efficiency of electricity distribution transformers, the "Green Lights" program to promote efficient lighting, and seasonal burns of natural gas in place of coal.

Studies in both groups indicate that significant reduction in NO_x and CO are possible as a result of policies aimed primarily at reducing CO_2 emissions (Scheraga and Herrod 1993). The studies vary in their predictions about reductions in SO_2 depending on their treatment of the emission allowance trading program under the 1990 Clean Air Act Amendments. 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 for the particular policies examined in the studies surveyed. Secondary pollutants (sulfates and nitrates as particulates, or ozone) are treated in an inconsistent manner across these studies, and often are not mentioned at all.

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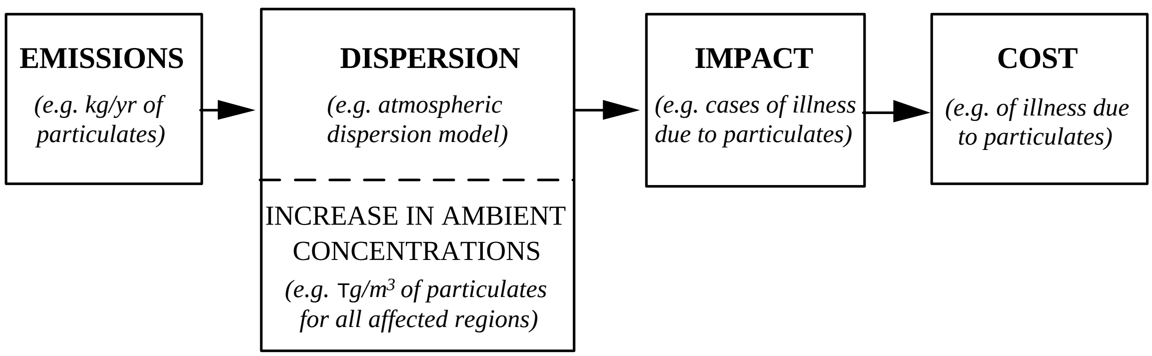
[3] US Department of Energy (1996).

Many of the studies that have attempted to calculate benefits rely on estimates 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. The organization of this "bottom up" approach, as shown in Figure 1 (EC 1995, vol. 1, Figure 2.2) has been used in several 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).

Figure 1. An illustration of the "bottom up" damage function approach



A major conclusion of the social cost studies is that the environmental impacts and the monetized value of those impacts resulting from changes in economic activity (in this case, electricity generation) depend on the geographic location of that activity.[4] This is not a surprising result, given that there is a much greater concentration of population affected by emissions in, for instance, New York than in New Mexico. However, it may be surprising that this finding is so robust. It applies not only to human health, which from an economic perspective is typically the most important pathway, but also to a variety of environmental pathways that are affected by location-specific geography.

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. For example, Krupnick and Burtraw (1997) 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 exposed populations, although atmospheric modeling remains an important

[4] For example, Lee et al. (1995) estimate that the human health impacts from operation of a new coal plant vary by an order of magnitude between a plant located in New Mexico and one located in Tennessee.

source of unpredictable variation.[5] They also find that the large majority of quantifiable damages from electricity fuel cycles are attributable to criteria air pollutants, so in many cases it may be sufficient to concentrate analysis on these pollutants.

An analysis of benefits requires a clear definition of a baseline against which the prospective scenario can be measured. The actual extent of emissions reductions depends critically not just on the energy type, but also on the technologies used for combusting the fossil fuels and trapping pollutants in the waste gas stream. It is necessary to specify these factors -- which depend on the characteristics and usage of current combustion technologies and how incentives for usage are altered by the GHG policy -- in calculating the ancillary environmental benefits of GHG control.[6]

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. It also is important to account for changes in population, especially since population trends have greatly outstripped energy prices over the last century.[7] U.S. population is expected to grow by 45 percent over just the next fifty years, suggesting that there will be greater exposure to a given level of pollution and consequently greater benefits from reducing that pollution. This demographic consideration suggests that the reported values for conventional pollutants in current studies underestimate damage in future years, if all other things are equal.

The issue is confounded, however, because of ongoing changes in the standards for criteria air pollutants. 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

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[5] The social cost studies also have enabled the development of tools that greatly accelerate the analysis of diverse environmental impacts. See the Tracking and Analysis Framework (TAF) presented in Bloyd et al. (1996) and Burtraw et al. (1997) for a model of acid rain benefits and costs. 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.

[6] To make the point more sharply, a shift from coal to biomass for electricity generation could increase particulate emissions in the absence of adequate control equipment. Increased energy efficiency could increase indoor air pollution, including radon exposure, and increased switching from coal to gas raises the issue of fugitive methane emissions, since methane is a more potent greenhouse gas than CO_2. While our focus in this paper is on the potential for environmental improvement, the possibility of some decrease in environmental performance should also be kept in mind.

[7] 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 (Bohi and Toman, 1996). The mean jumped slightly for the period after 1986 as compared to that before 1973.

than in the present. Estimates of future ancillary benefits based on historical or current values should be adjusted downward accordingly.

An important example of this issue concerning regulatory baselines is the impact on ancillary benefits from GHG policy of the cap on SO_2 emissions from electric utilities and emission allowance trading program 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 smaller-scale GHG emissions reductions. However, 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, then ancillary benefits from further reductions in SO_2 would be achieved. However, if the current cap is lowered as part of the effort to implement a tighter standard on fine particulates, then ancillary benefits arising from SO_2 control would be reduced accordingly.

There may be an economic benefit associated with ancillary SO_2 reductions even with a binding emissions cap. Under the cap, a facility that reduces its SO_2 emissions makes allowances available for another facility, displacing the need for abatement investment at that facility. In principle, then, this savings through avoided abatement investments should be reckoned as one of the ancillary benefits of the CO_2 policy.

The extent to which this cost reduction *benefit* should be counted in practice depends on the analytical framework being used to calculate environmental compliance *costs*. If the cost-side framework automatically captures the reallocation of SO_2 allowances and abatement effort when assessing the economic impacts of the CO_2 policy, then the abatement cost savings identified in the previous paragraph already are incorporated in calculating the opportunity cost of the CO_2 policy. In this case it would be incorrect double-counting to also include avoided SO_2 abatement costs as an ancillary benefit. In practice, the computable general equilibrium models used in the ancillary estimates reviewed below appear to be calibrated with data from years that do not reflect the costs of the SO_2 cap and trade program in the electricity sector. Consequently, the appropriate ancillary benefit measure to compare with CO_2 abatement costs derived from these models should include the avoided costs of investments in SO_2 abatement.

With particulate and ozone standards recently revised, and with new NO_X reduction rules for electric utility boilers and others in the offing through the workings of the Ozone Transport Region (OTR) and the Ozone Transport Assessment Group (OTAG), should estimates of the current benefits of reducing emissions of criteria pollutants be modified to reflect expected declines in emissions in the future?[8] If one proceeds on the basis of historical standards and ignores expected changes in the standards, the ancillary benefit estimate will overstate environmental savings. By the same token, however, historically based CO_2 abatement cost estimates that do not incorporate the effects of new pollutant caps will overstate the opportunity cost of CO_2 reductions.

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[8] The new particulate standard will be reviewed after five years.

The economic principle that guides our analysis is that *the ancillary benefit assessment should employ assumptions consistent with those underlying the assessment of GHG abatement costs*. Hence, a comparison of the benefits from criteria air pollutants with the cost of climate policies estimated by the CGE models to date should use estimates of SO_2 emission allowance prices as a proxy for avoided marginal abatement cost, and add this estimate of economic benefit to the other ancillary benefits from reduced criteria pollutants that are not capped. For other pollutants, we suggest that use of historic emission rates rather than ones expected in the future may be more appropriate for assessment of ancillary benefits if these also have been used in assessing the costs of GHG policies with which benefits are to be compared.

IV. REVIEW OF PREVIOUS ANCILLARY BENEFITS ESTIMATES

Previous efforts to characterize ancillary benefits from changes in emissions of conventional air pollutants in the U.S. have employed general and partial equilibrium models of the economy, but all 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 1 summarizes some of the key studies.

Goulder (1993) is one of three modeling efforts that have examined fiscal policies aimed at reducing CO_2 emissions within a general equilibrium model. The model 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 initial specification. In sensitivity analysis, SO_2 emissions from the electric utility industry are held constant, in light of the emission allowance trading program, and NO_x, VOCs and CO emission rates are varied over time to reflect changes in mobile source emissions. NO_x emission changes from Title IV of the 1990 Clean Air Act are not modeled. There is also no modeling of the economic value of avoided external damages.

The base case in the Goulder model, which ignores the SO_2 cap and other expected changes in emissions, 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.[9] 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. They estimate reductions in VOCs, SO_x, particulates and NO_x emissions resulting from the carbon tax, yielding benefits in the range of $300 million to $3 billion, with benefits about 33 percent greater for a Btu tax. Although the authors do not make this comparison, a

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

Table 1. Description of previous studies of air pollution reduction benefits from greenhouse gas limitations

Study(*) and/or model exercised(**)	Model type	Carbon policy or target	Conventional pollutants and impacts considered	Does baseline include 1990 Clean Air Amendments (including SO_2 cap)?
Goulder (1993)*/ Scheraga and Leary (1993)*	dynamic general equilibrium	economy-wide carbon or Btu tax to return total US CO_2 emissions to 1990 levels in 2000 (emissions rise thereafter)	TSP, SO_2, NO_x, VOCs, CO, Pb, PM_{10} (no secondary particulates or ozone); human health effects only	No (considered in sensitivity analysis)
Jorgenson *et al.* (1995)*	dynamic general equilibrium	no specified GHG target; fuel taxes set to internalize conventional air pollution externalities	See entry for Viscusi et al. (1992) below	No
Boyd, Krutilla, Viscusi (1995)*	static general equilibrium	energy taxes set either to "optimally internalize" conventional externalities or to exploit all "no regrets" possibilities	See entry for Viscusi et al. (1992) below	No
ICF (1995)*	partial equilibrium regional model of electricity sector	Voluntary programs under Climate Change Action Plan	CO, TSP, VOCs, NO_X and PM_{10} (SO_2 assumed constant, no secondary particulates); health effects only	Yes
Dowlatabadi et al. (1993)*	partial equlbrium regional model of electricity sector	technology policy to improve efficiency and reduce emissions	TSP, NO_X, and SO_2 (no secondary particulates)	No
Viscusi et al. (1993)*	valuation only, average for nation	estimated average damages per unit of emission for various pollutants	TSP, SO_2, NO_x, VOCs, CO, Pb, PM_{10} (damage from secondary particulates and ozone inferred and attributed to primary pollutants); human health and visibility effects	No
EXMOD (Hagler-Bailly, 1995)**	detailed electricity sector for NY State, atmospheric transport and valuation	facility specific emissions and damages; used for sensitivity analysis of other studies	TSP, SO_2, NO_x, VOCs, CO, Pb, PM_{10}, (secondary particulates and ozone modeled); all human health, visibility and other environmental effects	Yes
PREMIERE (Palmer and Burtraw, 1997)**	regional electricity sector, atmospheric transport and valuation	regionally specific emissions and damages; sensitivity analysis of other studies	only NO_x (and secondary nitrates) modeled; human health effects only	Yes

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. Externalities related to global climate change and to criteria air pollutants and acid rain resulting from energy use are modeled. The climate damage values rise over time to reflect the relationship between accumulated greenhouse gases and damages. The 1990 Clean Air Amendments are not reflected in the study. The externality values for reductions in conventional pollutants are unit values adapted from the survey of cost-benefit studies and other research compiled in Viscusi et al. (1993), adjusted down to reduce the estimate of premature mortality associated with sulfur oxides.

These energy related externalities are converted into tax rates under several different scenarios accommodating a range of values for climate and conventional externalities, and they are internalized into prices through *ad valorem* energy taxes, ranging from a 1 percent markup for natural gas to a 197% markup for coal, under their benchmark scenario. The authors also investigate the performance of several strategies for recycling revenue from an energy tax. Their results 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.[10] Further, when revenue is recycled by reducing labor taxes, in which case the net economic cost of abatement is positive, the authors find the net benefits of the policy to be positive once reduced conventional pollutant damages are taken into account (not including climate related benefits).

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, with revenues rebated in lump-sum fashion to taxpayers (so there are no gains from recycling revenues to reduce other taxes). Pollutants considered are the same as in Jorgenson et al. (1995) and environmental benefit estimates are drawn directly from Viscusi et al. (1993). The "optimal" tax levels in the analysis 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 $8/ton carbon charge.[11] The authors also identify the "no regrets" level of reduction in the analysis as the point at which

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[10] This strong finding is contradictory to a large share of recent studies on the subject (Oates, 1995; Goulder, 1995). The main reason for this result is the large economic cost (marginal cost of funds) assumed to result from the use of property or capital taxes to raise government revenues, compared to other studies, as well as the relatively large economic cost of taxes in general represented in the model. However, as noted in the text, they find a less striking result when revenues are recycled to reduce labor taxes, which is the usual assumption.

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

net benefits from internalizing conventional environmental externalities drop to zero. This is equal to 0.5 billion tons (a 29 percent reduction), which would be achieved with a $13 tax per ton carbon (leading to a 54 percent *ad valorem* tax on coal). In the case of a higher substitution elasticity between energy and other factors of production, the no regrets level of carbon reduction is estimated to be about 0.8 billion tons (49 percent reduction).

Two other modeling efforts are based on frameworks that include considerable detail about the electricity industry. ICF (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 (ICF, 1995). These actions included expansion of the Green Lights Program, energy efficient electrical motor systems (Motor Challenge), improvement of hydroelectric generation, and reform of electricity transmission pricing. 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. Regional variation in emission changes stems in large part from the variation in technologies providing electricity at the margin and that would be affected by each of the actions. In some regions of the country, for example, gas facilities would be more likely to be displaced while in other regions coal facilities may be displaced, and these fuels and technologies typically have very different emission rates. The study 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.

The study results could be used for a geographic analysis of atmospheric transport of pollution and exposure of the population, and economic valuation of emission changes, but this was not attempted. To supplement this analysis, we fed these emission changes into PREMIERE, a model built at Resources for the Future that employs a reduced-form atmospheric transport model linked to monetary valuation of health impacts at a NERC region level.[12] We consider the emission reductions for NO_x that would result from the most influential action studied, Motor Challenge, and estimate health benefits resulting from changes in direct emissions and secondary nitrate concentrations to be $352 per ton of avoided NO_x emissions (54,120 tons), totaling $19.4 million (1992$). These benefits accrue with a 6.2 million ton reduction in carbon emissions.

[12] PREMIERE is a derivative of the Tracking and Analysis Framework (see footnote 5), a peer-reviewed integrated assessment model developed in support of the National Acid Precipitation Assessment Program (Bloyd et al., 1996). See also Palmer and Burtraw (1997).

The regional percentages of total health benefits that result from these emission reductions vary significantly from the percentages of emission changes themselves. For example, ECAR (the Ohio Valley) produces 19 percent of the emission reductions, but captures 30 percent of the health benefits, due largely to long-range transport from downwind regions to its west. This estimate excludes the contribution of NO_x to ozone formation, and does not address visibility impairment and other environmental impacts of nitrogen deposition. However, it is likely to capture the lion's share of measurable economic value due to the inclusion of suspected mortality effects, which tend to dominate the economic valuation of conventional pollutant impacts.

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. In common with the ICF model, this model reported results 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.

A main contribution of the study was to illuminate the potential importance of double-counting of emission changes when individual policies affect the same endpoints. The emission changes from these policies are not additive because the policies taken separately would each capture the same low-cost substitution opportunities that would not be available in similar degree to the policies taken as a group. The ratio of the emission changes for NO_X for the strategies considered collectively is 11 percent less than the sum of emission changes when the policies are considered separately in the short run scenario. The study also illuminates potential perverse effects from technology policy. For example, the NO_x emissions that could result as people switch to gas use for home and water heating because of the effect on electricity prices of a policy could be greater than the emissions from controlled electricity generation sources to provide the same energy services. In addition, distributed emissions throughout a metropolitan area could have greater environmental damages than emissions from sources more distant from population centers, potentially offsetting some of the ancillary benefits from carbon policies.

Again, we supplement the analysis by feeding predicted emission changes into PREMIERE. We consider the short run emission reductions for NO_x that would result from the seasonal gas burn policy. The health benefits that result from direct emissions and secondary nitrate concentrations are estimated by PREMIERE to be $121 per ton of avoided NO_x emissions (1.04 million tons), totaling $126 million (1992$). These benefits accrue with a 47 million ton reduction in carbon emissions. Note that the benefits per ton are about one-third of the benefits that result from ICF/PREMIERE. This reflects the difference in the location of emission changes in the two models which produces a difference in the atmospheric transport of pollutants and the size of the exposed populations.

Finally, we refer to another body of literature that has emerged in the European context. These studies suggest that ancillary benefits are likely to exist and may be significant, but they are unreliable sources for concrete benefit estimates. Pearce (1992) uses average emission coefficients to relate potential changes in emissions of criteria pollutants to CO_2 emissions in the UK and unit values for damages per ton from a "restricted" report to value future reductions. Barker (1993), Barker et al. (1993) and Alfsen (1993) use macro level data or models to develop more careful predictions of changes in secondary emissions from various sectors of the economy for the UK and Norway, respectively.

For economic valuation of these changes Barker uses aggregated unit values from Ottinger et al. (1990) for a measure of damage, and Newberry (1990) for a measure of avoided abatement investments. Both these measures are on the high side of valuation measures identified by recent social cost studies reviewed in Krupnick and Burtraw (1997), lending an upward bias to estimates of ancillary benefits. Alfsen (1993) uses benefit estimates developed in the Norwegian context with respect to commodity values for timber and fish, and contingent valuation studies of recreational opportunities, the economic life of materials, and road traffic, so it is difficult to compare them to other estimates. The basis for their health benefits are U.S. epidemiological studies, "expert assessment" and assumptions used where necessary to fill in for missing values. This approach leads to emission-related benefits of slightly more than $100/ton carbon, which are lower than those for Barker and for Pearce, and which are coupled with non-emission related benefits from reduced fuel use that are 1.5 times as great to yield total benefits comparable in magnitude to Barker and to Pearce.

Ekins (1996) reviews the European literature and suggests a benchmark of $227 in ancillary benefits per ton carbon reduction (1990$), 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, which we discuss below, and consider in adjusting this benchmark.

V. AN ILLUSTRATION OF THE NEED FOR GREATER RESOLUTION IN ANCILLARY BENEFITS ESTIMATION

In this section we explore the sensitivity of benefit estimates for emission reductions in the electricity sector with respect to several factors: emission rates of pollutants for different technologies, the impact of emissions in different locations, and the valuation of impacts. We conduct this analysis by constructing alternatives scenarios in the EXMOD modeling framework (see footnote 5), which accommodates alternative specification of technologies and location of electricity generation in New York, and predicts impacts and monetized damages that result. The application to New York State is intended to illustrate of the importance of these variables in the national context.

In Table 2 we report the variation in tons of particulates, sulfur oxides, nitrogen oxides and carbon dioxide per kWh of electricity generation from three hypothetical vintage 1995 technology applications as calculated in EXMOD. We also report comparable rates for generic technologies based on Viscusi et al. (1993),[13] which formed the basis for benefit numbers used by Boyd et al. and Jorgenson et al. In addition, we report emission rates for an average in-place coal-fired power plant in New York in 1992.[14] The fact that emission rates vary dramatically with fuel type is no surprise. However, new and existing facilities using the same fuel type also have significantly different emission rates, as illustrated in the comparison of coal technologies. For instance, the emission rate for nitrogen oxides from an average existing coal plant in New York State in 1992 is 1.5 times that which would result from a coal plant constructed under 1995 standards; a relatively dirty plant is likely to have emission rates several times as great.

Table 2. Emission rates for various pollutants under alternative technological assumptions

pounds/megawatt hour	**Particulates**	**Sulfur Dioxide**	**Nitrogen Oxides**	**Carbon Dioxide**
New plants in New York State using EXMOD (Hagler-Bailly, 1995)				
Natural Gas Combustion Turbine	0.14	0.02	0.58	1698
Natural Gas Combined Cycle	0.08	0	0.16	906
Coal (steam)	0.32	3.84	4.14	2168
Average emissions at 1980 facilities (Viscusi et al., 1993)				
Natural Gas Combustion Turbine	0.04	0.02	6.54	1698
Natural Gas Combined Cycle	0.02	0	3.5	906
Coal (steam)	0.58	19.94	8.76	2168
Existing NY average plant (Rowe et al., 1996; and Hagler-Bailly, 1995)				
Coal (steam)	0.4	19.96	6.4	2168

The policy that is used to achieve a given climate goal will affect the ancillary benefits that are realized. For example, if it is geared only at new sources it is likely to affect natural gas facilities with an emission rate for NO_x that is 1/30 that of existing coal steam plants. Such policies impose an anti-new source bias that may delay investment in new facilities and lead to increased utilization of existing facilities with higher emission rates (Palmer et al, 1995).

The most important issues related to criteria air pollutants do not concern direct emissions, but rather chemical transformations of those direct emissions into secondary air pollutants, such as ground level ozone and particulates. Transformation of primary pollutants

[13] These rates serve as the basis for estimates in the Boyd et al. 1995 study discussed previously. The emission rates for CO_2 associated with Viscusi are estimated from EXMOD, since Viscusi does not report these rates.

[14] The technology parameters for the existing plant are described in Rowe et al. (1996). The emission rates we model using EXMOD vary only slightly from those estimated by Rowe et al. using parameters in their Table 4, for Facility B.

into these secondary pollutants takes place over space and time.[15] Linear reduced-form relationships, even if very simple, can provide meaningful approximations of these transformation processes that heretofore have been represented in an arbitrary fashion or ignored in studies of the ancillary benefits of CO_2 policies.

Table 3 reports damages (1992 $) per kWh for a new coal steam plant sited at three different locations in New York State--rural, suburban and urban -- as calculated by EXMOD. SO_2 damages are characterized with and without the influence of the SO_2 emission allowance cap and trading program. With the cap, net emissions of SO_2 from electric utilities at a national level are constant but the impacts of emissions nonetheless vary with their location. EXMOD values offsetting emission changes according to the relative population density in the vicinity where emissions occur. As noted previously, for comparison with costs of climate policies under an emissions cap, it may be appropriate to include economic benefits from avoided abatement investments at other facilities. The "TOTAL w/cap" reported in the right-hand column includes estimated benefits from avoided investment in SO_2 abatement at another facility.[16] Damages estimated without the cap represent benefits of emission reductions if total SO_2 emissions were to fall below the level of the cap.

The range of estimates in Table 3 characterized as low, mid, and high correspond to the 20th, 50th and 80th percentiles of a confidence interval for damages. The estimates in Table 3 indicate that while the range of values typically differ by over a factor of two between the low and high, they differ almost as much between the rural and urban locations.

Table 4 reports the mid value of secondary damages per kWh for three vintage 1995 facilities at the suburban (Capital) location using EXMOD, compared with mid values based on Viscusi (1993), and with the mid value for a typical existing coal steam plant with average emission rates for New York State.[17] The existing plant is located at the urban (JFK) location, to reflect the more probable location of in-place facilities. The values are comparable for the natural gas facilities, but differ importantly for the coal facilities. The existing coal plant in New York is expected to have environmental damages of over 6 mills/kWh, an order of magnitude greater than would a new coal plant at a suburban location. The Viscusi estimate is four times greater still, or forty times greater than the EXMOD estimate for a new plant. The reasons for the higher Viscusi estimate are that it does not reflect the role of emission trading for SO_2, and it places a high value on SO_4 mortality; in addition, it is based on national average emission rates in the late 1980s, which have since fallen not only due to the 1990 Clean Air Act Amendments but also due to a sizable shift toward increased use of lower sulfur

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[15] Ozone is of interest spatially because of the number of nonattainment areas relative to current National Ambient Air Quality Standards in various parts of the country. Ozone also is primarily a summer problem.

[16] We use the current value of allowances of about $100/ton as a proxy for the present discounted value of average avoided investments in abatement of about $300/ton when the program is fully binding around the year 2010 (Bohi and Burtraw, 1997). This results in an estimate of additional benefits of $0.00058 per kWh.

[17] The damages per ton of emissions are not necessarily constant across technologies because of differences in design parameters such as stack height, the velocity of emissions from the stack, etc.

coal for strictly economic reasons. Partially offsetting this is a lower average population density exposed to these emissions at the national level than in New York State examples, which tends to lower the Viscusi estimates.

Table 3. Range of levelized externality estimates for three conventional pollutants for a new (vintage 1995) coal steam plant at three locations in New York State

1992$ per megawatt hour	**Particulates**	**Sulfur Oxides w/o cap**	**Sulfur Oxides w/cap**	**Nitrogen Oxides**	**TOTAL w/cap and avoided abatement investments**
JFK airport site (urban location)					
low	1.80	1.15	0.28	-0.02	2.64
mid	2.42	1.59	0.44	1.03	4.47
high	2.92	1.96	0.58	2.06	6.14
Capital site (suburban location)					
low	0.49	1.08	0.24	1.44	2.75
mid	0.64	1.48	0.40	2.19	3.81
high	0.77	1.81	0.52	2.79	4.66
Sterling site (rural location)					
low	0.29	0.98	-0.01	1.43	2.29
mid	0.41	1.39	0.11	2.05	3.14
high	0.50	1.73	0.21	2.54	3.82

Source: Hagler-Bailly, 1995.

Table 4. Monetized ancillary benefits in electricity generation

	$ per megawatt hour	**$/ton CO_2**	**$/ton carbon**
New plants in New York State using EXMOD (Hagler-Bailly, 1995)			
Natural Gas Combustion Turbine	0.60	0.70	2.58
Natural Gas Combined Cycle	0.37	0.81	2.97
Coal (steam)*	3.81	3.51	12.87
Average emissions at 1980 facilities (Viscusi *et al.*, 1993)			
Natural Gas Combustion Turbine	0.25	0.30	1.08
Natural Gas Combined Cycle	0.16	0.35	1.29
Coal (steam)*	23.69	21.85	80.08
Existing NY average plant (Rowe et al., 1996; and Hagler-Bailly, 1995)			
Coal (steam)*	7.47	6.89	25.25

* Estimates include avoided investments in abatement under the SO_2 emission cap.

Estimates in the second column of Table 4 describe the ratio of secondary damages per kWh to CO_2 emissions per kWh, or in other words, the value of ancillary benefits that would be achieved per ton of reduction in CO_2 emissions achieved by reduced utilization of each of these technologies. The third column converts these estimates to benefits per ton carbon reduction. For example, reducing carbon emissions by one ton by reducing utilization of an average coal steam plant in New York is predicted to yield $25 in ancillary benefits. The ancillary benefits illustrated in Table 4 can be compared to the conventional measure of cost per ton of carbon emission reductions to arrive at an estimate of the net costs of reducing GHG emissions.[18]

VI. A COMPARISON OF THE ESTIMATES

The previous section demonstrated the potential difference that could result from using facility-specific emission rates in place of the national average emission rates in modeling emission changes in the electricity sector. In this section we attempt to compare previous ancillary benefit estimates along a common metric, by expressing several of the mid-value estimates per ton reduction in carbon emissions. These estimates are reported in Table 5. Note that in every case there is a wide range of values around the mid-range estimate, which we do not report. Lower and upper bounds for each estimate range varies from its midpoint by a factor of 2 to 10 or more.

Table 5 indicates a large variation across various studies in their mid-range ancillary benefit estimates. Three types of differences in the models account for the bulk of the differences in the results. One is the modeling of criteria pollutant emissions reductions. The general equilibrium models have the advantage in predicting emissions changes in the future because they can account for changes in the quantity of electricity demand and substitution among technologies. However, they are likely to have less accuracy for near-term emission changes than the partial equilibrium models because they have less detailed modeling of technology.

Second, the estimation and valuation of effects from emission changes varies among the studies, and we believe it is relatively weak in the general equilibrium models. The health epidemiology and valuation literatures have developed considerably in the last few years, and have shown the importance of spatial aspects in developing such estimates, which are missing

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[18] Our advice presumes that policy will be shaped taking an emission reduction goal as given, or that such a goal will be developed independent of estimates of the direct benefits of GHG reductions. However, the preferred approach would be to combine ancillary benefits with direct benefits for comparison with costs. One reason is that when considering uncertainty in policy design (Weitzman, 1974), the measure of costs should reflect behavioral responses. Including ancillary benefits in the cost function reduces the estimate of social cost and would understate behavioral responses, since those responses in reality would be based on costs born privately in compliance with the program absent consideration of ancillary social benefits. Hence, if the analysis is used to consider what we term "net costs" to identify a preferred emission target, a quantitative benefit estimate is implicit, and ancillary benefits should be included on this side of the benefit-cost calculus. However, if the emission goal is explicit and fixed, then we advise that ancillary benefits should be considered with costs to find the least net cost means of achieving that goal.

Table 5. Comparisons of Estimates of Ancillary Benefits per ton of Carbon Reduction

Source	Targeted sectors, pollutants and policy	Average ancillary benefit per ton carbon reduction (1992$)
(1) ICF/ PREMIERE	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	$2.88
(2) Dowlatabadi et al./PREMIERE	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	$2.64
(3) EXMOD	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	$23.96
(4) Coal/PREMIERE	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	$7.02
(5) Coal/ PREMIERE/RIA	Equal percentage reduction in utilization of existing (1994) coal plants analyzed at state level; only NO_X related mortality changes valued using PREMIERE, including secondary particulates and excluding ozone, and using 1997 EPA RIA estimates of impacts and valuations	$23.92
(6) Goulder/ Scheraga and Leary	Economy-wide carbon tax with stabilization at 1990 levels in 2000; human health effects from all criteria pollutants, no secondary particulates or ozone.	$29.84
(7) Boyd et al.	Economy-wide carbon tax; human health and visibility effects calculated from reduced total emissions of all criteria pollutants	$35.58
(8) Viscusi et al.	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	$78.85

in the general equilibrium models. A third reason for the difference in per ton benefit estimates is differences in sectoral coverage and coverage of pollutants or impacts. For example, the estimates presented range from a small program affecting the electricity sector to estimates for the economy as a whole. Also, for the most part they do not account for the SO_2 emission cap.

With the goal to identify the ancillary benefit per ton of carbon reductions for a *modest* carbon abatement program, we place greater confidence in the first four estimates in Table 5, 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 they take into account the role of the SO_2 cap in limiting ancillary benefits. Note that these estimates suggest modest (less than $7/ton) benefits on average for the United States as a whole, though benefits could be significantly higher in certain areas. 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, and the sector where reductions may be least expensive. The higher fifth estimate in the Table 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 it.

The first two studies in Table 5 indicate that subtle aspects of behavioral responses to policies tend to mitigate the desired emission reductions.[19] The ICF/PREMIERE example estimates health benefits from changes in NO_x emissions and transport (excluding ozone effects) for a voluntary policy. This estimate is low due to the fact that some of the reduced electricity generation resulting from energy efficiency improvements will come from natural gas units that have lower emission rates for NO_x than do coal units and hence fewer ancillary benefits obtain. Dowlatabadi et al./PREMIERE reflects a seasonal (summer) burn of natural gas in place of coal, and models health benefits from changes in NO_x emissions and their transport (excluding ozone effects). These results are low because increased emissions of NO_x from gas offsets somewhat the reductions from coal.[20]

The EXMOD estimate is greater than the two preceding because it does not account for the bounceback effect that may result from increased utilization of another technology such as natural gas to replace coal utilization, and because it is cast in a densely populated area. The EXMOD 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, and it accounts for SO_2 trading as discussed above. 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

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19 The Dowlatabadi et al. estimates may exaggerate this effect because they reflect the capital stock circa 1987 and do not reflect improvements in gas technologies.

20 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.

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 estimate is comparable to the third, except that it is applied on a weighted average national basis. These four estimates suggest modest (less than $7/ton) benefits on average for the United States as a whole, though benefits could be significantly higher in certain areas.

The sensitivity of conclusions to the valuation of damages is illustrated by comparing the PREMIERE and EXMOD estimates to the fifth estimate in Table 5, which uses assumptions drawn from the recent Draft Regulatory Impact Analysis (RIA) for new particulate and ozone standards (USEPA, 1996b). The Coal/PREMIERE example considers a 1 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.[21]

The Coal/PREMIERE/RIA example considers the same change in emissions, with atmospheric transport calculated with PREMIERE, but with an assumption in the health epidemiology that the mortality coefficient used in the RIA for $PM_{2.5}$ applies to nitrates. The RIA also places greater weight on one mortality 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 approach yields a valuation of mortality impacts from NO_X changes (excluding ozone impacts) of three times that from PREMIERE.[22]

The final three estimates are the results from general equilibrium modeling. We feel the base on which valuations in the general equilibrium models have been constructed is narrow, as illustrated by the fact that the estimates in Boyd et al., like those in Jorgenson et al., are based on Viscusi et al. (The Jorgenson et al. 1995 estimate is expressed as a percentage of carbon tax revenue, and GHG reductions are not reported, so it is not shown in Table 5.) The Viscusi et al. value is reproduced from Table 4 for comparison. This value reflects a reduction in secondary pollutants absent geographic resolution, and the authors report the value per ton of secondary pollutant. We convert this using their source data to dollars per kilowatt-hour of generation from a generic existing coal plant in the late 1980s, and then convert to dollars per ton carbon reduction reflecting an assumption that the relative

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[21] SO_X changes are not included due to the SO_2 cap, but they would amount to $87 per ton carbon were emissions not made up through the trading program.

[22] 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., 1997 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.

emission rates remain constant. The Goulder/Scheraga-Leary valuation is based on a different review of EPA Regulatory Impact Assessments from the 1980s, which provides a little more breadth to the analyses as a group.

The treatment of the SO_2 cap represents another important distinction among the studies. When the cap is binding, emission reductions in one location are made up in another, but emissions at one location are likely to reduce the need for investment in SO_2 abatement at another location. This is usually not considered in cost estimates for CO_2 reduction. Our estimates using PREMIERE and EXMOD include a secondary benefit of about $3 per ton of carbon reduction from avoided investment in SO_2 abatement stemming from reduced utilization of coal. This benefit 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., 1997).

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.

We briefly summarize the European literature by starting with Ekins (1996) point estimate of about $227 (converted to 1990 dollars) per ton in total benefits, based on his analysis and evaluation of the half dozen or so studies he reviews. About half of the estimated benefits would come from reduced sulfur emissions, and this estimate does not take into account the SO_2 emission reductions that will result from the signing of the European Second Sulphur Protocol in 1994. Following the reasoning provided by Ekins and the studies he reviews, we reduce this estimate to account for the Second Sulphur Protocol, to arrive at a range of $33-$71 per ton (1990 dollars) for sulfur benefits only.[23] Adding in benefits of about

[23] 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 SO2 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) if benefits are realized through additional emission reductions.

$105 per ton from reduced emissions of other pollutants increases this to a range of $138-$176, with a mid-value of $157. 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,[24] and the ecological effects resulting from on-shore atmospheric transport of sulfur, in contrast to off-shore transport in the eastern U.S.

VII. CONCLUSIONS

How does one make sense of the welter of estimates in Table 5? The first point is that firm conclusions are all but impossible to draw at present, given the current state of knowledge. Accordingly, we do not believe it is possible at this time to identify a single numerical "best estimate" of benefits per ton carbon reduced for any particular GHG limitation, let alone for all possible GHG limitations. As discussed in more detail below, we believe there are modest but nonetheless important ancillary benefits per ton of carbon emission reduction that would result from a modest level of GHG control, and that the benefits may be more than modest in certain locations (those with denser populations and greater exposures to damaging criteria pollutants). The benefits per ton of carbon reduction could be larger with a greater degree of GHG control, though it is difficult to gauge by how much.

In identifying the large uncertainties surrounding current estimates of ancillary benefits, we have focused especially on the location of emissions reductions, the role of the SO_2 emissions cap, and the means by which emissions reductions are achieved (e.g., voluntary versus involuntary measures, and comprehensive measures versus measures that allow increases in emissions from uncovered sources). Additional factors include basic questions about the baseline against which to measure the effects of policy options (e.g. trends in criteria pollutant emissions), atmospheric modeling of the transport of these emissions, the incidence of adverse effects of these emissions, and the economic valuation of avoided adverse impacts. The literature provides little in the way of estimates for ancillary benefits other than those associated with the electricity sector.[25] A more reliable and comprehensive set of estimates must await the analysis of how GHG abatement policies would affect other emissions sources, among other advances in knowledge.

The applicability of all these results is necessarily limited. Specific utility-sector policies for CO_2 reduction may have different effects in different geographic areas than the effects assumed in these estimates, including changes in the utilization of other technologies besides coal-fired plants. For example, an energy efficiency policy could reduce use of natural gas as well as use of coal. Moreover, policies affecting other sectors -- notably transportation -- could also generate nontrivial ancillary environmental benefits.[26] Further,

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[24] See Krupnick and Burtraw (1997) for a related discussion.

[25] There are some estimates related to the social costs of transportation. See Green et al. (1997).

[26] Green et al. (1997).

health effects do not exhaust all the environmental benefits. Finally, benefits would be larger with nonmarginal GHG mitigation policies that drive SO_2 emissions below the regulatory cap.

In light of these limitations, it is tempting to embrace the last three, economy-wide studies in Table 5 that attempt to describe the effects of nonmarginal GHG reductions and include a variety of pollutants and impacts. However, the methodologies in these studies simply compute a total economic benefit from a national reduction in criteria pollutant emissions. They lack attention to locational differences in emissions and exposures, and they inherently overestimate the total ancillary benefits from SO_2 reduction by failing to take into account the effect of the SO_2 cap. Hence, they may be better suited for examining the effect of more substantial and broad scale GHG mitigation policies than for examining the effect of more modest policies.

It is of interest to compare the various figures in Table 5 with the costs of GHG abatement, although it is difficult to formulate such a comparison with the simple per-unit values we have calculated for a number reasons. The models that have been used to estimate abatement costs give a wide range of answers, depending on critical assumptions in the various models and on the level of abatement undertaken.

Both the Clinton Administration's analysis and a 1993 study by the Energy Modeling Forum suggest that the *marginal* cost of achieving *stabilization* of U.S. emissions at 1990 levels in the year 2010 might be on the order of $100/ton (costs could be lower with greater technical progress or robust international GHG emissions trading but they could be higher if domestic GHG policies are poorly designed or technical progress lags). The marginal costs of smaller initial reductions are likely to be considerably lower; indeed there is reason to think they would be close to zero (some would even argue less than zero, though we remain skeptical). This low cost suggests that the ancillary environmental benefits of even $3/ton of carbon reduced, let alone $7-10/ton, could have a significant effect on the volume of emissions reduction that is "no regret." On the other hand, marginal ancillary benefits of even $25/ton of carbon removed are clearly smaller than the marginal cost of significant GHG reductions, and even the prospect of additional ancillary benefits from sulfate reductions with a nonbinding SO_2 cap would not close the gap. Nevertheless, in assessing the cost of GHG control for comparison with subjective estimates of the value of climate change risk reduction, these ancillary benefits clearly warrant attention.

Our analysis indicates that national average ancillary benefits from modest reductions in greenhouse gases from coal-burning electric utilities, where the average cost of each ton of carbon reduced may be in the order of $10-20 are likely to be modest ($3-7 benefit per ton of carbon reduced). Larger ancillary benefits on the order of $12-18 per ton of carbon reduced on average, and $20-$30 at the margin, could be obtained with a more substantial national policy for GHG control, as would be needed to stabilize national emissions at 1990 levels (where the average costs of each ton of carbon reduced may be on the order of $40-50 and marginal cost around $100 per ton). We identify a rough rule of thumb to characterize the relationship between ancillary benefits and the costs of carbon mitigation policies. The evidence suggests ancillary benefits average about 30 percent of the cost of carbon reduction, over the range of policies we consider, though we emphasize there is large uncertainty and variability in these estimates.

Lessons for Policy

Some lessons for the design of policy can be derived from our analysis, though these lessons must be interpreted with care. Ancillary benefits may be larger for GHG policies that more heavily target coal use, but this has at least as much to do with the continued use of old, relatively polluting boilers as with the use of coal itself. And GHG abatement policies that have relatively greater effects and impose greater costs on newer plants will have the perverse effect of creating a new bias against construction of new facilities, resulting in continued use of older facilities and lower ancillary benefits. By the same token, energy efficiency programs whose effects displace gas use to a significant extent, as well as coal, will have smaller ancillary benefits.

A second set of lessons concerns spatial differentiation in ancillary benefits. GHG mitigation that occurs in areas especially conducive to the formation of secondary pollutants (ozone and secondary PM), and at sources whose effluent reaches large populations, confer larger ancillary benefits compared to other options.

The possible trend in ancillary benefits over time also is of interest. It is often argued that abatement costs associated with a goal like GHG emissions stabilization will rise over time because of growing energy demand, though this trend will be ameliorated by technical progress and ultimately by a transition to noncarbon backstop energy resources. While this argument is reasonable, one might also expect the ancillary benefits per ton of pollutant to rise over time as well. This is because of growth in population density and congestion, as well as growth in income, can be expected to yield an increase in the willingness to pay for environmental protection.[27] This may be ameliorated by improvements in air quality over time, which would lower the ancillary effects that could be obtained by a GHG policy.

Cost estimates of GHG policies generally fail to anticipate a changing regulatory baseline that is expected to lead to air quality improvements over time and raise the cost of more heavily polluting fuels. Hence, these GHG cost estimates would overstate the relative opportunity cost of GHG policies. In comparing benefits and costs, it would be misleading to include improvements in baseline air quality in calculating ancillary benefits while not including the effect these changes have on the opportunity cost of GHG policies. We correct for this in some of the studies we review in Table 5 by adding in the benefits of avoided investments in SO_2 abatement under the cap that would result from GHG policies.

It is important to be cautious about the implications of ancillary benefits for the desired level of GHG control. Ancillary benefits are important enough that they should be considered jointly with costs of carbon reduction to identify the preferred policies for society. However, the policies that maximize net benefits for society may not be ones that maximize

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[27] Krutilla (1967).

ancillary benefits nor ones that achieve GHG reductions at the lowest gross cost. For instance, a GHG emissions trading program may minimize the direct cost of abatement associated with a GHG reduction target, but it will not necessarily minimize the social cost including ancillary benefits. The preferred policy for achieving a stated level of emission reduction is the one with the lowest net costs of GHG control after allowing for ancillary benefits. An ideal policy would force emitters to recognize the social opportunity costs of GHG emissions together with the costs of criteria air pollutant emissions. At the same time, the choice of policies can have important distributional effects, both in economic costs and ancillary benefits, that must be considered as well.

Finally, we note that ancillary benefits from GHG policies in developing nations may be even more significant relative to the cost of these policies than those measured in the U.S. and Europe because of lower existing levels of pollution control and lower efficiency in energy use in these countries. The short run and geographically proximate nature of these benefits can play an important role in shaping GHG policies in developing countries.[28]

[28] Ongoing efforts to assess these issues are described in Dowlatabadi (1997) and Davis et al. (1997).

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