ESTIMATING THE ANCILLARY BENEFITS OF GREENHOUSE GAS MITIGATION POLICIES IN THE US

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1. Introduction

To a large extent, policies for limiting emissions of greenhouse gases (GHGs) have been analyzed in terms of their costs and potential for reducing the rate of increase in atmospheric concentrations of these gases. However, actions to slow atmospheric GHG accumulation could have a number of other impacts, such as a reduction in conventional environmental pollutants. The benefits (or costs) that result are often referred to as “ancillary” to the benefits and costs of GHG abatement (though there is controversy surrounding this terminology and the underlying concepts).

A failure to adequately consider ancillary benefits and costs of GHG policy could lead to an inaccurate assessment of the overall impacts of mitigation policies. In particular, not accounting for ancillary benefits and costs would lead to an incorrect identification of a “no regrets” level of GHG mitigation. It also could lead to the choice of an unnecessarily expensive policy because of its failure to fully exploit potential ancillary benefits.

In this paper we first review briefly the concept of ancillary benefit, as it is developed in more detail in other papers in this proceedings and elsewhere in the literature. The concept turns out to be surprisingly difficult to define precisely. What is considered an ancillary benefit depends on the scope of policies being considered, the policy objectives being pursued, and the identity of the interests being served. That said, however, we describe what we believe is a serviceable definition of ancillary benefits from the perspective of evaluating GHG mitigation policies within the “Annex I” countries who would have emission limitation obligations under the Kyoto Protocol. We focus on mitigation in this paper, while acknowledging that adaptation policies also could have ancillary effects (for example, improved surveillance of tropical diseases could yield immediate health dividends; protection of coastal lands could harm wetland habitats in the more immediate term).

Having established a workable definition, we then turn to issues related to measuring ancillary benefits. To illustrate these issues, we consider how lower GHG levels resulting from less fossil fuel use could also reduce various "criteria" air pollutants (as defined in the U.S. Clean Air Act). 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, excluding climate change and species biodiversity (Lee *et al.*, 1995; Rowe *et al.*, 1995; EC, 1995). Thus, focusing on the air-health pathway of ancillary benefits is likely to provide a fairly reliable picture of total ancillary benefits, though controversy remains regarding the magnitudes of non-health effects.

We find in our review that estimates of ancillary health benefits for the US vary considerably. Previous estimates have ranged from over $60 per ton of carbon reduced (or greater in one special context) to $3 per ton. The dispersion of US estimates reflects partly underlying parametric uncertainty, in particular the economic valuation of health impacts. There also are several important differences in the identification of baselines, in particular the effect of current and future regulatory standards for conventional pollutants (see the paper by Morgenstern). Still other differences arise in the scale of modeling, in particular the distinction between more detailed sector-specific analyses (in practice these involve the electricity sector), and specific geographic locations, in contrast to economy-wide estimates based on much simpler modeling of environmental impacts.

For a variety of reasons that are evident below, we have much more confidence in more conservative (lower) estimates of ancillary benefits (especially those drawn from more detailed models) compared to estimates that equal or exceed the costs of GHG control. Ancillary benefits could offset a significant fraction of the costs of carbon reduction with moderate GHG policies. It also may be possible to orient GHG abatement policies in certain ways to take greater advantage of ancillary benefits. However, the considerable variation in baseline assumptions and in policy scenarios, coupled with uncertainty about the size of ancillary benefits, leads to tremendous variation in estimates, precluding identification of a single "best estimate" of their magnitude.

In the next section of the paper we briefly review our working definition of ancillary benefit. Section III contains a review of estimates from a number of US studies. Section IV provides a more detailed discussion of methods and results from ongoing research at RFF on ancillary benefits from GHG restrictions in the electricity sector. This approach reflects what might be seen as a "best practice" in the development and use of detailed methodology for linking GHG policies to changes in conventional pollutant emissions, ambient consequences, health effects assessment, and economic valuation. Section 5 interprets and critiques the various estimates presented in Sections 3 and 4. Section 6 offers concluding remarks and suggestions for further research.

2. Defining and measuring ancillary benefit or cost

2.1 Definitional issues

An ancillary benefit of a GHG mitigation policy is understood by many analysts to refer to a benefit (derived from GHG mitigation) that is reaped in addition to the benefit targeted by the policy, which is reduction in the adverse impacts of global climate change. An ancillary cost would be a negative impact experienced in addition to the targeted benefit. The key elements of this definition, and the sources of much of the controversy surrounding the notion of ancillary, are "in addition" and "targeted."

In the context we have used for defining ancillary benefits and costs, the principal policy goal is GHG mitigation in order to reduce adverse climate impacts. Asserting that ancillary benefits are additional to the benefits of reducing climate change does not mean these benefits are necessarily less important, or that other policy goals are less important than addressing climate change. Benefits that are ancillary to climate change could be bigger in magnitude and more salient for the affected citizens and their decision makers. Our definition simply puts ancillary benefits in a certain policy context.

That policy context can be and is debated. Developing countries have argued with justification that they have more pressing development and environmental needs than reducing their GHGs. In this broader policy context, what we refer to as ancillary benefits could be considered as “co-benefits” of policies designed to promote various objectives. Our own view is that when discussing climate change policies, the benefits and costs targeted by the policies should be considered as those associated with GHG mitigation and climate change risk reduction; other benefits and costs should be treated as ancillary in the sense we have defined the term above, but not given short shrift.

Some more specific but related considerations that arise in defining ancillary benefits and costs involve the scope of what is included in the calculation and the perspective of the decision maker evaluating benefits and costs. A number of kinds of impacts can be considered when evaluating ancillary benefits and costs. Much of the emphasis in these calculations has been on near-term health impacts in relatively close proximity to the GHG mitigation (for example, reduced incidence of lung disease in the same area as a coal-fired power plant if that plant is used less as a consequence of GHG mitigation measures), but a variety of other impacts also could be important.

For example, ecological systems could be affected by reductions in the flow of conventional pollutants (for example, less fossil fuel use could mean less nitrogen oxide deposition into water bodies). Reduced pollutants also could reduce some direct costs, such as maintenance of infrastructure and pollution-related reductions in crop yields. Also, traffic accidents could be reduced from less driving or slower traffic speeds. Reduced traffic could lower road maintenance costs. Similarly, increased forest areas dedicated to carbon sequestration could increase recreational opportunities and reduce erosion. GHG policies could also stimulate technical innovation.

Ancillary costs can arise if energy substitution leads to other health and environmental risks (e.g. from nuclear power, uncontrolled particulate emissions from biomass combustion, or use of diesel fuel in lieu of gasoline, since diesel fuel has lower carbon emissions but greater emissions of other pollutants). Better building insulation can add to indoor air pollution, including radon, and switching from coal to gas raises the specter of fugitive emissions of methane, a more potent greenhouse gas than CO_2. Also, policies that promote reforestation could encourage destruction of old growth natural forests because younger forests allow more carbon storage. Further, GHG mitigation policies could mainly redirect innovation efforts away from other productive activities, rather than increasing it. In addition, relatively expensive GHG mitigation policies could have some negative side effects on health by reducing the resources available to households for other health-improving investments.

An economic perspective on ancillary benefits sees them as part of a larger concern with economic efficiency, as typically expressed in measures of aggregate benefits and costs. From this perspective, it is important not to isolate ancillary benefit and cost information from other relevant benefit and cost information associated with GHG policy. Ancillary benefits of a policy could be substantial, but they are nonetheless a questionable achievement if the cost of garnering these benefits is much larger. Often ancillary benefits are expressed in terms of a monetary measure per ton of carbon not emitted to the atmosphere as a consequence of the mitigation policy. Expressed this way, ancillary benefits (and costs) can be compared to the cost of mitigation. This is usually a meaningful and useful comparison, since ancillary benefits often (but not always) occur on the same relatively shorter-term time scale as mitigation costs, while the benefits of reducing climate change will be realized in the more distant future.

A final related point is that the scope and magnitude of ancillary benefits and costs depends on the perspective of the decision maker as to what constitutes policy relevant impacts. From the perspective of a hypothetical global decision maker concerned with global social well-being, ancillary benefits and costs are important wherever they are incurred. From this perspective it thus is important to consider how a redistribution in the location of GHG mitigation could affect ancillary benefits and costs.

In particular, policy mechanisms like international emissions trading or the Clean Development Mechanism will redistribute ancillary impacts toward those countries undertaking more GHG mitigation. And efforts by Annex I alone to mitigate GHGs could have collateral effects in developing countries not bound by quantitative emissions limits, in that lower energy prices in international markets will stimulate some additional energy use and associated local environmental effects in those countries. On the other hand, for an Annex I decision maker evaluating the benefits and costs of GHG mitigation policies in his or her own jurisdiction, the relevant ancillary benefits and costs are likely to consist primarily of those affecting individuals in that political jurisdiction. Cross-boundary spillovers like those illustrated above are relevant for the Annex I decision maker only to the extent that a sense of ethical responsibility or altruism motivates a broader concern for the spillovers.

Still another perspective would be adopted by the developing country decision maker contemplating involvement in the Clean Development Mechanism. In this case, the primary benefits in terms of importance for the developing country considering hosting a GHG-reducing investment are likely to be the benefits that are ancillary to the GHG control according to our definition of the term.

2.2 Empirical challenges

To calculate ancillary benefits and costs over time, one must compare two hypothetical situations. The first is a baseline scenario without any modification of GHG mitigation policy. This is sometimes referred to as “business as usual,” but this term is somewhat misleading since over time, the status quo can change even without modification of GHG policies. The baseline is compared to an even more hypothetical scenario that involves changing the current and future “state of the world” by modifying GHG mitigation. To carry out this exercise in practice means addressing a number of challenges.

How the baseline is defined crucially affects the magnitude of ancillary benefits and costs generated by a change in GHG mitigation policy. The paper by Morgenstern in this proceedings identifies a number of important influences on the baseline. One is the status of non-climate policies. This can be vividly illustrated with two environmental examples. Suppose that even in the absence of climate policy, conventional air pollutants are expected to drop sharply because of trends in policies for the regulation of conventional pollutants. (Note that such a trend requires not just tougher standards over time but also a maintenance or increase in the degree of compliance with those standards.) In this case, we would expect the incremental benefits from a reduction of conventional air pollutants in the wake of tougher GHG controls to be smaller than if the increased GHG controls were being applied to a dirtier baseline environment.

The second example involves the establishment of total emission caps for conventional pollutants, like the cap on sulfur dioxide (SO_2) from power plants in the U.S. If such a cap is imposed, then a stronger GHG mitigation policy will not have an effect on the total emissions of conventional pollutants unless a much tougher GHG policy is imposed, so tough that it leads to polluters reducing conventional emissions below the legal cap. What would be affected in less stringent cases is the *location* of the conventional emissions, which can have an important effect on the size of exposed populations, etc. This example also illustrates the need for careful cost and benefit accounting when calculating ancillary benefits and costs.

Aside from the interaction of GHG policies and conventional pollutant policies over time, there are several other important elements in specifying the baseline. All the factors driving the evolution of the economic system are included in this list. The state of technology will affect the energy and emissions-intensity of economic activity. The size and location of the population, and the volume and location of total economic output, will affect both the scale of physical impacts on the environment and the risks posed to the population. Finally, the status of natural systems is also part of the baseline; it indicates the sensitivity of humans and ecological resources to changes in conventional pollutants.

Another important set of influences on estimates of ancillary benefits and costs include the scale of analysis, the level of aggregation, and the stringency of the GHG policy being considered. As discussed below, we find that estimates of ancillary health benefits from reduced conventional air pollutants (expressed as dollars per ton of carbon release avoided) tend to get smaller when the analysis shifts from an aggregate perspective to one that considers more carefully the effects of GHG policies on specific sectors at specific locations. These latter analyses appear better able to model the distribution of gains and losses, and the behavioral responses to GHG policies. As for the stringency of GHG policy, we would expect that a stronger GHG program will generate successively smaller increments in ancillary benefits and more ancillary costs as other risks decline relative to baseline levels.

One must remain critical of the assessment of the ancillary impacts themselves. In the area of conventional air pollutants and human health, which has received more research support than others, there nonetheless continues to be considerable uncertainty about how a change in ambient environmental conditions will affect health endpoints (for example, how many fewer cases of disease will result from somewhat cleaner air), and how much society values these changes. We illustrate the effects of these uncertainties below. The uncertainties are especially acute and troubling when one tries to use studies of impacts and valuations from developed countries to assess ancillary benefits in developing countries with lower incomes, different health status and infrastructure, and different cultural norms. Other health and non-health ancillary environmental benefits and costs are even less researched or understood.

Finally, we note that ancillary benefits may not just physical, but may be economic. One important example is illustrated by returning to the example of the cap on SO_2 from power plants in the U.S. Though there may be no ancillary reductions in emissions of SO_2 as noted, there will be an effect on the cost of compliance under the SO_2 program. 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. If a carbon policy reduces the use of coal in electricity generation, it will lead to a reduction in the demand for SO_2 allowances, thereby avoiding investment in SO_2 abatement. In addition, many studies of the cost of carbon reduction use historically based carbon abatement cost estimates that do not incorporate the effects of the SO_2 cap and thereby *overstate the opportunity cost* of carbon reductions. For instance, the imposition of controls on a conventional pollutant such as SO_2 may reduce the cost advantage that coal has over gas for electricity generation. Layered on top of a control on SO_2, the reduction of carbon emissions (achieved by substitution from coal to gas) would be less expensive than it would appear were the model to ignore SO_2 controls. Hence, the baseline for comparison of ancillary benefits with costs would be inconsistent, in a potentially important way.

3. Adverse human health effects of conventional air pollutants: a review of US studies

Table 1 summarizes a variety of models and assumptions used to calculate ancillary benefit estimates. References for the estimates are given in Appendix A to this paper. Table 2 summarizes the estimates that are achieved in some of these studies, expressed in the common metric of dollars per ton reduction of carbon emissions. In every case the original studies that produced these data identified a wide range of possible estimates around the midpoint estimate for ancillary benefits per ton of carbon emission reduction that we report. Lower and upper bounds for each estimate vary from the midpoints by a factor of 2 to 10 or more.

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

Study(*) and/or model exercised(**) See Appendix A and Appendix B	*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.* (1992)*	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 particu-lates 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}, (second-ary particulates and ozone modeled); all human health, visibility and other environmental effects	Yes
PREMIERE (Palmer *et al.*, 1996)**	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
HAIKU (Burtraw, et al. 2000)*	Same, detailed electricity sector model	Same	NO_X and SO_2 (and secondary pollutants modelled); SO_2 cap binding; human health only	Yes, additional reductions
Abt/Pechan (McCubbin *et al.* 1999)*	Same, for all economic sectors	Same; special attention to avoided abatement costs	SO_2, NO_X, PM, CO, O_3; Visibility, materials analysed; only health monetized	Yes, additional reductions
Lutter and Shogren (1999)*	Los Angeles	Same, no sensitivity analysis; special attention to avoided abatement costs	Only PM	Yes, additional reductions

Table 2. Comparisons of estimates of ancillary benefits per ton of carbon reduction

Source (see Appendix A and B)	**Targeted sectors, pollutants, and policy** (carbon taxes expressed in 1996 dollars, rounded to the nearest dollar)	**Average ancillary benefit per ton carbon reduction** (1996 dollars)
(1) HAIKU/ TAF	Nationwide carbon tax of $25 per ton carbon in electricity sector, analyzed at state level; only health effects from NO_x changes valued, including secondary particulates, excluding ozone effects. Range of estimates reflect with, and without, NO_x "SIP call" reductions included in baseline.	$2-$5
(2) ICF/ PREMIERE	Nationwide Motor Challenge voluntary program (industry), analyzed at regional level; only health effects from NO_x changes valued, including secondary particulates, excluding ozone effects.	$3
(3) 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	$3
(4) EXMOD	Reduced utilization of existing coal steam plant at a suburban New York location; only PM, NO_x and SO_2 (under emission cap) changes valued (based on 1992 average emissions), including secondary particulates and ozone effects; all health, visibility and environmental effects that could be quantified are included.	$26
(5) Coal/PREMIERE	Equal percentage reduction in utilization of all existing (1994) coal plants in U.S. analyzed at state level; only health effects from NO_x changes valued, including secondary particulates and excluding ozone.	$8
(6) Coal/ PREMIERE/RIA	Equal percentage reduction in utilization of all existing (1994) coal plants in U.S. analyzed at state level; only NO_x related mortality changes valued, including secondary particulates and excluding ozone, using new EPA RIA estimates of impacts and valuations.	$26

Table 2 (continued)

Source (See Appendix A and B)	**Targeted sectors, pollutants, and policy** (carbon taxes expressed in 1996 dollars, rounded to the nearest dollar)	**Average ancillary benefit per ton carbon reduction** (1996 dollars)
(7) Abt/Pechan	Carbon taxes of \$30 and \$67 per ton carbon; modeled changes in conventional emissions and concentrations of particulates (no ozone) and changes in health status, visibility and materials damages. Estimates include avoided abatement costs for NO_X and SO_2. Attainment areas realize cost savings, nonattainment areas realize air quality improvements. All scenarios include NO_X "SIP call" reductions in baseline. Estimates reflect outcomes with and without reductions in SO_2 below 1990 Clean Air Act, based on size of carbon tax (high tax leads to net SO_2 reductions).	\$8 - \$68
(8) Goulder/ Scheraga and Leary	Economy-wide carbon tax of \$144 per ton carbon with stabilization at 1990 levels in 2000; human health effects calculated from reduced total emissions of all criteria pollutants, no secondary particulates or ozone.	\$32
(9) Boyd *et al.*	Economy-wide carbon tax of \$9 per ton carbon; human health and visibility effects calculated from reduced total emissions of all criteria pollutants.	\$39
(10) Viscusi *et al.*	Equal percentage reduction in utilization of existing (1980 average) coal steam plants nationwide; human health and visibility effects calculated from reduced total emissions of all criteria pollutants.	\$86

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.[1] 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).

Goulder *et al.* 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 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.* (1992), adjusted downward 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.[2] 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).

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

[2] 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.

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.* (1992). 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.[3] The authors also identify the "no regrets" level of reduction in the analysis as the point at which 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. Holmes *et al.* (1995) (ICF) use 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. These actions include 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.

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

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 in response to changes in electricity prices could be greater than the NO_x emissions from centralized electricity generation sources providing the same energy services. In addition, emissions from gas use in the home are distributed throughout a metropolitan area. This could have greater environmental damages than emissions from sources more distant from population centers, potentially offsetting some of the ancillary benefits from carbon policies.

McCubbin *et al.* (1999) (Abt/Pechan) is a detailed analysis similar to the HAIKU/TAF analysis that we characterize below as “best practice.” McCubbin *et al.* assume the implementation of carbon taxes and estimate changes in energy consumption by region and sector of the economy. These changes are translated into changes in emissions, and then translated into changes in concentrations of particulates using a source-receptor matrix. Finally, these are mapped into changes in health status and valued in monetary terms. The modeling steps are those used in other detailed, peer-reviewed studies conducted by the US EPA. McCubbin *et al.* paid careful attention to revisions in the US air quality standards in constructing their baselines. The study accounted for reductions in compliance costs for achieving ambient air quality standards in regions of the country that are in attainment of air quality standards, as well as improvements in air quality and health status in regions that are in nonattainment.

A limitation of the study is that the total carbon reductions that are achieved under the tax is not reported, probably because of the political sensitivity of the question of the cost of achieving carbon reductions in the US. This omission makes estimation of ancillary benefits per ton of carbon reduced difficult. In some cases additional reductions of SO_2 in the baseline are achieved through new air quality standards that reduce the annual cap. However, when they are not achieved in the baseline, then the carbon policy yields reductions because annual emissions fall below the cap established in the 1990 Clean Air Act. This yields the high end estimates they present. We note that the proportion of SO_2 reductions that are achieved relative to carbon reductions is greater than that in HAIKU/TAF.

One other study that we do not include in our review of estimates is Lutter and Shogren (1999). This study offers an analytical description of how changes in carbon emissions affect the emissions of other pollutants and includes an accounting of the reduction in compliance costs in achieving air quality standards for conventional pollutants. This point is embodied in some of the other papers we review. Lutter and Shogren illustrate this point in the special context of Los Angeles where the compliance cost of strict new ambient standards would be especially dramatic. In this case, carbon reductions yield large ancillary benefits of around $300 per ton from reduced compliance costs. The authors point out that ancillary benefits would have an effect on whether a nation should choose to reduce emissions domestically or seek to acquire permits in a trading program.

4. The HAIKU/TAF model: An illustration of best practice

The study by Burtraw *et al.* (2000), which uses the HAIKU/TAF integrated framework, is one we believe illustrates best practice (as noted, the methods are similar to those in McCubbin *et al.* (1999)). Burtraw *et al.* exercise an electricity market model to predict changes in nitrogen oxides (NO_x), sulfur dioxide (SO_2), and mercury 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. 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.

The study directly addresses three methodological issues that 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.

4.1 Emissions

Burtraw *et al.* focus exclusively on air emissions and their potential health effects, which as noted account for 85 percent or more of the quantifiable environmental concerns in previous studies of the electricity sector. Also, they focus exclusively 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 as much as three-quarters of CO_2 emission reductions in the U.S. under potential implementation of the Kyoto Protocol (EIA, 1998). Hence, this sector will be especially important as the least expensive and likely source of reductions under moderate reduction scenarios.

4.2 Health effects

This paper uses the “damage function approach” to focus on estimating the social cost of electricity generation from facilities examined on an individual basis. The 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 approach involves an atmospheric transport model linking changes in emissions at a specific geographic location with changes in exposure at other locations. Concentration-response functions are used to predict changes in mortality and a number of morbidity endpoints, and these changes are valued in monetary terms drawing on estimates from the economics literature.

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. These are important considerations since population and income trends have greatly outstripped energy prices over the last century. 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.

4.3 The baseline

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.

Burtraw *et al.* include alternative baselines for NO_x controls beyond Phase II of Title IV of the 1990 Clean Air Act Amendments. One baseline adds a cap and trade program for the summer months for the Ozone Transport Commission member states in the northeast. This trading program began in 1999. An alternative adds a cap and trade program for a larger region that includes all the eastern states in the Ozone Transport Rulemaking Region (the so-called "SIP call region") affected by the EPA's September 1998 proposed rule regarding NO_x emissions.

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 emission 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.

Burtraw *et al.* assume the SO_2 cap is binding and hence they do not anticipate ancillary benefits from changes in SO_2 emissions for moderate policies. However, they do anticipate reduced costs of compliance with the SO_2 cap to result as a consequence of climate policies, and these savings are reflected in expected change in electricity prices and consumer and producer surplus. If new standards regarding NO_x emissions from power plants take the form of a cap and trade program analogous to the SO_2 program, but applied only during the summer months, then further emissions in NO_x will be less than under a performance standard. However, in this case we would expect a greater 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.

Finally, the issue of baselines is complicated further by the changes in the regulation of the electricity industry. At the time of this writing (summer 2000) over half of the US population reside in states that have committed themselves to a path of restructuring that would culminate in a move away from cost of service pricing for electricity and toward market-based, marginal cost pricing. This change has the potential and is expected by many to affect dramatically the emissions of various pollutants. Burtraw *et al.* adopt a cautious assumption regarding the future regulation of the industry by assuming that traditional average cost pricing continues in effect in regions that have not committed to marginal cost pricing by 2000.

4.4 The models

The study employs an electricity market equilibrium model called HAIKU to simulate market equilibrium in regional electricity markets and inter-regional electricity trade, with a fully integrated algorithm for NO_x and SO_2 emission control technology choice. The model simulates electricity demand, electricity prices, the composition of electricity supply, inter-regional electricity trading activity among NERC regions, and emissions of key pollutants such as NO_X, SO_2, mercury 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 13 NERC regions. 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.

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. Most new investment is in conventional technologies including integrated combined cycle natural gas units and gas turbines. Fuel supply is price responsive according to a schedule derived from EIA models.

To estimate the potential for carbon emission reductions, Burtraw *et al.* impose a tax on all emissions in the industry. This tax is collected through the price of electricity and affects dispatch and investment decisions. Tax levels of \$10-\$50 per metric ton of carbon 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.

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 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.

4.5 Results

We use the HAIKU/TAF model to evaluate two scenarios, and results from the analysis are presented in Table 3. (See Burtraw *et al.* 2000 for a fuller discussion.) In the first scenario, identified as Baseline OTC, NO_x standards implemented in the 1990 Clean Air Act are maintained, except for an additional cap and trade program that applies during the five month summer season in the Northeast states. A carbon tax of \$23 per metric ton of carbon in the year 2010 would yield ancillary benefits from reductions in NO_x of \$7 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.

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.

Measured against the Baseline OTC case, an $83 tax increases ancillary benefits in the aggregate but has little effect on the value per ton of carbon, which increases slightly to $8. The quantity of carbon emission reductions that are achieved by an $83 tax is proportionately less than that achieved by a $ 23 tax, which illustrates that the marginal abatement cost curve for carbon reductions is convex over this range. The proportional change in NO_x emissions is also less than the change in the tax rates, but it is not strictly tied to changes in carbon emissions. The difference in the ratios of NO_x and carbon reductions stem from many factors including cost thresholds for new investment and retirement, and from the geographic location of changes in emissions. In other scenarios the benefits per ton fall slightly or stay relatively constant with different levels of a carbon tax.

Table 3. **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)**

	Baseline - OTC		**Baseline - SIP**	
Level of Carbon Tax ($/metric ton)	**23**	**83**	**23**	**83**
Emission Reductions (metric tons)				
Carbon (millions)	79	214	88	215
NO_x (thousands)	874	2586	974	2564
NO_x Related Health Benefits (million dollars)				
Morbidity	115	368	157	388
Mortality	437	1,382	585	1460
Total	552	1,750	742	1848
NO_x Related Health Benefits per Ton Carbon (dollars)				
Morbidity	1.5	1.7	1.8	1.8
Mortality	5.5	6.5	6.6	6.8
Total	**7.0**	**8.2**	**8.4**	**8.6**

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 under the two levels of tax. From Table 3, the benefits from a reduction in NO_X emissions fall from $676 per ton under an $83 carbon tax, to $632 per ton of NO_X at a $23 carbon tax. This reduction in the benefit per ton of NO_X reduction is due in part to difference in the location of reductions and generation technology. In essence, this means that the additional sources reacting to the higher carbon tax have different emission rates for NO_X and are located in areas where the conversion of NO_X to nitrates is less efficient, or where fewer people are being exposed to the nitrate concentrations, or both. Taken together, the nonlinearity in emission reductions and in the benefits of those reductions provides an indication of the importance of using a regionally disaggregated model to investigate this issue, unlike some of the previous studies that are discussed below.

The emission reductions are achieved by a dramatic shift from generation with coal to generation with gas. Table 4 indicates that generation by coal under the $83 tax falls to 39 percent of that in the baseline. In contrast, generation by natural gas increases to 158 percent of that in the baseline. These changes are achieved in 2010 and result from a policy that is implemented in 2001. The results would differ if the policy were implemented later.

Table 4. **The ratio of generation under tax to generation under the baseline for each respective scenario**

	Baseline - OTC		Baseline - SIP	
Level of Carbon Tax ($/metric ton)	**23**	**83**	**23**	**83**
Gas Generation	1.18	1.58	1.22	1.60
Coal Generation	.79	.39	.77	.40

In an alternative scenario, we consider implementation of a summertime NO_X cap and trade program in the larger eastern US (the SIP call region) during the summer months. These results are labeled the Baseline - SIP scenario in Table 3. The estimate of ancillary benefits per ton of carbon reduction under an $83 tax is $8.6 in this setting, and under a $23 tax it is $8.4. Compared to the results for the previous case, the Baseline - SIP scenario yields a less of a reduction in NO_X under an $83 tax but greater NO_X related health benefits and greater benefits per ton of carbon reduction. Again, this illustrates the importance of specificity in modeling the location of carbon reductions and the technology choice. Table 4 reports differences in generation for this scenario as well.

SO_2 emissions are presumed to be unchanged in these scenarios for the size of carbon taxes we consider. However, ancillary savings associated with reduced investment in SO_2 abatement that results from decreased use of coal in electricity generation would add roughly an additional $3 per ton of carbon emission reductions.

As noted, the results pertain to the year 2010 from policies implemented beginning in 2001. Hence, the cost of the policy is incurred earlier than 2010, but also there are reductions achieved before 2010. The schedule of costs and benefits over time is important in calculating a present discounted value of ancillary benefits, and is discussed in Burtraw *et al.* Also, the estimates developed under these scenarios correspond to carbon taxes that reflect the expected marginal cost of carbon abatement. The *average* cost per ton of carbon reduced will be less than the tax on a per ton basis, and hence ancillary benefits may come close to justifying the carbon tax at moderate levels. Burtraw *et al.* discuss the cost of the policies in terms of changes in consumer and producer surplus in a manner that can be directly compared with ancillary benefits, as well as direct benefits of GHG mitigation, though the latter is notoriously controversial and difficult to quantify.

5. Interpretation of the estimates

5.1 General observations

In this section we attempt to compare previous ancillary benefit estimates along a common metric, by expressing mid-value estimates per ton reduction in carbon emissions where such a calculation can be made given the information from the studies. In preparing Table 2, we have supplemented the per-ton of carbon estimates directly available from the studies in Table 1 in two ways. The results of the Holmes *et al.* (1995) study could be used for a geographic analysis of atmospheric transport of pollution and exposure of the population, and economic valuation of emission changes. However, this was not attempted in the report. To supplement this analysis, we fed the 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] Similarly, we supplement the Dowlatabadi *et al.* analysis listed in Table 1 by feeding predicted emission changes into PREMIERE. These calculations are described in more detail in Appendix B.

The comparison of estimates is reported in Table 2, which indicates a large variation across studies in their mid-range ancillary benefit estimates. 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. Several 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 because they have less detailed modeling of technology.

However, longer-term future changes in pollution standards are not accounted for in any of the studies assessing GHG policies that we discuss below (including our own). As a practical matter, this means our estimates of ancillary benefits should be considered more reliable for near-term GHG policies than for policies that are actually implemented in the 2008-2012 “commitment period” identified in the Kyoto Protocol. Other things equal (which in practice is not the case), we would expect progress toward improved air quality in the U.S. to reduce ancillary benefits below the amounts shown in Table 2.

The estimation and valuation of effects from emission changes varies among the studies. It is relatively weak in the general equilibrium models, which do not treat locational differences. More aggregated analyses calculate total emissions changes and apply a single unit value to value the avoided health impacts. In contrast, disaggregated models can more precisely model the location of emissions, their transport through the atmosphere, and the exposure of affected populations. These analyses show that benefits do not have a simple proportional relationship to reduced emissions. Sensitivity analyses show that the above-mentioned aspects are important influences on ancillary benefits, so the greater precision with which they are calculated in disaggregated models give us greater confidence in these results.

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5 Palmer et al. (1996). PREMIERE is a derivative of the Tracking and Analysis Framework (TAF) discussed above.

Another 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 voluntary program affecting the electricity sector to estimates for the economy as a whole.

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. For example, our estimates using PREMIERE and EXMOD (discussed below) incorporate 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.*, 1998).

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.

5.2 Comments on the studies

With these thoughts in mind, if one wants to identify the ancillary benefit per ton of carbon reductions for a *modest* carbon abatement program *given the presumed baseline conditions*, we would place more confidence in the first five estimates in Table 2. All of these estimates 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 ancillary benefits (less than $8 per ton carbon) for studies averaging over the United States as a whole from electricity sector GHG reductions, though benefits could be significantly higher in certain areas (New York).

The first three studies in Table 2 indicate that subtle aspects of behavioral responses to policies tend to mitigate the desired emission reductions.[6] The HAIKU/TAF example demonstrates that the location of carbon emissions and the choice of technology for generation in response to a carbon tax will vary over time and space. This leads to variation in the value of ancillary health benefits per ton of carbon reduced. Nonetheless, the values in the two scenarios we compare are within a fairly small range around $8 per ton of carbon reduction.

[6] 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.

The ICF/PREMIERE example also 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.[7]

The EXMOD estimate is greater than the three preceeding ones 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 set 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 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 fifth estimate, Coal/PREMIERE, is comparable to the fourth, except that it is applied on a weighted average national basis. This 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.[8]

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

8 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.

The sensitivity of conclusions to the valuation of damages is illustrated by comparing the PREMIERE and EXMOD estimates to the sixth estimate in Table 2, which uses assumptions drawn from a recent Draft Regulatory Impact Analysis (RIA) for new particulate and ozone standards (USEPA, 1996). 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 estimate in a distribution of possible estimates. Finally, the valuation of mortality effects in the RIA is about 1.5 times that in PREMIERE (USEPA, 1996). On net this approach yields a valuation of mortality impacts from NO_X changes (excluding ozone impacts) of three times that from PREMIERE.[9] However, given the controversy surrounding these specific assumptions and our belief that these assumptions overstate ancillary benefits, we put less stock in it.[10]

The seventh study, Abt/Pechan (McCubben *et al.* 1999), is another detailed analysis and it achieves estimates very similar to other studies when exercised under similar scenarios. This is reflected in the low end of the estimates cited in Table 2. The low end of the estimates does not include benefits from reductions in SO_2 under the assumption that a cap and trade program is operative. However, the cap is one-half of that mandated in the 1990 Clean Air Act Amendments. In the scenario yielding the high end estimate, the SO_2 cap is left at the levels in the 1990 legislation in the baseline, and in this case the study achieves high benefit estimates because the carbon tax that is modeled makes this constraint slack, resulting in reductions in SO_2 below the cap. The results differ from those in HAIKU/TAF, which does not find reductions in SO_2 under a comparable (larger) carbon tax because the cap remains binding at the levels in the 1990 legislation.

The next 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 2.) Viscusi *et al.* report values that reflect 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 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.

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9 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.

10 One recent analysis (Krupnick et al. 2000) suggests that the value of reducing premature mortality, when considered in the context of reduction in conventional air pollutants, is significantly lower than the usual estimates applied in all of the studies reported here. On the other hand, there is some evidence of a stronger link between ozone concentrations and premature mortality then is represented in the existing studies considered here.

We have not addressed previous European studies, many of which are described elsewhere in this volume, but some comparison of the estimates is useful. Ekins (1996) provided a review of the first generation of European study and arrived at a point estimate of about $272 (1996 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 $40-$85 per ton (1996 dollars) for sulfur benefits only.[11] Adding in benefits of about $126 per ton from reduced emissions of other pollutants increases this to a range of $166-$211, with a mid-value of $188. 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, and the ecological effects resulting from on-shore atmospheric transport of sulfur, in contrast to off-shore transport in the eastern U.S.[12]

6. Conclusions

6.1 The scale of ancillary benefits

How does one make sense of the welter of estimates in Table 2? 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.

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11 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.

12 See Krupnick and Burtraw (1997) for a related discussion.

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.[13] 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. Further, health effects do not exhaust all the environmental benefits. Finally, benefits would be larger with non-marginal 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 2 that attempt to describe the effects of non-marginal 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.

Our analysis using RFF's HAIKU/TAF framework (which underlies the first row in Table 2) leads us to conclude that at least for relatively modest GHG control levels, ancillary benefits may be a significant fraction of costs. The marginal costs of small initial reductions are likely to be fairly low; indeed there is reason to think they would be close to zero (some would even argue less than zero, though we remain skeptical of this). As compared to such a low cost, ancillary environmental benefits of even \$3 per ton of carbon reduced, let alone \$8/ton, could have a significant effect on the volume of no-regrets emissions reduction, especially for moderate carbon taxes of around \$2 per ton. Under such a marginal tax, the average cost per ton of carbon reduced will be less than \$25 per ton and hence ancillary benefits may come close to justifying the moderate carbon tax.

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

6.2 Lessons for policy

Some lessons for the design of policy can be derived from our analysis, though they must be interpreted with care. Ancillary benefits may be larger for GHG policies that 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 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 non-carbon backstop energy resources. While this argument is reasonable, one might also expect upward pressure on ancillary benefits per ton of GHGs. 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 (Krutilla, 1967). On the other hand, improvements in air quality over time will lower the ancillary effects that could be obtained by a GHG policy. There is no way to reach a resolution of these conflicting forces without further analysis.

Cost estimates of GHG policies often 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. Such 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 2 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 clearly 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 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.[14] 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, which must be considered as well.

6.3 Lessons for methodology and needs for further research

The apparent systematic difference between the estimates achieved in more aggregate models and those in detailed sector specific models suggests an important lesson for further research. The more detailed models provide a fuller characterization of many variables that emerge as important. Among these is behavioral response and detailed characterization of the baseline, both particularly important features of policy analysis.

The virtue of detailed modeling also applies to underlying issues of technological change and demographics. We have noted that changes in population will yield changes in willingness to pay and in the number of people benefiting from environmental improvement. But it is also the case that the location of the population is important to exposure, and demographic trends in the US have implications for how many individuals are exposed to criteria pollutants from electricity generation, as well as their age, an important variable in the concentration-response calculus.

[14] 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. 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. To reduce estimates of cost by including ancillary benefits in the cost function would understate behavioral responses, since those responses in reality would be based on costs born privately in compliance with the program independent of ancillary social benefits. Hence, 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.

However, aggregate and general equilibrium models also have virtues. One is the consistency they impose among changes in various sectors in the economy, and another is the linkage to capital and labor markets, which can be important for large policy changes. Perhaps the most important, for the estimation of benefits and costs of climate policies, is the interaction of changes in policy with pre-existing policies and taxes. Evidence of the so-called "tax interaction effect" suggests policies that impose additional costs through regulation are much more expensive from a social perspective than is apparent in partial equilibrium (sector) models.[15] Conversely, the ancillary benefits of GHG policy may be larger than is reflected in sector models because of the reduction in the tax interaction costs from other regulatory policies that, as we have noted, should be specified carefully in the baseline. However, none of the general equilibrium studies we review have addressed this issue.

Another important frontier for research is the calculation of ancillary benefits from GHG policies in developing nations. Review of existing estimates for these countries is beyond the scope of our paper.[16] These benefits may be quite a bit more significant relative to the cost of abatement policies than those measured in the US and Europe, because of lower existing levels of pollution control and lower efficiency in energy use in these latter countries. Speaking in general terms, however, existing developing country studies of ancillary benefits are limited in number and generate highly variable conclusions. The estimates are fraught with uncertainty, for several reasons.

Detailed modeling of how emissions disperse in the atmosphere is rarely available, and detailed emission inventories are rare, so studies often have simply applied "unit values" expressing a change in health status resulting from a change in emissions without modeling emissions diffusion, population exposure, and health responses. Even when these intermediate steps are modeled, studies have used relationships from the US and elsewhere that may not be applicable because of other important influences on health status including differences in expected lifetimes and other risk factors. There is no doubt that lots of potential exists for health improvements in developing countries, but continued uncertainty about how GHG restrictions might contribute to this.

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15 Goulder et al. (1999), Parry et al. (1999).

16 Efforts to assess these issues are described in Dowlatabadi (1997) and Davis et al. (1997), as well as other papers in this volume and the forthcoming Third Assessment Report of the IPCC.

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APPENDIX A: SOURCE INFORMATION (GUIDE TO ACRONYMS)

A. HAIKU/TAF: Burtraw, *et al.* 2000.

(2) ICF/PREMIERE: Holmes, *et al.* 1995. Results from this study were combined with analysis using the PREMIERE model cited below.

(3) Dowlatabadi *et al.*/PREMIERE: Dowlatabadi, *et al.* 1993. Results from this study were combined with analysis using the PREMIERE model cited below.

(4) EXMOD: Rowe, *et al.* 1995.

(5) Coal/PREMIERE: Palmer and Burtraw. 1997. Bloyd, *et al*. 1996.

(6) Coal/PREMIERE/RIA - same as above, plus: U.S. Environmental Protection Agency (USEPA). 1996.

(7) Abt/Pechan: McCubbin, *et al.* 1999.

(8) Goulder/Scheraga and Leary: Goulder, 1993. Scheraga and Herrod. 1993. Scheraga and Leary. 1993.

(9) Boyd *et al.* Boyd, *et al.* 1995.

(10) Viscusi *et al.* Viscusi, *et al.* 1994.

APPENDIX B: DEVELOPMENT OF THE HYBRID ICF/PREMIERE AND DOWLATABADI/PREMIERE ESTIMATES

To feed the emissions reductions from the ICF study into PREMIERE, 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 $394 per ton of avoided NO_X emissions (54,120 tons), totaling $21.7 million (1996$). These benefits accrue with a 6.2 million ton reduction in carbon emissions.

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.

To feed the Dowlatabadi *et al.* analysis 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 $135 per ton of avoided NO_X emissions (1.04 million tons), totaling $141 million (1996$). 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.