An Introduction to the **economics** of **climate change** policy

Prepared for the Pew Center on Global Climate Change

by

John P. Weyant
STANFORD UNIVERSITY

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Foreword *Eileen Claussen, President, Pew Center on Global Climate Change*

What are the potential costs of cutting greenhouse gas emissions? Can such reductions be achieved without sacrificing economic growth or the standard of living we have come to enjoy? These are important questions, and they come up again and again as the United States and other nations consider what actions are needed in response to climate change.

Many participants in the climate change debate — in government, industry, academia, and non-governmental organizations — have conducted economic assessments to determine the costs of taking various actions to address climate change, with the number of economic assessments increasing exponentially in recent years. Differences among their quality and predicted cost of action, or inaction, have also grown, making it difficult to have faith in any one analysis.

The primary example of varying model results can be seen among the numerous reports predicting the domestic costs of complying with the Kyoto Protocol. Some have concluded the United States can reduce its emissions significantly below its Kyoto target (7 percent below 1990 levels), with net economic savings. Others have predicted dire effects on the U.S. economy. The truth most likely lies somewhere in-between.

Behind each analysis is an economic model with its own set of assumptions, its own definitions of how the economy works, and its own data sets. Unfortunately, these models often seem to be impenetrable "black boxes" allowing only a select few to decipher and interpret their results.

Fortunately, along with the rise in economic modeling there has also been a focus on identifying the differences among models. Professor John Weyant of Stanford University, the author of this report, has been at the forefront of these efforts as Director of the Energy Modeling Forum of Stanford University (EMF). His EMF working group convenes the world's leading energy and climate modelers to discuss and model current energy policy topics.

In this report, Professor Weyant identifies the five determinants that together explain the majority of differences in modeling cost estimates. This is great news for those engaged in the climate change policy arena who are consumers of economic modeling results. Five key questions can be raised to help policy-makers understand the projected costs of climate change policy: What level of greenhouse gas emissions are projected under current policies? What climate policies are assumed to be put in place to achieve emissions reductions? What assumptions are made about how advances in technology might affect these emissions? To what extent are environmental impacts of climate change included? And is the full set of choices that firms and consumers have when presented with rising energy prices accounted for?

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Executive Summary

This paper is an introduction to the economics of climate change policy. The goal is to help the reader understand how analysts use computer models to make projections of mitigation costs and climate change impacts, and why projections made by different groups differ. In order to accomplish this goal, the paper will describe five key determinants of greenhouse gas (GHG) mitigation cost estimates.

The paper starts with a discussion of how the economy would adjust to restrictions on GHG emissions, especially carbon dioxide, the dominant, and easiest to measure GHG produced in the United States. Combustion of fossil fuels — oil, gas, and coal — produces large amounts of carbon dioxide. Central to this discussion is the role of energy price increases in providing the incentives for corporations and individuals to reduce their consumption of these fuels.

Energy price increases cause producers to substitute among the inputs they use to make goods and services, and consumers to substitute among the products they buy. Simultaneously, these price increases provide incentives for the development of new technologies that consume less energy in providing the goods and services that people desire. How a model represents these substitution and innovation responses of the economy are important determinants of the economic impacts of restrictions on GHGs.

Three other factors are crucial to economic impact projections.

First, the projected level of baseline GHG emissions (i.e., without any control policies) determines the amount of emissions that must be reduced in order to achieve a particular emissions target. Thus, other things being equal, the higher the level of base case emissions, the greater the economic impacts of achieving a specific emissions target. The level of base case emissions depends, in turn, on how population, economic output, the availability of energy fuels, and technologies are expected to evolve over time without climate change policies.

The second factor is the policy regime considered, i.e., the rules that govern the possible adjustments that the economy might make. International or domestic trading of GHG emissions rights, inter-gas trading among all GHGs, inclusion of tree planting and carbon sequestration as mitigation options, and complementary economic policies (e.g., using carbon tax revenues to reduce the most distortionary taxes in the economy) are all elements of the policy regime. Other things being equal, the more flexibility provided in the policy regime under consideration, the smaller the economic impacts of achieving a particular emissions target.

The third factor is whether the benefits of reducing GHG emissions are explicitly considered. An analyst may subtract such benefits from the mitigation cost projection to get a "net" cost figure or produce a "gross" cost figure that policy-makers can weigh against a benefit estimate. The kind of cost figure produced often depends on whether the analyst is trying to do a cost-benefit analysis or an analysis focused on minimizing the cost of reaching a particular emissions target.

Thus, this paper will describe the major input assumptions and model features to look for in interpreting and comparing the available model-based projections of the costs and benefits of GHG reductions. Two of the five key determinants — (1) substitution, and (2) innovation — are structural features of the economic models used to make emissions projections. The other three determinants are external factors, or assumptions. They are: (3) the base case projections, (4) the policy regime considered, and (5) the extent to which emissions reduction benefits are considered.

The results summarized in this paper illustrate the importance of these five determinants and the large role played by the external factors or assumptions. Cost projections for a given set of assumptions can vary by a factor of two or four across models because of differences in the models' representation of substitution and innovation processes. However, for an individual model, differences in assumptions about the baseline, policy regime, and emissions reduction benefits can easily lead to a factor of ten or more difference in the cost estimates. Together these five determinants explain the majority of differences in economic modeling results of climate policy.

I. Introduction

Interest groups active in the climate change debate believe that the stakes are high. Some fear the environmental and socioeconomic costs of climate change itself. Others are more fearful of the economic consequences of trying to avoid climate change.

This debate is, to a large extent, played out through economic analysis of climate change policy. Hundreds of these analyses have been published over the past decade, and this pace is likely to continue. Several federal agencies perform in-house analyses or fund independent research to determine the costs of various policy options. Interest groups on all sides of the debate do the same. These analyses are rich and extensive, but widely divergent in their results.

Through these economic analyses, people translate their expectations into concrete assumptions about the future. The set of assumptions that describe what happens in the future if nothing is done to control greenhouse gas (GHG) emissions is known as the “base case” (or as the “baseline” or “business-as-usual” case). The base case may embody optimism or pessimism about GHG emissions, about the changes in climate that will occur as a result of these emissions, and about what will happen to the environment as a result of this climate change.

The base case also may embody optimism or pessimism about what will happen to the economy. The higher the base case emissions, the more emissions must be reduced to achieve a particular target, and therefore the higher the control costs. The greater the base case climate impacts, the greater the benefits of controlling emissions.

Another set of assumptions drives projections of what will happen if society does control GHGs. Will new, low-cost, low-emitting technologies become available? Will consumers and producers respond cleverly, meeting their needs differently but equally well through lower-emitting products and services? Economic analyses may embody optimism or pessimism on either of these fronts.

A third set of assumptions is related to how society goes about requiring GHG control, i.e., what policies the government will put in place. Will the policies be flexible, allowing targets to be met at significantly lower costs? For example, one key aspect of the policy regime is the extent to which emissions trading is allowed. Another key aspect is the inclusiveness of the policy. Will carbon-absorbing activities, such as tree-planting, count as an offset to carbon emissions? Will all GHG emissions count, and will inter-gas trading be permitted?

Finally, most quantitative analyses only address the control costs, and not the environmental benefits, of reducing GHGs. Cost-benefit analyses may show either net benefits or net costs of GHG controls, depending, to a large extent, on the range of environmental benefits that are included in the analyses.

The tools people employ to perform these complex economic analyses are large computer models. Model results vary widely due mainly to differences in the above assumptions. For example, among the 14 models and dozens of model runs reviewed for this paper, the base case forecasts range from a 20 percent to a 75 percent increase in carbon emissions by 2010.

One rough measure of economic costs is the carbon price—the amount of money one would have to pay to reduce emissions by a ton of carbon. Among the model results reviewed here, carbon price forecasts for meeting the U.S. emissions targets of the Kyoto Protocol ranged from less than $20 per ton to over $400 per ton. This variation may result from using different models, as well as from using the same model with different input assumptions.

The economic consulting firm Wharton Econometric Forecasting Associates (WEFA) issued a report in 1998 projecting a carbon price of $360 per ton associated with U.S. GHG reductions. WEFA is pessimistic about both the development of new technologies and the ability of businesses to think ahead and begin responding early. WEFA also assumes relatively inflexible government policies — i.e., it assumes that it will not be possible to reduce GHGs other than carbon dioxide(CO_2), employ carbon sinks, or engage in international emissions trading by the time of the first Kyoto budget period (2008-2012). In contrast, the President's Council on Economic Advisors published an "official" analysis in 1998 in which the carbon price under Kyoto would be quite low — on the order of $20 per ton — largely because it assumed that the United States would purchase most of its emissions reductions overseas through international emissions trading.

In many cases the assumptions that drive economic models are readily apparent; in other cases they are difficult to tease out because they are embedded in detailed aspects of the model's structure. The goal of this paper is to demystify what is driving these model results, thereby enabling the reader to participate fully in one of the most important debates of our time.

II. An Economics Approach to Climate Change Policy Analysis

Economic analysis is a rigorous approach to evaluating the costs and benefits of alternative policies. Different economic analysts use different "analytical frameworks" — i.e., they differ as to how they measure costs, what impacts they consider, and how they handle uncertainty. In dealing with climate change, economists are particularly interested in how energy price increases cause corporations and individuals to reduce their consumption of carbon-based fuels. The goal of this section is to help the reader understand how economists approach climate change policy analysis.

A. Analytical Frameworks

A climate policy analysis often proceeds in a linear manner. It begins with the initial projection of GHG emissions to the atmosphere, followed by several calculations based on climate change science, and eventually ends with a projection of the resulting climate change impacts from those emissions. Thus, one could simply calculate the climate change impacts resulting from a particular emissions trajectory. Alternatively, one could work backwards from an acceptable set of climate impacts to find the emissions trajectories that are consistent with those impacts. One could also set a target for the maximum level of GHG emissions, concentration level of GHGs in the atmosphere, magnitude of climate change, or extent of climate impacts and compute the least-cost way to achieve that objective. This formulation is referred to as cost-effectiveness analysis and, if there is a range of "acceptable impacts," as the "tolerable windows" approach.

If one can estimate the value of all the climate change impacts in a common unit of measurement, one can add them together. Then the net benefits (i.e., the benefits of reduced climate change impacts, minus the costs of climate change mitigation) of an emissions reduction policy can be calculated. This approach is referred to as cost-benefit analysis. The result of a cost-benefit analysis is the optimal GHG "price" and the corresponding level of emissions reduction. The studies looking at impacts differ in three ways: (1) the cost measure employed, (2) the range of climate change impacts considered, and (3) how uncertainty is handled.

Cost Measure

There are numerous methods for measuring the economic costs and/or benefits employed in economic models. These methods can range from total resource costs,[1] to measures of aggregate economic output like Gross National Product, to rough measures of economic welfare like the discounted present value of consumption,[2] to more precise measures of economic welfare like "compensating variation." Compensating variation measures the amount of additional income that would have to be provided to consumers to make them as well off after a policy is implemented as they were before the policy's imposition. The selection of the cost measure to be optimized depends on the structure of the model and on the interests and objectives of the model users. For example, a model that does not include a utility function[3] in its objective cannot produce the discounted utility of consumption or compensating variation measures. On the other hand, someone who is particularly interested in the magnitude of the impact on the energy sector may use a model with a great deal of energy sector detail and use the change in total resource costs as a measure of that impact.

Range of Impacts Considered

Sometimes the costs of climate change impacts and the reductions in those impacts that are attributable to emissions reduction policies are considered in economic models, and sometimes they are not. Also, different studies may consider different impacts. (See Section III.E for more description of these impacts).

Uncertainty

There are considerable uncertainties about mitigation costs, and even greater uncertainties about climate change impacts. There is uncertainty about societal values and uncertainty about model structure. It is important to understand how a given analytical framework treats these uncertainties.

To many analysts, the best way to formulate the problem of climate change is as a problem of sequential decision-making under uncertainty. These methods are still in their infancy and lacking important data necessary for analysis, such as data on alternative policies, preferences of stakeholders (e.g., developing country citizens), and probabilities of various outcomes (Kann and Weyant, 2000). This report's focus is on U.S. cost and benefit estimates.

B. The Role of Energy Prices

The price of energy is very important in climate change economic models. Most economic models solve a set of mathematical equations to obtain the prices of goods and services. The simultaneous solution of these equations represents an equilibrium in which supply equals demand among consumers and producers. In this framework, an energy price increase can be either the motivation for, or the result of, GHG emissions reductions. For example, governments may impose emissions taxes to motivate GHG reductions. Emissions taxes raise the costs of fuels directly, and economies will adjust to reduce the use of those higher-cost fuels, substituting goods and services that result in fewer GHG emissions. On the other hand, governments may cap the total amount of emissions, distribute or sell emissions “allowances,” and let the market determine the price and distribution of these allowances. Such a “cap and trade” system will induce changes in prices that are difficult to predict. Since a cap would essentially restrict the supply of carbon-based fuels, GHG consumers would bid up the price until demand for such fuels no longer exceeded supply. In this way the higher prices reduce emissions, but also allocate the GHGs to their highest-value uses.

The effects of higher fossil fuel prices would diffuse throughout the economy. Prices of secondary energy sources, like electricity and oil products, would rise as the higher primary fuel costs are passed through into electricity rates, fuel oil, and gasoline prices. Higher fuel costs would also increase operating costs in transportation, agriculture, and especially industry. Although energy costs make up only 2.2 percent of the total costs in U.S. industry, they constitute up to 25 percent of the total costs in the most energy-intensive sectors (e.g., iron and steel, aluminum, paper-making, and chemicals). Each industry’s ability to pass these cost increases along to customers through higher product prices would depend on the strength of the demand for its products, and on the severity of international competition. Since many of the major trading partners of the United States would also be implementing similar climate policies, it is likely that the energy cost increase would result in higher prices for a broad range of consumer products. Households could also be affected through increased heating, transportation, and utility bills and, to a lesser degree, food bills and other costs of living.

A host of adjustments by producers and consumers in the economy would take place in parallel with the price increases, and, in fact, these substitutions would also serve to limit the extent of the price increases that would ultimately result. Higher energy costs would induce firms to accelerate the replacement of coal-based or obsolete plants with more energy-efficient or less carbon-intensive equipment. Utilities and their customers would seek alternatives to carbon-intensive coal-fired power plants, stimulating the market for hydro-powered, nuclear, gas-fired, and renewable electricity. As coal prices rise relative to natural gas prices, modern gas-fired combined cycle power plants would become even more competitive. Older, less-efficient coal-fired plants would probably be retired from service, or reserved for intermittent operations. Energy-intensive industries would also face a number of adjustment decisions: whether to retire obsolete facilities and concentrate production at more modern, low-cost facilities; whether to modify their furnaces to burn gas instead of coal; whether to generate their own electricity; whether to invest in a wide variety of energy-conserving process changes; whether to redesign products to save energy; and whether to alter their product mix. Ultimately, there would be an effective diminution in the value of the existing stock of plant and equipment because the existing capital stock is optimized for the set of input prices that prevailed when it was installed and would be sub-optimal for the new price regime.

In the short run, consumers and producers would reduce their energy consumption by either consuming fewer energy services (for example, turning their thermostats down or driving their automobiles less), or producing less output. Consumers and producers may also, potentially, reduce energy use without reducing output by identifying energy efficiency measures previously believed not to be economical.

In the intermediate time frame, there might be opportunities for fuel switching (or substitutions between other inputs) that would not involve substantial outlays for new equipment or infrastructure (for example, switching the fuel used in a multi-fuel-capable boiler from oil or coal to gas). In addition, consumers may be able to substitute goods that require less energy to produce (which would become relatively less expensive) for more energy-intensive ones (which would become relatively more expensive).

In the long term, new technologies would be purchased that either use less GHG-intensive fuel or are more fuel-efficient. In addition, new, less GHG-intensive technologies might become available over time as a result of research and development (R&D) expenditures or cumulative experience. The emergence of these new technologies might be related to the energy price increases, the base case trend of all other prices, or simply the passage of time. Higher energy prices would lead to less energy use, and less energy use would decrease the productivity of capital and labor. These productivity changes would, in turn, generally result in a slowdown in the accumulation of capital equipment and infrastructure, and in lower wages for workers. Ultimately, even after all the adjustments have been made, consumers would have somewhat less income. This might cause them to adjust the amount of time they spend on work rather than leisure.[4] This last adjustment would involve an additional change in welfare. Offsetting these welfare losses would be the benefits of reduced climate change, and the benefit of making those responsible for GHG emissions pay for the damages they cause.

The complicated web of economic adjustments that would take place in response to rising prices of energy, or energy scarcity, makes the task of projecting the costs of GHG mitigation a challenge. Interpreting the results different models produce is further complicated because different modeling systems emphasize different dimensions of the adjustment process. Also, different policy-makers may be interested in different policy regimes, and in different impacts of climate change and climate change policies.

III. Five Determinants of Climate Change Cost Estimates

Five major determinants of GHG mitigation cost and benefit projections are discussed in this paper. Understanding how different forecasters deal with these determinants can go a long way toward understanding how individual estimates differ from one another. The five major determinants considered in this chapter are:

- projections for base case GHG emissions and climate damages;
- the climate policy regime considered (especially the degree of flexibility allowed in meeting the emissions constraints);
- the representation of substitution possibilities by producers and consumers, including how the turnover of capital equipment is handled;
- how the rate and processes of technological change are incorporated in the analysis; and
- the characterization of the benefits of GHG emissions reductions in the study, including especially how and what benefits are included.

A. Projections of Base Case Emissions and Climate Damages

Projecting the costs associated with reducing GHG emissions starts with a projection of GHG emissions over time, assuming no new climate policies. This "base case" is often an important and under-appreciated determinant of the results. The higher the base case emissions projection, the more GHG emissions must be reduced to achieve a specified emissions target. If a base case is higher, though, there may be more opportunities for cheap GHG mitigation due to a slow rate of technological progress assumed in the base case.

The base case emissions[5] and climate impact scenarios, against which the costs and benefits of GHG mitigation policies are assessed, are largely the product of assumptions that are external to the analysis.

Each GHG mitigation cost analysis relies on input assumptions in three areas:

- population and economic activity;
- energy resource availability and prices; and
- technology availability and costs.

Most of the researchers projecting the cost of reducing carbon emissions have relied on worldwide population growth projections made by others (e.g., the World Bank or the United Nations). These external projections are generally based on results from very simple demographic models. There is less uncertainty about projections for the developed countries, where population is expected to peak very soon, than for the developing countries, where population is typically assumed to peak somewhere around the middle of this century. Very few of the researchers analyzing GHG emissions reductions make their own projections of economic growth.[6] Most rely on economic growth projections made by others, or on external assumptions about labor force participation and productivity growth.

Another set of key assumptions concerns the price and/or availability of energy resources. The prices of fossil fuels — oil, natural gas, and coal — are important because producers and consumers generally need to substitute away from these fuels when carbon emissions are restricted. Optimistic assumptions about natural gas availability and/or substitutability[7] can make carbon emissions reductions easier to achieve in the short run. This is because carbon emissions from natural gas per unit of energy consumed are about 60 percent of those from coal, and 80 percent of those from oil. In addition, the amount of unconventional oil and gas production that will ultimately be technically and economically feasible is highly uncertain. It depends on future economic incentives for oil and gas exploration and production, which could (absent climate policies) retard the development of carbon-free renewable and higher-efficiency end-use energy technologies. How oil exporters would react to a climate policy that would reduce the demand for oil imports is another key dimension of the energy supply picture.

Other key assumptions are made about the costs and efficiencies of current and future energy-supply and energy-using technologies. These tend to be critical determinants of energy use in both the base case and control scenarios. Most analysts use a combination of statistical analysis of historical data on the demand for individual fuels, and process analysis of individual technologies in use or under development, in order to represent trends in energy technologies. Particularly important, but difficult, is projecting technological progress within the energy sector itself. Attempts to systematically and empirically estimate future trends in energy productivity at a national level are rare (see Jorgenson and Wilcoxen, 1991, for one prominent example). Typically, analysts take one of the following two approaches or a hybrid of the two: (1) the costs and efficiencies of energy-using and energy-producing technologies are projected based on process analysis, and the characteristics of these technologies are extrapolated into the future, or (2) some assumption is made about the trend in energy demand per unit of economic activity, independent of future price increases. (See Section III. D on technological change for a more detailed description). Some recent analyses have attempted to blend the two approaches. At some point these two approaches tend to converge, as the end-use process analyst usually runs out of new technologies to predict. It is then assumed that the efficiency of the most efficient technologies for which there is an actual proposed design will continue to improve as time goes on.

Projections of the benefits of reductions in GHG emissions are also highly dependent on the base case scenario employed. The greater the base case damages (i.e., the damages that would occur in the absence of any new climate policies), the greater the benefits of a specific emissions target. The magnitude of the benefits from emissions reductions depends not only on the base case level of impacts but also on where they occur, and on what sectors are being considered. In fact, a number of additional socio-economic inputs (e.g., income by economic class and region, infrastructure, and institutional capability to adapt to changes, etc.) are required because they determine how well the affected populations can cope with any changes that occur. The task of projecting base case climate change impacts is particularly challenging because: (1) most assessments project that serious impacts resulting from climate change will not begin for several decades, and (2) most of the impacts are projected to occur in developing countries where future conditions are highly uncertain. How well developing countries can cope with future climate change will depend largely on their rate of economic development.

B. The Climate Policy Regime Considered

The policy regime considered is a crucial source of differences in cost and benefit projections and is largely independent of the model methodology used. Once a base case scenario is constructed, the types of policies that nations may use to satisfy their GHG emissions obligations must be specified.

The Kyoto Protocol represents a broad approach to undertaking emissions reductions. This approach tentatively includes flexibility in determining which GHGs can be reduced, where they can be reduced, and, to a lesser extent, when they can be reduced. These flexibility mechanisms are explicitly mentioned in the Kyoto Protocol. However, the flexibility mechanisms are:

- already explicitly limited (as in the five-year emissions averaging period — rather than a longer one);
- potentially subject to restrictions as a result of further negotiations (like those being contemplated on international emissions rights trading under the Kyoto Protocol); or
- potentially difficult to implement because of measurement, monitoring, and data limitations (as in the case of non-carbon dioxide GHG emissions and carbon sinks).

Thus, there are large uncertainties about the extent to which the Kyoto flexibility mechanisms can be employed, and therefore about their value. If the parties to the Protocol can avoid restricting these mechanisms, and can surmount definitional and other obstacles to their implementation, the flexibility mechanisms can reduce the price increases (and associated impacts) required to achieve the objectives of the Protocol by a factor of ten or more.

An important flexibility mechanism in the Kyoto Protocol is that nations have agreed to consider six principal GHGs: CO_2, methane (CH_4), nitrous oxide (N_2O), sulfur hexaflouride (SF_6), perfluourocarbons (PFCs), and hydrofluorocarbons (HFCs), and to allow inter-gas trading.[8] These GHGs differ both in their heat-trapping capacity and in the length of time they remain in the atmosphere. CO_2 is the most significant contributor to global climate change among global GHG emissions. The Protocol also specifies that taking CO_2 out of the atmosphere (i.e., through carbon "sinks") can count towards each country's emissions reduction commitment.[9]

Another flexibility mechanism included in the Kyoto Protocol is international emissions trading. There are benefits from international emissions trading because there are differences in the costs of reducing emissions among countries.[10] If the cost of emissions reductions in any country is higher than it is in any other country, it is advantageous to both countries for the higher cost country to buy emissions "rights" from the lower cost country at a price that is between the two cost levels.[11] If one aggregates all regions participating in the trading system together, one can compute the supply and demand for emissions rights at any price, as well as the equilibrium emissions rights price that balances the available supply with the amount demanded.

The Protocol also allows participants to average emissions over a five-year period (2008-2012, also known as the first budget period) in satisfying their emissions reduction requirements. Averaging allows corporations and households to shift their reductions in time to reduce the economic impact of the required emissions reductions. A number of studies indicate that this emissions averaging can be helpful in cutting the cost of reducing cumulative emissions but that an even longer averaging period would be more advantageous.[12]

Revenue Recycling

An important issue in climate-policy discussions has been the extent to which the costs of carbon taxes (or carbon permit auctions) can be reduced by judicious "recycling" of the revenues from such taxes — i.e., using the carbon tax revenues to justify, and to offset, decreases in other taxes. This is primarily a domestic policy flexibility mechanism, although the international negotiations at some point may address how carbon tax revenues can be recycled. Economists' understanding of this issue has advanced considerably in recent years. Theoretical work indicates that the costs of carbon taxes can be significantly reduced by using the revenues to finance cuts in the marginal rates of existing income taxes, as compared with returning the revenues to the economy in a "lump-sum" fashion. Lump-sum distributions are those in which the transfers are independent of taxpayer behavior (for example, the personal exemptions in income taxes are lump-sum transfers). Numerical studies consistently confirm this result (see Shackleton, 1996; Goulder, 1995; Jorgenson and Wilcoxen, 1995).

A more controversial issue has been whether revenue recycling can make the gross costs of revenue-neutral carbon tax policies vanish or become negative. If this were the case, the revenue-neutral environmental tax would generate a "double dividend" by both: (1) improving the environment, and (2) reducing the costs of the tax system. Recent theoretical work on this issue tends to cast doubt on the likelihood of a double dividend (Bovenberg and de Mooij, 1994; Parry, 1995; Bovenberg and Goulder, 1997). This work indicates that carbon taxes may be less efficient sources of revenue than the income taxes they would replace. The key to this result is the recognition that carbon taxes (like other taxes) cause output prices to rise, and thereby lower the real returns to primary inputs into production like labor and capital. As a result, carbon taxes cause market distortions that are quite similar to those posed by income taxes. Carbon taxes also have an efficiency disadvantage attributable to their relatively narrow base.

Still, economic theory leaves room for the double dividend under some special circumstances. In particular, it can arise if: (1) the original tax system (prior to introducing the carbon tax) is seriously inefficient along some non-environmental dimension (e.g., capital might be highly overtaxed relative to labor), and (2) the revenue-neutral reform reduces this inefficiency enough to offset the carbon tax's efficiency disadvantage. Whether or not the double dividend would arise thus depends on some empirical issues. Analyses with numerical general equilibrium models[13] tend to cast doubt on the prospects for the double dividend in the United States (Bovenberg and Goulder, 1997). However, the prospects could be better in other countries, especially in economies with subsidized energy. Removing energy subsidies is likely to lower the costs of the tax system while promoting an improvement in the environment. Energy is subsidized in a number of developing countries, and thus the costs of reducing carbon emissions may be minimal or negative in these countries. Further empirical investigations of this issue could be valuable to policy-makers.

A practical difficulty in studying revenue recycling is what assumptions about recycling are most realistic. Since tax systems are continually debated and revised, it is not clear whether the most inefficient taxes would be eliminated at some point, independent of the availability of carbon tax revenues to offset them as a source of revenue. There is also a political economy challenge to using revenue recycling as part of a carbon emissions reduction strategy. Rather than using the new tax revenues to reduce other more distortionary taxes, society could easily use them to support additional government spending. Such government outlays could have lower or higher productivity than the same amount of private sector spending (see Nordhaus, 1993). If the government expenditure has lower productivity, the overall costs of the carbon tax would be considerably higher than when revenues are employed to finance cuts in distortionary taxes. Thus, to fully analyze the impact of revenue recycling alternatives on the overall cost of carbon taxation, one needs not only to analyze the impact of a carbon tax, but also to speculate about how the government would employ the revenues from the tax.

International emissions trading, inclusion of GHGs other than CO_2, credit for carbon sinks such as planting trees, and judicious revenue recycling can all help reduce the costs of GHG mitigation policies. Any of these approaches can reduce the necessary rise in energy prices and the associated impacts on economic activity. The resulting costs will depend on how easy it is for businesses and households to change their mix of inputs, and for consumers to change their mix of purchases, in ways that reduce GHG emissions.

C. Representation of Substitution Possibilities by Producers and Consumers

As efforts are made to reduce GHG emissions, fossil fuel combustion and other GHG-generating activities become more expensive. Producers adjust to these price increases by substituting inputs (i.e., switching to inputs that generate fewer GHG emissions in manufacturing any particular product), and by changing their product mix (i.e., producing different products that require fewer GHG emissions to make).

The extent to which inputs can be shifted depends on the availability and cost of appropriate technologies as well as the turnover rate of capital equipment and infrastructure. These two factors, as well as consumer preferences, determine an industry's ability to produce and sell alternative mixes of products. Increases in the costs both of fossil fuels and of products that depend on fossil fuel combustion will reduce consumers' real incomes. Consumers will simultaneously decide: (1) the extent to which they wish to adjust their mix of purchases towards less carbon-intensive products, and (2) how to adjust their mix of work and leisure time to compensate for the reduction in their real income.

Short-term vs. Long-term Substitution

If businesses and households have several decades to complete the substitution process, the current stock of energy equipment and associated infrastructure does not constrain the substitutions that they may make. Businesses and households are limited primarily by the available technologies, and by their own preferences regarding how much of each available product they would buy at the prevailing prices. If climate policy is long-term, and if economic incentives are designed to motivate producers and consumers to invest in more energy-efficient and less carbon-intensive equipment when their existing equipment has reached the end of its useful life, the transition to a lower carbon energy system will be relatively smooth and the costs relatively moderate. Over shorter time spans, however, existing plant and equipment can significantly constrain the behavior of firms and households, adding transition costs to the long-run costs of GHG control policies. Policies implemented on this time scale (i.e., within ten years) will lead to reductions in energy services (e.g., industrial process heat and home heating and cooling), some easy fuel switching, and an increase in the purchase and use of available energy-efficient products and services. They will also influence the rate of retirement and replacement of existing equipment. Energy-producing and energy-using equipment is relatively expensive and long-lived. Thus, it will generally take a substantial increase in energy prices to induce those who own such equipment to replace it before the end of its useful life.[14]

The importance of capital stock dynamics creates a formidable challenge for the analytical community. Some data on the characteristics of the energy-producing and energy-using capital stock are available. It would be ideal to have information on the costs of operating and maintaining every piece of equipment currently in use. This would enable analysts to calculate all the trade-offs between retiring equipment early and using other strategies to achieve the specified targets. Unfortunately, the data that are available are generally aggregated across large classes of consumers and generally include all existing capacity without regard to when it was installed. An important exception is power plant data, which are very disaggregated and include the age of the equipment. However, even these data are generally not sufficient to ascertain precisely the point at which the carbon price incentives will influence the rate of replacement of plant and equipment. Limitations on data require the analyst to make a number of assumptions regarding the aggregation and interpretation of the available data.

Two Approaches to Representing Substitution Possibilities

In many models, technologies are represented with “production functions” that specify what combinations of inputs are needed to produce particular outputs. The production function specifies the rate at which each input can be substituted for each other input in response to shifts in input prices. As new capital investment occurs and older capital is retired, the technology mix within the model will change.

Two basic types of production functions may be specified:

- aggregate production functions; and
- technology-by-technology production functions, also known as “process analysis.”

Some models (e.g., G-Cubed, SGM, and EPPA — see Box 1 for model identification) use smooth and continuous aggregate production functions that allow incremental input substitutions as prices change, even if the resulting input configuration does not correspond to a known technology. These models do not represent individual technologies. Such models often assume "nested" production functions. For example, at one level, substitutions are possible between energy, capital, and labor in producing final commodities; at a second level, substitutions are possible between electricity and fuel oil in producing energy; and, at a third level, substitutions are possible between coal and natural gas in producing electricity. Models employing continuous aggregate production functions do not account for individual technologies.

Box 1

A Guide to Economic Models of Climate Change

MODEL	AUTHORS
ABARE-GTEM (Australian Bureau of Agriculture and Resources Economics — Global Trade and Environment Model)	B. Fisher, V. Tulpule, D. Kennedy, S. Brown (ABARE)
AIM (Asian-Pacific Integrated Model)	T. Morita, M. Kainuma (NIES, Japan) Y. Matsuoka (Kyoto University)
CETA (Carbon Emissions Trajectory Assessment)	S. Peck (EPRI) T. Teisberg (Teisberg Assoc.)
G-Cubed (Global General Equilibrium Growth Model)	W. McKibben (Australian National University) P. Wilcoxen (University of Texas), R. Shackleton (U.S. OMB)
IGEM (Intertemporal General Equilibrium Model)	D. Jorgenson (Harvard University) P. Wilcoxen (University of Texas) R. Goettle, M. Sing Ho, D. Slesnick (Dale W. Jorgenson Associates)
MARKAL-Macro	S. Morris (Brookhaven National Laboratory) A. Manne (Stanford University), P. Tseng (U.S. DOE)
MERGE 3 (Model for Evaluating Regional and Global Effects of GHG Reductions Policies)	A. Manne (Stanford University) R. Richels (EPRI)
MIT-EPPA (Emissions Projection and Policy Analysis Model)	H. Jacoby, J. Reiner, I.S. Wing (MIT)
MS-MRT (Multi-Sector—Multi-Region Trade Model)	D. Montgomery, P. Bernstein (Charles River Associates) T. Rutherford (U. Colorado)
NEMS (National Energy Modeling System)	R. Earley, S. Holte, M. Hutzler, A. Kydes, R. Eynon, et. al. (U.S. Energy Information Agency)
Oxford Model (Oxford Econometrics Model)	A. Cooper, J. Walker (Oxford Econometrics)
RICE (Regional Integrated Climate and Economy Model)	W. Nordhaus, J. Boyer (Yale University)
SGM (Second Generation Model)	J. Edmonds, H. Pitcher, R. Sands (Pacific Northwest National Lab)
Worldscan (Central Planning Bureau/ Rijksinstitut voor Volksgezondheid Milieuhygiene)	A. Gielen, H. Timmer (Central Planning Bureau, Netherlands) J. Bollen (RIVM, Netherlands)

In contrast, process analysis models (e.g., MARKAL-Macro and NEMS) draw from a menu of discrete technologies, each requiring fixed input combinations — i.e., each technology is essentially represented with its own production function. These combinations correspond to those employed in actual, or anticipated, technologies that the modeler specifies. The technology-rich MARKAL-Macro model specifies over 200 separate technologies. For discrete technology models, different technologies become cost-effective as input prices change. Modelers then assume that these technologies are selected and used to produce outputs. The process analysis models represent capital stock turnover on a technology-by-technology basis. The data and analysis requirements for this type of model can be substantial.

A number of models use a process analysis approach within the energy sector and an aggregate production approach for the remainder of the economy (e.g., MERGE 3, MARKAL-Macro). When using either approach, it is important to be able to distinguish between the causes of changes in the selections the models make among the existing technologies. Sometimes the technology choice changes because prices change, and sometimes it changes because new technologies become available.

Some models represent both individual energy supply technologies and individual energy consumption technologies, and do not represent the remainder of the economy explicitly. With these models, however, the analyst must either: (1) assume that "end-use" energy demands (such as the demand for home heating and automotive transport) do not respond to changes in the prices of those services, or (2) employ a complex statistical estimation technique (that requires some historical data on the cost of end-use energy equipment) to estimate the price responsiveness.

The choice of production function depends, in part, on the timeframe under consideration and the level of technological disaggregation. Short-term models intended to shed light on precise technology choices specify production functions for large numbers of separate technologies. In contrast, models concerned with longer-term effects can safely characterize technological trends using aggregate production functions. Many models blend the two approaches. Models that have so-called "putty-clay" vintaging (for more on "putty," "clay," and "putty-clay" vintaging, see Box 2) will allow for smooth input substitution in determining new capital investment, yet fix input proportions for each vintage (i.e., all equipment of a particular age) once it has been installed. Similarly, a model may have smooth production functions for conventional fuels, yet stipulate discrete technologies for a particular non-carbon fuel (e.g., EPPA).

Box 2

Putty and Clay Assumptions and Capital Stock Malleability

In modeling capital investment (investment in physical plant and equipment) and turnover, assumptions need to be made about the flexibility the investor has in choosing technologies, and in changing the characteristics of that capital after it has been installed. Data availability and computational considerations limit the choice of modeling assumptions that can be employed. Fortunately, there are some simple formulations that seem to give plausible results in most circumstances.

In almost all models it is assumed that in making decisions about new capital investment, the decision-maker (firm, individual, or government entity) has complete flexibility (particularly in the mix of capital and energy inputs required) in choosing among available technologies before their purchase. The models differ, however, in their assumptions about how much the characteristics of the capital equipment can be changed after it has been installed. These adjustments may be desirable if changes in input prices occur, but retrofitting to a certain set of characteristics is generally more expensive than installing equipment with the same characteristics initially. On the other hand, technological improvements may reduce the costs of the retrofitting over time.

Most models make one of two polar assumptions about this process. To describe these assumptions, the metaphor of soft putty and hardened clay has proved useful ("putty" representing a flexible scenario and "clay" representing a hardened or inflexible scenario). In a "putty-clay" or "putty-putty" formulation, the first term refers to the assumption about the degree of flexibility in original capital investment, and the second term refers to the assumption about the degree of flexibility in modifying that capital after it is installed.

In a *putty-clay* formulation, it is assumed that the original equipment cannot be modified once installed. Putty-clay assumptions are realistic in cases where relative prices are changing rapidly. Here, new capital investments embody state-of-the-art technology, and use input mixes that are appropriate for the price expectations that exist at the time of the investment. These characteristics then remain with that vintage until it is scrapped.

The term *putty-putty* is used to indicate that capital can be continuously reshaped both before and after investment has taken place. The inherited capital stock adjusts to changes in prices and technology as fully as brand new capital. In effect, the entire capital stock continually adapts itself to reflect current technologies and prices.

The precise details of the capital adjustment process differ from model to model. In some, there is a composite stock of old capital that reflects some average mix of inputs. In others, each vintage is identified and depreciated separately. In many models the old capital stock cannot be altered. In others (e.g., NEMS) it can be retrofitted if doing so is more profitable than making brand new investments, or if it is required by regulation.

Modelers are just starting to experiment with various hybrids of the two, titled "putty-semi-putty" formulations, in which some retrofitting is allowed at some additional cost. One type of "putty-semi-putty" specification allows plant and equipment to be retired before the end of its useful life if the operating cost of the old equipment is greater than the operating plus capital costs of replacement equipment. In this case, the remaining capital costs of the old equipment would have to be written off, so the changes in prices or new technologies would have to be quite significant for this to occur. Prices do rise to these levels in some models in Kyoto Protocol simulations in which the flexibility mechanisms are severely restricted.

Models Employing Aggregate Production Functions

Three characteristics of these economics models are important in analyzing the time horizon for meeting the Kyoto targets (Jacoby and Wing, 1999):

- the timeframe;
- the level of detail about capital stock and production structure; and
- the specification of economic foresight.

The first and most obvious characteristic is the time interval over which a model solves its equations. If a model uses a ten-year time interval, this limits its ability to be used in analyzing phenomena occurring within a decade, such as the consequences of accepting a 2008-2012 Kyoto target after the year 2000. The results of such models may thus obscure important short-run dynamics of adjustment.

The second important attribute of the models is the level of aggregation in the capital stock and the production structure. The level of aggregation affects how models represent the sources of rigidity in the production sectors of the economy. For example, the choice about whether to aggregate output and capital by sector or by technology, determines the degree of substitution that is possible within the model's structure. Within a specific aggregate, substitutions are, by construction, assumed to be costless. Additional capital stock produces outputs using a combination of inputs that reflect: (1) current and expected input prices, and (2) the constraints and limits of existing technologies.

Models capture the aging of capital in different ways. In evaluating short-term adjustment to climate policies, the distinction between putty-putty and putty-clay specifications is critical (see Box 2). In the face of a stringent near-term policy, the putty-putty assumption may produce unrealistic results because this specification implies that large parts of the current capital stock can be transformed into more efficient and less carbon-intensive alternatives. However, for analysis of the long run, after fuel prices have settled at a new equilibrium level relative to other goods and services, the distinction is less important. In this post-adjustment phase, the inherited capital stock will be increasingly fuel-efficient and competitive under prevailing conditions, because those conditions will more closely match the conditions in place at the time the investments were made.

The third important characteristic of models of the capital stock turnover process is the way they treat foresight. Models may specify economic behavior as forward-looking or myopic. Forward-looking models assume that agents with perfect foresight find the path of emissions reductions that minimize discounted costs over the entire modeling horizon, choosing the timing and stringency of control measures so as to optimally smooth the costs of adjustment. In contrast, myopic models assume that economic agents seek to minimize the costs of policy on a period-by-period basis, and take little or no action in advance of the onset of carbon constraints. Model results can be very sensitive to assumptions about investor foresight. Models that assume perfect foresight allow emissions targets to be met at lower costs because investment decisions are made in the full certainty that emissions limits will be set and achieved. Models that assume some degree of myopia generate higher costs because investors must scramble to alter the capital stock as the target period approaches, prematurely scrapping existing capital (e.g., coal-fired power stations) and quickly investing in less carbon-intensive alternatives.

Of the models reviewed here, the great majority assume perfect foresight, while only one is constrained to be myopic (i.e., EPPA). Some models (like G-Cubed) allow alternative assumptions under different runs and/or can set expectations differently for different sectors. The NEMS and SGM models can allow industrial or utility investors to give greater consideration to future conditions than individual consumers do.

In practice, investors do not have perfect foresight, nor do they suffer from complete myopia. While there is inevitable uncertainty regarding future economic conditions, policy-makers can reduce uncertainties by making credible commitments to meet targets or to initiate market-based policies. Model results clearly demonstrate that the more convinced investors are that emissions targets will become binding, the less costly the transition to lower carbon emissions.

D. Technological Change

Technological change can be thought of as increasing the amount of a product that can be made from a given amount of inputs, or as expanding the universe of opportunities for substitution of inputs and products. Technological change is discussed separately from input and product substitution here because the underlying determinants are somewhat different, because technological change is less understood, and because of the opportunities for synergy between public support and private investment in stimulating new technology development.

As originally observed by Schumpeter (1942), there are three distinct types of technological change that take place continually in modern economies:

- invention of completely new ways of satisfying human needs and wants, or the creation of new needs not previously identified or satisfied;
- innovation, which takes place through continual improvement and refinement of existing ways of doing things; and
- diffusion of new technologies throughout and across economies.

These processes are all important for climate policy. It often takes decades for innovation and invention to pay off. Even diffusion may be difficult to accelerate over a decade, though, because it involves spreading information, analysis, and experience from place to place, which takes time.

New technologies can allow firms to produce a particular product using a mix of inputs not previously available, including, for example, less energy. In addition, new technologies can lead to new products. These new products compete with existing products, with further implications for carbon emissions reduction policies. If these new technologies and new products produce less carbon, then carbon emissions will be lower, fewer emissions reductions will be needed, and/or emissions reductions will be less expensive. Projecting how technological change might progress over time, both with and without climate policies, is challenging. The processes by which technological change occurs are very complex and the data required to estimate how these changes have been made in the past are generally not available. However, there are several ways economic models represent technological change, as presented below.

Induced Technological Change

Inventions of productive technologies or processes are, by their very nature, hard to predict. However, past experience has shown that they can be revolutionary enough to justify large expenditures in basic research in strategic areas. Innovations could be of great help in lowering the costs of reducing GHG emissions. Thus it would be worthwhile to find an appropriate combination of government interventions and private sector incentives that encourage innovation. Thus far, however, most of the policy debate on the influence of technological change on climate change policy has focused not on technology policy options, but rather on how restrictions on GHG emissions affect the cost of GHG reductions over time. This effect has been labeled “induced technological change” (ITC). ITC has to do with price-induced behavior — i.e., what private firms will do in response to higher prices, as opposed to what firms will do anyway in trying to become more competitive through investing in research and development (R&D), or what they would do in response to government sponsorship of R&D or other direct government technology policies. There has been a good deal of discussion about the potential for ITC to substantially lower, and perhaps even eliminate, the costs of CO_2 abatement policies. These discussions have exposed very divergent views as to whether technological change can be induced at no cost, or at some cost.

Every ITC model must represent some incentive to induce technical change in one or more ways such as:

- the form of profits from innovations, as in the top-down models, which focus on the behavior of economic aggregates rather than the behavior of individual actors or the use of individual technologies;
- at a more aggregate and abstract level, by means of cost-functions, R&D production functions, or empirical estimates. Similarly, the decision-maker(s) considered may either be decentralized industries, representative firms, or a central planner;
- by the inclusion of intra-sectoral knowledge spillovers which are advances that individual firms within a sector cannot keep to themselves. For example, the level of investment may be determined by the rate of return the firm expects to earn on the R&D investment as compared with other available investment opportunities. However, the rate of innovation may far exceed that implied by the rate of return alone because other firms in the industry may be able to replicate the innovation; and
- by the dimension in which technological change is assumed to progress (i.e., new products or processes, substitution of inputs, or reorganization of production and distribution arrangements).

Kline and Rosenberg (1986) emphasize that there is no simple, single measure of innovation.

Some ITC models are based on empirical observations of past responses to energy price and policy changes. One advantage of this type of model is that different sectors may exhibit different rates of technological progress. However, only one model, IGEM, estimates all these parameters simultaneously because of the large amount of data necessary and the heavy computational burdens of such estimations. Another advantage is that this type of model implicitly takes into account real-world factors that are relevant to technological change and that are difficult to incorporate into conventional economic frameworks. That is, this model relies on observations of the real thing, not a simplified representation of it. All types and sources of short-term technical change are included. One disadvantage of this aggregation, though, is that information about the underlying costs of R&D is lost. Also missing is explicit attention to how firms determine their R&D investments. Firms take into account both the cost of engaging in R&D and the expected benefits in terms of future profitability. Thus, models are unable to evaluate optimal policies with full consideration of the costs of R&D. Another disadvantage is that the model is as limited as the data set from which it is constructed. Only one historical path can be observed, and it is assumed that tomorrow's economy will respond to energy price changes in the same way as yesterday's economy. Thus, long-term technological change is beyond the feasible reach of this type of model. "Long-term" here refers to periods over which substantial technological development and major inventions may occur.

Nonetheless, empirical modeling of ITC may be valuable for short- to medium-term projections, or for estimating the short- to medium-term cost of policies on the economy. Empirical models may also be valuable in comparing or calibrating short-term projections from other types of ITC models. Also, the consideration of ITC helps clarify two key matters of debate: (1) whether prior studies (without ITC) have overstated the cost of achieving given emissions reduction targets, and (2) the optimal size and timing of a carbon tax.

Autonomous Energy Efficiency Improvement (AEEI)

In contrast to the ITC models, many models include exogenous technical change. "Exogenous" can mean external to the model, or independent of price, or both. A simple characterization of technological improvement, employed in many of the models, is a single scaling factor — the autonomous energy efficiency improvement (AEEI) — that makes aggregate energy use per unit of output decline over time, independent of any changes in energy prices. (Many modelers specify the AEEI as a percentage of

Gross Domestic Product (GDP) growth, so that the value changes over time). Although the definition of the AEEI varies from model to model, in all models it implicitly represents the effect of technological progress. In some models it also represents one or both of two additional trends: (1) changes in the structure of the economy, resulting in a shift in the relative contribution of energy-intensive industry output to total economic output and (2) an improvement in energy efficiency over time, reflecting the gradual removal of market barriers that prevent some energy consumers from choosing more efficient energy technologies.

Although the AEEI approach allows for energy improvements over time, it is limited in two respects. First, using the AEEI approach to represent technological change ignores price-induced technological progress (i.e., ITC). In reality, higher prices do spur greater innovation and more rapid diffusion of energy-saving technologies. Second, it is not clear what an appropriate rate for AEEI should be. This is important, especially for longer-term projections, which are very sensitive to differences in assumed rates. More sophisticated specifications (often used in conjunction with an AEEI parameter) attempt to paint a more detailed picture of technological change by incorporating some degree of price sensitivity, distinguishing different sectors, and assessing changes to specific technologies.

Learning By Doing

In practice, much technological advancement comes from learning-by-doing (LBD) — the incremental improvement of processes through small modifications and adjustments. It is not until a technology is actually used that important lessons are learned that can be applied to its subsequent development. LBD is an integral part of the innovation process. Observation of past technological innovations show that initial installations are quite expensive, but that costs drop significantly the more the technology is used, and the more lessons are learned from using it. This type of learning may be the result of either exogenous or endogenous (induced) technological change.

Although most models do not attempt to capture LBD, two models do mimic the process. MERGE assumes endogenous diffusion rates: the more investment there is in advanced technologies in the early years of the model projection, the greater is the rate of adoption in the later years. In the NEMS model, learning-by-doing is represented in the electricity generation sector, where the capital costs of particular types of new plants decline as more such plants are built.[15]

E. Characterization of Benefits

The motivation for policies to reduce emissions of GHGs is the reduction in climate change impacts, such as sea-level rise. Some analyses focus exclusively on mitigation costs, showing both the likely range of costs under different policy regimes and the sensitivity of the cost estimates to key model inputs and parameters. These studies often start with emissions targets proposed during the international negotiation process. These studies, sometimes called "cost-effectiveness" analyses, do not estimate the benefits of the reduction in climate impacts or any other accompanying benefits from the emissions reductions.

Other analysts, however, have projected base case climate impacts, and the change in those impacts resulting from climate policies (Watson et al., 1996). The impact categories considered have included a number of broad themes as seen in Table 1.

Table 1

Environmental Impacts in Economic Models

Environmental Impact	Description
Agriculture	Impacts on the level of productivity of different crops and on farmers' choice of crops to grow
Forestry	Impacts on the level of productivity of commercial forests
Sea-Level Rise	Impacts of rising sea levels on coastal development
Ecosystems	Impacts on ecosystem function and vegetation patterns
Human Health	Impacts on the incidence of vector- and water-borne diseases and heat and cold stresses
Wildlife	Impacts on animal life
Biodiversity	Impacts on plant and animal species diversity
Fisheries	Impacts on commercial fisheries
Amenity Values	Values individuals place on opportunities such as participation in various recreational activities. (Climate change could affect some forms of recreation either positively or negatively).

Aggregate impact/benefit studies differ as to whether they include only "market" impacts or both "market" and "non-market" impacts. Changes in market prices and demands can be used to assess the value of market impacts in agriculture and forestry, as well as parts of the fisheries and human health sectors. There are also market impacts of sea-level rise on a number of sectors — for example, on coastal development.

Non-market impacts refer to climate-induced physical changes that do not affect marketed products. Non-market sectors likely to be affected by climate change include ecosystems, human health, wildlife, and biodiversity. Most amenity values relate to non-market sectors. Economists have developed a number of indirect methods for valuing these impacts in dollar terms. The methods are widely used, but controversial, and the estimated values remain uncertain. Thus, some analysts prefer to report these impacts in physical terms only. This strategy prevents an easy aggregation of impacts across all sectors in dollar terms, so that any attempt to compare mitigation costs with benefits must compare such costs with the physical impacts for a short list of critical indicators. Other analysts are perfectly comfortable translating impacts into dollar terms using the best available methods.

The measures that people feel comfortable using may depend significantly on the specific impact category being considered. In valuing agricultural, forestry, and fishery impacts, analysts may be comfortable with resource cost as a measure. For biodiversity, they may prefer a long-term growth measure such as a percentage change in GDP, while for health, wildlife, ecosystems, and amenity values only a welfare measure may be acceptable. Since it is clear that there will be significant economic impacts of climate change, it is important to take into account the benefits of avoiding these impacts in some fashion, despite the uncertainties. It is also important that researchers continue to improve the available methods for measuring these impacts.

A final set of key assumptions in any climate change impact analysis concerns the efficiency of climate change detection and adaptation. If those exposed to climate change can detect it early and accurately (especially as distinguished from inter-annual variability), and they have the resources to adapt to it easily, the costs they incur will be much lower than they would be for those without that level of detection capability and adaptive capacity. Also important here is the distinction between “reactive adaptation” (acting after events occur) and “anticipative adaptation” (acting before events occur). Policy-makers and the private sector may differ in the amounts of anticipative and reactive adaptation they employ.

Range of Impacts Considered

Sometimes the costs of climate change impacts, and the lessening of those impacts that are attributable to emissions reductions policies are considered, and sometimes they are not. In addition, sometimes benefits occur as a byproduct of the climate policy. These positive side effects of climate change policies are often referred to as “ancillary benefits.” Some analyses take into account such benefits. For example, reductions in fossil fuel combustion would not only reduce carbon emissions, but would also reduce other air pollution (e.g., sulfur, nitrogen, volatile organic compounds (VOCs), and particulate emissions, each of which can damage human health and property). These analyses generally do not address the independent costs and benefits of actions to reduce emissions of the other pollutants. What would be most useful where there are interactions among the costs and benefits of controlling a range of pollutants would be a joint analysis of all emissions. The objective might be maximizing the net benefits of all the policy interventions over all of the pollutants. If performing this joint “optimization” is not feasible, the base case against which ancillary benefits of climate change are measured is exceedingly important. For example, if one were computing ancillary benefits of climate change policies over many decades, it would not necessarily be a good idea to assume that there would be no new policies regarding emissions of the other pollutants.

Uncertainty in Climate Change Impacts

Despite the growing amount of research that has been done on climate change impacts, there remain considerable uncertainties about what sectors will be affected, how they will be affected, and how to value any effects. In addition, much of the impacts research has been on expected future climate change and expected adjustments by the affected sectors. These studies, therefore, omit consideration of the unexpected — the less likely, but still possible, discontinuities in the climate system and the affected sectors. Such discontinuities could be far more significant than those impacts that are anticipated. In addition, it has been observed that it is the variability in climate, and indeed variability in the weather, that causes the most serious (negative) impacts. Thus, the concern is not that the mean level of the sea is rising, but rather that a higher mean sea level makes storm surges more devastating. Likewise, it is not the potential change in mean temperature and precipitation in the midwestern United States that has a major impact on agricultural productivity, but the potential for increases in long, hot, dry spells. This observation brings with it three implications for climate policy analysis:

- a change in base case climate may bring about more frequent and severe impacts by making the effects of variability around that new base case more extreme;
- the change in climate may lead to an increase in variability around the new base case climate; and

- there are climate and impact sector outcomes that may be less likely, but much more difficult to cope with, than what might be anticipated under expected conditions.

There have been a number of preliminary studies on the impact of uncertainty on climate policies (see Kann and Weyant, 2000, for a summary of these studies). These studies all try to look at the impact of uncertainty on appropriate climate change policies. Although there are still considerable uncertainties about mitigation costs, the level of uncertainty about climate impacts (and the corresponding benefits of reducing those impacts through GHG mitigation) is much greater. This is, in part, because the costs start immediately, and most experts feel the most substantial benefits will not occur for several decades. Thus, many of the more interesting studies focus on the effect of uncertainty on the value of emissions reductions. These studies consistently suggest that uncertainty implies a higher value for emissions reductions than what is calculated assuming expected climate change impacts. This result stems from the asymmetry of the costs of under- and over-controlling GHG emissions. In general, the penalty (in terms of both the additional impacts that would occur and the subsequent rapid mitigation that would be required) for under-controlling is larger than the penalty for over-controlling (in terms of higher mitigation costs). Put differently, the odds of climate change impacts being much worse than currently expected are high enough to justify buying insurance against those outcomes. “Insurance” in the form of early additional control provides a cushion in case the impacts of climate change do, in fact, turn out to be worse than currently expected.

There are some additional categories of uncertainty analysis, including uncertainty about societal values and uncertainty about model structure. Two prime examples of uncertainty about societal values are the value of a human life and the inter-temporal discount rate. Attempting to place an economic value on a human life is analytically challenging and fraught with controversy.

The discount rate is an economic tool to adjust for the fact that individuals prefer to incur benefits sooner and costs later. For example, a person who takes out a 30-year home loan at a 6 percent annual interest or discount rate indicates a willingness to pay over ten dollars three decades in the future to obtain just one dollar in the present. Policy choices that affect future generations tend to be very sensitive to the choice of discount rate, and most climate change models can obtain results on all ends of the spectrum by varying the discount rate. There is disagreement about the “true” value of a discount rate and the extent to which it is tied to the rate of return on capital (Portney and Weyant, 1999).

A “descriptive” perspective, based on how economies are actually behaving in making intertemporal trade-offs within the generations that are currently alive, suggests the use of a discount rate that is closely tied to the rate of return on capital (say 5 or 6 percent per year). On the other hand, a “prescriptive” perspective based on trade-offs between the incomes of the present generation and future successive generations can lead to much lower discount rates (say 1 to 2 percent).

IV. Information and Insights From Applications of Economic Models

This section discusses modeling analyses of the economic impacts of meeting short-run emissions targets like those specified in the Kyoto Protocol.[16] This discussion parallels that developed in the "Five Determinants" section (Section III) as much as possible. Section A is on base case emissions projections because they set the stage for the cost and benefit calculations. Section B covers the policy regime assumed because it strongly influences the options available to consumers and businesses. Sections C and D discuss substitution possibilities and technological change, respectively, because these reflect the available options represented in the analyses. Section E is on the benefits of GHG emissions reductions because these provide the motivation for climate policies.

A. Base Case Emissions Projections

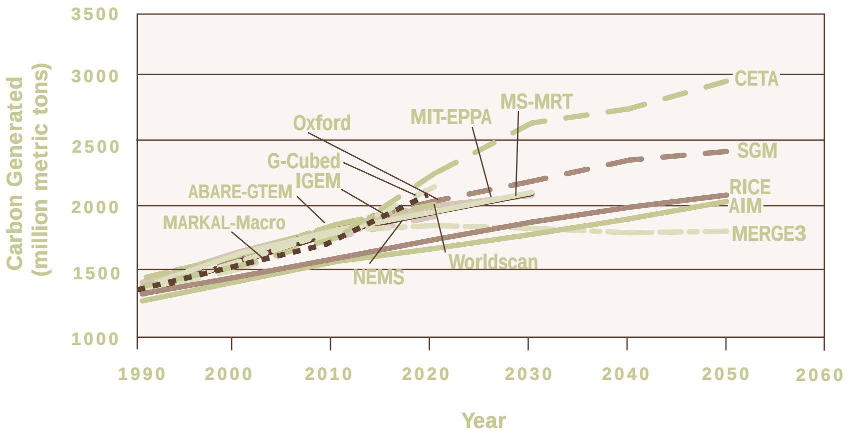
The Kyoto Protocol constrains emissions in certain countries (i.e., the developed or Annex I countries) to specified amounts in the first budget period (2008-2012). One of the major determinants of the cost of satisfying the constraint in each region is the level of emissions projected in the absence of the constraint. Other things being equal, the higher the projected base case emissions, the higher the cost of satisfying the GHG emissions constraint.

In a recent study organized by the Energy Modeling Forum (EMF) at Stanford University (called EMF 16), each modeling team was asked to prepare its own base case projection of carbon emissions in each world region.[17] Base case carbon emissions projections from this study (as well as a few recent studies) for the United States are shown in Figure 1.

There is a wide range of projected carbon emissions by the latter part of this century. Even by the time of the first (and only) budget period covered by the Kyoto Protocol, there are significant differences. These differences are the result of different assumptions, for example, about economic growth, fuel costs, and capital stock turnover. The range of projections for the year 2010 range from 1,576 to 1,853 metric tons of carbon (MtC) with a median of about 1,800 MtC, and for the year 2020 from 1,674 to 2,244 MtC with a median of about 1,950 MtC. Figure 2 shows how base case GDP, total primary energy, and carbon emissions are projected to change between 1990 and 2010 in each model. All the models project a significant decline in carbon emissions per unit of economic output (i.e., much more rapid GDP growth than carbon emissions growth) over the period between now and 2010. In addition, the models that report energy consumption all project that reductions in energy use per unit of economic output will be one major source of carbon emissions reductions. On the other hand, the models that report both energy consumption and carbon emissions differ in their projections of carbon emissions per unit of energy use (sometimes referred to as the carbon intensity). Four models — SGM, Oxford, CETA, and AIM — project a decline in carbon intensity, while three — MERGE3, MS-MRT, and G-Cubed — project an increase. For example, the MS-MRT model projects a 20 percent increase in energy use and a 34 percent increase in carbon emissions, while the Oxford model projects a 47 percent increase in energy use and a 34 percent increase in carbon emissions.

Figure 1

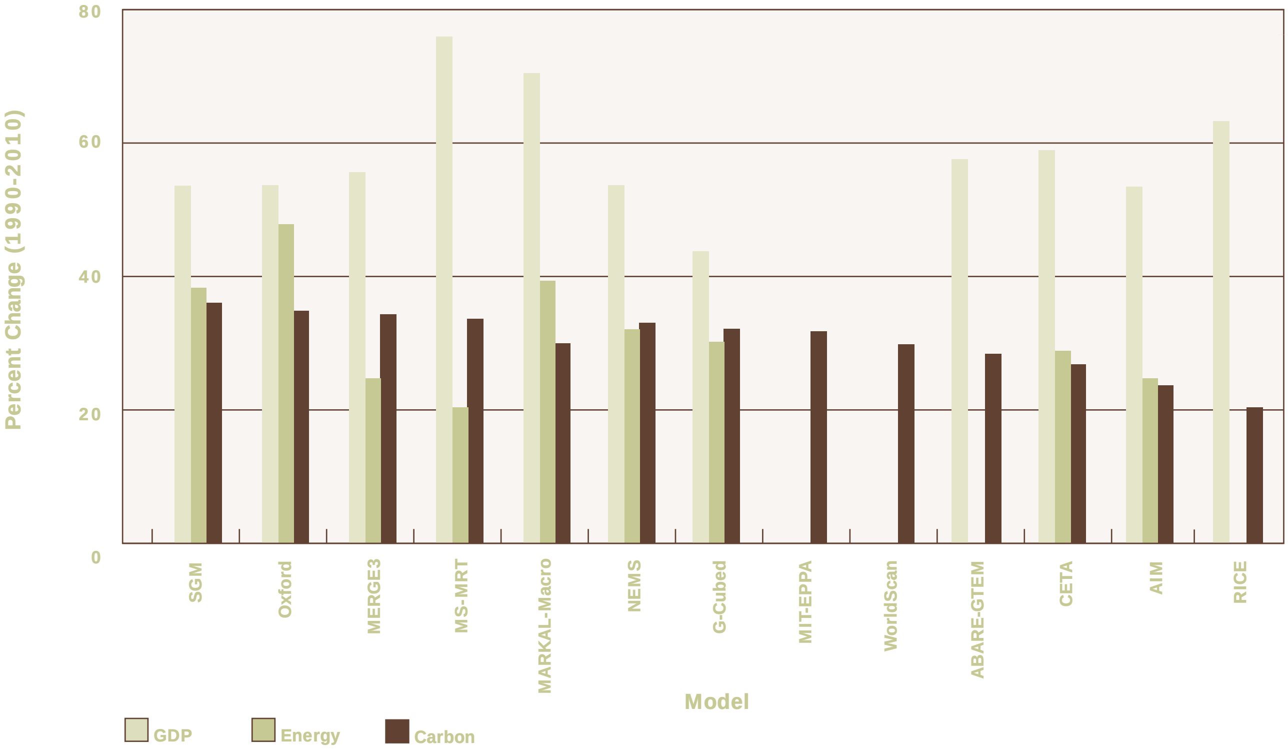
Base Case Carbon Emissions Projections for the U.S.



Other things being equal, the higher the base case emissions projection, the more emissions will need to be reduced to achieve a particular target, and the higher the cost of meeting that emissions target. The policy regime considered and the representation of opportunities for corporations and consumers to change the mix of products tends to be important determinants of mitigation costs as well.

Figure 2

Projected Changes in GDP, Energy, and Carbon Under a **Reference Scenario** for the U.S.



B. The Climate Policy Regime Considered

The policy regime includes flexibility mechanisms such as inter-gas trading, credit for carbon sinks, timing flexibility, carbon emissions trading, and revenue recycling. Inter-gas trading, credit for carbon sinks, and revenue recycling are not discussed here. Currently, only a small group of analysts are incorporating these factors into their calculations.[18] Also, the rules governing the monitoring, measurement, and crediting for these mechanisms are less well developed than for CO_2 emissions.

Emissions Trading

Although the Kyoto Protocol explicitly mentions international trading of carbon emissions rights, the negotiators have yet to agree on who can trade, what can be traded and how much trading will be allowed. EMF started with some relatively simple alternative interpretations of the trading provisions in the Protocol in order to get a rough idea of what is at stake in determining the rules governing the trading regime.

In a recent EMF study (Weyant and Hill, 1999), results for four alternative scenarios were compared: (1) No Trading of international emissions rights, (2) Full Annex I (or Annex B[19]) Trading of emissions rights, (3) the Double Bubble, which considers separate trading blocks for the European Union (EU) and for the rest of the Annex I countries, and (4) Full Global Trading of emissions rights, with the non-Annex I countries constrained to their base case emissions.

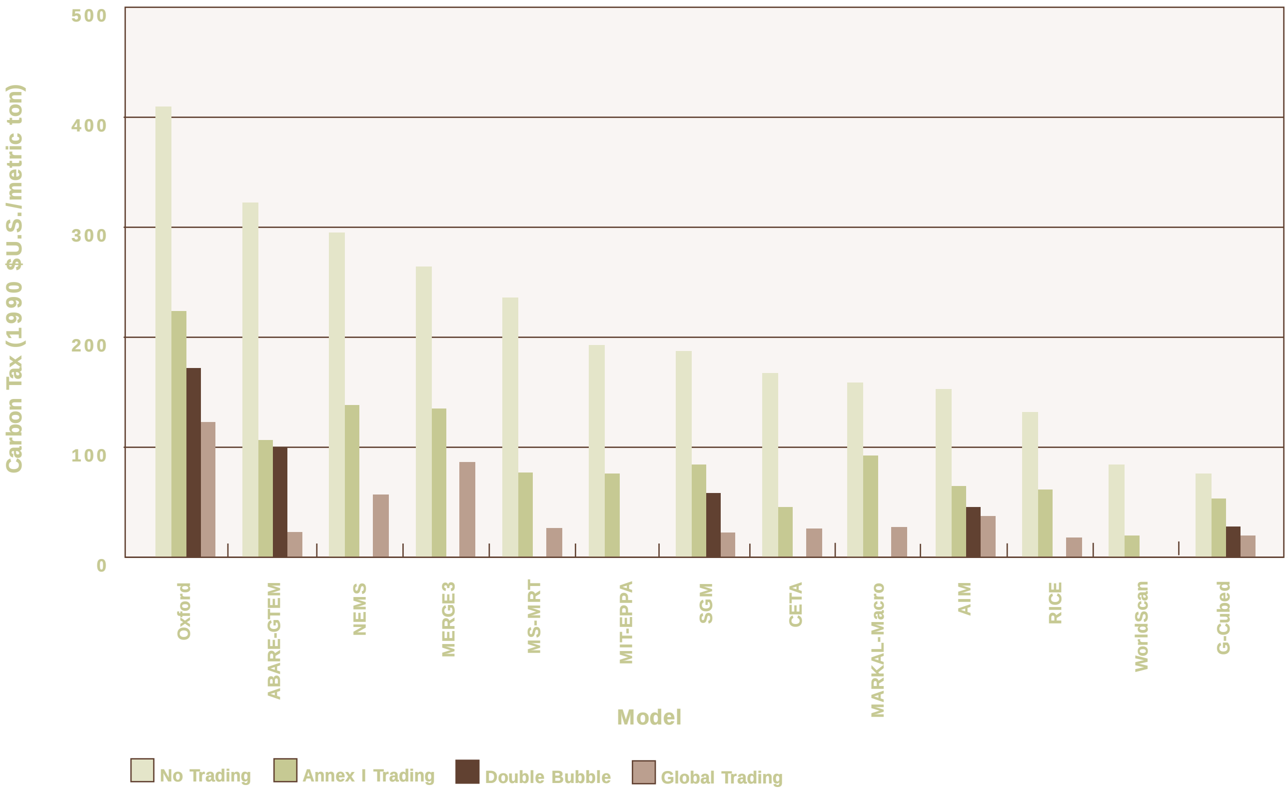
Several conclusions emerged from running these scenarios. First, virtually all of the modeling teams were uncomfortable running the Full Global Trading scenario as a realistic outcome of the current negotiating process. These teams believe that there is simply not enough time between now and the first budget period to agree upon and design a trading regime involving all the participants in the United Nations Framework Convention on Climate Change. Thus, this scenario was run only as a benchmark for what ultimately might be achieved. Second, in many of the models, carbon prices in the No Trade scenario rise to levels that made the modeling teams question whether the economic impact of the additional unemployment that is left out of most of the models could be as large as the costs that are considered. Despite these limitations, a number of general conclusions can be drawn from the model results.

Figure 3 shows carbon price results for the United States for the four alternative trading regimes (here results for the Double Bubble scenario are added to those for the three “core” trading scenarios). The potential advantages of expanding the scope of the trading regime are evident in the figures. Moving from the No Trade to the Annex I Trading case lowers the carbon price required in the four regions by a factor of two. This is a result of equalizing the marginal (i.e., incremental) abatement cost across regions. This effect is particularly significant in this case because almost all models project that a significant amount of carbon emissions rights will be available from Russia. (Under the Kyoto Protocol, emissions rights are allocated based on 1990 emissions. Due to the split of the former Soviet Union in the early 1990s and subsequent economic downturn, forecasters expect Russia’s uncontrolled carbon emissions in 2010 to be lower than its 1990 level allocation).

The advantages of Global Trading relative to Annex I Trading are also significant. They result primarily because non-Annex I countries can reduce emissions more inexpensively (due to their unconstrained allocation of emissions rights) than can the Annex I countries (due to their much more

Figure 3

Year 2010 Carbon Tax Comparison for the U.S.



tightly constrained Kyoto allocation). For example, in the base case, most of the models project about a 30 percent increase in carbon emissions in the United States in 2010 relative to 1990. By contrast, the Protocol calls for a 7 percent decline in U.S. emissions from 1990 levels, while base case emissions in China are projected to increase by 100 percent or more over that time period.[20]

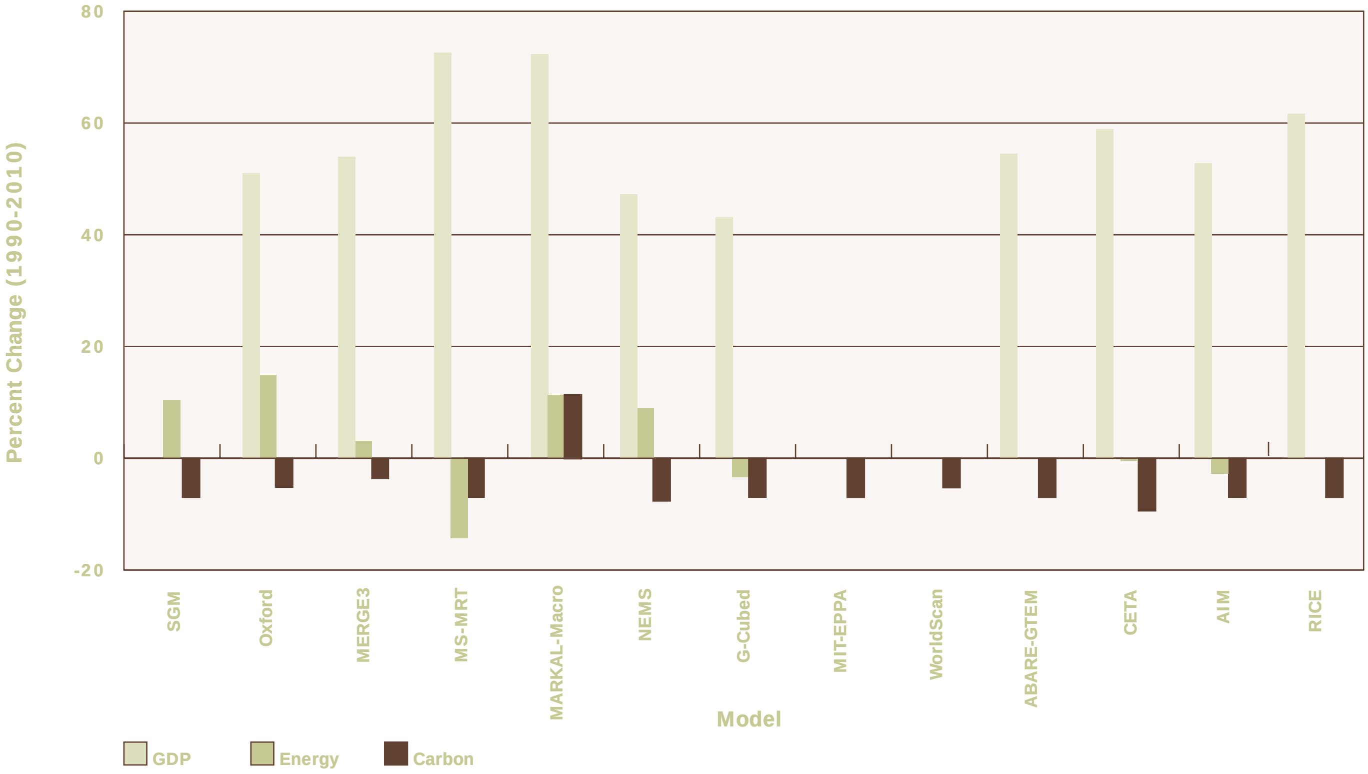
Although all the models show a similar pattern of results for the relative costs of the alternative trading regimes, there are significant differences in the models' projections of the magnitude of the economic dislocations under each regime. Part of the explanation for these differences is the difference in base case carbon emissions. However, this observation provides only an incomplete explanation of the different cost estimates from the models.

The characteristics of the emissions reduction scenarios and the base case scenario are different for each model. Figure 4 shows how characteristics such as base case GDP, total primary energy, and carbon emissions are projected to change between 1990 and 2010 in each model. Here all models have to reduce carbon emissions enough to meet the targets, but the models differ in how much of the adjustment takes place through reductions in energy use as opposed to reductions in carbon intensity. For example, the SGM model projects that a great deal of the adjustment will take place through reductions in energy use, while the MERGE3 model projects that more of it will occur through substitution of less carbon-intensive fuels. In order to meet a fixed carbon emissions target, a model that projects increasing base case carbon intensity must project greater required reductions in energy intensity than one which projects decreasing base case carbon intensity.

This comparison, together with the price results, suggests that the other reason for the observed differences is the degree of difficulty of adjusting energy demands in each model. Important dimensions of the adjustment dynamics include the rate at which energy demand responds to price changes, the rate

Figure 4

Projected Changes in GDP, Energy, and Carbon Under a **No Trade Scenario** for the U.S.



Note: Same as Figure 2 only without trade.

at which the energy producing and consuming capital stock turns over, the rate at which new technologies are introduced, and the rate at which natural gas production is increased. This paper does not discuss all these differences individually, but rather uses model results to provide an aggregate picture of how they work together in each model.

C. Substitution Opportunities

How models depict the choices and level of flexibility consumers and producers have to substitute among inputs and outputs when faced with changing energy prices is very important to climate policy cost estimates. Unfortunately, it is very difficult to compare how models treat this substitution since definitions, points of measurement, and level of aggregation of parameters differ greatly from model to model. However, Figure 5 is an extremely valuable starting point in the process of understanding differences in model results by plotting the projected carbon price against the percentage reduction in carbon emissions for

Figure 5a

Marginal Cost of U.S. Carbon Emissions Reductions in 2010 with No Emissions Trading Under Kyoto Scenarios

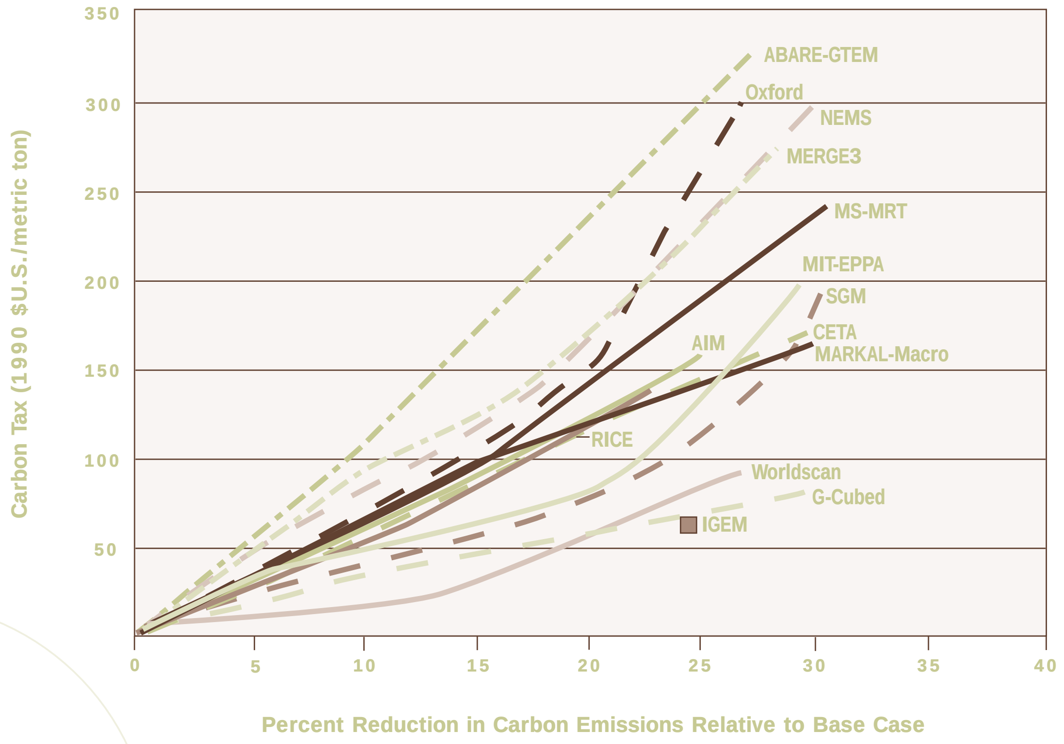
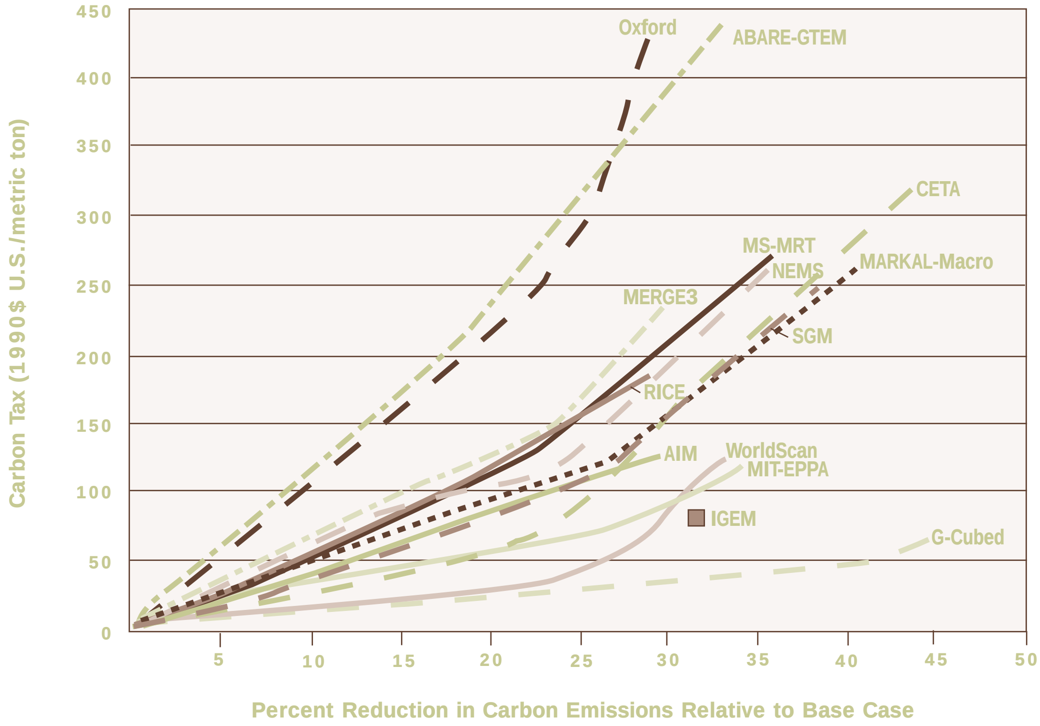


Figure 5b

Marginal Cost of U.S. Carbon Emissions Reductions in 2020 with No Emissions Trading Under Kyoto Scenarios



each of the trading regimes considered. This yields an approximate marginal carbon emissions reductions cost curve for each model for each region in each year.

Marginal cost curves for the United States in 2010 and 2020 are shown in Figures 5a and 5b. These figures contain a great deal of information about how and why the cost projections from the models differ. In addition, the plots show how difficult it will be to make the required adjustments. A steeper marginal cost curve for a model implies that it requires a larger price incentive to reduce carbon emissions by a given amount. That is, the steeper the marginal cost curve, the higher the carbon price required to achieve a given percentage reduction in base case emissions. The steepness of these curves depends on the base case emissions projected by the model, the magnitude of the substitution and demand elasticities[21] embedded in it, and the way capital stock turnover and energy demand adjustments are represented. All three factors work together, so that models with higher base case emissions lead to higher adjustment costs. If the elasticities were high and the adjustment dynamics rapid, adjustment costs would be lower.

Figure 5 shows the difference in the response of carbon emissions to higher carbon prices and different base cases. One can observe differences in both the absolute and percentage emissions reduction in response to successive increments of the carbon tax. Some of the models exhibit a nearly linear dependence of the carbon price on the percentage reduction in carbon emissions, while others exhibit a more steeply rising relationship.

Future studies looking at the sensitivity of substitution parameters within models rather than among models would be a very useful exercise in understanding why model cost estimates differ.

D. Technological Change

Economic models, with a time horizon of many decades, rely on some metric of technological change to capture the march of technical progress over long periods. This section discusses insights related to the representation of technological change in economic models. As mentioned in Section III. D, many existing models use a relatively simple exogenous representation of technological change. This discussion begins with a further elaboration of the AEEI method, then moves to some more recent attempts to model Induced Technological Change (ITC) and a description of models incorporating learning by doing (LBD).

Models using AEEI

These models show that ongoing evolutionary technological change can have a major impact on base case emissions, which in turn affect GHG mitigation projections. Based on detailed process-engineering models and historical trends, modelers cluster around an AEEI of 1 percent per year. This would translate into a 22 percent improvement over twenty years.

Induced Technological Change

Both empirical work on ITC, and the results of “top-down” conceptual models, reinforces the notion that the relationship between price changes and technological change is extremely complicated. There is also an emerging consensus that the effects of ITC will be modest in the short run, but much more significant in the longer term. Thus it will probably only have modest impacts on the 10-year emissions reduction cost projections presented here. ITC will have more of an impact on the 20-year projections and perhaps a dominant impact on cost projections for the middle to late century.

Empirical Modeling and Analysis of ITC

One early method of modeling ITC involved empirical observations of past responses to energy price and policy changes. Dowlatabadi and Oravetz (1997) studied aggregate energy efficiency trends in the United States from 1954-1994 to construct a model of price-induced energy efficiency. They suggest that this model should be used to replace the AEEI parameter in other models.

One of the best-known and most complete empirical models of ITC is the Jorgenson and Wilcoxen (IGEM, 1993) model of responses of the U.S. economy to energy price changes. Jorgensen and Wilcoxen apply this model in studying the cost of GHG abatement policies. The basic model is a top-down general equilibrium framework, which is a model that allocates output in each period according to supply and demand conditions and accumulates capital over time to maximize the value of consumption over time. This means that the model starts with economy-wide economic aggregates, and then disaggregates the behavior of economic agents by industry. Such models use "input-output" coefficients, which are the amounts of each input to an industry in each dollar of output from that industry. In the IGEM model, the input-output coefficients are allowed to vary to implicitly capture the effects of ITC. The projected input-output coefficient changes are based on extensive time-series data (1947-1985) on inter-industry transactions. Based on observations of the two oil price shocks in the 1970s, IGEM is able to empirically model the input-output coefficients as a function of energy prices. One reason that only IGEM estimates all these parameters simultaneously is the large amount of data necessary and the heavy computational burdens of such an estimate.

In addition to these two economy-wide empirical studies of ITC, a number of researchers have started to do empirical work on the factors influencing particular energy innovations. A recent empirical study of the energy sector by Newell et al. (1996) emphasized the importance of considering the multiple dimensions of technological change. Using data from 1958 to 1993, the authors analyzed data on room air conditioners, central air conditioners, and gas water heaters to estimate changes in cost and energy efficiency. These characteristics may advance through "proportional" innovation (i.e., all inputs to a particular appliance decline at the same rate over time) or "non-proportional" innovation (i.e., the use of one input declines faster than the others). Thus, the difference between the two types of innovation depends on whether the percentage change in energy use by a particular appliance over time is more or less than the percentage change in other inputs (primarily equipment costs in this instance) in providing a given amount of end-use services.[22]

The authors found evidence that the large cumulative energy efficiency improvement that occurred over a span of three decades in these products consisted largely of proportional improvement in technologies, combined with non-proportional components that favored cost reduction in the early years and energy efficiency improvements in later years. Moreover, the direction of change was found to respond significantly to the economic and regulatory environment. The authors empirically estimated the impacts of changes in prices, labeling requirements, and performance standards, and found that each of these instruments had noticeable effects on energy efficiency. They concluded that, in the last two decades, fully one-fifth to two-fifths of efficiency improvements were induced by historical changes in energy prices. Still, a large fraction of innovation was found to be exogenous — i.e., independent of energy prices and regulations. The lesson here is twofold: (1) technological characteristics may advance at different rates, with significant influence from endogenous factors, and (2) a significant component of technical advance is exogenous ITC.

Two economy-wide analytic approaches have been developed to help study how ITC might affect the costs of achieving given emissions reduction targets. In the first approach, Goulder and Schneider (1996) examined the ITC issue in a dynamic general equilibrium framework. The Goulder and Schneider framework includes an “endogenous growth” element that explicitly considers the links between policy changes, the supply and demand for knowledge-generating resources, and technical change. The production function of each industry treats knowledge much like other inputs (i.e., capital, labor, energy, and materials). The model considers the supply of knowledge-generating resources (e.g., skilled engineers, analysts, and consultants), as well as the demand. Since such resources are scarce, there is a cost involved in increasing the aggregate supply of knowledge-generating resources. Similarly, at any moment in time, if one industry bids R&D resources away from another, the acceleration in technological progress in the expanding industry is offset to some degree by the slow-down in technological progress in the other. In this model, the presence of ITC generally lowers the costs of achieving a given abatement target. At the same time, the gross costs of a given carbon price premium are generally higher in the presence of ITC than in its absence. In the presence of ITC, the economy responds more “elastically” to the carbon price, and endures greater costs in response to it. Although this heightened elasticity implies larger gross costs to the economy, it also implies larger net benefits, because the more elastic adjustment implies greater carbon abatement than would occur in the absence of ITC.

Goulder and Mathai (2000) investigated the impact of ITC on: (1) the optimal level and timing of a carbon tax, and (2) the optimal timing and level of emissions abatement. They considered two policy regimes: a cost-effectiveness regime (i.e., where the concentration target is given) and a benefit-cost regime (where the GHG concentrations over time are chosen to maximize net benefits — i.e., the benefits of emissions reductions minus the costs of achieving them). They considered knowledge accumulation, based on both R&D and LBD. They found that ITC significantly reduces the costs of achieving a concentration target if one considers LBD, if control costs are relatively insensitive to the level of abatement, or if one considers the cost-effectiveness (as opposed to benefit-cost) case.

In the second approach, Nordhaus (1997, 1999) built on his DICE model (Nordhaus, 1994) to create the R&DICE model, which incorporates ITC. The setting considered by R&DICE is one special case of the results considered by Goulder and Mathai — i.e., under a benefit-cost policy regime, and where R&D is the source of technical change. The R&DICE model represents the economy in a neoclassical growth framework, in which economic output is a function of capital, labor, and energy. (A neoclassical growth framework is one that balances the extra discounted value of the consumption that can be produced over time with an extra unit of capital investment today against the value of consuming that unit today and foregoing the investment.) In this model, exogenous technological improvement enhances economic output. In addition, Nordhaus assumes that there is an initial rate of improvement in energy-efficiency, or a rate of reduction in the influence of energy and carbon inputs on output.

The Nordhaus neoclassical growth model also offers insight into the influence of ITC on emissions reductions and technological change. Like Goulder and Mathai, Nordhaus finds that the opportunity cost of R&D severely restricts the influence of ITC if an atmospheric GHG concentration target is set based on cost-benefit analysis. In the Nordhaus model, though, the effect is so strong as to make the influence of ITC insignificant. The effect of the induced innovation is to increase energy R&D by less than 2 percent per decade, reduce the ratio of carbon to economic output by 0.0075 percent per decade, and reduce the carbon intensity (of energy use) in 2100 by about 0.5 percent relative to the base path. The key finding is that, due to the costliness of R&D, the effects of substitution of labor and capital for energy swamp the effects of induced innovation. The substitution impacts on demand and supply are responsible for approximately 99 percent of changes in emissions, concentrations, and temperature change. Again, this does not imply that all technological change is unimportant, but rather that the isolated effects of the additional ITC are small in a cost-benefit policy regime. However, under a fixed emissions target, the effects are large.

Technological change is sure to be one of the dominant solutions to the problem of global climate change over the next century. However, there are large uncertainties about the most cost-effective way to accelerate technological improvement over this time period. Different policies may be required to accelerate invention of brand new technologies, innovations in existing technologies, and the diffusion of new technologies. These processes also work on different time scales.

E. Benefits of Emissions Reductions

The benefits of GHG emissions reductions, in terms of avoiding climate impacts for individual sectors, are difficult to assess, although considerable progress has been made.[23] Valuation and aggregation across categories is difficult and controversial. In addition, climate change and impacts are more directly related to atmospheric concentrations of GHGs than to emissions, and GHGs can stay in the atmosphere for a hundred years or more. Thus, an assessment of the benefits of emissions reduction requires a long-run projection of the difference between climate impacts with and without controls. The difference must be aggregated over time with some sort of inter-temporal discounting. The assessment and the discounting also need to account for the risk that conditions could turn out to be much worse than expected in the future.

The current range of estimates for the direct benefits of reducing GHG emissions now is from $5 to $125 per ton (1990 U.S. dollars) (Bruce et al., 1996). The wide range of estimates reflects variations in model assumptions, as well as a high sensitivity to the choice of a discount rate. Although simulations based on a social discount rate of 5 percent tend to be in the $5 to $12 range, assuming a rate of 2 percent or less can lead to estimates that are a factor of ten greater. In interpreting these numbers, the reader is reminded of three previous points made in this paper:

- The range of benefits projections depends critically on assumptions about both base case impacts and the ability of people and institutions to adapt to these impacts;

- Many analysts and policy-makers believe that costs ought to be weighed against disaggregated impacts that are left in physical (and, therefore, more tangible) and not monetary form; and

- Most analysts now recognize the much greater relative importance of low-probability, but high-consequence extreme events, as opposed to more gradual, linear changes, in our vulnerability to climate change. However, they have only just begun to study them.

Projections of ancillary benefits range from $0 to $20 per metric ton of carbon (1990 U.S. dollars). These projections depend heavily on precisely where the emissions reductions occur. This is because: (1) most of the ancillary benefits are the result of reductions in other air pollutants (e.g., sulfur dioxide, oxides of nitrogen, VOCs, particulates, etc.), and (2) those air pollution benefits depend on both the prevailing meteorology and where people live relative to an emitting plant site or freeway system.

In summary, users of economic analyses should either: (1) focus on cost-effectiveness, taking emissions or concentration targets from other analysts or policy developers, or (2) factor in reductions in physical or monetary impacts and weigh them against mitigation costs. Above all, it is essential to keep the benefits of climate change policies transparent and separate from the costs, both in doing the analysis and in communicating the results. It would be unfortunate if cost estimates from a cost-effectiveness study that did not take into account climate change benefits were misinterpreted to include such benefits. And it would be equally unfortunate if a cost estimate that did account for climate change benefits was misinterpreted as excluding them.

V. Conclusions

Analysts have produced a wide range of projections of the costs and benefits of reducing GHG emissions. Understandably, policy-makers want to know what is behind these projections and why they often differ. This paper attempts to simplify the task of understanding differences in projections by focusing on five key areas in which differences in model configuration and in input assumptions drive differences in model results.

Two key determinants of costs and benefits are the base case emissions projection against which emissions reductions are compared, and the policy regime considered. These two factors primarily reflect differences in input assumptions. The model results summarized in this paper demonstrate that the higher the base case emissions, the greater the economic impacts of achieving a specific emissions target. In fact, in many models the relationship between the percentage reduction in GHG emissions and the carbon price is quite non-linear. It is also shown that key elements of the policy regime, like the extent to which international emissions trading is permitted, can have a profound effect on the economic impacts of emissions reduction. In general the more flexibility permitted in where, when, and which GHG reductions may be used to satisfy a commitment, the smaller the economic impacts. It also matters greatly how revenues raised through carbon taxation are reused, especially if certain uses are politically feasible.

A third determinant — the extent to which the model accounts for the benefits of emissions reductions — often comes from external sources or is omitted (as in a cost-effectiveness analysis). Sometimes, however, a cost-benefit analysis is performed or a benefits estimate is subtracted from the gross cost estimate to get a net benefits estimate.

These three external sources of differences in projections account for most, but not all, of the range of cost projections. The residual differences can be traced to how each model's structure accounts for two other key factors — the rate and extent to which available inputs and products can be substituted for one another, and the rate of improvement in the substitution possibilities themselves over time (i.e., technological change). The representation of the substitution possibilities depends both on the available technologies and on how the retirement of existing equipment and introduction of new technologies are represented. The more flexibility the model includes in the choice of technologies, retirement of old equipment, and introduction of new technologies, the lower the economic impacts of emissions reductions. It is important to understand that flexibility in substitution of less GHG-intensive activities is not a policy choice. It is a characteristic of the economy and depends ultimately on choices made by individual consumers and firms.

Analysts understand how the models used in making mitigation cost projections differ in representing substitution possibilities in the aggregate, although the details are still under investigation. These differences are important not only to interpreting and comparing model results, but also to understanding how effective various kinds of policy interventions might be in reducing GHG emissions at minimum cost.

Technological change occurs when new technologies allow a particular good or service to be produced with fewer inputs, or when a new product is developed. Most models used to project GHG emissions and mitigation costs assume that technological change takes place steadily over time, but does not depend on changes in prices or the implementation of government policy options. Thus, different technologies are selected as prices change, but no new technologies are added to the menu. Recently, analysts have started developing ways by which price-induced technological change and price-induced increases in the rate of diffusion of new technologies can be included.

The technological change that occurs over time, and that is included in most of the models, reduces the costs of mitigating carbon emissions because it decreases the base case trajectory of GHG emissions. However, it is probably unrealistic to assume that changes in energy prices will not alter the course of technological progress. In the short run, price increases should encourage the diffusion of new technologies. In the intermediate term, they should lead to a more rapid rate of increase in the rate of improvement of existing technologies, and earlier replacement of other facilities and equipment. In the long run, price increases should stimulate the development of brand new technologies. Both kinds of changes should reduce the average rates of GHG emissions per unit of output.

Given the large number of detailed assumptions made in each modeling analysis of GHG policies, this paper has not attempted to ascribe the costs and benefits of GHG emissions reductions projected in any particular study to differences in input assumptions. Rather, its focus has been on the identification and description of the major input assumptions and key model features to consider when interpreting and comparing the available model-based projections of the costs and benefits of GHG reductions.

In understanding how these five determinants influence cost projections, decision-makers will be better equipped to evaluate the likely economic impacts of climate change mitigation.

Endnotes

1. Total resource costs are the direct costs of the substitutions resulting from the policy intervention. That is, they are the costs of the changes in capital, labor, and materials that result from the policy.

2. Consumption represents the total goods and services used by the economy. The discounted present value reflects the preferences that individuals express regarding trade-offs between costs and benefits that are realized at different points in time. It adds together the consumption in each year adjusted to take into account people's preferences for income in that year relative to income today.

3. A utility function is a measure of economic welfare that goes beyond mere monetary measures. For example, it may take into account the fact that a given amount of money would be more valuable to a poor person than to a rich person.

4. The resulting adjustment depends on two opposing effects on workers. Workers would want to work more to make up for their loss in real income, but working is worth less vis-à-vis leisure, which would make them want to work less.

5. In order to obtain such a base case emissions projection, one must estimate each of the following — population, economic output per person, energy per unit of economic output, and carbon per unit of energy — and then multiply them together. The projection of each of these factors is, in turn, either assumed or inferred from projections of other underlying factors. This is sometimes referred to as the Kaya identity since it was first observed by Yoichi Kaya (1989) of Tokyo/Keio University.

6. See, e.g., Bruce, et al. (1996).

7. In some control scenarios, some models show an increase in gas supply with substitution of gas for coal and oil. In other scenario-model combinations, overall energy demand is reduced enough that the share of gas in total energy demand rises, but the overall demand for gas decreases.

8. Thus, after converting to "CO_2 equivalents," base year emissions are increased, and whether or not the inclusion of the "other" gases increases or decreases mitigation costs depends on whether the cost of decreases in CO_2 are larger or smaller than the cost of equivalent reductions in the other GHGs. Early studies of the use of flexibility mechanisms in meeting the objectives of the Kyoto Protocol indicate that there may be some cost savings associated with moving from CO_2-only reductions to reductions in all GHGs (Reilly et al., 1999; Hayhoe et al., 1999). However, there are two critical implementation issues associated with this potentially valuable flexibility mechanism: (1) a lack of consensus on the appropriate relative global warming potential of different gases, and (2) if the institutions are not in place to assign credit for reductions in the non-CO_2 gases, then the adoption of a multi-gas approach may actually increase costs by putting more pressure on CO_2 abatement.

9. The Kyoto Protocol provides that "net changes in GHG emissions by sources and removals by sinks resulting from direct human-induced land-use change and forestry activities, limited to afforestation, reforestration and deforestation since 1990 ... shall be used to meet the commitments" (Article 3.3).

10. See the Pew Center's report on International Emissions Trading written by Edmonds et al. (1999).

11. This is just another example of the gains from trade (Bhagwatti and Scrinivasan, 1983), albeit for a good that is not now traded.

12. See, e.g., Manne and Richels (1999), Nordhaus and Boyer (1999), and Peck and Teisberg (1999).

13. Numerical general equilibrium models are calibrated to actual economic conditions in a particular economy and use parameter values that are as realistic as possible for that economy.

14. Useful life is an economic concept: it depends on the benefits and costs of the alternatives. One may buy a new and better computer after three years, even though the old computer could be "useful" for ten years, because the new one has superior cost and performance characteristics. Or one may keep an old car running because the performance advantage of the new car is not worth the cost.

15. Goulder and Mathai (1997) formulate an interesting partial equilibrium model that allows them to highlight the similarities and differences between ITC and LBD in both cost-effectiveness and cost-benefit analyses.

16. There is no discussion here of results from three other typical types of economic analyses: (1) the cost of meeting longer term limits on atmospheric concentrations of GHGs, temperature change, or climate impacts; (2) cost-benefit analyses; and (3) decision-making under uncertainty with respect to either cost-effectiveness or cost-benefit objectives. (See Weyant et al., 1996, for more on results from these other types of analyses.)

17. Of the thirteen global models included in EMF 16, eleven had an explicit U.S. region. In this report the authors have omitted the other two models — FUND and GRAPE — and added results from three U.S.-only models: IGEM, NEMS, and MARKAL-Macro.

18. See Reilly et al. (1999), Hayhoe et al. (1999), and Manne and Richels (2000) for recent studies of multi-gas approaches to climate policy.

19. Annex B refers to industrialized countries that are trying to return their GHG emissions to 1990 levels by the year 2000 as per Article 4.2 of the Kyoto Protocol.

20. For more on the potential for international emissions trading to reduce the costs of GHG mitigation, see Edmonds et al. (1999).

21. Elasticities measure the responsiveness of the demand for a product to the price of the product.

22. In the formulation used here, the whole set of available models of a particular appliance becomes more efficient in its use of inputs (energy and capital charges) over time. This is different than the substitution of factors through selection of a particular model that is available at any point in time.

23. See the Pew Center's Environmental Impact report series.

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