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Add

To list of reasons to wait: time value of money, discounting (vs. natural removal rate) introduce disct. rate
[[vs. on other side: rising marg. costs = first cuts are easiest.]]

WRE alt e paths for same conc. targets

Richels-Edmonds cost estimates: stab. e at 1990 levels soon is far more costly.

Effic't domestic imp. (vs. = least expensive reductions regardless of sector: low admin. & transactions costs; would fail under regulatory approach) requires mkt. mech.

Int. (vs. some countries don't sign, or fall short...)

Kosobud et al 1994

To achieve temp target in 2100, rather than concentn.

1°C (about half a bau)

Alt to early stab at 1990 levels stays relatively close to BAU path until 2020-2030 decade, doesn't return to 1990 until about 2050.

Marg. cost @ 1990 freeze $140/ton in 2000 to $250/ton in 2020.

Alt. path <$9/ton in 2000 rising thereafter

Reduces PDV of cost by $1.6 tr (1995 prices)

TRADABLE CUMULATIVE CO2 PERMITS AND GLOBAL ...

DOCUMENT 1 OF 1
EJ8500442953
* TRADABLE CUMULATIVE CO2 PERMITS AND GLOBAL WARMING CONTROL.
* By Richard F. Kosobud
and Thomas A. Daly
and David W. South
and Kevin G. Quinn
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INTRODUCTION

Finding an internationally acceptable and cost-effective global warming control policy remains a challenge. A start was made at the 1992 Rio Earth Summit, but the end products, the quantitative objectives of the policy process and the choice of the control measures, remain distant and hard to perceive. An ineffective or unenforceable policy, or no policy at all, that allows C|O.sub.2^ and other trace gas concentrations to continue to build up risks long-run changes in climate with uncertain but worrisome consequences, among them being: decreases in agricultural productivity, lower fresh and higher salt water levels, more frequent storms, alteration of ecological systems, and the likelihood of regional losers and winners (Intergovernmental Panel on Climate Change, 1990). Aggressive near-term mitigation action, on the other hand, risks significant expenditures that could later turn out to be unjustified in view of the many knowledge gaps and uncertainties that exist in the area.

This uncertain but ever accumulating problem has stimulated a growing body of research that provides estimates of control costs of carbon taxes and, to a lesser extent, estimates of climate change damages (for example, recent studies and references to other work may be found in Cline (1992), Manne and Richels (1994), Nordhaus (1992), and Peck and Teisberg (1992)). The wide range of estimates of control costs and damages, the analytical complexity of control measure choices, and the difficulty in timing of control leave room for new directions.

We take two new turns in this study. First, we assume the existence of an international agreement to stabilize induced climate change by the year 2100 which creates property rights to a given

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volume of the global atmosphere. Second, we assume that this international agreement will be designed to create a stock of, to develop markets for, and to allow trading of evaporative or
* cumulative emission permits that would fill that atmospheric space, but no more. These ideas open up some interesting areas for economic analysis. Implicit in this argument is that there is an agreed upon
* initial allocation of these permits that secures the cooperation of sufficient countries to make the proposal viable.

This proposal is addressed in a mathematical programming model of the global economy with detailed specifications of the energy sector and a linked climate change process that enables us to analyze the implications of both short-run emission reduction and long-run concentration stabilization policies. This is accomplished by placing constraints on greenhouse gas emissions or concentrations, which means raising the relative prices of fossil fuels generating these gases, and tracing the consequences for the price and quantity time paths of key economic and permit variables. The comparative cost-effectiveness of these varied policy choices is appraised in terms of the values of the model's objective function (consumer energy welfare), and in terms of the intertemporal efficiency requirement for marginal control costs.

* Our results reveal that high, initial tradable permit prices (or, in a world of certainty, the equivalent carbon tax rates) are required to freeze 1990 emission rates by 2000, or to reduce them from the no-policy or baseline path early in the next century. These short-term actions slow but do not halt the induced climate change. They require major changes in the energy sector and are cost-ineffective compared with the long-run policy option. They violate the intertemporal efficiency requirement for allocating control efforts.

Our results reveal that initial permit prices are low in the concentration stabilization scenarios and rise as the rate of interest to reach levels during the last half of the next century that induce the use of non-emitting energy technologies. This long-run choice brings the induced climate change to an end by 2100. It is cost-effective when compared to the short-run actions and satisfies the intertemporal efficiency requirement for allocating control efforts.

Strong assumptions are made in obtaining these results, among them being that earth-shaking agreements on policy are possible, that a focus on one major greenhouse gas is permissible at this early stage of research, that newly created markets are efficient in discovering permit prices, and that the global economy can be simulated over time in a programming framework. A key assumption is that the impacts of climate change will be largely due to the elevation of the global equilibrium surface temperature and not its

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rate of change. These and other assumptions will be discussed in more detail at the close where suggestions for additional research will be made.

FORMULATING LONG-RUN GOALS OF GLOBAL WARMING POLICY

The framework convention on climate change to monitor emission trends and national control policies, a key proposal of the Earth Summit held in Rio in June 1992, has been given a quantitative interpretation by the U.S. Administration with its commitment to reduce emissions by 2000 to their 1990 levels.(1) The major trace gas, C|O.sub.2^, is to be held to a 2% growth by 2000, one-third of the projected baseline increase. Other greenhouse gas emissions, primarily the chloroflourocarbons being phased out by the Montreal Protocol agreement, are expected to decline thereby making up the intended reduction of emissions to a global warming potential equal to that of 1990.

With these U.S. policy moves in mind, and those of other countries similar to them, we develop two scenarios for the analysis of near-term actions for purposes of comparison with two long-term stabilization scenarios. The first near-term scenario is a freeze of 1990 C|O.sub.2^ emissions by the year 2000 to be held at that level thereafter; the second is a 20% reduction of 1990 emissions by 2010 and a 50% reduction by 2050. These two scenarios not only span the set of recent policy proposals, but also have figured prominently among the scenarios analyzed by global warming modelers, see Energy Modeling Forum (1993).

The focus in this study is on the major gas, C|O.sub.2^, whose sources and sinks are better understood than those of nitrous oxide and methane. This focus will add to the clarity of the model, will permit a more ready example for the creation of permit markets, and will facilitate comparison with other relevant studies. Policy measures differing from those proposed for C|O.sub.2^ emission control may well be required for other greenhouse gases.

A key consequence of the scenarios that freeze emissions or aim for moderate percentage cuts in the near-term is shown to be a slowing but not a halting of global warming. Emissions continue above the capacity of sinks to absorb them, and temperature elevation continues through 2100 and beyond. The potential increase in concentrations, and induced climate change, in these cases would be limited only by the eventual scarcity of fossil fuel reserves causing market processes to suppress their use. The fossil fuel reserves in our model, consistent with present estimates, indicate that concentrations could increase up to ten times the present levels.

Cline calculates, using climate projections that allow for a long view, that increases in concentrations of this magnitude could mean an equilibrium global surface temperature elevation of 6 to 18

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degrees Celsius (|degrees^ C) by 2275, (1992, p. 57). The present value of impacts so far off would be negligible with any but the smallest or zero discount rate. Yet average temperature changes of that magnitude in that time span are unprecedented and would pose challenges to human behavior and institutions, and to the adaptability of the present spectrum of species, that are sobering. The benefits and costs of bringing such anthropogenic elevations to a halt by newly designed policy choices are worth serious attention.

A start may be made by considering the proposal of the Advisory Group on Greenhouse Gases of the World Meteorological Organization to define temperature targets in terms of risks to human and ecological systems in the following way: limiting the average absolute global temperature rise to 1 |degree^ C, after 1990, would entail a low risk, limiting it to between 1 and 2 |degrees^ C would entail a moderate risk, and permitting an increase above 2 |degrees^ C would entail a high risk scenario in terms of rapid, unpredictable, and nonlinear impacts.(2) These zones are indicated on Figure 1 as illustrations of a possible risk or damage function for determining temperature goals. The Advisory Group also indicated that the year 2100 was a plausible terminal point for temperature level goals, which we adopt in this study. However, the point in time to bring anthropogenic climate change to an end is also a proper item for negotiation and study.

Curve 1 of Figure 1, based on business-as-usual emissions generated by the economic model of this study, reveals an estimated average global surface temperature increase from all major gases of about 3 |degrees^ C by 2100 (assuming mid-range climate feedback sensitivities under C|O.sub.2^ doubling as proposed by the IPCC, 1992). Curve 3, on the other hand, represents a typical temperature change path associated with a short-run freeze of annual emissions at 1990 levels; equilibrium temperature increases by less than that of curve 1 by the year 2100 but continues to increase thereafter. Curve 2 represents a path associated with a long-run temperature stabilization target that brings induced increases to a halt at 2100. How control measures may be introduced into the model to generate curves 2 and 3 will be addressed shortly.

Curve 3 is drawn to illustrate the temperature consequences of a freeze policy. Curve 2 is drawn to illustrate the consequences of a long-run stabilization policy that reaches the same temperature elevation value at 2100 as does curve 3. This equivalence at 2100 provides the foundation for a comparison of the welfare costs of the two policies. The policy behind curve 3 generates temperature increases after 2100, the policy behind curve 2 does not.

We have shifted the initial or start-up point of Figure 1 to the year 1990 and have not depicted the pre-existing induced equilibrium global warming that has probably already occurred. This shift will

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* facilitate the portrayal of tradable permit price paths and the comparison of the results with those of other studies. The temperature points of Figure 1 must be interpreted as our integrated model's projections of the central values of broad probability distributions.

If damages depend solely on the level, then the options portrayed by curves 2 and 3 are equivalent at 2100, although 2 after that date has no further effect. If the rate of change of temperature is most important, then 2 and 3 are less damaging than 1, but the issue is complicated by the varying slopes of 2 and 3 and no easy further ranking is available. If the area under the curve is a determinant of impacts, or total damage borne, then 3 is better than the others (through 2100), and 2 is better than 1. In this study the assumption is made that temperature levels matter most.

We now turn to the specification of two long-run temperature, or concentration, stabilization scenarios to compare with the near-term actions. We set up these stabilization scenarios in order to run two distinct policy competitions. The first matches the C|O.sub.2^ concentration reached by the annual emissions freeze scenario at year 2100 with a long-run stabilization scenario in which the concentration stock is controlled at the same level at year 2100. The second matches the concentration reached by the 20% and 50% emission reduction scenario with a long-run stabilization scenario in which the concentration stock is controlled at the same level at year 2100. In each competition, we are comparing one policy that controls the time path of emissions but not the terminal concentration with another that controls the terminal concentration but not the emission time path. Scenarios in which the time path of emissions are not controlled by policy in effect allow the market to determine a least cost path to the controlled concentration level, as we shall show.

CONTROL MEASURES FOR ACHIEVING GLOBAL WARMING POLICY GOALS

In a world of widely varying cost functions, which surely characterizes the energy industries, it can be shown that decentralized environmental control systems based on incentives
* created by carbon taxes or tradable permits are cost-effective in leading producers to equate marginal control or mitigation costs to the tax rate or price. Those that can mitigate cheaply do so, those that cannot, pay the tax or buy the permit. The result is cost-effective control, very hard to duplicate by direct regulation
* or technology prescription. We shall provide a tradable permit interpretation of the policy control measures introduced into our model.

To illustrate this control measure in the case of a long-run stabilization goal, we may assume a unique relationship between the temperature elevations of Figure 1 and C|O.sub.2^ concentrations.

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This relationship will be specified shortly. Further assume that an
international agreement has been reached to stabilize concentrations
where curves 2 and 3 cross the year 2100 ordinate (2 |degrees^ C
temperature increase). The difference in concentration between the
2100 and the 1990 mass will be taken, in this illustration, as the
atmosphere space remaining to be filled by new C|O.sub.2^ emissions.
Property rights to that space will be created by defining an
* evaporative, undated, tradable emission permit, each permit
denominated, say, for one ton by carbon weight.
* The total volume of undated permits for that space will then be
issued immediately and allocated by some agreed upon formula among
* participating countries. Permits could be free or priced in a
revenue neutral manner. Developing countries could be given special
attention to secure their cooperation. An evaporative property right
means that an undated permit is required and canceled upon the
extraction of a unit of coal, oil, or gas, or related product that
will generate upon consumption one ton of emissions by carbon weight.
* Permits may be used, banked, or sold at any time at the discretion
of the owner. Note that although we have set a long-run temperature
or concentration constraint goal, we have not, in this illustration,
specified the time path or flow of emissions (or changes in fossil
fuel use). These time paths are to be determined by the pricing,
within newly created markets as simulated in our model, of this
* stock of exhaustible permits.
* Permits are denominated in emissions, and climate change control
is denominated in tons of concentrations. The relationship between
the two, to be specified in the next section, depends upon the
airborne fraction of emissions that remain in the atmosphere,
estimated to be approximately 0.5. If, for example, the space
allowed is for another 500 billion tons by carbon weight, then
* undated permits for twice that amount, or 1,000 billion tons, would
be issued initially. The design of the permit, creation and
distribution of market institutions around the globe, monitoring of
permit use, and enforcement of the process are key issues on which
work has just begun, see Grubb (1989).
* Tradable permits can also be designed to control annual emission
flows which would require that they have an expiration date for
* their use. These dated permits would be issued at the beginning of
each time period, be it year or decade, in distinction to the
* undated or cumulative permits. They will be discussed later as a
control measure for short-term policy goals.

Carbon taxes provide an alternative decentralized control measure
* to tradable emission permits. The choice could depend upon a wide
range of considerations. Concentrating on the uncertainties of
global warming, and on assumptions about the slopes of the damage
and control cost functions, Peck and Teisberg (1993) find on these

uncertainty
=> price control

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* grounds that tax control of emissions is preferable to tradable permit control. Grubb (1989) has brought into the analysis other factors, such as flexibility in making changes in tax rates or permit volumes and general acceptability of each measure. The choice of control measure remains an open issue.

ECONOMIC MODELING OF POLICY CHOICE CONSEQUENCES

To analyze long-run questions about climate change stabilization and about cost-effective permit price paths, the unique features of this study, we have chosen the global, dynamic Argonne Linear Programming model, an updated version of the well-known Nordhaus model (1979). Its characteristics are well suited for our purposes: it is price responsive, transparent for sensitivity analyses, flexible for varied long-run scenario projections, easily solvable, contains extensive energy sector and demand side detail, and can be disaggregated into major sectors--the U.S. and rest-of-the-world in this application.(3)

Changes in the objective function, consumer energy welfare, will provide our measure of scenario performance. On the supply-side, a broad set of energy resources (entered as supply curves) and technologies (thirteen generate electricity, for example) are specified with given wages, interest rates, and capital prices. Consumption of these energy resources satisfies consumer demand functions at least energy cost. The resultant mix of emitting and non-emitting energy commodities generates C|O.sub.2^ flows in a manner soon to be specified. On the demand-side, the quantities of four final energy services taken off the market depend on their prices relative to other commodities, on income, and on population growth. For exogenous variables such as income and population growth, the model has values close to the UN Medium Low Case studied by the IPCC.

The intertemporal solution to this equation system, a scenario output, provides (competitive) equilibrium time paths of prices and quantities of energy commodities, and is forward looking in anticipating atmospheric constraints on C|O.sub.2^ concentrations or exhaustion of fossil fuel reserves.

The base case dynamics are driven by demand curves shifted by population and income growth encountering supply curves shaped by finite fossil fuel reserves and expensive but inexhaustible (non-emitting) backstops on call. Energy efficiency increases occur at moderate rates. The policy case dynamics are driven by constraints on C|O.sub.2^ emission flows or concentrations that yield, because of the link to the economic model, shadow prices altering fossil fuel prices, and use, relative to non-emitting resources. Since other prices are given (in 1980 $) in the projections, it is relative prices that are changing within the energy sector, and between energy and other commodities.

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The model's updated features include putty-clay constraints on capital replacement, a revised data base, and, important to our analysis, an expanded climate change submodel. Every base case or policy scenario yields a new set of intertemporal solutions or trajectories of prices and quantities of energy variables which are inputs into the climate change submodel. More detail on the specification of this submodel is important in interpreting the study's results.

Linking the Climate Change Submodel to the Economic Model

C|O.sub.2^ emissions, E, in tons by carbon weight, are projected as a consequence of global economic activity utilizing fossil fuels, each major type, |x.sub.i^, having a specified C|O.sub.2^ coefficient, ||Gamma^.sub.i^, or

|E.sub.t^ = |summation of^ ||Gamma^.sub.i^|x.sub.it^ over i, (1)

where i runs over the energy resource variables including oil, coal, gas, and shale; and t runs over decades through 2100. The |x.sub.it^ quantities are endogenous and determined in each scenario by the economic model and specifically by the market clearing demand and supply equations of the programming model. Equation (1) is thus the link between the economic and climate change models. It provides the connection by which the impacts of a market externality can be internalized in the model.

C|O.sub.2^ concentrations, M, the greenhouse blanket that drives temperature change, depend in the submodel on the airborne fraction of emissions remaining in the atmosphere, |Alpha^, and the seepage fraction, |Delta^, of last period's C|O.sub.2^ stock into the deep ocean, or

|M.sub.t^ = |Alpha^|E.sub.t^ + (1 - |Delta^) |M.sub.t-1^. (2)

Equation (2) is a simplification of the sources and sinks of the carbon cycle and excludes other components such as net emissions from changes in land use, which are difficult to project over very long horizons. Although simplified, equation (2) tracks concentrations well over the periods for which data are available.

The final submodel equation represents the nonlinear radiative forcing property of increased concentrations on temperature change.

|Delta^|T.sub.t^ = |Beta^ + |Epsilon^ ln(|M.sub.t^/|M.sub.o^) (3)

|Delta^T measures the increase in equilibrium surface temperature in degrees Celsius above the global climatic average calculated from 1990 in this study. The nonlinearity of (3) reflects the declining radiative effect of increasing concentration of C|O.sub.2^ molecules in the atmosphere.(4) The constant term may be interpreted as the temperature change prior to 1990, which we set equal to zero, and the slope coefficient is the radiative forcing coefficient. For our purposes we solve a linear approximation of (3) for |M.sub.t^ which enables us to convert a temperature change goal into a concentration mass.

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These temperature equations, and especially (3), become the "thermostat dial" about which international negotiators can engage in policy debate about the appropriate temperature goal. An alternative approach, not followed in this study, is to specify temperature goals in the objective function, thus providing for substitution of temperature for other consumer goods. Utilizing equation (3) to establish temperature goals in our approach is equivalent to giving temperature an infinite weight in relation to consumption goods (energy consumption utility in our model). It is as if the climate were being stabilized for the benefit of future generations.

Introducing Policy Choices into the Linked Models

Equations (1) to (3) provide, together with the economic model, an integrated system for assessment of climate changes due to fossil fuel use. Within this system, the consequences of a choice to freeze emissions at the 1990 level, |Mathematical Expression Omitted^, may be more clearly seen if the definite solution to equation (2), a first order, nonhomogeneous linear difference equation, is written as

|Mathematical Expression Omitted^

In this case, M, converges to a constant given that (1-|Delta^) is strictly less than 1. As |Delta^ is the deep ocean absorption factor and very small, the convergence date could be centuries away. The end of induced climate change occurs in the model when emissions retained in the atmosphere equal see page into the deep ocean (when stable concentrations = |Mathematical Expression Omitted^). That (1-|Delta^) is close to unity and that realized change lags behind equilibrium commitment implies a slow convergence. A simulation of a policy to freeze 1990 emissions by 2000 results in C|O.sub.2^ concentrations increasing well beyond the year 2100. Hence, the study's interest in stabilizing M at an earlier date.

Recent work by Nordhaus (1992), Peck and Teisberg (1992), and Cline (1992) takes a different to control policy. In their work, temperature is either an argument in a damage function, which is linked to an optimization model so that the marginal benefits of reducing damages generated by the function can be equated at each point in time with marginal abatement costs, or side calculations are made with the same effect. The result is an efficient carbon tax trajectory, a thermostat set not by negotiation but by benefit-cost calculations. In contrast, this study will generate cost-effective trajectories of endogenous variables associated with particular temperature goals or thermostat settings.|5^

In our approach, policy choices may be represented in the extended model by either constraints on temperature change, on C|O.sub.2^ stock concentrations, on flow emissions, or on fossil fuel consumption directly. Since all are endogenous variables linked

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by deterministic equations, a constraint on one constrains them all. In a programming tableau, these constraints yield values of the dual solution or shadow prices that reveal the time varying marginal contribution to the objective function of relaxing the constraint by a unit. A constraint on temperature, concentration, or emissions, therefore, yields a shadow price on each fossil fuel in proportion to its carbon content.

Two examples will clarify our interpretation of the shadow price and pave the way for the results. In the first, we impose near-term constraints on the flow of C|O.sub.2^ emissions to simulate the freeze scenario. That is, we dictate the time path of emissions by constraining the flow and hence the use of fossil fuels. The shadow price obtained is the loss at the margin in objective function discounted value which is equal to the marginal control cost of substituting either less emitting fuels, or non-emitting fuels, or reducing energy consumption, all being permitted by the specification of the model. This shadow price may be considered the addition to the supply price of fossil fuels that brings about the desired reduction in their use. The shadow price internalizes the global warming externality.

* If dated tradable evaporative permits for a constant annual emission flow are issued with the proviso that they could not be banked, in order to achieve the freeze scenario, the annual equilibrium price determined in an efficient market would equal the shadow price. If permit prices were above that level, traders could
* do better by not buying permits and turning to controlling emissions by other means. If prices were too low, traders could do less
* control and buy permits. Equilibrium occurs when marginal control costs for the desired emission flow equal permit prices.

If emissions are cut back in the near-term, as in this first example, marginal control costs and permit prices will be high as costly adjustments are made. Marginal control costs, and permit prices, could decline later as new techniques are brought into play. The model contains putty-clay features that prevent instantaneous adjustment of capital stock and contains constraints on the growth of new technologies all of which mimic rigidities found in practice. Therefore, the permit price path is bound to reveal peaks and valleys as these adjustments are made. In these circumstances, it would be difficult for enterprises to introduce new technologies or practices in cost-effective ways.

* In a second example, cumulative or undated tradable permits are issued to cap the C|O.sub.2^ concentration stock in 2100 with the proviso that they can be banked. The equilibrium price determined in an efficient market would not only equal the shadow price at each point in tim, but also would change over time as the market
* appraised the declining stock of permits. Forward looking traders

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* would recognize that the value of permits would increase over time. Assuming certainty equivalence for all traders (including their ability to estimate backstop costs), the permit price, p, at any time, t, may be written,

|P.sub.t^ = |P.sub.T^|e.sup.-r(T-t)^ (5)

where |P.sub.T^ is the price of, and T is the transition time to, the non-emitting backstop and r is the long-term rate of interest or yield on capital. The present permit price is the discounted price of moving to expensive non-emitting technologies. Permit prices are denominated in carbon units which can be translated into energy units such as Btus for comparison with backstop prices.

Equation (5) implies, by dividing by a similar expression for the previous period's permit price, that

|P.sub.t^ = (1 + r) |P.sub.t-1^. (6)

* The market considers the quantity of evaporative permits initially issued to be an exhaustible resource and equation (6) is one (Hotelling) condition for equilibrium, and intertemporal cost-effectiveness. Permit prices rise along a cost-effective path as the long-run rate of interest (5% in our scenarios). As marginal control costs equal permit prices in equilibrium, marginal control costs are rising exponentially over time permitting micro decision makers to plan an intertemporally cost-effective introduction of increasingly expensive technologies or practices.

The terminal or stabilization point in time is an important variable that has been set for the year 2100 in this study. With that date given, the initial permit price will depend upon the
* quantity of permits issued as determined by policy, the interest rate, and the backstop cost. Moving the terminal point forward in time raises the initial permit price as does reducing the initial
* quantity of permits. The interest rate has a more complex effect; an increase raises the cost of the capital-intensive backstop thus increasing permit prices, but, as a discount factor, increases in the rate act to lower prices.

The example suggests the potential of the evaporative permit system as a means to achieve the environmental target in a cost-effective manner. It also enables the study to depict permit price paths associated with specific targets and calculate their welfare consequences.

Stabilization of induced temperature change and carbon dioxide concentrations does not imply the cessation of fossil fuel use. Continued consumption for highly valued uses (pharmacological use, for example) could be permitted up to the point where emissions equaled absorption by the deep ocean. Some form of "permanent"
* tradable emissions permit might be devised for this amount.

THE RESULTS: COMPARING THE COST-EFFECTIVENESS OF ALTERNATE GLOBAL WARMING CONTROL PATHS

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Our quantitative measure of the cost-effectiveness of alternate control choices will be, to repeat, the model's objective function value, or discounted consumer energy surplus. A related but indirect measure, of great interest, will be the time paths of emissions and of permit prices. These will provide indicators of the rate of the increase in fossil fuel prices that impact on the energy industries, and the consumer.

Equilibrium temperature changes for all subsequent figures are attributable to C|O.sub.2^ concentrations alone and not, as in Figure 1, to all major trace gases. It is as if other control measures had been found to stabilize concentrations of nitrous oxide and methane. It is also assumed that the control measures for the halocarbons proved successful and that stratospheric ozone has not increased significantly.

A Comparison of Scenario A (Freezing of 1990 Emissions By 2000) with Scenario A|prime^ (Temperature Stabilization by 2100)

Figure 2 plots temperature change, emissions, and permit price time paths for the two alternate control options. Panel (a) reveals that the baseline or business-as-usual case leads to an increase of equilibrium global average surface of 1.8 |degrees^ C by the year 2100. There is some slight evidence of a diminution of the rate of change due to a leveling of emissions in the later part of the century as cheap coal reserves decline and non-emitting backstop technologies begin to arrive on the scene as the result of market processes alone.

The two policy choices constrain temperature change as depicted in panel (a) to almost half the business-as-usual amount, about 1.0 degree by 2100. While both short- and long-run policy scenarios constrain temperature elevation to the same point at 2100, the time paths on the way to that point differ in important ways. A, the freeze scenario, constrains the path below that of A|prime^, the stabilization scenario, up to 2100. Beyond that date A continues to generate temperature increases compared with A|prime^ which has brought them to a halt. The slopes of the two curves, a possible impact variable, also differ, that of A|prime^ being above A through 2050 end then falling below.

The C|O.sub.2^ emission paths resulting from these two scenarios depicted in panel (b) of Figure 2 reveal the emission paths driving temperature change. Issuing annual marketable C|O.sub.2^ emission

* permits to hold emission levels constant, as in scenario A, yields the flat path of emissions shown, a path that opens a gap between the emissions of A and those of the business-as-usual path immediately after implementation.
* Issuing a large block of evaporative marketable permits that will yield the desired end point but that can be used at any time at the discretion of holders over the next hundred years, as in scenario

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A|prime^, yields a C|O.sub.2^ emission path that is close to the business-as-usual path until shortly after 2020, and above the path of A until 2050, but then declines below A toward the deep ocean absorption

The apparent departures from smoothness in the curves reflect the step function supply curves of fossil fuels that comprise the data base. They indicate the transition from one extraction cost category of reserve to another. The least energy cost paths chosen by the model to maximize energy welfare imply that the cheapest fossil fuel reserves will be used first.

Underlying these simulated emission paths is the story of the * energy industry, and traders, buying and selling permits as enterprises make cost-minimizing micro-adjustments to changing relative energy commodity prices. Consumers are also in theory making their adjustments to rising energy prices.

The most dramatic story unfolds in panel (c) where the model's discovery of permit prices (equated to shadow prices per ton of C|O.sub.2^ by carbon weight) is displayed. In scenario A, to repeat, * annual dated permits are issued each year in that amount to keep emissions constant at the 1990 level (aggregated to decades in the model), to be sharply distinguished from the undated evaporative * block of permits issued in the alternate scenario. The major reduction in emissions from baseline in the short-run required by scenario A is achieved by high initial permit prices and hence higher fossil fuel prices to induce conservation and to bring about as rapid changes as possible in energy technologies toward less emitting and non-emitting types. Permit prices rise by the year 2000 to about $80 per ton by carbon weight, adding about $64 to the price of a ton of coal (in 1980 prices) and over $6 per barrel of standard crude. Traders in the permit market are assumed to have forward looking expectations, but the annual limitation on permit use and banking prevents the use of portfolio holdings to smooth price paths and equate intertemporal marginal control costs.

As the model has putty-clay features restraining the decay of old and maximum growth rates constraining the introduction of new technologies, some time is required for less C|O.sub.2^ emitting technologies to play important roles. These rigidities, mimicking market realities, play a role in the rapid run-up of permit prices. The exhaustion of oil and especially natural gas toward the middle of the next century places heavy dependence on coal, which emits more C|O.sub.2^ per energy unit, thus requiring another rise in permit prices to induce the expensive backstop, non-emitting solar and nuclear technologies to replace coal. These inexhaustible energy resources are programmed to have constant costs and become competitive at about $275 per ton of C|O.sub.2^ by carbon weight.

In sharp contrast, scenario A|prime^, the graduated approach,

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reveals undated permit prices that start low, $5 per ton of C|O.sub.2^ by carbon weight, adding about $3.5 per ton of coal and * less than $0.5 per barrel of oil. Since all the permits have been issued at once at the start of this option and market traders are assumed to value them as an exhaustible resource, the price consequently rises as the rate of interest, or 5% in this study, and reaches levels of the freeze option only after 2050.

As cost-minimizing enterprises are envisioned to modify energy technology mixes to equate marginal mitigation costs to permit prices over time, real mitigation or control costs also rise as the rate of interest, thus achieving intertemporal cost-effectiveness in phasing down fossil fuels. The bottom line is that scenario A|prime^ yields a 900 billion dollar gain (1980 prices) over A in discounted (5%) consumer surplus during the period 1990 through 2100.

In scenario A|prime^ cumulative permit prices add to fossil fuel extraction and transportation costs so that backstop technologies become fully competitive between 2070 and 2080. The cost-effective phase-in of the backstops is a gradual time path, not an instantaneous shift, due in large part to the rigidities of change built into the model. For that reason, permit prices must "overshoot" backstop costs for a period of transition and continue to increase at 5% until the year 2100. The solid fork of the curve A|prime^ starting at 2070 depicts this overshooting whereas the dotted curve depicts the backstop cost which will determine the unit price of energy after 2100.

A Comparison of Scenario B (Reduction) with Scenario B|prime^ (Stabilization)

Temperature change is held to an increase of 0.7 |degrees^ C by 2100 in the control experiments of Figure 3, panel (a). The emissions reduction scenario B has a 20% reduction of 1990 emissions by 2010 and a 50% reduction by 2050. It reveals a temperature change time path that is below that of the stabilization scenario during the century, but continues to generate emissions leading to increases after that date. The stabilization scenario B|prime^ brings to a halt temperature change by 2100. It yields temperature increases close to the business-as-usual path until 2040 before departing significantly below.

Emission paths are revealed for the policy cases in panel (b) that are reduced appreciably from the business-as-usual case very early in the century for B and later for B|prime^. The latter emission path falls below that of the former after 2050 and reaches the deep ocean absorption rate at 2100.

The economic driving forces for these temperature and emission paths are revealed in panel (c). To reduce emissions by the amounts required for the two-staged reductions in B takes a rapid run-up of permit prices from over $100 in 2000 to $350 par ton of C|O.sub.2^

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shortly after 2020. Constraints on decay of old and growth of new
* energy technologies cause permits prices to rise for a time over the backstop costs of $275 per ton.

Permit prices for the stabilization scenario B|prime^ rise exponentially from 1990 to reach $10 per ton of C|O.sub.2^ in the year 2000 and finally $275 in 2060, the backstop rate. Again, overshooting is depicted by the fork at 2060. Scenario B|prime^ provides a cost-effective intertemporal path of permit prices permitting a smoother transition to non-emitting technologies. The bottom line is that B|prime^ yields a bonus of $2.2 trillion of discounted consumer surplus over B during the period 1900 through 2100.

CONCLUSIONS AND RESEARCH DIRECTIONS

Stabilization of induced temperature change at some future date has been analyzed in this study as an alternative to the frequently proposed but rarely implemented near-term emissions freeze or reduction scenarios. The stabilization scenarios were interpreted as
* the end result of introducing a cumulative tradable emissions permit
* system in which a block of undated permits are issued all at once for the volume of property rights carved out of atmospheric space as determined by international agreement. The stabilization policy leads to a market dictated time path of permit prices that start initially low and rise exponentially until the expensive backstop technologies become competitive, well into the next century. The stabilization policy is not a wait and see choice, but it is a policy calling for a low initial permit or internalization price that will increase as the rate of interest.

* The advantage of such a policy is that it permits micro-decision makers to equate marginal mitigation or control costs over time in an intertemporally cost-effective manner in addition to equating marginal costs across decision units at one point in time, the well-known cross-sectional cost-effectiveness. This study, using a dynamic, global linear programming model, has illustrated these policy alternatives and time paths for leading policy proposals. The model has permitted estimation of the gains in consumer energy welfare brought about by long-run stabilization scenarios when compared with temperature-equivalent near-term freeze or reduction actions. The gains, while small in terms of total energy welfare discounted over a very long-run horizon, are not trivial when comparing alternate policy choices.

Apparently contrary to these results are the conclusions of Nordhaus in a recent study (1992) in which he estimates that stabilizing realized temperature change to 1.5 degrees Celsius would be less optimal than freezing 1990 emissions for the global economy. The Nordhaus study sets the year 2040 for the stabilization target and sets realized not equilibrium temperature as the target

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dimension requiring almost 100% reductions in emissions by that date.
In our stabilization scenarios as revealed in Figure 2, emissions
are reduced less than 50% by 2040 and decline to the rate of
absorption of the deep ocean by 2100. Furthermore, the freeze
scenario of the Nordhaus study yields a temperature elevation of 2.5
|degrees^ C by 2100 compared with a final elevation of 1.5 |degrees^
C in his stabilization scenario. The apparent differences in the
studies reveal, in fact, the sensitivity of results to the choices
of a horizon date and of a temperature target.

Yet further research directions are suggested by our approach.
Priority ought to be given to studies of the impacts of various
aspects of induced climate change--this area remains in deep
informational uncertainty. One example of this is lack of knowledge
about the impacts of the various features of temperature change.

None of the scenarios of this study has built into them all the
potential energy efficiency gains advocated in recent studies,
efficiency gains that would, if realized, reduce C|O.sub.2^
emissions, perhaps 10% to 30% at little if not negative costs,
National Academy of Sciences (1991). Other studies of mitigation
costs have not always confirmed these gains suggesting that
reconciliation of these opposing views deserves careful research
investigation.

The policy instrument favored in this study policy was the
* cumulative tradable permit system presented here in a highly
simplified form, essentially a desk design rather than a prototype
model ready for adoption. The workings of such permit systems call
for new institutions that build trader confidence and assure proper
functioning, see, for example, Sandor (forthcoming).

* How to allocate permits among nations and among traders? The
issue is fraught with complexity, and opportunity. The proposal in
this study to issue at one time the entire stock of evaporative
* permits that would lead to the ultimate stable C|O.sub.2^
concentration was a simplifying device. While the intention to issue
* permits to achieve that goal could be pre-announced, as a practical
* matter the first block of permits to be issued could be some
* fraction of the entire stock. Issuing blocks of permits later to
particular countries could be made to depend upon observance of the
rules of monitoring and enforcement.

An international agency charged with managing the permit stock
and overseeing the permit markets could be of the nature of an
international bank or fund (the Global Environmental Facility?). To
it could be delegated the power of adjusting the outstanding stock
* of permits as new knowledge becomes available thus resembling the
activities of central banks in regulating the money supply.
* Designing, monitoring, and enforcing credible tradable permit
markets in the area of global warming, as in other environmental

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areas, deserves increased research attention, see Tietenberg (1985).

1. Clinton and Gore, Jr. (1993). Plans for reductions in emissions in later years are reported to be in preparation.

2. As reported in Rijsbermand and Swart, (1990). We recommend more attention to temperature and climate change impact studies; they have not received the support they deserve.

3. Specification of the programming set-up, a data base, and a user's guide are available from the authors on request.

4. The equations for the other trace gases are as follows: |N.sub.2^O and C|H.sub.4^ temperature effects vary as the square root of concentrations; and CFC11 and CFC12 effects are linear in concentrations. Lacis type equations are also specified in the model and provide estimates close to those portrayed in the figures. These equations for the major trace gases are used only in the illustrative Figure 1.

5. Note that temperature goals could be viewed as the elements of a damage function by attaching impact values to each goal.

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RECENT EVIDENCE ON THE APPROPRIATE TIMING OF REDUCTIONS IN GREENHOUSE GAS EMISSIONS

DAVID HARRISON, JR. AND ALBERT L. NICHOLS

PREPARED FOR

GLOBAL CLIMATE COALITION

JULY, 1996

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Executive Summary

Concerns about the potentially damaging effects of global climate change have led to proposals for substantial near-term reductions in emissions of carbon dioxide (CO_2) and other greenhouse gases. Although the push to "do something" is understandable, recent studies suggest that focusing on mandatory near-term reductions may not be cost-effective in light of the specific characteristics of global climate change. The major conclusions from our review of the relevant scientific and economic literature are the following:

- The *concentrations* of CO_2 and other greenhouse gases in the atmosphere drive potential changes in global climate.

- Because of the long residence time of greenhouse gases in the atmosphere, concentrations of greenhouse gases are due to *cumulative* emissions over many years, so that many different emission paths can lead to any given long-range concentration target.

- As a result, there will be ample opportunities to implement emission reductions in the future, if they prove needed, to achieve a wide range of possible global climate change targets.

- Future reductions will be *less expensive* than near-term reductions for several reasons: the present value of costs is lower the more distant in the future the costs are incurred; deferring emission reductions avoids transition costs from premature retirement of long-lived equipment, such as electric generating equipment; and technological progress promises to lower the cost of achieving CO_2 reductions.

- The cost savings from more flexible policies that shift reductions farther into the future are *substantial*; for example, Richels and Edmonds (1995) estimate that one such alternative emission path would reduce the cost of meeting a hypothetical long-run concentration target by 30 to 50 percent, depending upon the economic model used to evaluate the policies.

- Benefit-cost studies of climate change policy options conclude that substantial near-term reductions in CO_2 emissions probably are *not optimal*, even when account is taken of the substantial uncertainties. Peck and Teisberg (1992), Nordhaus (1994), and Manne and Richels (1995) all come to this same conclusion.

- Taking major uncertainties into account suggests that some additional hedging may be desirable, in the form of modest near-term efforts to slow the growth rate of emissions.

These studies do not suggest that nothing should be done now to limit possible climate impacts. For one thing, most studies indicate that some near-term reductions can be achieved at modest cost, and that such "low regret" measures make economic sense from a global perspective. A caveat: without coordinated international efforts, such low regret reductions may well not yield benefits commensurate with the costs to the country undertaking them. In addition, there is a potential payoff from accelerating the development and deployment of more efficient energy technologies. Finally, additional scientific and economic research is needed to increase our understanding of the costs and benefits of policy alternatives.

I. INTRODUCTION

Concerned about the potential effects of global climate change, some policy makers have called for specific timetables and targets to reduce emissions of carbon dioxide (CO_2) and other greenhouse gases. For example, the Conference of the Parties' Ad Hoc Group on the Berlin Mandate is considering various proposals to reduce emissions of CO_2 in the near term. One such proposal calls for a 20 percent reduction in CO_2 emissions below 1990 levels for the developed countries by the year 2005. Other proposals are less stringent, but nonetheless focus on near-term actions to reduce emissions as the best way to deal with the potential problem of global climate change.

This push to "do something" now to reduce emissions is motivated by several concerns. Some observers believe that failing to take action now simply postpones the inevitable. Others see immediate action as a way of avoiding the need for even larger cuts in the future, possibly at much greater expense. Still others worry that waiting to make significant cuts in emissions may be catastrophic, because it could lead to major changes in climate that could not be reversed even if massive costs were incurred to reduce future emissions.

The *Second Assessment Report* recently completed by the Intergovernmental Panel on Climate Change (IPCC)—a major effort that involved over 2,000 scientists and technical experts over almost three years—has been interpreted by some as a call for such a near-term commitment. However, a careful reading of that document—as well as recent studies that have been published after the IPCC study was completed—suggests a very different policy conclusion regarding the appropriate timing of actions:

> *Near-term efforts to freeze or reduce CO_2 emissions would be far more costly than necessary to achieve a wide range of potential long-term target concentrations of CO_2. The most cost-effective strategies appear to involve only limited, "low-regrets" actions for the next couple of decades, with continued research and technological development. Even if additional research shows that large reductions are warranted in the long run, it is more cost-effective to postpone the imposition of costly controls.*

The desirability of adopting a strategy with flexibility over time stems in large part from the fact that the effects of CO_2 and other greenhouse gases on global climate are determined by cumulative emissions over many decades and centuries. As a result, there will be ample opportunities to implement emission reductions in the future—on the basis of better information on the scientific and economic aspects of climate change, and with more cost-effective technologies developed in the interim—without endangering the ability to achieve whatever long-term goals ultimately are agreed upon.

Studies that have examined the optimal timing of emission reductions suggest that in the near term, only those reductions that can be achieved at very low cost should be pursued. At the same time, research should continue to better understand both the likely magnitude of climate change and its impacts, economic and other, on society. Research and development can reduce the cost of future reductions by developing more efficient ways to use energy and less carbon-intensive ways of providing it. Recognizing the long-term, global nature of the issue, it also makes sense to develop international mechanisms to coordinate actions where appropriate. Global climate change is not an issue amenable to short-term "fixes;" it cannot be settled "once and for all." Rather, global climate change is best seen as requiring a long-term sequential series of decisions, each informed by increasing bodies of knowledge.

This paper summarizes the results of these recent studies and provides a non-technical explanation of the factors that underlie the importance of flexible timing in addressing emissions of CO_2 and other greenhouse gases. The studies reviewed are striking in the unanimity of their conclusions on this key issue. Whether the authors are EPA economists, industry-sponsored researchers, or academic scholars, all agree that near-term efforts to freeze emissions or to reach other arbitrary short-term emissions targets are not cost-effective.

II. Factors Affecting the Efficient Timing of Emission Reductions

Before turning to the results of the various studies, it is useful to understand the key scientific and economic factors that help determine the most cost-effective paths for reducing greenhouse gas emissions.

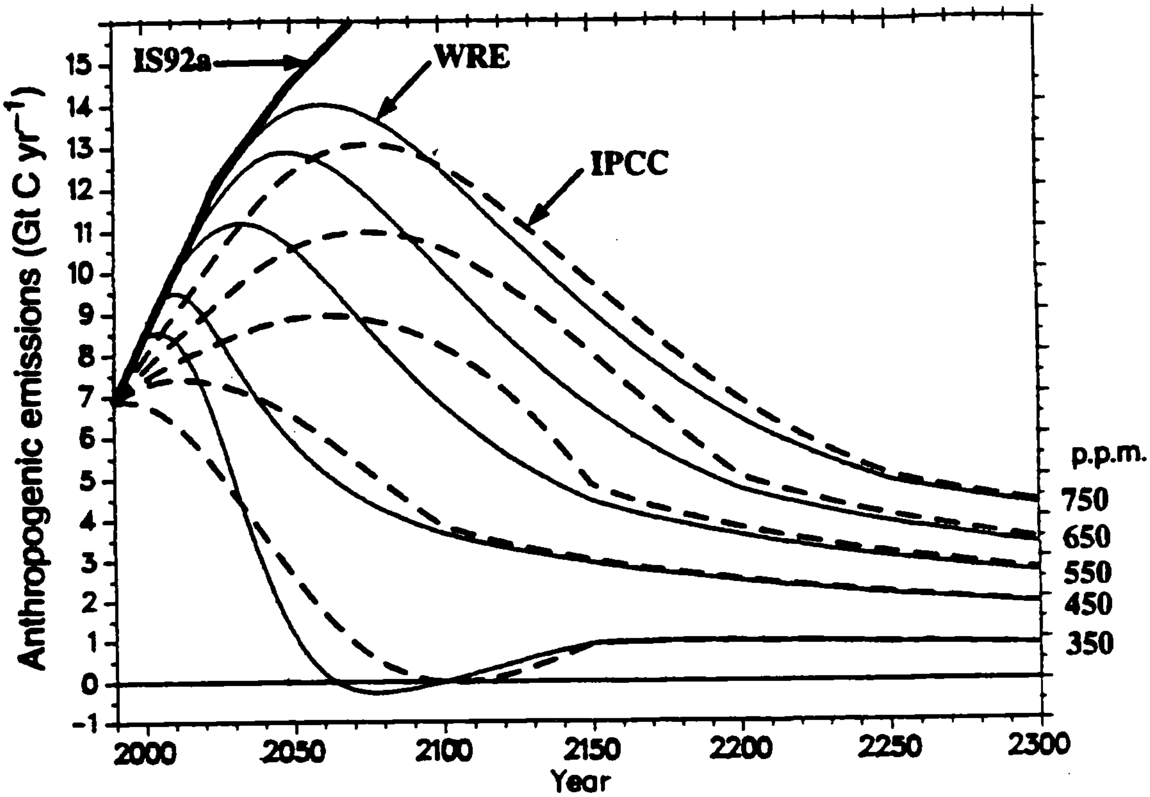
A. Scientific Factors

Sensible policy on greenhouse gas emissions is predicated on two key scientific characteristics of global climate change:

1. CO_2 and other greenhouse gases have the same effect on global climate regardless of where they are emitted in the world.
2. Climate effects depend on global atmospheric *concentrations* of greenhouse gases, which are the cumulative result of emissions over time periods measured in decades and even centuries.

The first proposition is widely acknowledged. The term "global climate change" implies that one must take a global perspective and consider emissions and emission-mitigation opportunities from all regions of the globe. This fact poses serious problems of international coordination, because it will always be in the self-interest of individual countries to reap whatever benefits arise from global reductions in emissions without having to incur the costs of making reductions themselves. However, all of the studies discussed here assume, at least implicitly, that the problems of international coordination have been solved, so that all nations work together to find the most efficient, least-cost approach to reduce greenhouse gas emissions.

The second proposition is key to understanding the results of recent studies on the cost-effective time path for controlling emissions. The greenhouse effect of CO_2 and the other gases that trap the earth's radiated heat depends upon their concentrations in the atmosphere. Future concentrations depend upon current concentrations, future emissions, and the removal rate from the atmosphere due to natural processes. The natural removal rate varies among the greenhouse gases; CO_2 has a long life, implying that the concentration of CO_2 in a future target year (e.g., 2100) is proportional to cumulative emissions over the preceding years (Edmonds and Wise

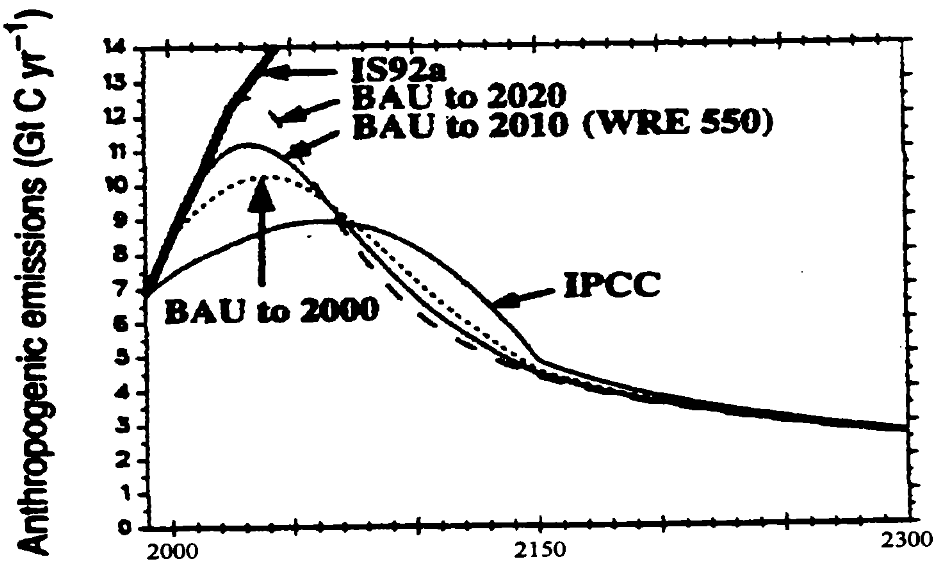


Note: IS92a is the reference IPCC business as usual (BAU) curve.
Source: IPCC as reported in Wigley, Richels and Edmonds (1996).

Figure 1. Target Concentrations and Corresponding Emission Alternate Paths Developed by Working Group I of the IPCC and by Wigley, Richards, and Edmonds (WRE)

1996, 77). However, emission reductions closer to the target year are more important than early reductions, because the natural carbon cycle results in a substantial portion of the CO_2 emitted now being absorbed by the oceans by 2100.

Because of the long-lived nature of CO_2 in the atmosphere, global concentrations depend on cumulative emissions and natural carbon cycle absorption over many decades. As a result, many emissions time paths can achieve the same concentration level at a particular point in the future. For example, the IPCC Working Group I published several different emission paths, each leading to a different long-term concentration of CO_2, ranging from 350 to 750 parts per million volume (ppmv). As shown by the dotted lines in Figure 1, all but the highest (750 ppmv) of these paths entail immediate reductions in emissions below the "Business as Usual" (BAU) path that would apply if no action were taken. With the exception of the lowest path (350 ppmv), however, these paths do allow for continued growth in global emissions for several



Source: Wigley, Richels and Edmonds (1996).

Figure 2. Wigley, Richels, and Edmonds' Alternative Emission Paths to Reach a Concentration of 550 ppmv in 2100

decades or more; they do not call for immediate stabilization of emissions. Nonetheless, the publication of these paths has helped spur calls for near-term action.

As Wigley, Richels, and Edmonds (1996) point out, these time paths for emissions are not unique; each of the concentration targets selected by the Working Group could be reached by a wide range of emission paths, many of which do not require near-term reductions below the BAU path. The authors illustrate the options for each target level, as shown by the solid lines in Figure 1. For a target of 550 ppmv in 2100, they compare the BAU and IPCC paths to three alternative paths that assume that no significant actions to reduce emissions would be taken for 10, 20, or 30 years, respectively. Figure 2 shows the three emission time paths the authors developed, as well as the original path published by the IPCC and the BAU path. Although very different, all four emission paths lead to the same long-term concentration.

B. Economic Factors

For any long-term target concentration of greenhouse gases, the world can be thought of as having a long-term emissions budget that can be used over time. If more is "spent" now, less will be available later. If we take the concentration target as fixed, cost-effectiveness analysis can help us determine the least-cost way of staying within that long-term global budget (assuming that problems of international coordination have been solved, so that in any time period emissions are reduced at least cost). Four important factors influence the shape of the cost-effective path. The first of these factors—marginal costs rise as the level of reduction grows at any point in time—is sometimes offered as an economic rationale by those who advocate substantial near-term reductions. However, the other three factors—the time value of money, the costs of premature replacement, and technological progress—all argue in favor of more flexible paths that postpone major reductions.

1. Rising Marginal Costs

At any point in time, as deeper cuts in emissions from the BAU path are made, the incremental cost per ton of CO_2 reduced rises. Intuitively, the first tons reduced are the easiest, obtained at virtually no cost. For example, they may involve increases in energy efficiency for which the savings in fuel costs are almost as great as the cost of more efficient equipment, or changes in fuel where the fuel prices are nearly equivalent. More drastic cuts, however, require making increasingly expensive changes in technology or fuel.

With rising marginal costs at any point in time, it is less expensive to make a series of small cuts over several years than one large one. This simple observation provides the basic economic rationale for calls to start reductions now so that large reductions will not be needed in the future. However, this rationale fails to provide reliable guidance because it ignores the other three important economic considerations.

2. Time Value of Money

Reductions in emissions of greenhouse gases can be thought of as investments—spending money today to yield benefits in the future in the form of reductions in potential damages from global climate change. In evaluating any potential investment, it is essential to recognize that it matters not only how large the investment is, but also *when* it is made. Funds tied up in one investment are not available for other purposes, where they can earn a return. Thus, investing money today to reduce CO_2 emissions must be compared to alternative investments. It is economically rational to make that investment in CO_2 reductions only if it yields a higher rate of return (in the form of savings in future control costs) than other investments available in the economy. To put alternative investments in equivalent terms, we must compare them either in terms of their present value today (which involves discounting) or in terms of their future value at some point in the future.

The significance of the interest rate in determining the correct timing of CO_2 controls can be illustrated with a simple example. Suppose that investing a dollar now can yield 5 percent in real interest (i.e., over and above inflation). This is a modest return, well below long term averages for investments in stocks. In 10 years, the value of that dollar investment will grow to $1.62. In 20 years, it will be $2.65, and after 30 years it will reach $4.32. Suppose that we are considering whether to invest that dollar in CO_2 control today, or to invest it elsewhere, where it can earn a 5 percent rate of return. If we invest the dollar elsewhere (i.e., we do not spend it on current reductions in CO_2 emissions), after 30 years we will have $4.32. If we wanted to do so, we could then invest that $4.32 in reductions in greenhouse gas emissions. Unless we think that $4.32 (inflation adjusted) will not buy as much reduction in emissions at the margin in 30 years as $1 will buy today, we are better off waiting to make the investment in emission reductions.

To account for the time value of money, economists and financial analysts routinely compute the present values of costs and benefits when comparing policies with different time paths. Similarly, the empirical results reported later in this paper generally are expressed as present values or, equivalently, as annualized figures that incorporate an interest rate.

3. Premature Replacement of Capital Stock

Many of the actions needed to reduce CO_2 emissions involve changes in long-lived capital equipment, such as electric generating plants, manufacturing equipment, and motor vehicles. Typically it is much more costly—if not simply impossible—to make these changes in existing equipment, rather than incorporating them in new equipment. By introducing flexibility in the timing of CO_2 reductions, it is possible to take advantage of normal replacement cycles for equipment and plants. Rather than requiring major investments to replace existing capital prematurely, the changes can be incorporated into new equipment, with relatively modest incremental costs (because replacement is needed independent of policies towards CO_2 and other greenhouse gases).

4. Technological Progress

During this century, energy efficiency has improved dramatically in the United States and other developed countries, with ever smaller amounts of energy needed per unit of output.[1] There is every reason to believe that this trend will continue. In addition, technological progress is likely to lower the relative cost of low-carbon or carbon-free substitute forms of energy, which will further cut the cost of reducing CO_2 emissions in the future. It may make sense to accelerate the rate of technological progress in these alternative technologies through stepped-up research and development programs. Even at normal, market-driven rates, however, it is clear that advances in technology will lower the cost over time of achieving any given reduction in CO_2 emissions per unit of output.

The prospect of lower costs due to technological progress also reinforces the desirability of avoiding policies that entail premature replacement of long-lived capital. Replacing equipment prematurely would mean locking in the current technology. In contrast, waiting until the end of the equipment's normal economic life means that it will be replaced with future, more energy-efficient capital equipment.

[1] From 1974 to 1994, energy consumption in the United States fell from 22,330 Btu per dollar of GDP to 16,556—a decline of almost 26 percent (EIA 1995).

÷ 20 yr = 1.3% / yr

III. Cost-Effectiveness Analyses of Alternative Time Paths

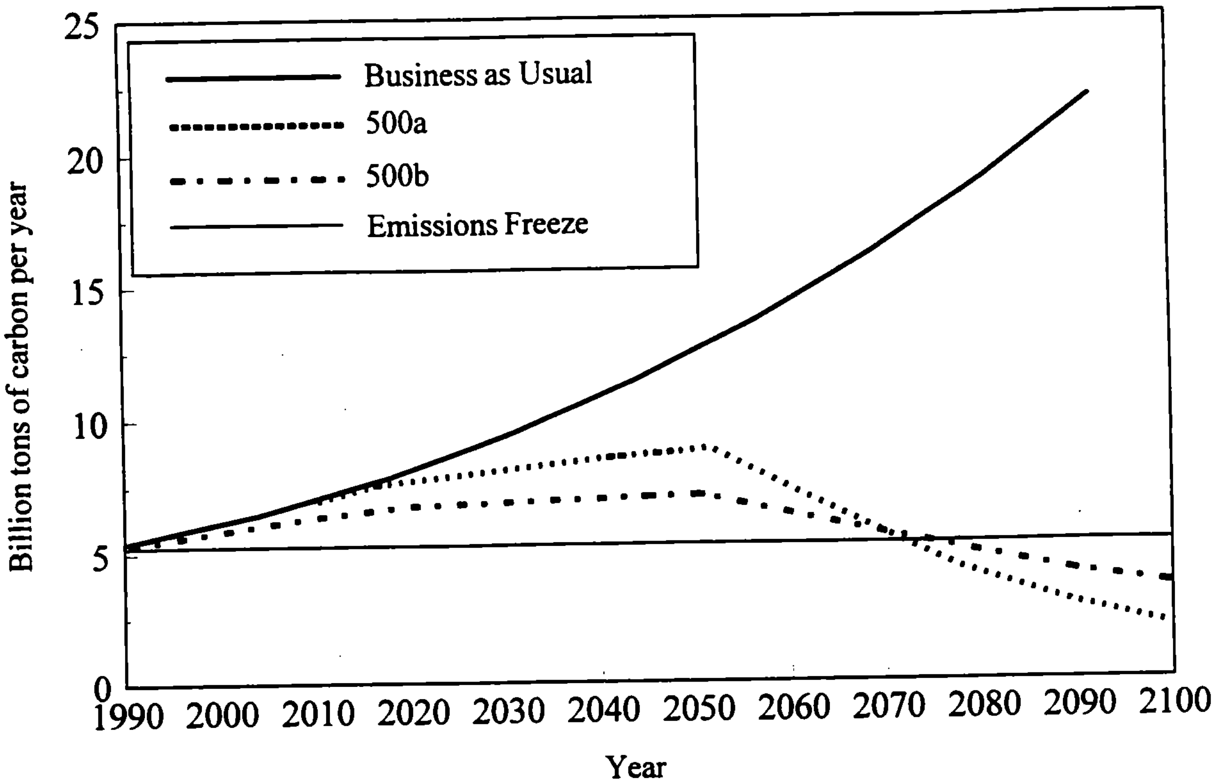
The scientific and economic considerations outlined above have been incorporated in several recent studies that estimate the global cost of alternative time paths of emissions to achieve specified target concentrations of CO_2.[2] These studies conclude that near-term freezes or reductions in emissions are unnecessarily costly, and that more flexible temporal strategies can reduce costs substantially.

A. Richels and Edmonds (1995)

Richels and Edmonds (1995) evaluate the costs of alternative emissions time paths that achieve a CO_2 concentration of 500 ppmv in the year 2100; although that specific target is arbitrary, it lies within the range of hypothetical targets offered by the IPCC and others. Figure 3 shows the alternative emissions trajectories evaluated. The top line shows emissions under the business as usual (BAU) scenario. The horizontal line represents the oft-proposed policy of stabilizing emissions at their 1990 level, which requires increasingly stringent reductions from the BAU path, starting immediately. The line labeled 500a is a scenario in which emissions follow the BAU path until roughly 2010, are reduced gradually below the BAU path between 2010 and 2050, and are reduced sharply thereafter so as to keep concentrations below 500 ppmv in 2100. The line labeled 500b represents an emissions path between the 500a path and the emissions stabilization path. Richels and Edmonds point out that the cumulative emissions under the three scenarios (as represented by the areas under the curves) are approximately the same, reflecting the fact that all three are designed to lead to the same concentration in 2100.

Richels and Edmonds estimate the costs of these alternative paths using two different models of long-term energy-economy interactions: Global 2100 and the Edmonds-Reilly-Barns Model (ERB). Both models can be used to simulate the effects of different policies and to

[2] Manne and Richels (1992) provide an earlier indication of the potential cost savings from delaying carbon reductions. They show that postponing emissions stabilization by 10 and 20 years reduces the present value (discounted) of cumulative cost by 25 percent and 40 percent, respectively. However, the authors do not estimate the effect of these different policies on concentration or temperature change (although they do show that the cumulative emissions over the period from 1990 to 2100 differ little under the alternative policies).

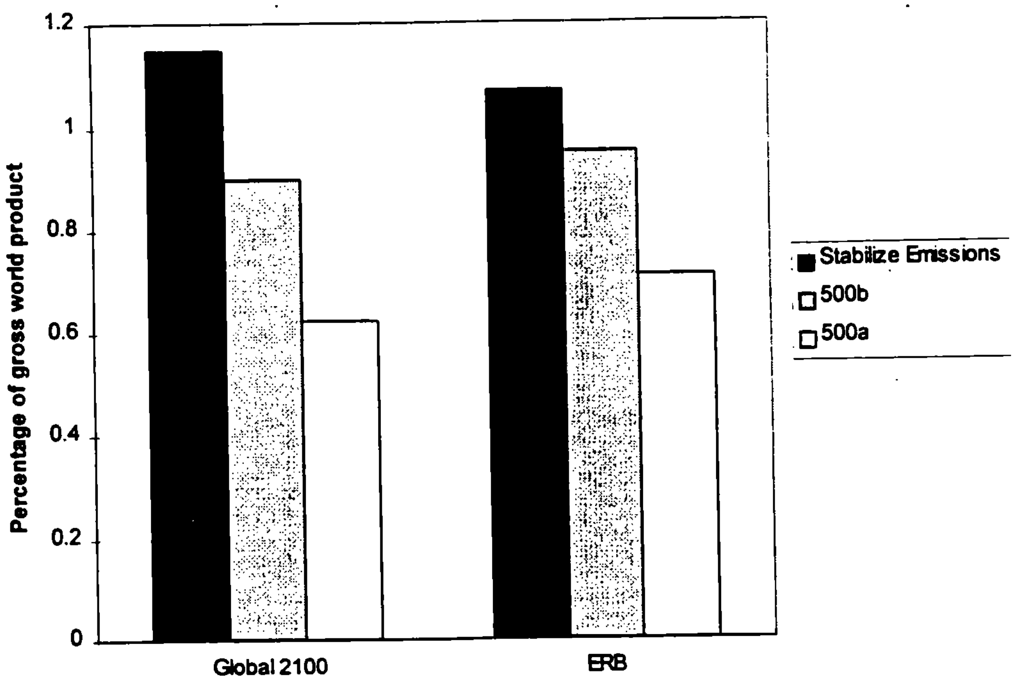


Source: Richels and Edmonds (1995).

Figure 3. Alternative Emission Time Paths Evaluated by Richels and Edmonds

estimate their costs. In estimating the costs of alternative time paths of emissions, both models were run assuming that the policies implementing these time paths would be designed as efficiently as possible; i.e., that incentive-based flexible policies would be used that ensured that the least-expensive reductions would be achieved first, independent of the sector or global region in which they occurred. In reality, policies to reduce emissions almost certainly would be much less efficient, raising the costs of all policies, but especially of those requiring near-term reductions by only the developed nations. The models share several common features, but also differ in important ways, thus providing a useful indication of the sensitivity of the conclusions to model specification.[3]

[3] These differences include the ways in which the models find the least-cost mix of actions, how flexible they assume the capital stock is in response to changing prices, and the regional breakdowns they use.



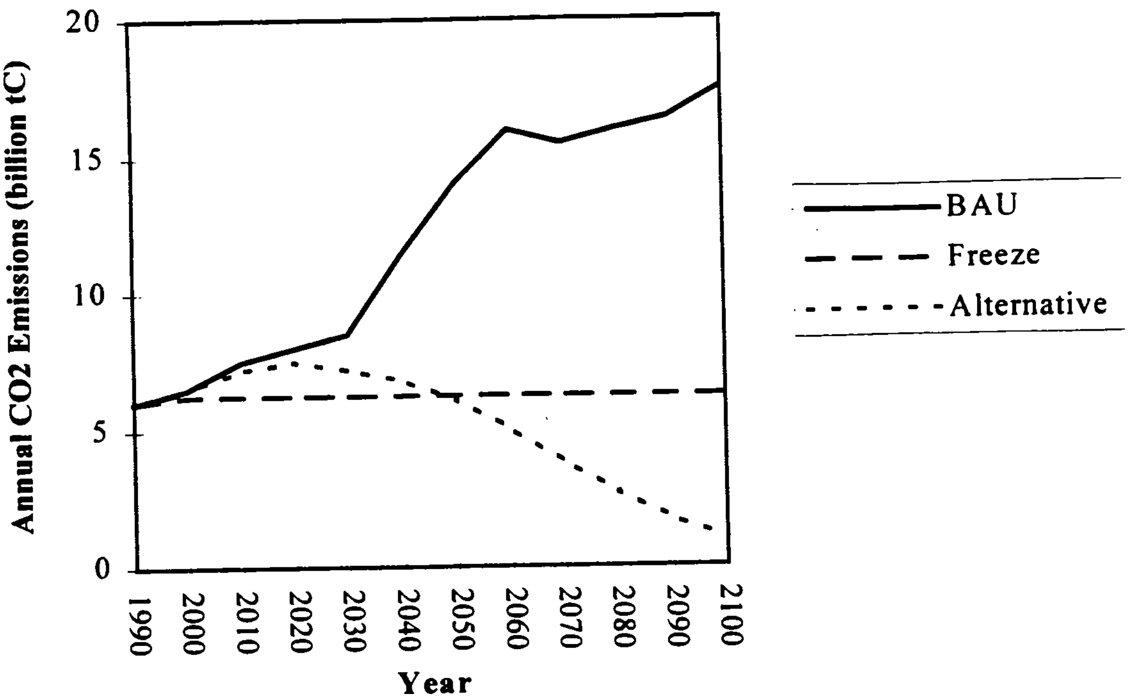
Source: Richels and Edmonds (1995).

Figure 4. Richels and Edmonds' Estimates of the Costs of Alternative Time Paths to a 500 ppmv Concentration

Figure 4 shows the alternative estimates of the costs of the three emission trajectories. Although the absolute estimates differ, the fundamental finding is the same. *Stabilizing emissions at 1990 levels is by far the most costly strategy.* Shifting emission reductions to the later years reduces the present value of overall costs substantially, although they are still large in absolute terms. Relative to immediate stabilization, the path labeled 500a reduces estimated costs by about 50 percent according to the Global 2100 model and about 30 percent according to the ERB model.

B. Kosobud et al. (1994)

Kosobud et al. (1994) also evaluate the costs of alternative emission paths to achieve a given target in 2100. They measure their target in terms of temperature change predicted by a model, rather than CO_2 concentration. However, they reach the same conclusion as Richels and Edmonds—an immediate global freeze on emissions is far more costly than a more flexible approach that only gradually diverges from the BAU path.



Source: Kosobud et al. (1995).

Figure 5. Two Alternative Paths to BAU that Achieve the Same Long-Term Global Temperature

Figure 5 shows the BAU path along with two alternatives that Kosobud et al. predict would limit temperature change to 1.0 °C by 2100 (about half of what they predict would occur under the BAU scenario). The emissions-freeze strategy keeps emissions constant at 1990 levels over the next century. The alternative path rises and is relatively close to the BAU path until shortly after 2020. In future years, emissions decline, but they do not reach their 1990 levels until about 2050. These two trajectories have very different implications for the marginal abatement costs and cumulative costs. The marginal abatement cost would be about $140 per ton of carbon (1995 dollars) in the year 2000 under the emissions-freeze scenario, rising to about $250 per ton by 2020.[4] In contrast, the alternative strategy involves an initial marginal cost of less than $9 per ton of carbon and does not rise to the level of the freeze strategy until

[4] Throughout this paper, we have updated all dollar estimates to 1995 dollars using the GDP deflator.

after 2050. Kosobud et al. estimate that the temporally flexible alternative path reduces the present value of the cost of achieving the target by a total of $1.6 trillion (1995 prices, discounted at 5 percent).

C. Leary and Scheraga (1994)

Leary and Scheraga, both economists at the U.S. Environmental Protection Agency, review two major issues related to the design and implementation of efficient plans to reduce CO_2 emissions. The first is the substantial cost savings from using flexible market-based mechanisms (e.g., tradable carbon permits or a carbon tax) as opposed to more prescriptive command-and-control regulations.

The second issue is the question of the timing of emission reductions. Although the paper does not develop new empirical evidence on the effects of alternative time paths and it was completed before Richels and Edmonds (1995) was published, the authors' review of the empirical evidence comes to the following conclusion:

> The evidence reviewed here suggests that proposed targets and timetables that call for reducing or even stabilizing annual CO_2 emissions by 2000 or 2010 are overly aggressive. Even modest delays of a few years in the target dates have the potential to yield substantial cost savings (Leary and Scheraga 1994, 109).

IV. BENEFIT-COST ANALYSES OF ALTERNATIVE TIME PATHS

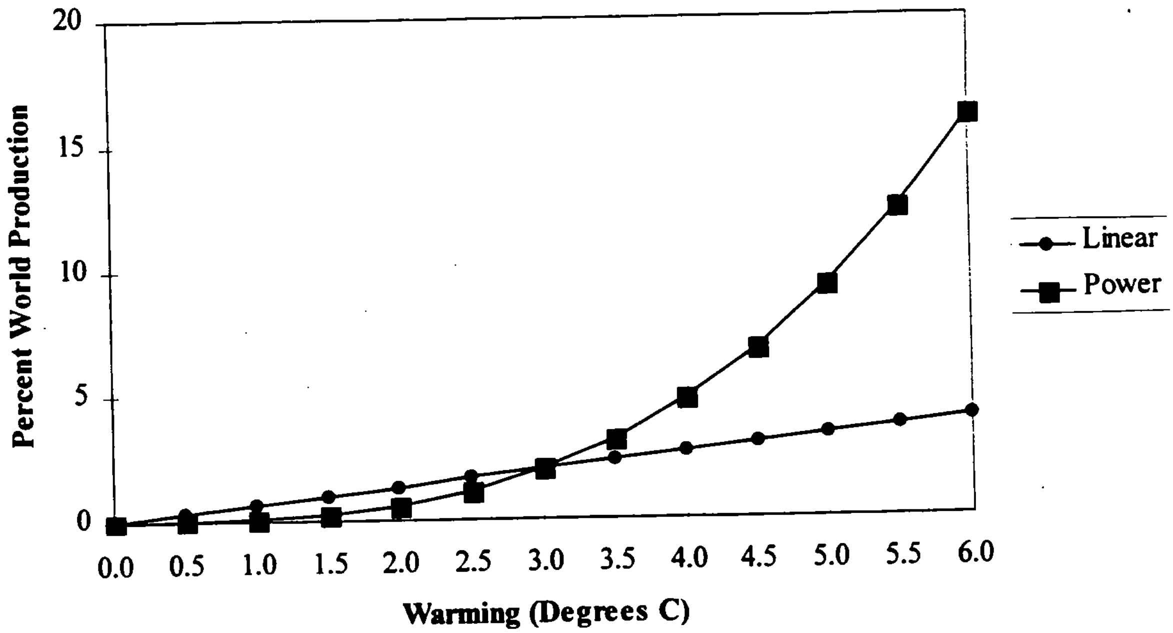
The cost-effectiveness analyses discussed in the previous section take a target concentration of CO_2 (or temperature) as given for some future year and then compare the costs of alternative paths to reach that goal. That approach avoids the difficult task of estimating the damages (or benefits, in at least some regions) that may be caused by global climate change. However, the cost-effectiveness approach suffers from two important limitations:

1. It is based on arbitrary targets, which may be far from optimal in the balance they strike between the costs of emission reductions and the potential damages caused by climate change.
2. It does not account for differences in damages caused by different time paths of concentrations using alternative emission trajectories to the same long-term target.

Several studies have attempted to avoid these limitations by adopting a broader benefit-cost framework that accounts for benefits as well as costs over time. Despite the difference in approach, these studies come to the same fundamental conclusion: optimal policies do *not* impose near-term freezes or reductions in emissions, but rather take a more flexible approach.

A. Peck and Teisberg (1992)

Peck and Teisberg (1992) derive emission paths that maximize the estimated global net benefits over time; rather than take the target as fixed, they find the target and the path that maximize the present value of the estimated difference between the benefits of reduced climate change and the costs of emission reductions. They base their cost estimates on the Global 2100 model, which was developed by Manne and Richels (1992) and which was one of the two cost models used by Richels and Edmonds (1995) in the cost-effectiveness analysis discussed above. They base their benefit estimates on estimates of damages developed in Nordhaus (1991) for a 3 °C temperature rise; to estimate benefits for lower and higher temperature changes, they fit two alternative damage functions, as shown in Figure 6. One function is linear; it assumes that marginal damages are constant as a proportion of the size of the economy, so that total damages rise in proportion to the change in temperature and increases in the size of the global economy. The other function is a nonlinear power function, with marginal damages

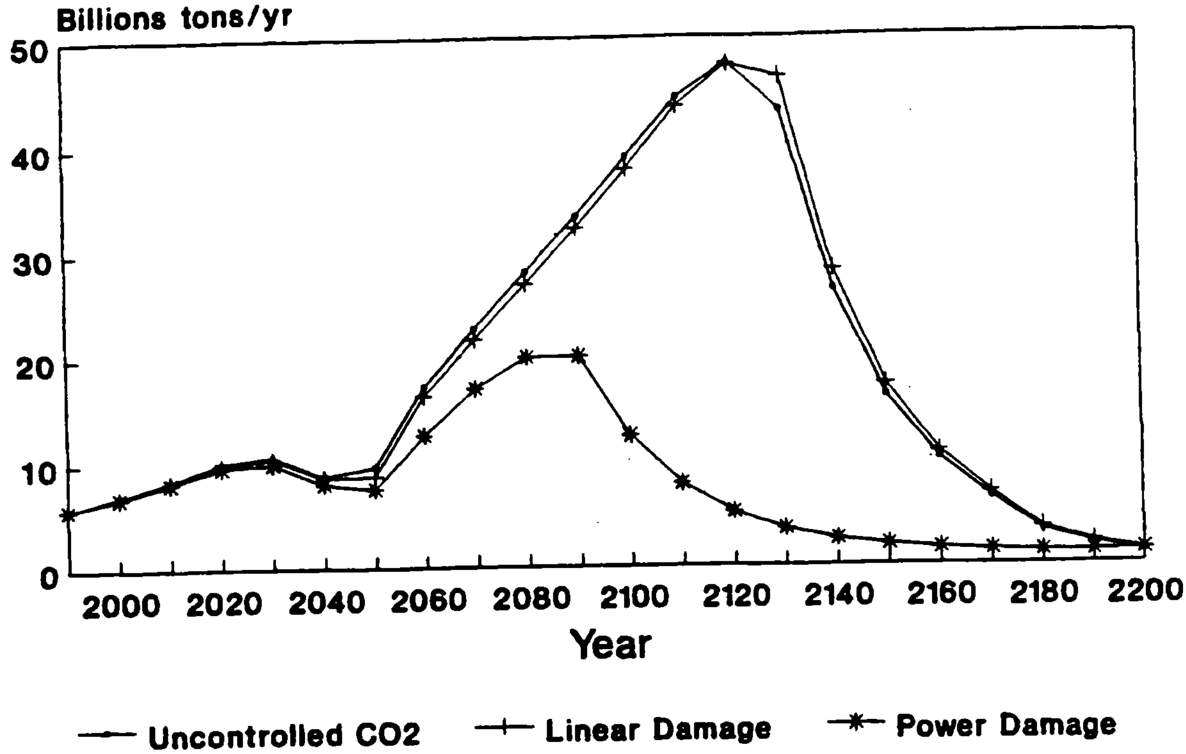


Source: Peck and Teisberg (1992).

Figure 6. Alternative Damage Functions Used by Peck and Teisberg

(as a fraction of the size of the world economy) rising with emissions, so that damages rise more than in proportion to temperature change (though still in proportion to the economy's size). Both functions imply that the damages caused by a 3° C temperature change would be 2.0 percent of global output. If the temperature change were doubled, to 6° C, the linear function predicts that damages also would double, to 4.0 percent. The nonlinear function, however, predicts drastically higher damages of 16 percent of world output for the 6° C change.

Using Global 2100 for costs, Peck and Teisberg find the time paths of emissions that maximize global net benefits (i.e., benefits minus costs) under the two different damage functions. Figure 7 plots the results, along with the BAU reference case. The BAU emissions path reaches a peak of nearly 50 billion tons per year, or about ten times the current level. (This path reflects the mix of energy technologies projected over time; the emissions peak occurs when synthetic fuel use is at a peak.) The optimal emissions path under the linear damage function is very similar to the uncontrolled case, though slightly lower for the next century. The optimal emissions path assuming the nonlinear damage function is very different in the later years; it peaks earlier and at a much lower level than under either the linear function or the



Source: Peck and Teisberg (1992).

Figure 7. Optimal Emission Time Paths Estimated by Peck and Teisberg for Alternative Damage Functions

BAU case. However, although the long-run differences are major, the paths are very similar up through the middle of the next century, with significant divergence only after 2050. Thus, even under the non-linear damage function assumption, mandatory near-term emission reductions are not warranted.

B. Nordhaus (1994)

In a recent book, Nordhaus (1994) has estimated the costs and benefits of different emission paths for slowing or arresting the rate of global climate change. The cost components of the model are based upon a detailed set of economic relationships. The benefit estimates are based upon geophysical relationships that link emissions of CO_2 and other greenhouse gases, atmospheric concentrations of these gases, average temperature change, and damages from global climate change. Nordhaus uses his model to evaluate alternative approaches to climate change policy and to find the policy that maximizes the present value of estimated global net benefits. As with the Peck and Teisberg study and the cost-effectiveness analyses discussed earlier, he assumes that all policies are implemented in a cost-effective and flexible but coordinated manner that minimizes the worldwide costs of achieving the specified emission levels in any given period. In addition to CO_2 reductions, his analysis includes chlorofluorocarbons (CFCs)[5] as well as forestry programs to provide sinks for carbon. Thus, all of his results are in terms of "CO_2 equivalents."

Nordhaus' book is notable for its explicit treatment of the large uncertainties that surround estimates of the costs and benefits of slowing climate change. However, it is useful to begin by looking at his "best case," one in which Nordhaus determines the time path that maximizes predicted net benefits using his best estimates of the uncertain parameter values. Figure 8 plots three emission paths: the one that Nordhaus estimates to be optimal given his "best" estimates, his projection of BAU, and the ubiquitous alternative of freezing emissions at their 1990 level. Nordhaus' optimal path lies well above that followed under the policy of freezing emissions at 1990 levels. Relative to the BAU line, the reductions under the optimal path are small, rising gradually from just under 9 percent from 1990-2010 to a little over 13 percent in the 2070s. Note that the reductions in the first decade include the phaseout of CFCs and the introduction of forestry programs that provide carbon sinks, as well as reductions in CO_2 emissions per se. In contrast, although the freeze policy starts off with a 9 percent reduction in the 1990s, it rises quickly to 24 percent in 2000-2010 and to 62 percent in the 2070s.[6]

Table 1 shows the results under the optimal policy. Nordhaus' estimate of the optimal control pattern has a marginal cost of \$6.30 per ton of carbon equivalent in the 1990s and reaches only \$10 per ton in the first two decades of the 21st century. In contrast, he estimates that the marginal cost of a 1990 freeze would start at \$11/ton in the 1990s and rise to over \$110/ton in 20 years (1995 dollars).

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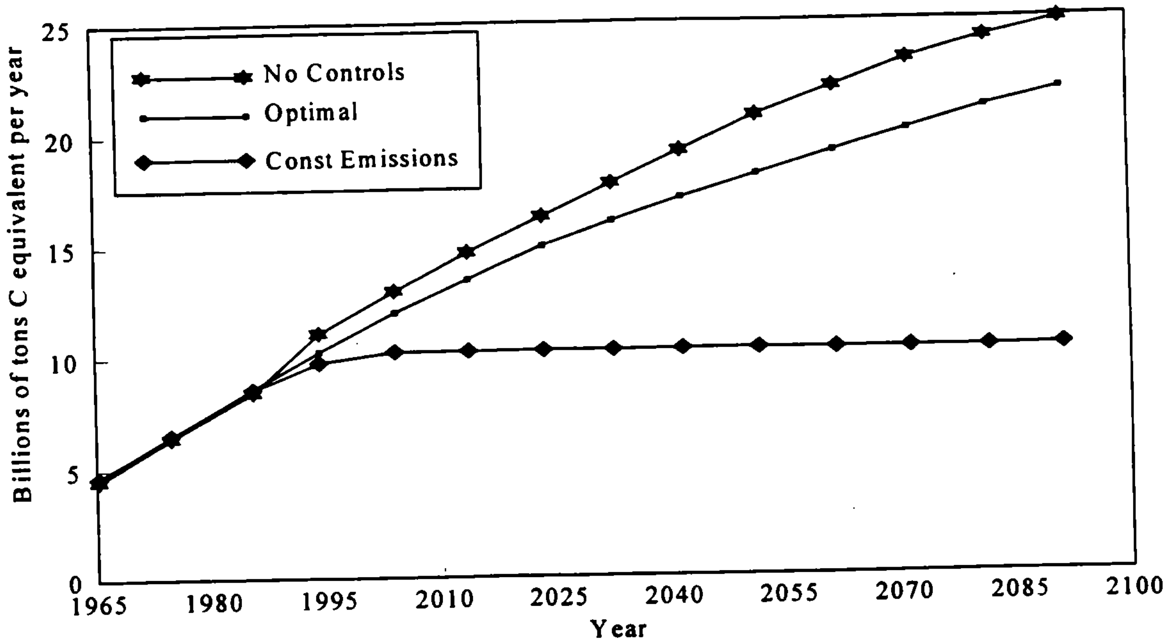
[5] CFCs have been banned from most uses in most countries primarily because they deplete stratospheric ozone. However, they also are very powerful greenhouse gases.

[6] Nordhaus estimates that emissions of CO_2 plus CFCs were equivalent to 8.45 billion tons of carbon equivalent in 1990 (Nordhaus 1994, Table 4.7). His projections for BAU and the Optimal path are in Table 5.4.



Source: Nordhaus (1994).

Figure 8. Comparison of BAU and Optimal Time Paths Using Nordhaus' Best Estimates of Parameter Values

Table 1. Levels of Control and Corresponding Marginal Expenditures on Control of Greenhouse Gases

Decade Centered on Year	Optimum Rate of Control of GHGs (percent)	Optimum Marginal Cost (1995$ per ton carbon equivalent)
1965	0.0	$0.00
1975	0.0	0.00
1985	0.0	0.00
1995	8.8	6.30
2005	9.6	8.10
2025	11.1	12.00
2075	13.4	21.30

Notes: Control rate is percent of uncontrolled greenhouse gas (GHG) emissions. Marginal cost is per ton of CO_2 equivalent, carbon weight.
Cost updated from 1989 to 1995 dollars using GDP deflator.

Source: Nordhaus (1994).

Table 2 shows Nordhaus' estimates of the net benefits of alternative policy options. Not surprisingly, the estimated net benefits of Nordaus' optimal path relative to the BAU path are very small—on the order of 0.04 percent of worldwide consumption—because his optimal path is not very different from BAU. On the other hand, the estimated net *loss* from stabilizing

Table 2. Nordhaus' Estimates of Net Benefits of Alternative Policies

Policy	Present Value of Net Benefits	
	Billions of 1995$	Percent of World Consumption
Optimum	$325	0.04%
Stabilize emissions at 1990 level	($8,480)	(0.98)%

Notes: Net benefits calculated as difference in the present value of consumption between the BAU case and the policy in question. Values in parentheses indicate negative net benefits. Nordhaus uses a discount rate that varies with the growth of the economy over the period under consideration. Generally speaking, this discount rate is about 6 percent for the first few years and then slowly declines over the remainder of the period.

Net benefits updated from 1989 to 1995 dollars using GDP deflator.

Source: Nordhaus (1994).

emissions at their 1990 level is more than an order of magnitude larger, approaching 1 percent of global consumption.

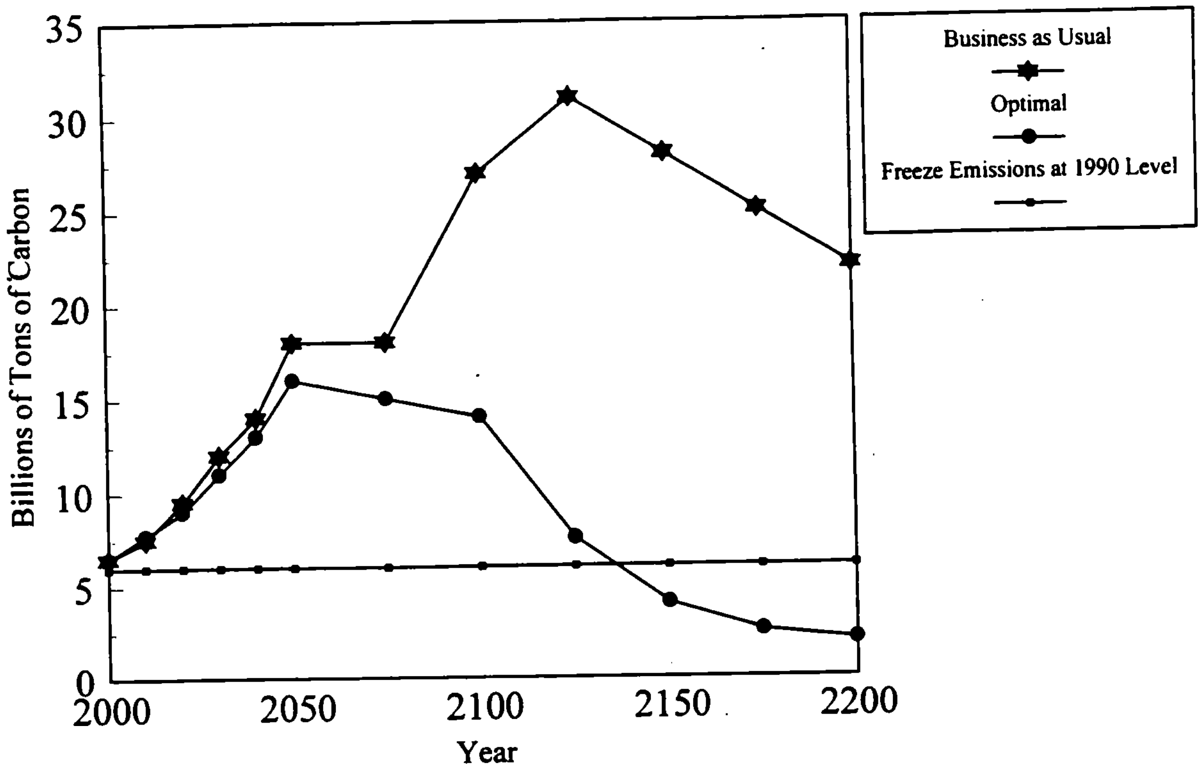
C. Manne and Richels (1995)

Manne and Richels develop a model in the tradition of Nordhaus (1994) and Peck and Teisberg (1992) that includes both cost and benefit components. Their model keeps track of effects on five geopolitical regions.[7] It also includes estimates of non-market as well as more easily monetized market damages from climate change.[8] As in the other benefit-cost studies, Manne and Richels use their model to identify a time path of emission controls that maximizes the present value of net benefits, the difference between estimates of reduced damages from climate change and increased costs from reducing carbon emissions.

Figure 9 plots three different emission trajectories analyzed by Manne and Richels: as in earlier graphs, the top curve is their estimate of the BAU path, while the lowest line is the policy of freezing emissions at their 1990 levels. The middle curve is the optimal path given their estimates of benefits and costs. It remains close to the BAU line until about 2050, after which it starts falling. However, emissions do not fall back to their 1990 level until well into the 22nd century. Manne and Richels estimate that relative to the BAU path, the optimal strategy

[7] The regions are the U.S., other OECD countries, the former Soviet Union, China, and the Rest of the World.

[8] "Market damages" include such potential effects as increased costs of raising crops. "Non-market damages" include potential effects that are not captured in market transactions, such as aesthetic concerns about changes in vegetation. Manne and Richels assume that non-market effects vary with the per capita income of the region.



Source: Manne and Richels (1995).

Figure 9. Three Emissions Trajectories Analyzed by Manne and Richels

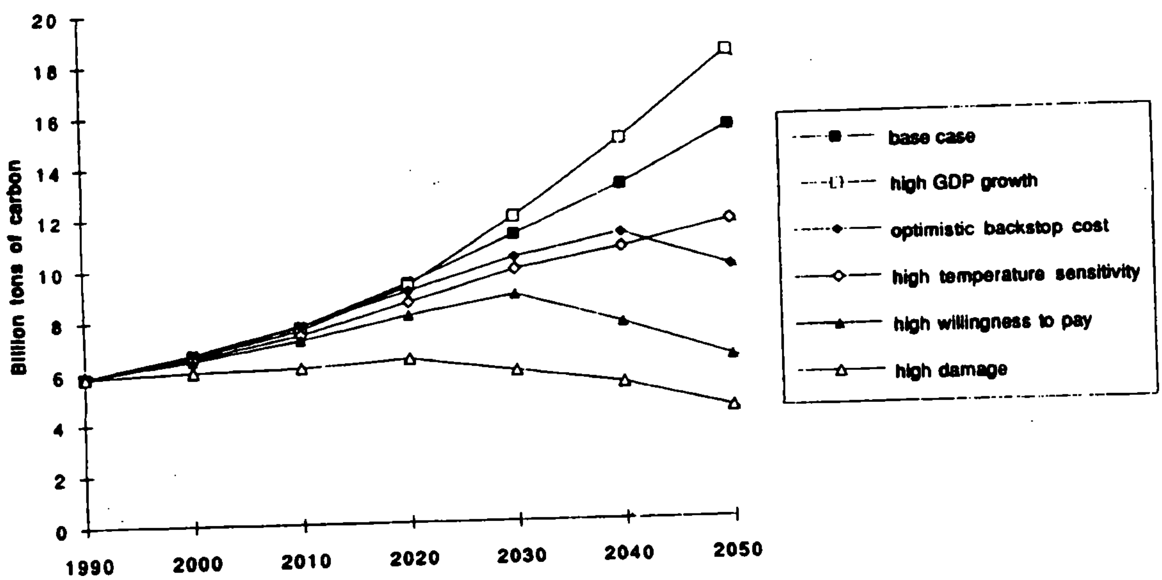
increases the present value (5 percent discount) of net benefits by about $200 billion dollars. In contrast, freezing emissions at their 1990 level *reduces* net benefits by an estimated $4 trillion.

V. OPTIMAL TIME PATHS UNDER UNCERTAINTY

The results described above are based upon the authors' "best" estimates of the costs and environmental effects of different time paths for greenhouse gas emissions. Virtually every study, however, emphasizes the enormous uncertainties involved in these assessments, particularly for the environmental effects. Several studies have analyzed these uncertainties explicitly to see how they affect the optimal policy, and how the possibility of resolving those uncertainties over time should be incorporated into strategies.

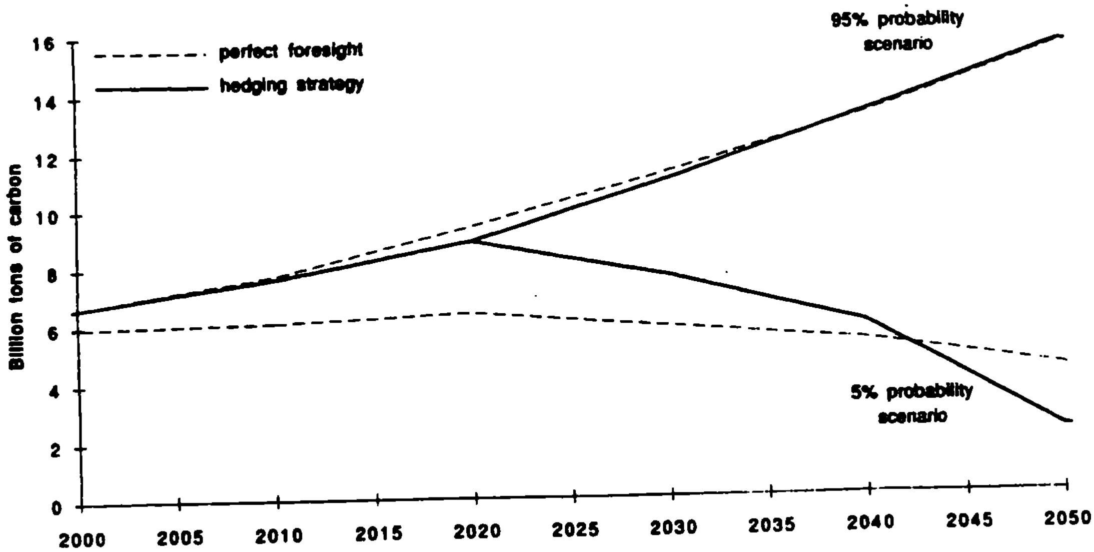
A. Manne and Richels (1995)

In addition to the results described in the previous section, Manne and Richels (1995) illustrate how uncertainties change the way in which decisions on global climate change should be viewed. As they emphasize, it is unrealistic to think of policy towards greenhouse gas emissions as a one-time decision that can be settled "once and for all." Instead, such policies should be viewed from a long-term perspective, one in which policies can be adjusted over time in response to changing conditions and new information. Choices made today should incorporate the possibility of such future adjustments.



Source: Manne and Richels (1995).

Figure 10. Optimal Emission Paths Under Alternative Cases



Source: Manne and Richels (1995).

Figure 11. Carbon Emissions Under Perfect Foresight and Hedging

The first step in Manne and Richels' analysis of uncertainty is to test for the sensitivity of their optimal strategy to potential uncertainties. In addition to the optimal strategy under their base-case assumptions, they estimate the optimal strategies for five additional cases, each of which reflects alternative values for one or more parameters that are uncertain. These alternatives include one case in which optimal emissions would increase relative to the base-case assumptions (because of higher than expected growth in the economy) and four in which the optimal level of emissions would be lower than in the base case as the result of some combination of lower-than-expected costs and higher-than-expected damages. Figure 10 shows the optimal emission paths under the six different cases. What is striking about the results is that, with the exception of the high-damage scenario, the optimal path of emissions in the next couple of decades is not very sensitive to these uncertainties; all are fairly close to the optimum under the base-case assumptions (which in turn is close to Manne and Richels' BAU projection, as shown earlier in Figure 9).

These sensitivity results suggest that the key uncertainty is whether the extremely unfavorable high-damage case—which assumes both high temperature sensitivity and high willingness to pay to avoid nonmarket damages—will materialize. Manne and Richels illustrate how a rational hedging strategy can be selected on the basis of such uncertainty. Figure 11 shows a situation in which there are two possible future outcomes—the base case and the high damage scenario—*and* we know which one applies. The dashed lines show the emissions paths with such perfect foresight. The upper dashed line shows the optimal emissions path corresponding to the base case, while the lower dashed line shows the optimal path if we knew today that temperature sensitivity and nonmarket damages were both high.

In reality, of course, we do not know which outcome will occur, although over time we will gain additional information that will allow us to refine our estimates. For illustrative purposes, Manne and Richels assume that by 2020, we will know whether the high-damage case is correct. In the meantime, what policy is optimal given our uncertainty? With imperfect information about which outcome will occur, the optimal strategy is likely to involve "hedging," picking a path somewhere between the two extremes. Where the optimal path lies within that band depends on various factors, the most important of which is how likely we think it is that the high-damage case will prove to be correct. Because of its extreme nature, Manne and Richels assign it only a 5 percent probability. In that case, the optimal near-term strategy is shown by the solid line in Figure 11. This hedging strategy consists of reducing emissions slightly more than would be optimal under Manne and Richels' base-case assumptions. If we then learn in 2020 which set of assumptions is correct, we then can change the policy based on which outcome occurs. If the base-case assumptions are borne out, control efforts can be relaxed a bit, as shown by the rising solid line after 2020. On the other hand, if the high-damage case proves correct, contrary to expectations, then control efforts will have to be tightened significantly, as shown by the falling solid line after 2020.

In addition to estimating the optimal emission paths, Manne and Richels calculate the marginal abatement costs associated with each of the illustrative emissions paths. With perfect foresight under the base-case assumptions, the marginal cost along the optimal path starts at less than $7 per ton of carbon (1995 dollars) in 2000 and rises slowly. In contrast, if we knew now that the high-damage case was correct, it would be optimal to spend over $131 per ton of carbon controlled in 2000, with a more rapid rate of increase. Under their optimal hedging strategy, Manne and Richels estimate that the marginal abatement cost would still be less than $12 per ton initially.

B. Nordhaus (1994)

The Nordhaus study provides estimates of the implications of uncertainty based upon a similar framework. For each of the key parameters, Nordhaus estimates probability distributions for a range of alternative values. Taking into account these distributions, rather than the "best guess" parameters, results in changes in the optimal policy. Nordhaus also evaluates the impact of the timing of resolving uncertainties on the optimum near-term policy.

Nordhaus finds that explicitly accounting for uncertainty does reduce his estimate of optimal emission levels over time. However, his estimates of the optimal level of control effort remain modest. As noted earlier, when Nordhaus optimizes using his "best guesses," the optimal strategy entails worldwide reductions in carbon-equivalent emissions (including CFCs and credits for carbon sinks), of less than 12 percent in the decade centered around 2005. When Nordhaus explicitly incorporates uncertainty, the optimal control rate rises, but remains less than 16 percent. Thus, his results are consistent with those of Manne and Richels in finding that hedging against uncertainty makes some additional control effort in the near term desirable, but that arbitrary targets, such as a freeze at 1990 emission levels, make little sense.

C. Edmonds and Wise (1996)

Most analyses of uncertainties tend to focus on the possibility that environmental damages from climate change would be more substantial than current estimates suggest. However, it is useful to consider upside possibilities as well. For example, the cost estimates embedded in the models described above are based largely upon current technologies and energy systems. It is possible that advanced energy technologies will be developed that substantially lower the costs of reducing CO_2 emissions.

Edmonds and Wise (1996) consider the implications of assumptions regarding the future availability and costs of the following three types of energy technologies that were identified by the IPCC Working Group II: (1) advanced liquefied hydrogen fuel cells; (2) solar, wind, and fusion power; and (3) biomass energy supply. Edmonds and Wise assume that these technologies become available between 2005 and 2020 and reduce costs by 0.5 percent per year. They show that the availability of these technologies would virtually eliminate the costs of reaching a target concentration of 550 ppmv in 2100; deployment of these advanced (and inexpensive) technologies would reduce emissions close to the level required to achieve that target.

These results illustrate the potential gains from shifting mandatory emissions reductions to later years, when improvements in energy efficiency would serve to lower substantially the global costs of reducing CO_2 emissions. The regional results reported by Edmonds and Wise show that the cost savings from these technologies would be particularly great for China and the former Soviet Union. Given the likelihood of burden sharing arrangements, these cost savings are likely to accrue ultimately to the developed OECD countries as well.

VI. CONCLUSIONS: WHAT SHOULD BE DONE NOW?

These recent studies provide powerful arguments against locking the nations of the world into rigid schedules for freezing or reducing CO_2 emissions in the near term. The major conclusions from our review of the relevant scientific and economic literature are the following:

- The *concentrations* of CO_2 and other greenhouse gases in the atmosphere drive potential changes in global climate.
- Because of the long residence time of greenhouse gases in the atmosphere, concentrations of greenhouse gases are due to *cumulative* emissions over many years, so that many different emission paths can lead to any given long-range concentration target.
- As a result, there will be ample opportunities to implement emission reductions in the future, if they prove needed, to achieve a wide range of possible global climate change targets.
- Future reductions will be *less expensive* than near-term reductions for several reasons: the present value of costs is lower the more distant in the future the costs are incurred; deferring emission reductions avoids transition costs from premature retirement of long-lived equipment, such as electric generating equipment; and technological progress promises to lower the cost of achieving CO_2 reductions.
- The cost savings from more flexible policies that shift reductions farther into the future are *substantial*; for example, Richels and Edmonds (1995) estimate that one such alternative emission path would reduce the cost of meeting a hypothetical long-run concentration target by 30 to 50 percent, depending upon the economic model used to evaluate the policies.
- Benefit-cost studies of climate change policy options conclude that substantial near-term reductions in CO_2 emissions probably are *not optimal*. Peck and Teisberg (1992), Nordhaus (1994) and Manne and Richels (1995) all come to this same conclusion.
- Taking major uncertainties into account suggests that some additional hedging may be desirable, in the form of modest near-term efforts to slow the growth rate of emissions.

The arguments for avoiding the adoption of rigid emission targets in the near term are even stronger if one takes into account the difficulty of achieving international coordination. The studies summarized in this paper all implicitly assume that the countries of the world act in a unified manner to minimize global costs and maximize global benefits, without regard to the interests of individual countries. Moreover, reductions within each country are assumed to be achieved at the lowest possible cost. In reality, of course, the policies adopted are unlikely to be least-cost, and the world is far from unified on this issue. Few countries are likely to adopt policies that impose large costs on their own citizens to generate potential benefits spread over the world as a whole. As Harrison and Nichols (forthcoming) suggest, the arguments for postponing the imposition of mandatory emissions reductions are even more compelling when this altruistic (and clearly unrealistic) assumption is relaxed.

The problems outlined above with regard to premature commitment to a freeze or other rigid emission schedule do not mean that nothing should be done now to address concerns about the possible adverse affects of long-run change in global climate. The studies reviewed here suggest that to the extent that reductions can be achieved through "low-regrets" action, they may be worth making in the near term. The work of Nordhaus (1994) and Manne and Richels (1995) suggests that the marginal value of reductions in the next couple of decades may be on the order of $5 to $15 per ton of carbon equivalent, with the higher end of that range incorporating hedging against uncertainty. Even such low-cost reductions, however, are worthwhile only if the countries making them take a completely altruistic approach, recognizing that while they will bear all of the costs of the reductions, the benefits will be spread over the world as a whole, with only a small portion returning to the citizens of the countries making the reductions. The international community could encourage these "low regrets" control options through a variety of policies.

The studies that explicitly analyze uncertainty also point to the importance of continued research, not just on potential changes in temperature, but also on other aspects of climate change. Moreover, it is essential to gain a firmer understanding of the consequences of such changes, which will be a mix of positive and negative effects, with the balance affecting different regions in different ways. Nordhaus (1994) and Manne and Richels (1995) emphasize the importance of developing more reliable information on the consequences of global climate change. Additional research and development of technologies that can deliver the same energy and other services with lower emissions of CO_2 and other greenhouse gases also could have high payoffs. Edmonds and Wise (1996) illustrate the potential payoff from the development and deployment of more efficient energy technologies. More broadly, the importance of uncertainties and their likely resolution over time make it essential to think of policies in terms of flexible long-term strategies that can be adapted and changed in response to new information and changing conditions.

Finally, countries can develop the institutional capacity to make coordinated decisions on global climate change. Both Manne and Richels (1995) and Harrison (1995) show that the costs and benefits of policies to affect global climate change are very different for different regions of the world, as well as for different sectors of the world economy. The world community needs to develop mechanisms that take such differences into account while at the same time achieving the gains from coordinated and cost-effective policy choices.

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Return to 1990:
The Cost of Mitigating United States Carbon Emissions in the Post-2000 Period

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Return to 1990
The Cost of Mitigating United States Carbon Emissions in the Post-2000 Period

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More than 160 nations have signed the Framework Convention on Climate Change (FCCC). That agreement required Annex I nations, the developed nations of the world plus economies of the Former Soviet Union and Eastern Europe,[1] to undertake measures to return emissions to 1990 levels or below in the year 2000. The parties to the FCCC met in Berlin in the Spring of 1995 and determined that additional measures were required to implement the ultimate objective of the FCCC, "*to stabilize the concentration of greenhouse gases in the atmosphere at a level which would prevent dangerous anthropogenic interference with the climate system.*"

Subsequent to the Berlin discussions, nations of the world have begun to consider measures that would set quantifiable emissions limitation requirements in the post-2000 period for Annex I nations.[2] A variety of measures have been considered. The purpose of this paper is to explore the economic consequences of efficient policy instruments—carbon taxes or tradable emissions permits—which might be employed to achieve a variety of targets in the post-2000 time frame.

We begin by describing our general approach and the variety of policy runs to be considered. We then review some of the necessary assumptions for this exercise, as well as the structure and calibration of the Second Generation Model (SGM). Finally, we discuss the results of our analysis, including time paths of emissions and measures of cost.

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[1] Australia, Austria, Belarus, Belgium, Bulgaria, Canada, Czechoslovakia, Denmark, European Economic Community, Estonia, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Italy, Japan, Latvia, Lithuania, Luxembourg, Netherlands, New Zealand, Norway, Poland, Portugal, Romania, Russian Federation, Spain, Sweden, Switzerland, Turkey, Ukraine, United Kingdom of Great Britain and Northern Ireland, and the United States.

[2] In the United States, efforts were undertaken by the Interagency Analytical Team, and results were summarized in United States Government (1997). The Second Generation Modeling team was one of three modeling teams which participated in the evaluation of potential emission mitigation measures under discussion.

EMISSIONS MITIGATION SCENARIOS

Four scenarios were constructed that reduce carbon emissions in Annex I countries by 2010. The SGM was used to simulate the impact of these scenarios on the United States economy. In each scenario, emissions are reduced linearly from 2000 to the emissions target in 2010. Since the SGM operates with five-year time steps, emissions in the year 2000 are at reference case levels. and emissions targets in 2005 are half-way between year 2000 emissions and the target emissions level required in year 2010. Figure 1 shows United States emissions paths for the four scenarios as well as reference emissions.

M1990 — Emissions from Annex I regions must be no greater than 1990 emissions levels beginning in the year 2010.

M1990+10% — Emissions from Annex I regions must be no greater than 10% above 1990 emissions levels, beginning in the year 2010.

M1990-10% — Emissions from Annex I regions must be no greater than 10% below 1990 emissions levels, beginning in the year 2010.

M1995 — Emissions from Annex I regions must be no greater than 1995 emissions levels beginning in the year 2010.

[Figure 1. Carbon Emissions Scenarios for the United States]

These mitigation policies were run under three emissions trading regimes: independent emissions mitigation, Annex I joint mitigation, and Annex I mitigation with global permit trading. In the independent emissions mitigation case, each Annex I region must individually reach the stated emissions target without any trading of permits across regions. The Annex I joint mitigation case allows Annex I regions to trade permits amongst themselves so long as the total constraint is met in each time period. The global permit trading case allows permit trading across all regions, including those not in Annex I. The Annex I joint mitigation and global permit trading regimes result in a single Annex I or global permit price common to all regions in the market for carbon permits.

In none of the above scenarios and trading combinations are non-Annex I regions forced to constrain their emissions. No mitigation targets or emissions trajectories are imposed on those regions. Under the global permit trading regime, non-Annex I regions participate in the market for carbon permits only when it is to their economic benefit to do so. These regions are allocated permits equal to their projected baseline emissions, so they are only required to reduce their emissions by an amount equal to the number of permits they wish to sell.

Eastern Europe and Former Soviet Union Permit Allocations

Eastern Europe and the Former Soviet Union (EEFSU) present a special case because carbon emissions are currently below the benchmark year of 1990. Two approaches to permit allocations for EEFSU regions have been discussed in recent months. The first allocates permits based on the stated policy scenario (e.g., M1990 allocates permits based on 1990 emissions level) so that permits are allocated to EEFSU in the same way as they are to other Annex I regions. Because of the decline in emissions in those regions from 1990 to 1995, however, this approach results in 'paper credits' equal to the difference between the lower post-1990 emissions and the policy-level (i.e., 1990) emissions being granted to EEFSU. For example, the FSU's baseline emissions level in 2010 is 836 TgC, significantly lower than its 1990 emissions of 1050 TgC. If granted permits equal to its 1990 emissions, the FSU would have 214 TgC worth of permits more in 2010 than its projected emissions, giving the region 214 TgC worth of permits to sell without incurring any emissions reductions of its own.

The second approach to allocating permits to EEFSU is to grant permits equal to reference emissions in each period until the projected path is constrained by the policy. For example, in the M1990-10% case, the FSU would be granted permits equal to its projected baseline emissions because emissions in the policy years never recover to 1990 levels.

For the purpose of this exercise, we chose to use the latter approach in allocating emissions to Eastern Europe and the Former Soviet Union. This baseline allocation scheme ensures that the stated Annex I emissions targets are achieved in both the independent mitigation and permit trading scenarios.

APPROACH

The SGM is a computable general equilibrium economic model that projects economic activity, energy consumption, and carbon emissions for twelve world regions, including the United States. The twelve SGM regions listed in Table 1 provide the necessary global coverage to simulate a system of global carbon permit trading. We also simulate a carbon permit trading system among the Annex I countries only, which are represented by seven of the twelve SGM regions. Our strategy has been to continually expand the number of regions by breaking them out of the Rest of World region. The Rest of World includes Latin America, Africa, and other Asian countries.

Table 1. Regions in the SGM

Annex I	Non-Annex I
United States	China
Canada	India
Western Europe	Mexico
Japan	South Korea
Australia	Rest of World
Former Soviet Union	
Eastern Europe	

While carbon emissions in most regions are anticipated to increase over time, this is not true for the Eastern Europe and Former Soviet Union Regions. Emissions in these regions have declined since 1990.

Each of the four emissions mitigation scenarios defines a set of emissions rights for the Annex I regions. Carbon taxes are used to constrain emissions for the cases of independent emissions mitigation, Annex I joint mitigation, and Annex I mitigation with global trading of emissions rights.

In the independent case, each Annex I region meets its own emissions targets independently. A time series of carbon taxes is determined for each region to reduce emissions to be equal to its emissions rights.

With Annex I joint mitigation, a common carbon tax is applied to all Annex I regions to meet the overall Annex I emissions target. However, regions that emit more carbon than their emissions rights must pay the other Annex I regions an amount equal to the difference in emissions valued at the common carbon tax.

In the global trading case, emissions are reduced from the global reference case by the same amount as the difference between Annex I reference emissions and Annex I emissions rights. The SGM is used to determine a global carbon tax just large enough to meet the global emissions target. This global carbon tax turns out to be lower than the carbon taxes required for independent mitigation by Annex I countries. Therefore, Annex I countries emit more carbon than in the independent case, but still less than in the reference case. Annex I countries must purchase rights to emit carbon from the non-Annex I countries. The non-Annex I regions must reduce their own emissions levels to sell those permits to the Annex I regions.

In this paper, we summarize the following results for the United States for each scenario: time series of carbon emissions; carbon taxes required for emissions mitigation; and measures of the cost of mitigation.

MODEL OVERVIEW

The SGM is designed specifically to address issues associated with global change. The model is designed to perform the following types of analysis:

1. Provide estimates of future time paths of environmentally important emissions associated with economic activity.

2. Provide estimates of the economic cost of actions to reduce greenhouse gas emissions.

Sectors

The SGM has nine producing sectors and twelve inputs to production. The inputs are labor, land, capital, and the nine produced goods. Economic detail is maintained in the energy supply and transformation sectors, but collapsed elsewhere into one large "everything else" sector. Price stability is maintained by keeping the price for goods produced by the "everything else" sector equal to 1.0 during all time periods.

Five different fuels are used for producing electricity, resulting in five subsectors for the electric generating sector. A separate economic production function, of the constant elasticity of substitution (CES) functional form, is used for each sector or subsector. Capital investment decisions depend on an assumed lifetime of capital for each sector or subsector. Capital lifetimes range from 15 years in the oil, gas, and coal production sectors to 70 years for hydroelectric power. The relative size of each production sector and subsector is shown in Table 2.

Table 2. Producing Sectors in the SGM

	Producing Sector	Gross Output in 1985 (millions of 1985 $)	
1	Agriculture	468,618	
2	Everything Else	5,086,486	
3	Oil Production	64,171	
4	Gas Production	45,804	
5	Coal Production	20,006	
6	Uranium Processing	2,195	
7	Electricity Generation	165,800	
	a. oil		10,959
	b. gas		34,152
	c. coal		85,930
	d. nuclear		21,370
	e. hydro		13,389
8	Petroleum Refining	145,015	
9	Gas Transmission and Distribution	105,330	

Market Clearing

In the SGM, markets are said to *clear*. In other words, the SGM solves for the set of prices for all markets (or sectors) in the modeled economy so that demands and supplies of each market are in equilibrium. The set of prices in which the equilibrium holds is called the *market-clearing* price set. In an equilibrium model like the SGM, markets are linked to other markets through the market-clearing process. For example, a change in the demand for coal will have an effect on not just the price of coal, but also the prices of oil, gas, and, at least indirectly, the prices of all markets in the economy.

Carbon permit prices and taxes are also solved by the SGM as part of the market equilibrium. Specifically, the SGM finds the carbon price such that, given that market-clearing equilibrium prices hold in the rest of the markets, the amount of carbon emitted is just equal to the carbon constraint of the region or group of regions under a carbon emissions limitation constraint.

Carbon Taxes and Revenue Recycling

The SGM uses a carbon tax within each region to provide an economic incentive for the economy to substitute away from carbon. Revenues obtained from the carbon tax can be very large and it makes a difference, in terms of final economic cost, how the revenues are recycled. For this exercise, we assume that all carbon tax revenues are recycled back to consumers through a lump-sum government transfer.

For the cases where emissions rights are traded between countries, each SGM region is allocated an initial amount of carbon emissions permits. Carbon permits can then be traded between countries at a price that clears the global market in these permits.

Modes of Operation

All of the SGM regions were initially developed as single-region models with a base year of 1985. Each regional model operates in five-year time steps through either 2030, 2050, or 2100. Often, the models were developed in collaboration with experts from that country. It is possible to run all of the regions simultaneously in a global model with international trade. The three modes of operation for the SGM are:

1. Single Region
2. Global with Partial Market Clearing
3. Global with Full Market Clearing

Single-region operation. For each SGM region, all produced goods are classified as being tradable, nontradable, or traded at a fixed quantity. When SGM regions are operated independently, a fixed world price is assumed for each tradable good; regions may import or export as much of that good as desired at that fixed world price, subject to an overall balance of payments constraint. For all nontradable goods, the quantity of trade is fixed in advance. The following assignments are used when the United States model is operated independently:

Numeraire Sector:	everything else (price always equals 1)
Fixed World Price:	crude oil
Fixed Trade Quantities:	agriculture, coal, nuclear fuel, refined petroleum, electricity
Nontradables:	distributed gas, land, labor

Since only relative prices matter, we are allowed to fix the price of either one produced good or one primary factor of production. For each region, the large 'everything else' sector is the numeraire, with its price fixed at 1 for all time periods. This 'everything else' good is a tradable good for all regions. An exogenous balance of payments constraint is specified in advance for each region. Most regions are assumed to move linearly from a historical trade balance in 1985 to balanced trade by 2005.

Given a trial set of prices, the SGM computes supply and demand for all producing sectors and primary factors of production. Markets for the nontradables and goods traded at fixed quantities are brought into equilibrium by searching for a set of prices that equate supply and demand. Prices are adjusted until supply and demand are within 0.01% of each other.

Global model with partial market clearing. The global version of the SGM is used when there is at least one market that must clear globally. For the scenarios described in this paper, that market is tradable carbon emission permits. The model searches for a global carbon tax, which can be interpreted as a world carbon permit price, that clears the market for permits.

Each region is initially allocated a number of carbon permits and may trade those permits at the world permit price. Some regions will be sellers of permits and some will be buyers. After trading permits, all regions must hold permits equal to the domestic level of carbon emissions.

All regions are still subject to a period by period balance of payments constraint. The model does not allow borrowing to pay for carbon emissions permits. Imports of permits must be paid for with exports of some other good.

Global model with full market clearing. There are no longer any markets with a fixed world price. A set of world prices is found that clears all world markets. Also, world markets can be created for goods that were traded in fixed quantities in the single-region model.

All of the scenarios described in this paper were run in the second mode, global with partial market clearing. This mode was chosen for two reasons. The first is that we were asked to assume a fixed time path of world oil prices for SGM model runs that were completed for the United States Government during the spring of 1997. This meant that the world oil market would not be allowed to clear in the model. The second reason is that model results are often easier to interpret when some variables in the model remain fixed over time. Although we are missing any feedback from reduced world oil consumption to lower world oil prices, the magnitude of this feedback is highly uncertain and difficult to model.

Data Requirements

Three types of data are used to construct and calibrate each region of the SGM.

1. Economic and Demographic Data
2. Energy Balances
3. Technology Descriptions

Economic data include input-output tables and supplemental information from the national income accounts. Population projections were obtained from the World Bank. Energy balance tables were obtained either from the International Energy Agency or from government agencies within a region.

Input-output tables describe, in value terms, the flow of goods between industries and consumers in an economy. However, a model concerned with quantities of carbon emissions must also be concerned with quantities of energy. An input-output table, by itself, is not sufficient to determine the quantities of oil, gas, coal, electricity, and refined petroleum that are produced and consumed. Supplemental information on energy quantities is required to map currency units from an input-output table to energy units needed to calculate levels of carbon emissions. We combine economic input-output tables with energy balance tables to create a hybrid input-output table with units of joules for energy products and real dollars for all other products. Miller and Blair (1985) provide a general description of, and the motivation for using, hybrid input-output tables.

Individual energy technologies are characterized by the annualized cost of providing an energy service. Data needed to determine the annualized cost include capital cost, equipment lifetime, annual fuel requirements, the interest rate, and other annual maintenance and operating costs.

REFERENCE CASE AND CALIBRATION

The cost of reducing greenhouse gas emissions is very dependent on the reference case. The greater the level of reference case emissions, the higher the cost of returning to 1990 emissions. Therefore, much effort is expended on creating an acceptable reference case before running any of the mitigation scenarios.

The SGM operates in five-year time steps from 1985 through 2050; results for this study are reported for 1990 through 2020. The United States reference case was closely calibrated to the Annual Energy Outlook 1997 (AEO97). Since AEO97 projects only up to the year 2015, projections beyond 2015 are SGM model results and are not calibrated to any other established projections. Projections of carbon emissions, population, GDP, primary energy consumption, and electricity generation for the United States are described below.

For the other global regions, economic and primary energy consumption growth rates were roughly calibrated to regional projections from the World Energy Outlook 1996 (WEO96). For the Former Soviet Union region, projected primary energy consumption levels were adjusted down from the WEO96 projection. Population projections for these regions were based on the World Population Projections 1994-1995, published by the World Bank. In addition to the exogenously set population levels, the international crude oil price trajectory from the AEO97 was used as an exogenously set price. Prices for all other fuels and goods in the model were determined endogenously.

The general calibration procedure is to first match GDP growth by adjusting parameters that control total factor productivity in the 'everything else' sector. Then energy consumption by primary fuel is calibrated by adjusting input-specific technical change parameters. Carbon emissions are derived directly from primary energy consumption by applying fuel-specific emission factors.

Carbon Emissions

In 1990, total carbon dioxide emissions from the combustion of fossil fuels in the United States were 1,350 million metric tons of carbon. Model results show that total carbon dioxide emissions continue to rise as fossil fuel consumption increases and emissions reach 1,871 million metric ton by 2020. This amounts to a 39 percent increase in total emission and an emissions growth rate of 1 percent per year. Reference case carbon emissions were shown earlier in Figure 1.

Gross Domestic Product

The two most important determinants of GDP are population growth and rates of change in productivity. Total population levels for the United States were taken directly from AEO97. United States population grows from 250 million in 1990 to 323 million in 2020. This represents an annual population growth rate of 0.85 percent per year.

GDP for the United States was matched to AEO97 projections by changing the total factor productivity parameter for the 'everything else' sector. Beginning with the 1990 GDP of 6.1 trillion dollars, the economy grows at 2 percent annually to reach 10.6 trillion dollars by 2020.

Primary Energy Consumption

Total primary energy consumption from 1990 to 2015 was calibrated to be within 2 percent of projections from AEO97. Primary energy consumption by fuel is shown for the United States in Figure 2. Energy consumption rises from 86 EJ in 1990 to 116 EJ in 2015. This increase represents an annual growth rate of 1 percent. The energy consumption growth rate decreases with time and in 2020, the total consumption is 119 EJ and the annual growth rate is 0.5 percent.

Crude oil is the major source of primary energy in the early years; however, natural gas competes with crude oil as the leading source of fossil fuel by 2020. Coal is the third largest source of primary energy and its consumption grows steadily at slightly less than 1 percent per year. Nuclear energy's contribution to primary energy consumption declines, while energy from renewable sources increases with time.

[Figure 2. Primary Energy Consumption – United States Reference Case]

Primary energy consumption does not grow as fast as GDP, which implies that the energy-GDP is ration is falling over time. Figure 3 shows the energy-GDP ratio generated by the SGM for the United States.

[Figure 3. Energy-GDP Ratio – United States Reference Case]]

Electricity Generation

Projections of electricity generation are similar to that of the AEO97. SGM total electricity generation results are higher than the AEO97 projections by approximately 10 percent. Electricity generation from natural gas is the reason for the higher result. Total electricity generated in 1990 is nearly 11 EJ, which grows at 1.5 percent per year and expands to 17 EJ by 2020. The major source of electricity is from the combustion of coal; however, electricity generation from natural gas plays a significantly larger role with time. In 1990, electricity generation from coal contributed to 53 percent share of the total generation, while that from natural gas combustion contributed to 17 percent of the total. By 2020, the shares of electricity generation from coal and natural gas are closer. Electricity generation from coal and natural gas comprise 44 and 34 percent share of the total respectively. Highly efficient and low cost natural gas combined cycle power plants incorporated into the SGM contribute to the growth of natural gas as the fuel for electricity generation. Nuclear power's contribution to the overall demand for electricity decline with time as existing power plants are retired and no new additional plants are constructed. Renewable energy sources for electricity generation include hydroelectricity, solar photovoltaics and others. Generation of electricity from renewable sources increases slightly from 1990 to 2020; however, renewable energy's share of total electricity remains below 10 percent of the total.

COST OF EMISSIONS MITIGATION

Although this exercise did employ the 12-region version of the SGM, discussion of results in this paper will focus on the United States. The SGM provides output on regional GDP and its components and a detailed description of the composition of energy supply. In this analysis, we will focus on the broad economic impacts on the economy. Specifically, we will discuss the permit prices required to meet the various mitigation requirements and the costs to the United States economy of undertaking such policies. We will also discuss the impacts of the domestic carbon taxes on primary energy consumption.

Permit Prices

Table 3 shows the permit prices by trading regime required for the United States to meet its emissions targets under the four mitigation scenarios. Permit prices in the United States must reach $108 per metric ton of carbon to reduce United States emissions to 1990 levels in 2010. This price increases significantly with the tighter constraint imposed under the M1990-10% case. Permit prices in the M1995 and M1990+10% scenarios are very similar as only 5 TgC separate the constraints in the two cases.

Table 3. United States Carbon Taxes Required to Meet Policy Goal Eastern Europe & FSU Allocated Reference Case Permits (1992 US$ per Metric Ton of Carbon)

	Independent Mitigation		Annex I Joint Mitigation		Annex I Mitigation with Global Trade	
	2010	2020	2010	2020	2010	2020
M1990	108	170	72	87	26	27
M1990+10%	60	110	42	58	16	18
M1990–10%	173	260	109	122	38	36
M1995	61	112	70	106	26	32

Permit prices fall as more regions are included in the market for carbon permits. In the independent emissions mitigation case, carbon emitters in the United States may undertake emissions mitigation options available only within the United States. In the Annex I joint and global permit cases, however, regions are included that have mitigation options with significantly lower costs, thereby lowering the marginal cost to the carbon permit market of meeting the desired emissions targets. As we will discuss, this 'where' flexibility in meeting emissions targets has a significant impact on costs as well as permit prices.

Permit prices tend to increase over time as it becomes more expensive to reduce emissions to the desired goal. Increasing population in the United States, and the economic growth that accompanies it, put upward pressure on emissions that, in turn, forces larger shifts away from inexpensive coal toward more expensive natural gas and renewable energy sources. The availability of relatively inexpensive abatement options in the developing world allows the permit price to remain relatively constant over time in those cases.

As the permit prices decrease across trading regimes, the United States purchases more and more permits from abroad, thereby enabling it to emit more than its allocated permits alone would allow. Figure 4 shows United States emissions for the M1990 case across the three trading regimes. Under the independent emissions mitigation regime, the United States is limited to emitting only what it is allocated under the scenario, its 1990 emissions level. With Annex I trading, however, the United States purchases 209 TgC worth of permits in 2010 and 244 TgC in 2020. The purchases increase to 316 TgC and 436 TgC in 2010 and 2020, respectively, under the global trading regime. This 'where' flexibility reduces the amount by which a permit-buying region must reduce its emissions and, therefore, reduces the cost to the region.

[Figure 4. United States Carbon Emissions – M1990 Cases]

Primary Energy Consumption

Emissions mitigation is achieved through reduction in total primary energy consumption and fuel substitution in the electricity sector. The domestic carbon tax of $108 in 2010 in the M1990 case results in a reduction of total primary energy consumption by 16 percent relative to the reference case. Primary energy consumption of coal drops by 57 percent while consumption of crude oil drops by 12 percent. Consumption of natural gas increases by 1 percent due to fuel switching. For reductions in primary energy consumption by fuel, refer to Figure 5.

[Figure 5. United States Primary Energy Consumption in 2010]

Fuel substitution in the electricity sector results in the share of electricity generated from coal dropping from 45 in the reference case to 20 percent in the M1990 case. The reduction in electricity generation from coal is compensated for by increased generation from natural gas. The share of electricity generation from natural gas increases from 29 percent in the reference case to 51 percent M1990 case.

Cost Calculations

A very convenient way to characterize the response of any SGM region to a carbon tax is by constructing a marginal cost of carbon curve. Figure 6 is a scatter plot of various carbon taxes applied to the United States economy, and the corresponding reduction in carbon emissions. Data points plotted in Figure 6 are from the four independent mitigation scenarios for the United States. Note that a positive tax is required to achieve any reductions in carbon emissions

[Figure 6. Marginal Cost of Carbon]

The marginal cost curve is used to calculate one measure of cost that we will call the *direct cost*. For any level of carbon emissions mitigation, the direct cost is defined as the area under the marginal cost curve up to that amount of mitigation. The first units of emissions reductions are very inexpensive, successive units become more and more expensive. Figure 7 shows the shows the size of these direct costs for the United States for the four independent mitigation scenarios. Direct costs are shown at five-year intervals through 2020 as a percentage of GDP. These costs are plotted as negative numbers in Figure 7. As expected, the M1990-10% scenario shows the greatest costs.

[Figure 7. Cost of Emissions Mitigation – No Trading]

Figure 8 focuses on the M1990 case and shows how costs to the United Sates are reduced with trade in emissions permits between countries. The 'independent' cost line shown in Figure 8 is the same as the M1990 cost line in Figure 7. In 2010, costs are reduced somewhat with Annex I trading and reduced by about one-half with global trading. In later years, the flexibility in where emissions reductions are undertaken impacts mitigation costs even more significantly.

[Figure 8. Illustration of 'Where' Flexibility – Costs for M1990 Cases]

Cost calculations for the emissions trading cases are different than in the independent case. Costs for the trading case take into account the value of permits traded. For a seller of permits, such as the United States, net cost includes the direct cost plus expenditures on carbon permits. A breakdown of these two cost components is shown for the M1990 Annex I trading case in Figure 9. Direct cost is roughly half of the net cost. The remaining cost, the difference between the 'direct cost' and 'net cost' lines in Figure 9, is the value of emissions permits that would be purchased from other Annex I countries.

[Figure 9. Cost Breakdown – M1990 Annex I Trading Case]

DISCUSSION

Several important issues have arisen during the development and operation of the SGM. In this section, we summarize some of the insights gained from our modeling activities. First, economic costs depend a great deal on our assumptions about future carbon emissions. Second, several measures of cost are available from the SGM. Third, the distribution of costs among countries in a system of global permit trading is sensitive to assumptions on exchange rates as well as the initial allocation of permits. Fourth, any system of global trade in carbon permits implies potentially large transfers of wealth from developed to developing nations. Finally, we discuss how some of our assumptions affect the results on costs.

Role of Reference Emissions in Shaping Marginal Mitigation Costs

All of the results in this study depend on assumptions used to create a reference emissions scenario from the present to 2020. The amount of mitigation required to return to 1990 levels depends directly on reference case emissions for each region. In the Annex I trading cases, carbon permit prices are particularly sensitive to reference scenarios for potential sellers of permits, especially Eastern Europe and the Former Soviet Union.

Among the Annex I countries, projecting future carbon emissions is especially uncertain for Eastern Europe and the Former Soviet Union. Of particular importance is when emissions in these regions will once again reach 1990 levels. If this point is reached before 2010, then we model EE and FSU just as any other Annex I country. If this point is reached after 2010, then emissions restrictions are not binding in EE and FSU until that point in time.

Measuring and Reporting Costs

At least two measures of cost are available from the SGM and from other models as well. The first measure, which we call the *direct cost*, can be thought of as either a deadweight loss or the integral under the marginal cost curve for carbon. Using either approach, direct cost is approximately equal to one-half of the carbon tax (or permit price) times the reduction in carbon emissions. For the permit trading cases, direct costs are then adjusted by the value of transfer payments required to purchase or sell permits. This measure of net cost is simple to construct and is comparable across models.

Of ultimate interest, however, is the net impact on some broader measure of economic activity (such as GDP) or on economic welfare (such as real consumption). There are many reasons why the change in GDP (or real consumption) is different than direct cost net of transfer payments. These other components of cost include the effects of pre-existing distortionary taxes, changes in terms of trade, and how tax revenues are recycled. In addition, measurement of GDP (or real consumption) depends on the choice of index and base year used to construct that index. This reflects real world problems in constructing a quantity index for GDP when relative prices are changing.

Foreign Exchange Rates

Permit prices for the global permit trading cases are very sensitive to assumptions on exchange rates. This is particularly true for developing countries where market exchange rates, in local currency per U.S. dollar, are three to five times the corresponding exchange rate based on purchasing power parity. A global permit price of $100 per metric ton translates, at market exchange rates, into a much higher relative price in the developing countries than in the United States.

Exchange rates based on purchasing power parity are usually used to compare income levels between countries, but market exchange rates must be used for goods actually traded between countries. This creates a potential problem for developing countries considering participation in a global permit trading program; carbon permits would be traded at market exchange rates, while GDP losses are better measured using purchasing power parity. For developing countries, losses in GDP could be greater than the value of carbon permits sold.

International Transfer Payments

Transfer payments required by some of the permit trading scenarios can become quite large. From the point of view of a buyer of permits, the amount spent on permits should be more than offset by the avoided cost of further emissions reductions.

Transfer payments of this size will affect the pattern of other goods traded internationally. Our model does not allow regions to borrow between time periods; trade must balance during each time period. Buyers of permits must export more of other goods to pay for the permits and adhere to a balance of payments constraint.

Sensitivity of Costs to Model Assumptions

Economic costs reported by the SGM for the United States are sensitive to many of the model inputs. These include the choice of exchange rate, the inclusion of paper permits, and the method of revenue recycling.

If purchasing power parity exchange rates were used instead of market exchange rates for the developing countries, then any given world permit price would translate into a lower carbon tax in that country's local currency. For global trading cases, this would increase the global permit price needed to meet a global emissions limit, and the SGM would report higher costs for the United States

For regions with emissions below 1990 levels, carbon permits were allocated based on their reference case, and not on 1990 emissions. If we had allocated permits based on 1990 levels, these extra 'paper permits' would create a less-stringent Annex I target. The model would then report a lower permit price for the trading cases, and a lower cost to the United States.

In this study, we assumed that all revenues from a carbon tax would be recycled as a lump sum to consumers. Another option is to use the carbon tax revenues to offset other taxes. This has the potential to reduce overall costs, since carbon tax revenues would displace other distortionary taxes.

KEY OBSERVATIONS

Economic costs are reduced with a permit-trading program that equalizes the marginal cost of carbon between countries. The least expensive emissions reductions are taken first, regardless of where they occur. Costs shown in Figure 8 provide a good example of the importance of this 'where' flexibility.

For the four mitigation scenarios in this study, economic costs to the United States remain below 1% of GDP through at least the year 2020. This was the case even in the scenarios where the United States met its mitigation targets without international trading of carbon permits.

Each region in the SGM can be characterized by a marginal cost of carbon curve, as was shown in Figure 6. This shows the approximate carbon tax required for any given level of carbon emissions reduction. For the amount of emissions reductions needed in 2010 to return to 1990 levels, a carbon tax of $108 per metric ton of carbon is required.

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Figure 1. Carbon Dioxide Emissions Scenarios for the United States

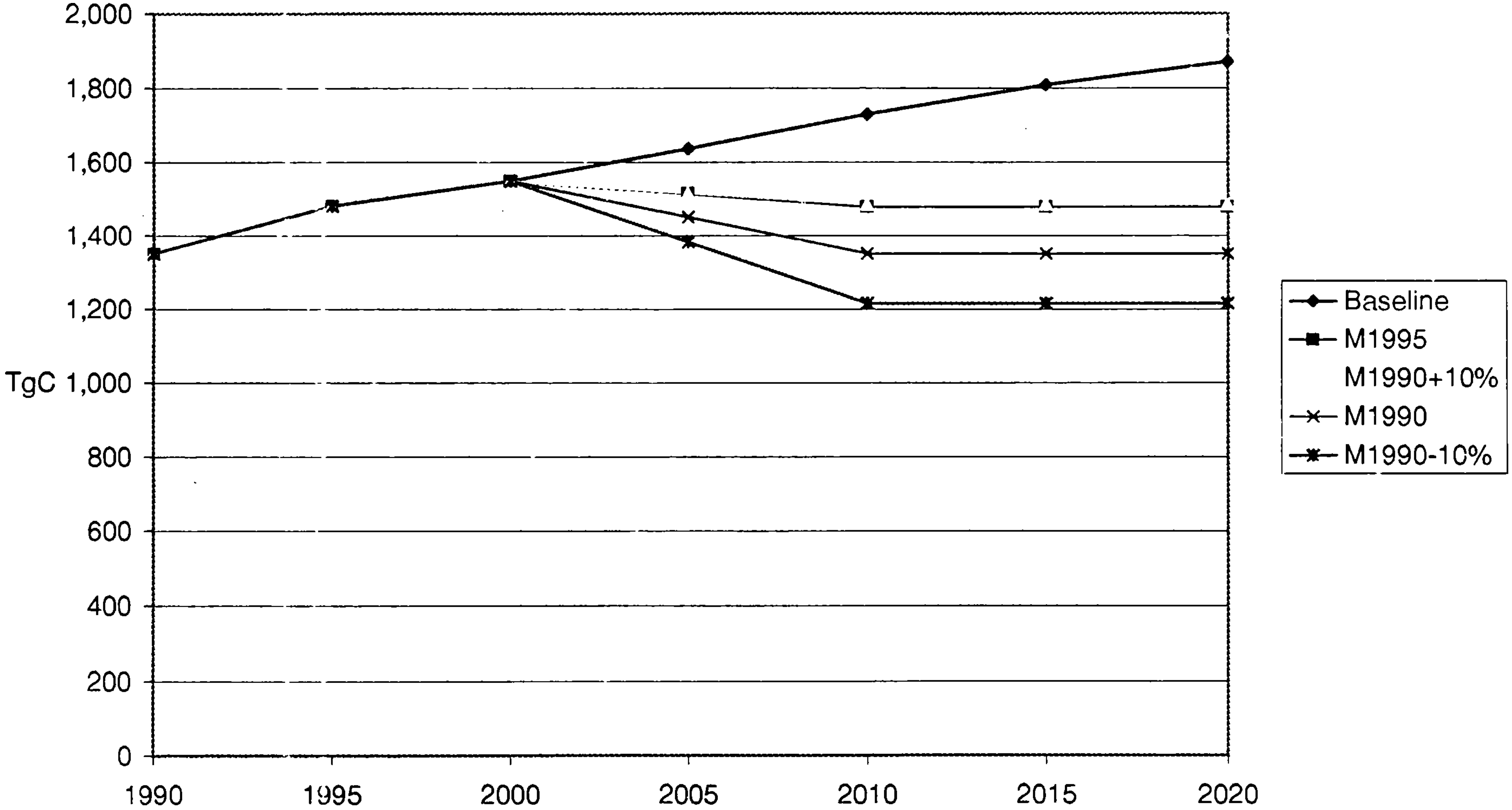


Figure 2. Primary Energy Consumption
United States Reference Case

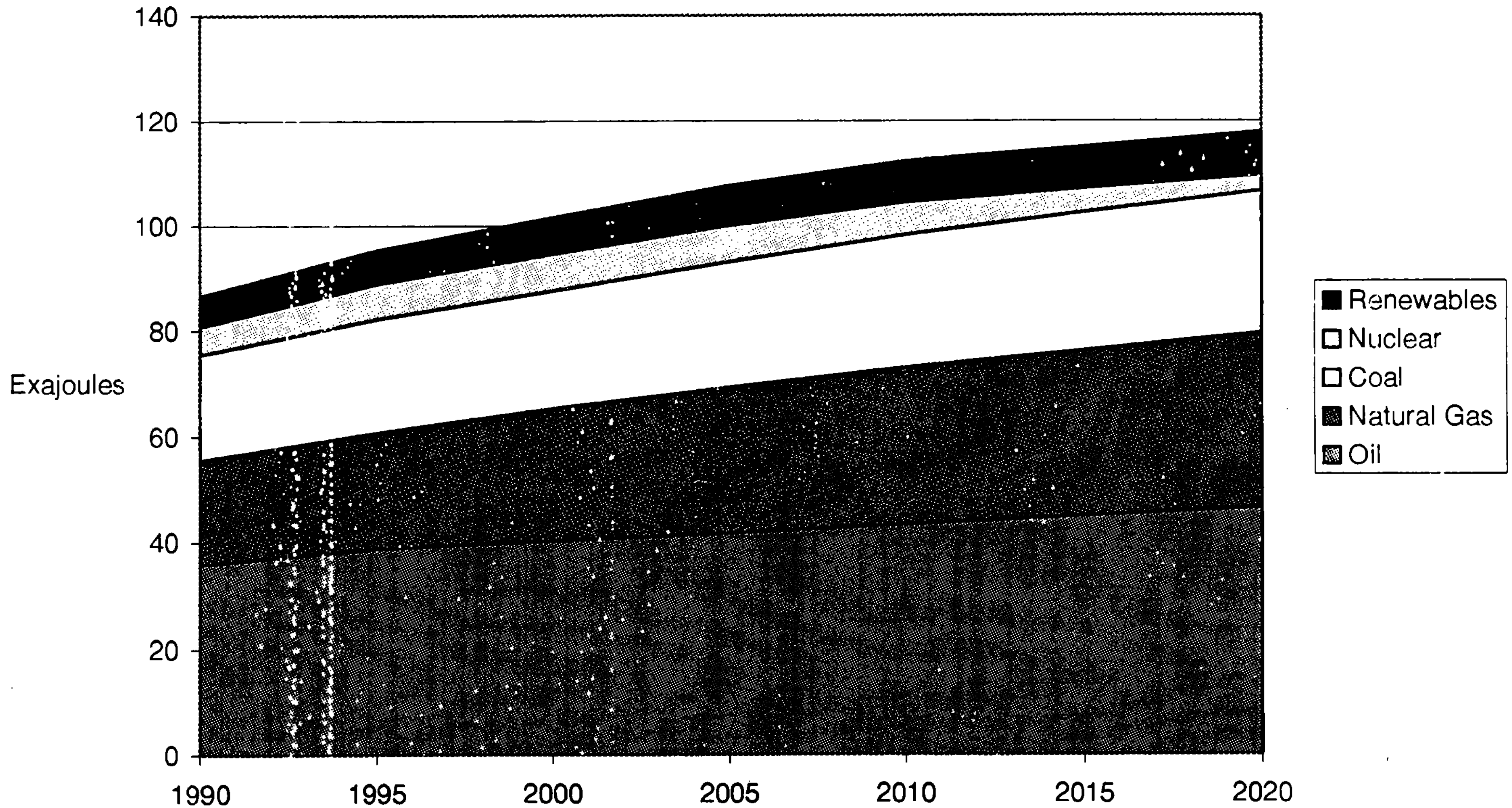


Figure 3. Energy-GDP Ratio
United States Reference Case

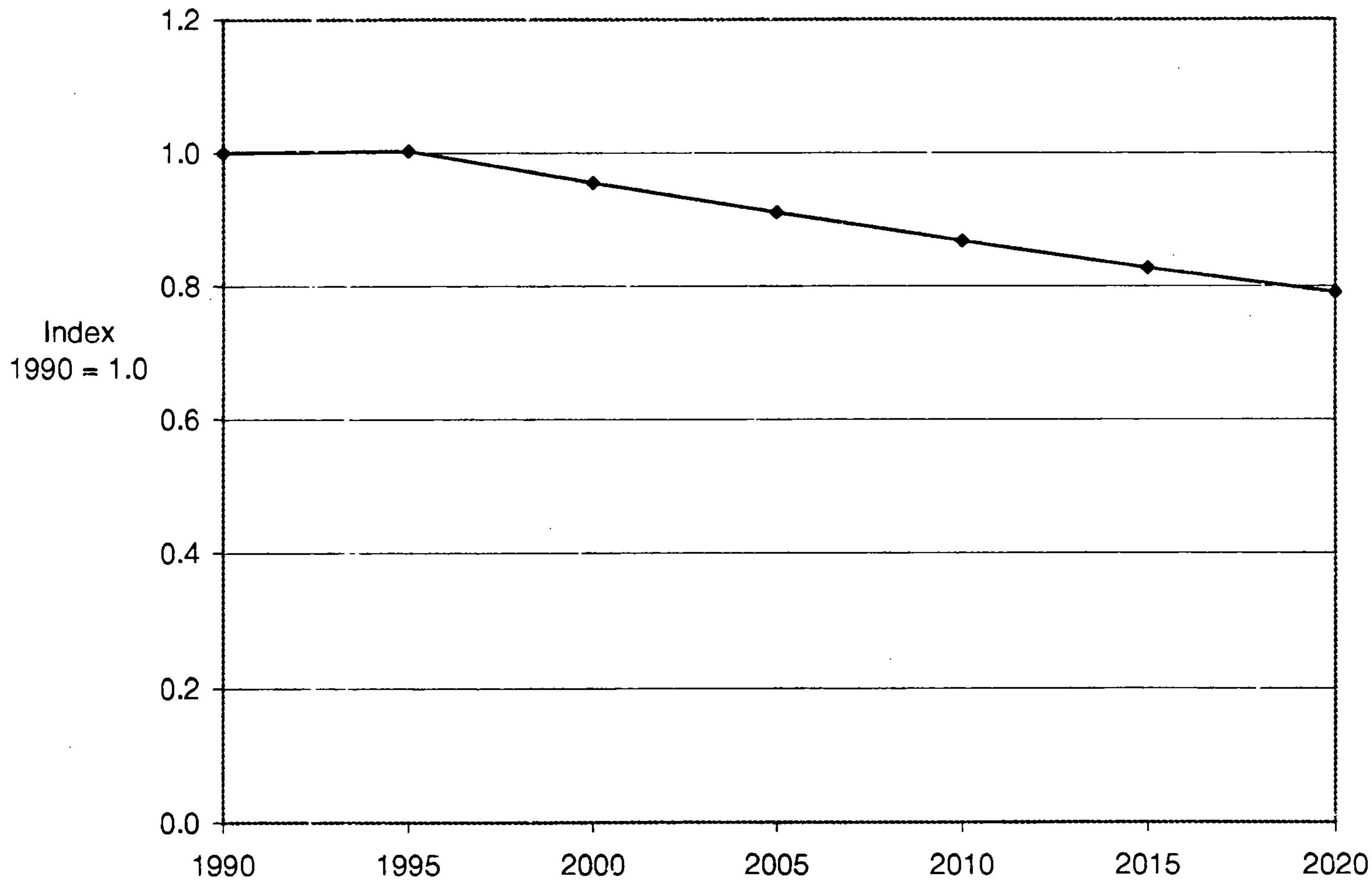


Figure 4. United States Carbon Emissions
M1990 Cases

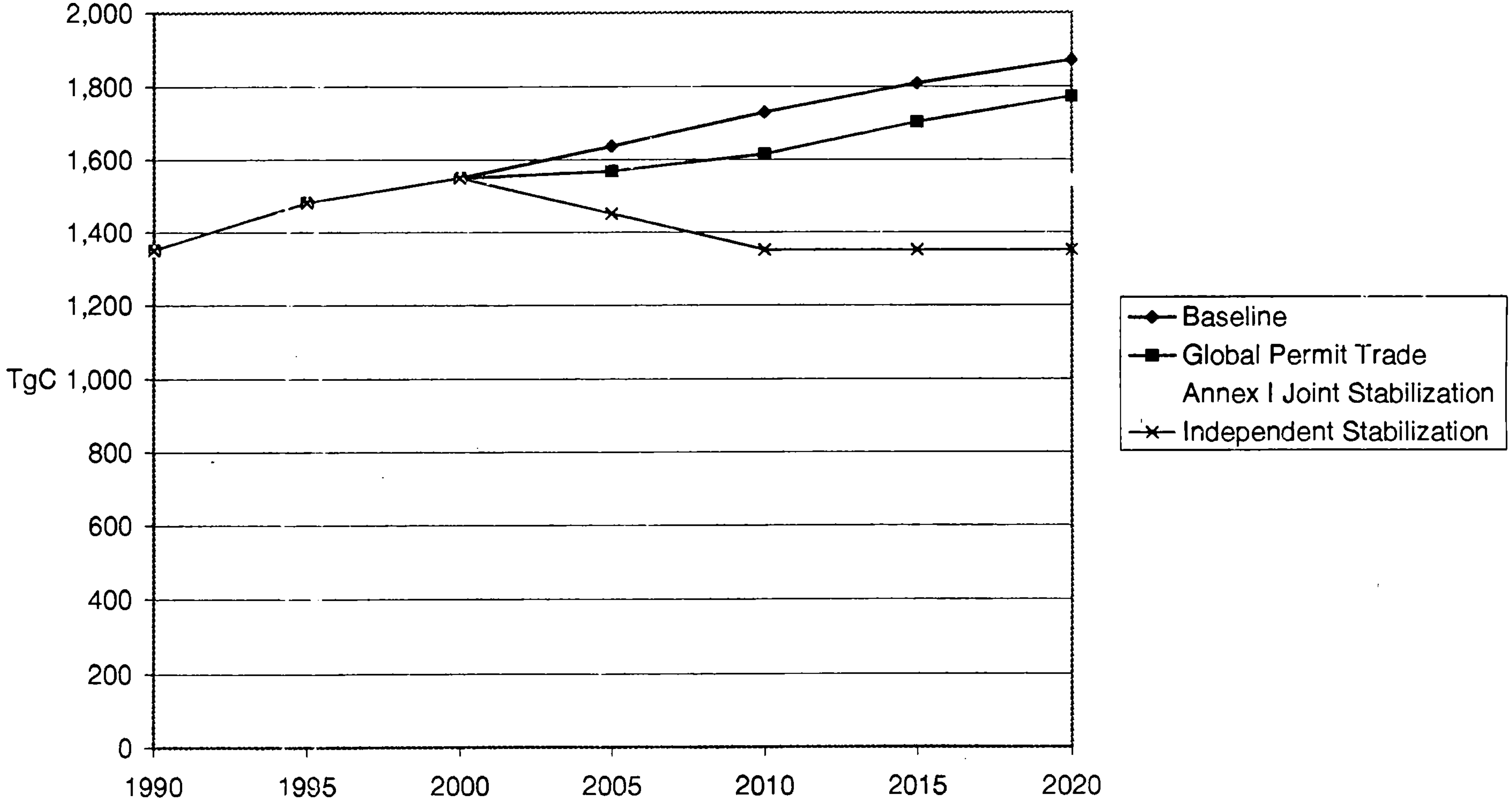


Figure 5. US Primary Energy Consumption in 2010

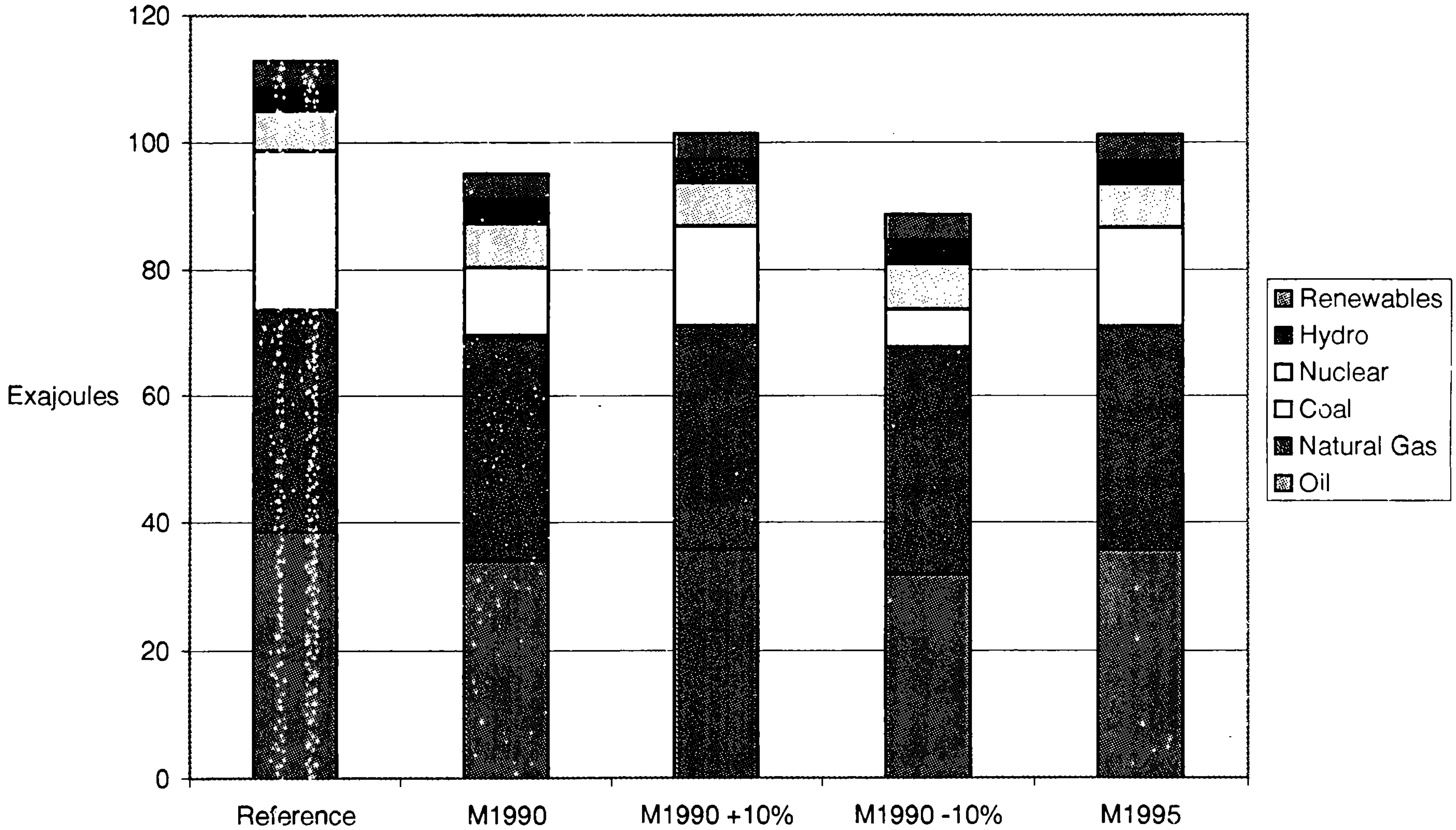


Figure 6. Marginal Cost of Carbon

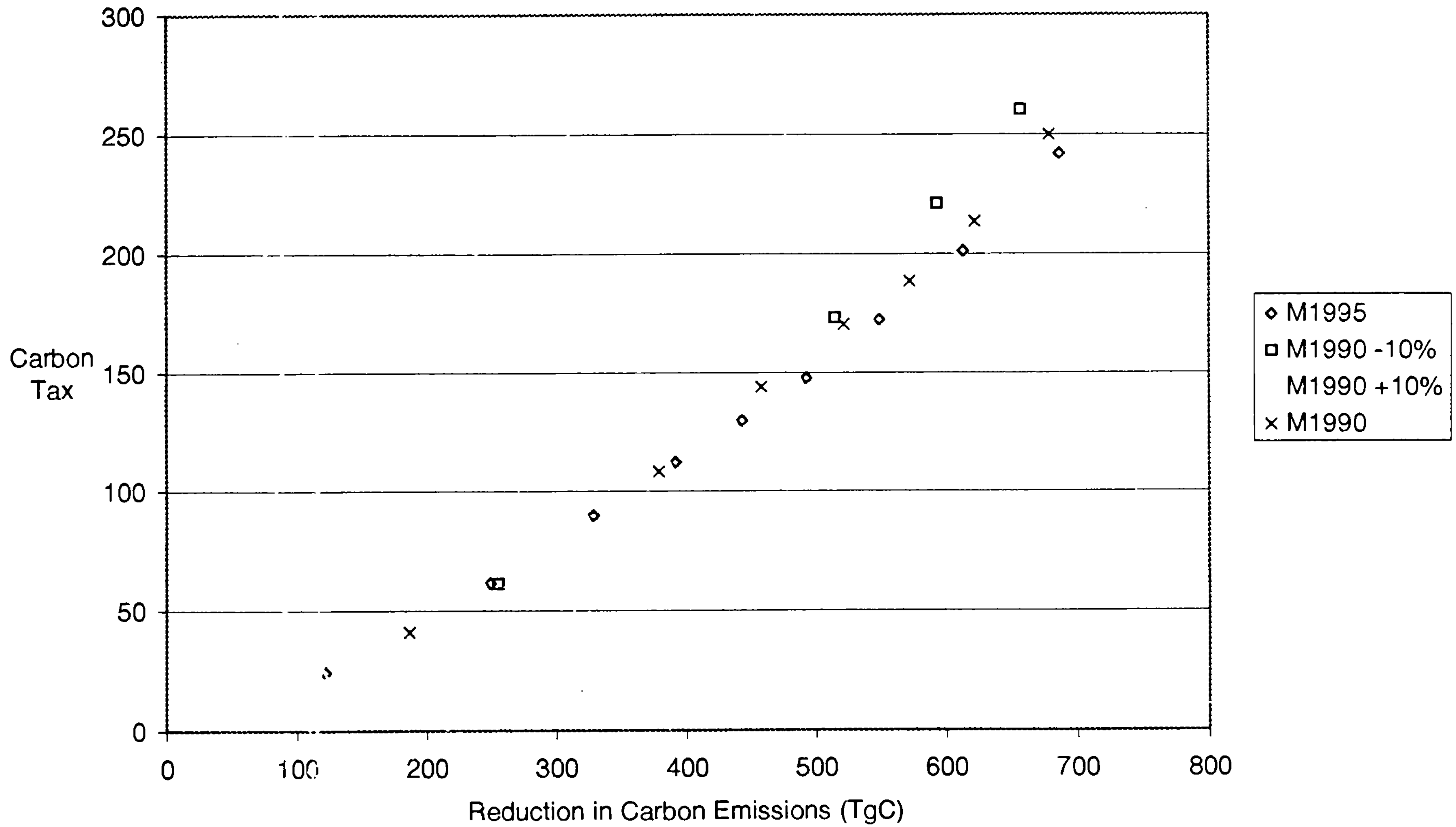


Figure 7. Cost of Emissions Mitigation
No Trading

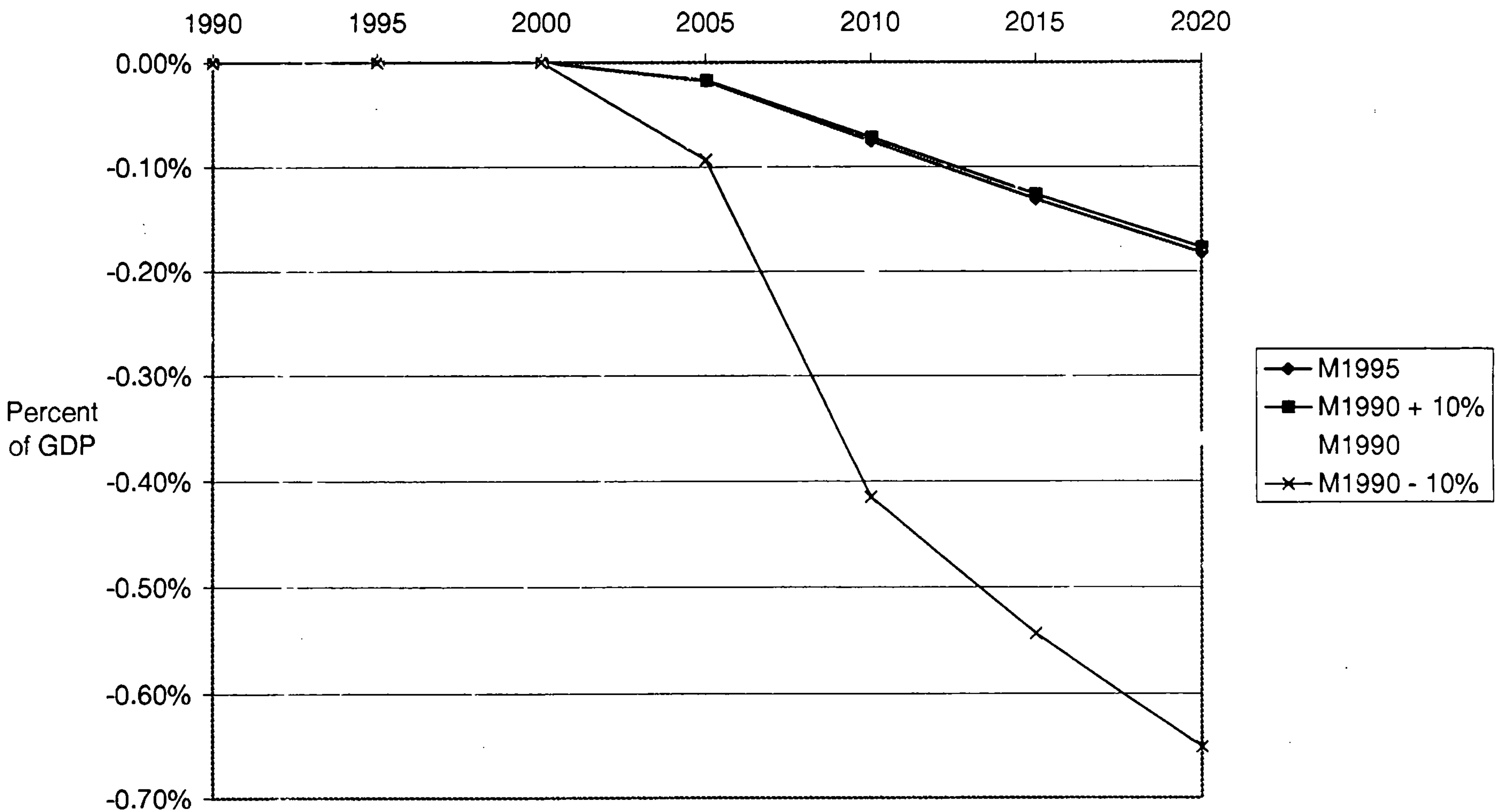


Figure 8. Illustration of 'Where' Flexibility
Costs for M1990 Cases

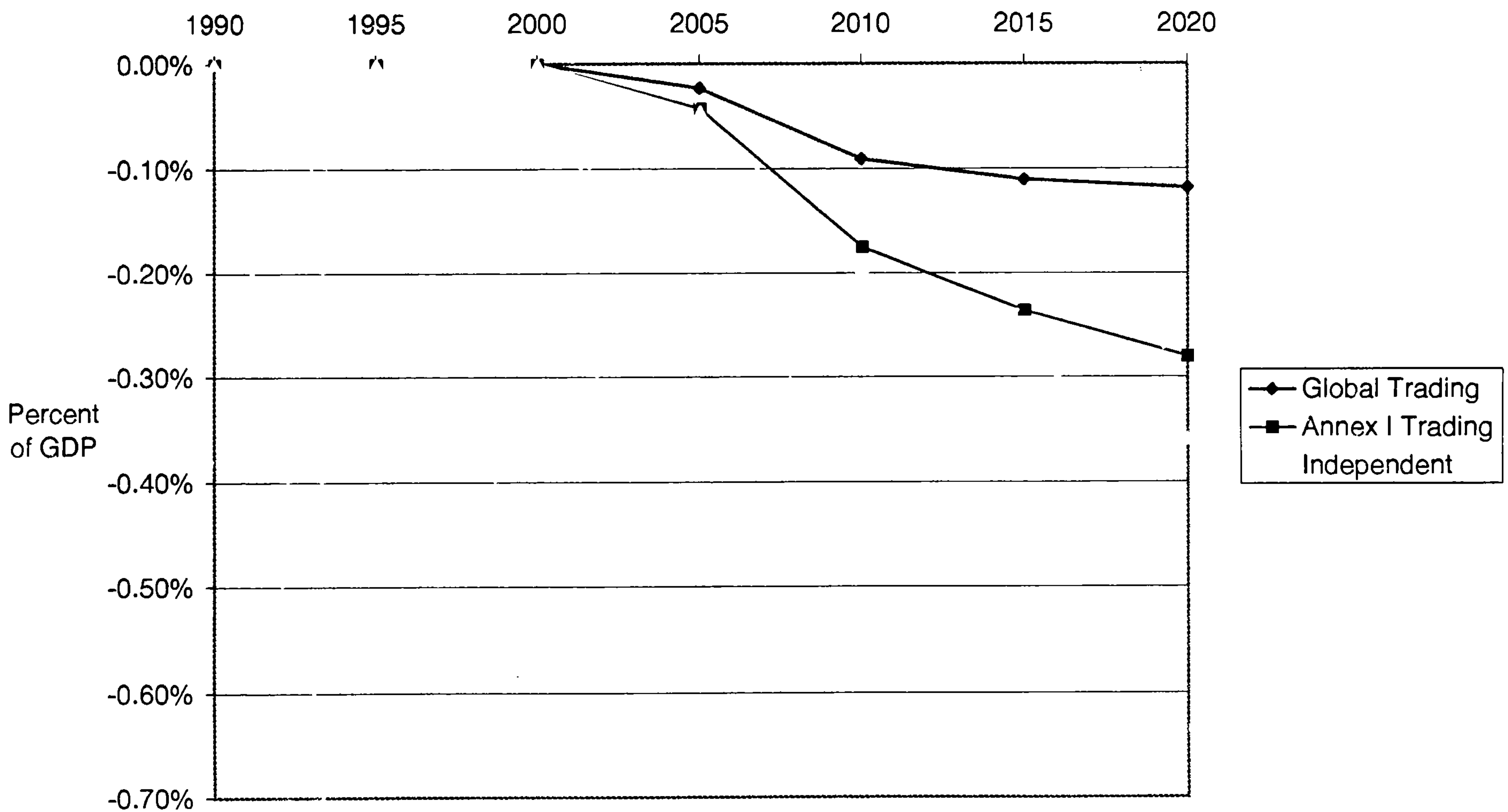
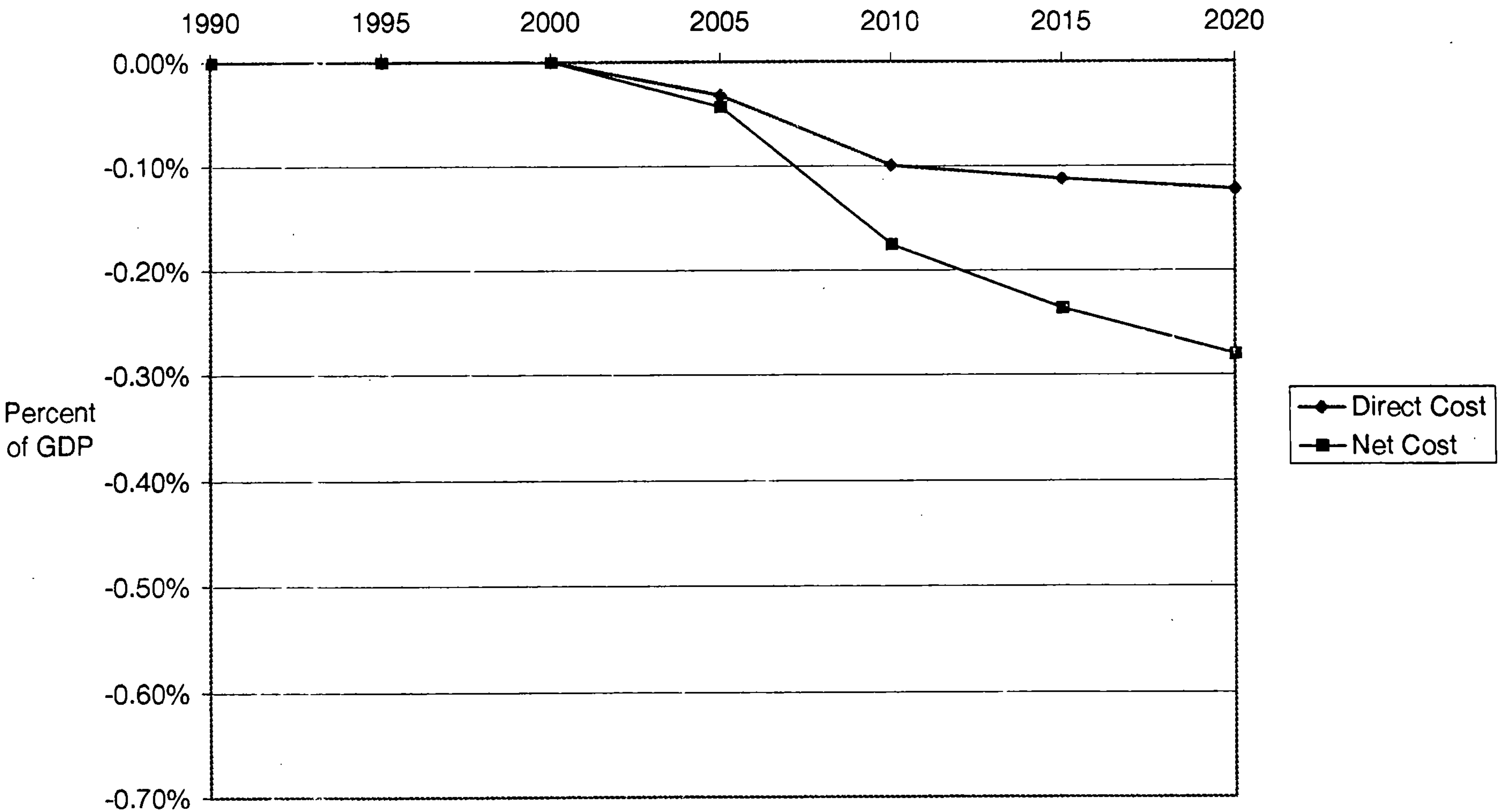


Figure 9. Cost Breakdown
M1990 Annex I Trading Case



Model Comparisons of the Costs of Reducing CO_2 Emissions

By DARIUS W. GASKINS, JR., AND JOHN P. WEYANT *

Concern about the extent of global climate change and its potential consequences has increased dramatically in recent years. Many believe that unprecedented climate changes are—or soon will be—occurring as the result of man-made emissions of greenhouse gases. The largest man-made source of greenhouse gases is carbon dioxide produced by the combustion of fossil fuels in utility and industrial boilers and in internal combustion engines. Thus, any effort to reduce greenhouse-gas emissions will start with efforts to restrict these activities. Therefore, it seems essential to develop a range of projections of the likely costs of alternative levels of control of carbon emissions from the energy sector.

The EMF 12 working group of the Energy Modeling Forum specified 13 standardized scenarios reflecting a range of carbon emission-control levels, as well as sensitivities on key standardized inputs. These scenarios were ultimately implemented by 14 modeling teams employing a wide variety of technoeconomic models, although not every model could implement every scenario. In addition to these model comparisons, ten study groups were formed to analyze issues not being addressed by the 14 models and 13 scenarios. These groups used additional models and methods to analyze issues not addressed in the 13 original scenarios.

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I. Basic Control Scenarios

Six of the 13 EMF 12 scenarios employed the same GDP, population, resource availability, and technology assumptions, but considered different levels and rates of CO_2 emissions control:

(i) *Reference.*—No control;
(ii) *20-percent Reduction.*—A 20-percent reduction in CO_2 emissions in the developed countries and no more than a 50-percent increase in the developing countries relative to 1990 levels by 2010;
(iii) *50-percent Reduction.*—The same as (ii), but with an additional reduction in CO_2 emissions in the developed countries to 50-percent below their 1990 levels by 2050;
(iv) *Stabilization.*—Hold CO_2 emissions in the developed countries to their 1990 levels by the year 2000, with the developing countries again constrained to no more than 50-percent above their 1990 levels;
(v) *Phased-In Carbon Tax.*—A tax that escalates from $15 per ton in 1990 at 5 percent real per year;
(vi) *2 Percentage Points Per Year Reduction.*—Annual reduction in emissions relative to the reference case.

In implementing these scenarios the modeling teams generally used taxes based on the carbon content of fossil fuels to achieve the emissions reductions (except for the government revenues a carbon tax would produce, this formulation is equivalent to a system of carbon-emission permit trading). These carbon-tax projections provide us with a rough estimate of the degree of market intervention that will be required to achieve the carbon-emission reductions. Most of the models included anticipated results from new technology development and conservation programs in the reference case. However, in these models there is no explicit consideration of market imperfections that may be causing current energy consumption patterns to differ from what perfectly functioning competitive markets would produce. More efficient, but more expensive, technologies are generally selected in the control scenarios, but no additional technology development is generally assumed to occur. Only one model adds additional conservation programs explicitly in those scenarios, and only one model includes endogenously determined rates of technological change. Finally, in their initial implementation of these scenarios the modeling teams assumed no international emissions trading, lump-sum rebate of any tax revenues collected, and no carbon offsets, such as those that might result from tree planting. A number of general points can be made from examining cost-of-control projections for these scenarios:

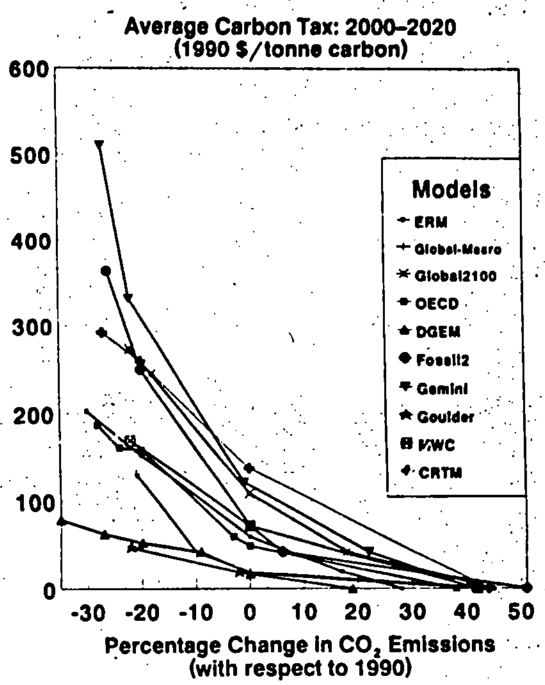

FIGURE 1. CARBON TAXES REQUIRED TO ACHIEVE CARBON-EMISSION REDUCTIONS IN THE UNITED STATES IN 2020

1.—The impact of these control options on global climate change over the next 20 years may be quite limited. Even in the most tightly controlled scenarios, the reduction in cumulative CO_2 emissions over this period are projected to be no more than 25 percent relative to the reference case. The impact of the control programs on atmospheric concentrations of CO_2 and climate change over that time period would be even less. By 2050, however, the 50-percent reduction scenario results in cumulative emissions that are as much as 55-percent below those projected in the reference case.

2.—Despite the inclusion of improved technologies and improved energy efficiencies in the reference case, all models project that market intervention will be required to achieve each of the emissions targets in all regions. When the more stringent carbon limits are considered, many models project the intervention required to be equivalent to carbon taxes of hundreds of dollars per metric ton. For example, the projections of the average carbon tax required during 2000–2020 to reduce U.S. carbon emissions by 20 percent by the year 2010 with respect to their 1990 level range from $50 to $330 dollars per metric ton as shown in Figure 1.

3.—These carbon taxes would generate substantial tax revenues that could be used for a number of purposes including reducing other taxes, deficit reduction, and additional government spending. For example, the projections of the average annual tax revenues raised in the United States from 2000 to 2020 to achieve the 20-percent reduction in CO_2 emissions range from $65 billion to $300 billion.

4.—The impact of a carbon tax on gross domestic product (GDP) measures its costs to the economy in terms of lost output resulting from the increase in the price of goods requiring carbon emissions; those goods must either be produced with less carbon or by more expensive processes. The GDP loss also includes the impact of the carbon tax on capital stock accumulation and technological progress, although not all models capture these phenomena. The models initially assumed lump-sum redistribution of tax revenues; That is, tax revenues are used to reduce total tax payments by individuals and corporations without affecting marginal tax rates (e.g., by increasing the standard deduction). The GDP losses calculated in this manner measure the cost of the distortions to the economy caused by the imposition of the carbon tax without either adding a credit or subtracting a penalty for the way the revenues are used. Under this assumption, and assuming no adverse trade effects, the model projections of the cost of stabilizing CO_2 emissions at today's levels range from 0.1 percent to 0.5 percent of GDP in 2000 for the United States, and the cost of achieving a 20-percent reduction in CO_2 emissions relative to today's level range from 0.9 percent to 1.7 percent of U.S. GDP in 2010. Although 1.7 percent of U.S. GDP in 2010 amounts to about $130 billion 1990 dollars, the implied reduction in the GDP growth rate between 1990 and 2010 would only be from about 2.3 percent per year to 2.25 percent per year. Thus, it is possible to reduce emissions significantly from their noncontrolled level without significantly reducing the growth of the economy.

5.—The way in which carbon-tax revenues are used has an important impact on the projected GDP loss. The projected GDP losses could be reduced substantially (relative to those calculated for the lump-sum recycling case) by using the carbon-tax revenues to reduce existing taxes that discourage economic activity, particularly capital formation. Simulations with four models of the U.S. economy indicate that from 35 percent to more than 100 percent of the GDP losses could ultimately be offset by recycling revenues through cuts in existing taxes. On the other hand, if the revenues are used to fund low-return government projects, the cost of achieving the carbon-emission reductions could be substantially greater than when they are recycled in lump-sum fashion.

6.—Regardless of where a model ranks in terms of the cost of controlling emissions, there is a great deal of similarity in how the models project that costs will vary over time for a particular level of control, and with respect to the level of control in any particular year. First, the cost of a particular level of control generally increases over time as the reference level of emissions grows and more adjustments must be made to reach a fixed level of emissions. For example, assuming lump-sum recycling of carbon-tax revenues, projections of the cost of stabilizing emissions in the United States range from 0.1 percent to 0.5 percent of GDP in 2000 and from 0.2 percent to 0.75 percent of GDP in 2010. In the longer term, say by 2050 or 2060, low-cost oil and gas reserves are near depletion, and the incremental cost of reducing emissions tends to stabilize at the difference between the cost of carbon-free sources of energy, like solar cells and advanced-technology nuclear reactors, and carbon-based sources of energy, like synthetic oil and gas made from coal or advanced coal-fired power plants.

7.—Second, the cost of control appears to be nonlinear with respect to the level of control in any given year, especially up to about 2040 before old fossil-fuel-based energy-producing and energy-consuming equipment can be fully retired and new carbon-free technologies can be fully introduced. That is, incremental reductions in allowable emissions cost more as the absolute level of allowed emissions in any particular year is reduced. For example, the cost of stabilizing emissions in the United States range from 0.2 percent to 0.75 percent of GDP in 2010, while the cost of reducing emissions by 20 percent in that year ranges from 0.9 percent to 1.7 percent of GDP, as shown in Figure 2. Fig 2

8.—If the OECD, or any other group of countries unilaterally implements a carbon-reduction program, resulting changes in international energy prices will cause carbon emissions in other countries to increase relative to reference-case levels. Increased carbon emissions by nonparticipating regions occurs both as a result of increased energy

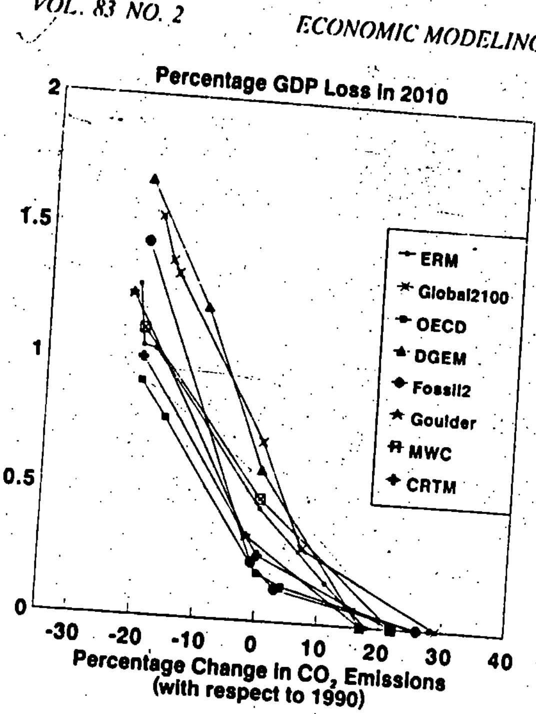

FIGURE 2. GDP LOSSES ASSOCIATED WITH CARBON-EMISSION REDUCTIONS IN THE UNITED STATES IN 2010

intensity of economic activity and through the migration of energy-intensive production into unconstrained regions. Carbon restrictions place countries that control emissions at a competitive disadvantage in energy-intensive industries. Thus, the cost to countries that control increases with the level of cutback, but the impact on global emissions may drop off sharply if large groups of countries fail to cooperate.

9.—The nonlinearity of year-by-year costs of control, the tendency of this nonlinearity to decrease over time as new technologies can be more fully phased in, and potential problems with recycling large amounts of tax revenues and dealing with large international trade shifts suggest that there is a trade-off between the cost of meeting an annual emissions target and the emissions generated before the target is reached. Moreover, the cost of meeting any cumulative emissions-reduction target can be reduced if it is phased in over a longer period of time. If a fixed annual emissions-rate target is specified, cumulative costs can be reduced with some increase in short-term emissions if (a) more time is allowed for reaching the target and (b) the instrument used to achieve it—say, a carbon tax—is phased in gradually rather than abruptly. The cost reduction can be particularly significant if the target date and rate of implementation are set to allow new carbon-free technologies to be phased in smoothly. If discounting of future costs is included in the calculation (as some would argue is required to insure an optimal allocation of society's resources over time), the reduction in costs resulting from a slower phase-in of controls is even greater.

10.—More greenhouse gases in the atmosphere may impose additional costs on society, though, so it may not be optimal to delay the imposition of constraints indefinitely. These costs depend on atmospheric concentrations of greenhouse gases, which depend on cumulative emissions over time rather than a single year's emissions rate. The 20-percent reduction scenario leads to high short-run adjustment costs according to the models included in this study. They project that almost the same reduction in cumulative CO_2 emissions reductions (and no more than a 20-percent increase in cumulative carbon emissions) can be achieved with the phased-in tax by the middle of the next century with a reduction of 30–40 percent in cumulative costs (even without discounting of future costs).

II. Sensitivity Analyses

The cost-of-control projections are sensitive to variations in standardized input assumptions:

1.—The cost of carbon constraints also depends significantly on the assumptions made about the cost of carbon-free technologies relative to the cost of carbon-emitting ones. To explore this sensitivity, the group examined an *accelerated technology* scenario in which the cost of noncarbon energy supply technologies (e.g., solar or advanced nuclear) in the 20-percent reduction scenario are assumed to be reduced to the cost of carbon-based ones (synfuels and coal-fired electric generation) by 2010. According to all the models, this scenario reduces the annual cost of achieving the carbon constraint to zero by the latter part of the 21st century. The costs of the constraint during the early part of the next century are not nearly as significantly reduced (only 10–30 percent), however, because conventional fossil-fuel technologies are still being used and because of constraints on the introduction of the new carbon-free technologies that cause additional costs to be incurred until large-scale introduction of the new technologies can be completed. This latter effect reinforces the large cost-of-adjustment effect observed above. Up until about 2040, the required carbon tax exceeds the zero difference in the costs of carbon-based and carbon-free backstop technologies by a substantial margin.

2.—The study design includes a 2.2-percent growth rate in GDP for the United States over the next 30 years. Two of the models included in the study produced independent GDP projections of 2.0 percent and 1.4 percent per year over that time frame. This results in lower carbon taxes being required to meet any particular emissions target. Interestingly, though, the computed GDP losses are not significantly less than in the other models, because higher energy prices are projected to diminish productivity growth. The lower GDP growth rate was adopted for a *low GDP growth* sensitivity scenario. This scenario does lead to a significant reduction in the cost of control because it directly reduces the reference level of emissions projected by each model. In addition, when all the models are run with the assumption of a low GDP growth rate, they produce carbon taxes that are more closely consistent with those projected by the lower-growth models.

3.—The cost of the transition to the non-carbon-based energy technologies can be significantly affected by the availability of natural-gas resources. Since gas has a lower carbon emissions rate than oil or gas, more fossil energy can be consumed within any emissions constraint if the use of natural gas can be increased. The *high natural-gas resources* scenario postulates a quadrupling of natural-gas resources in each region in the 20-percent emissions-reduction case. Although a number of analysts would now argue for more gas reserves than assumed in the EMF 12 study design, the quadrupling assumption is probably quite a bit more optimistic than anyone currently projects. This assumption does lead to a 30–40-percent reduction in the discounted cost of satisfying the emissions constraint over the next 20 years.

III. Differences in Model Projections

Estimates of the cost of achieving an emissions target relative to the 1990 level of CO_2 emissions by some future date are sensitive to the reference-case emissions trajectory projected by the model. A model with a higher reference-case projection of total emissions will require more adjustments to reach the fixed target than one with a lower reference-case emissions projection.

1.—Even when GDP growth rates are standardized, a wide range of reference-case emission projections are produced by the models included in the study. By the year 2100, projections of CO_2 emissions range from a 20-percent to a 200-percent increase over 1990 levels. Much of the differences in model projections from the models for 2100 can be explained by differences in the assumed rate of decrease in energy use per unit of economic output independent of energy price changes. For example, the "Global 2100" model uses a value of 0.5 percent per year for this parameter, while the Edmonds-Reilly model employs a 1.0 percent per year assumption, which over 110 years leads to aggregate energy use and emissions projections that differ by almost a factor of two. Estimates of this aggregate parameter based on historical data range from a rate of decrease of about 0.5 percent per year to an increase at about that rate. Researchers who have attempted to extrapolate the types and efficiencies of energy-using equipment into the future have argued that the potential exists for a rate of decrease in energy use per unit of economic output from 1 percent per year to more than 2 percent per year.

2.—In the reference scenario, all models project steady improvements (about 1 percent per year in the United States) in energy intensity over the study's time horizon, but no strong movement toward or away from carbon-based fuels. Decreases in energy intensity and switching to less carbon-intensive fuels are the major means of satisfying the requirements of the 20-percent reduction scenario, with the fuel-switching response being greater in the models with more end-use technology detail.

Figure 3. GDP Losses Associated With Carbon Emission Reductions in the United States in 2010.

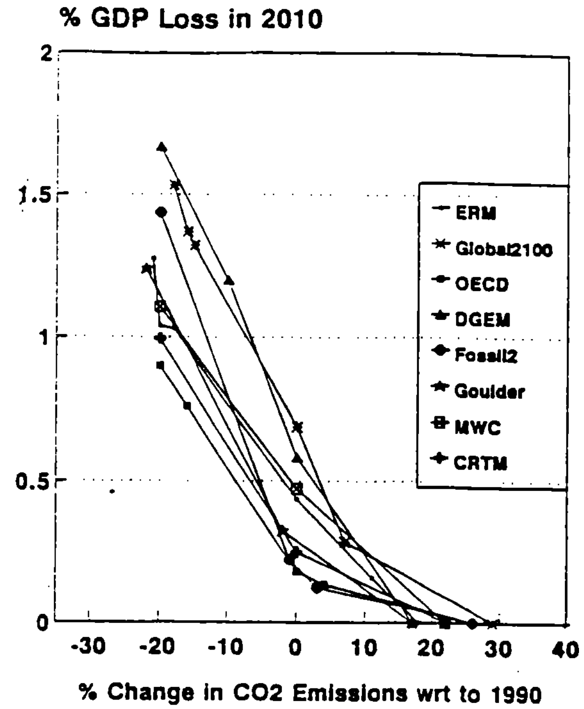

Figure 4. Carbon Taxes Required to Achieve Carbon Emission Reductions in the United States in 2020.