BUTTERWORTH HEINEMANN

Energy Policy, Vol. 23, No. 1, pp. 17–34, 1995
Elsevier Science Ltd
Printed in Great Britain
0301–4215/95 $10.00 + 0.00

MERGE

A model for evaluating regional and global effects of GHG reduction policies

Alan Manne
Department of Operations Research, Stanford University, Stanford, CA 94305, USA

Robert Mendelsohn
School of Forestry and Environmental Studies, Yale University, New Haven, CT 06511, USA

Richard Richels
Electric Power Research Institute, 3412 Hillview Avenue, Palo Alto, CA 94303, USA

MERGE provides a framework for thinking about climate change management proposals. The model is designed to be sufficiently flexible to be used to explore alternative views on a wide range of contentious issues, eg costs, damages, valuation and discounting. We begin with a description of the model's individual components and show how they fit together. We then provide an initial application to illustrate how the framework can be used in the assessment of alternative policy options. Given the level of uncertainty which pervades the climate debate, it would be unrealistic to expect cost–benefit analysis to lead to consensus on a bottom line – at least any time soon. Rather, models such as MERGE should be viewed as research tools capable of providing insights into which aspects of the debate may be most important. In this way, they can help focus the discussion and identify the areas where additional research may have the highest pay-off.

Keywords: Climate change; Integrated assessment; Cost–benefit analysis

To date, much of the greenhouse debate has focused on the costs of emissions abatement. At one end of the spectrum, there are those who believe that substantial reductions can be achieved at negligible costs. All that is needed is to remove energy subsidies, and to dismantle the artificial barriers which limit investment in cost-effective conservation and renewables. If this view is correct, emissions abatement represents an inexpensive hedge against the possibility of unacceptable climate changes.

Toward the other end of the spectrum, there are those who believe that energy markets are already operating efficiently. This group is considerably less sanguine about the costs of greenhouse insurance. Its members find difficulties in believing that economically attractive alternatives currently exist, and are not automatically entering the marketplace. If this view is correct, emission abatement will be far from costless.

As with most policy issues, the answer is apt to lie somewhere between the polar points of view. There are certainly cost-effective opportunities for improving energy efficiency and reducing greenhouse gas emissions. These 'no regrets' options would be worthwhile in themselves. But the global abatement targets currently under discussion are likely to entail substantial reductions below a no regrets emissions path. Few believe that this can be accomplished at a negligible cost.

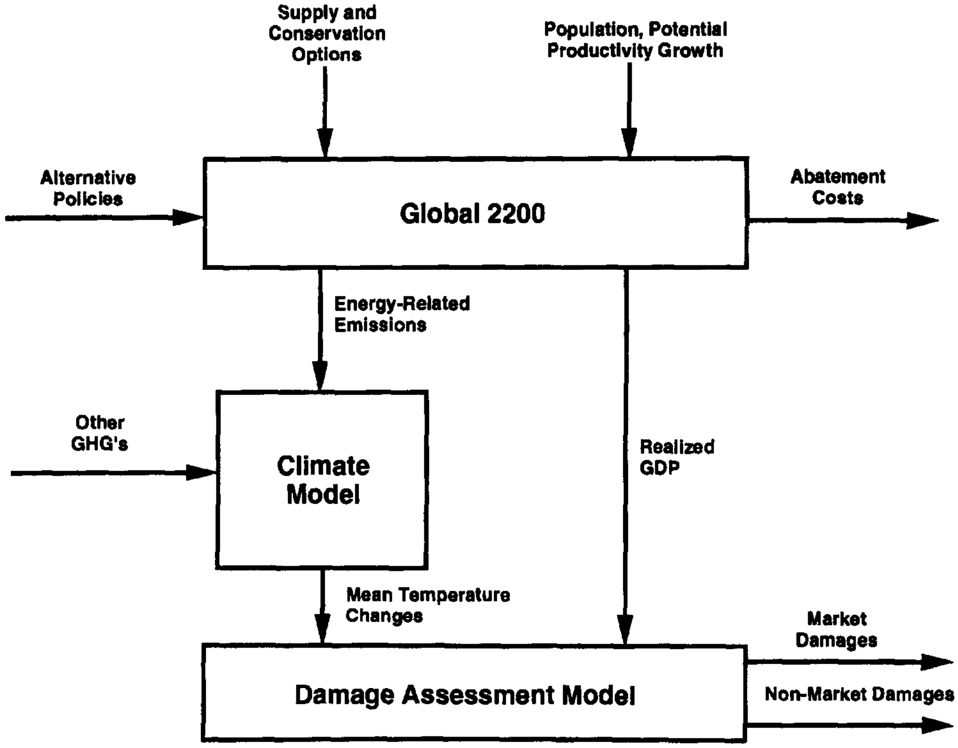

Figure 1 An overview of MERGE (model for evaluating regional and global effects of GHG reductions)

Once we recognize that there are limits to the possibilities for 'free lunch', we are forced to make difficult choices. Limited resources must be allocated among competing ends. It then becomes essential to analyze the trade-offs, and to ask what the proposed reductions will buy in terms of reducing the undesirable impacts of global climate change. There are many claimants for scarce resources – health, education and welfare expenditures. How much of today's limited budget is it worthwhile to spend on the purchase of greenhouse insurance?

Climate cost–benefit analysts face a daunting task. In recent years, considerable attention has been devoted to the economy-wide costs of emission abatement proposals. Although the range of uncertainty is narrowing, we have yet to arrive at a consensus. It is even more difficult to assess what such measures will buy in terms of reduced environmental damages.

Why is it so hard to assess the benefits? To begin with, there remain important gaps in our understanding of the science of global climate change. Increased concentrations of greenhouse gases are likely to lead to global warming. But by how much? Over what time frame? And what will be the impacts on different regions of the globe? Without a better understanding of these issues, it will be difficult to assess the effectiveness of various countermeasures.

There is also the difficult problem of valuation. Critics often complain that economists count what they can count, and not necessarily what counts. It is far easier to value damages to agriculture, energy, and coastal structures than to biodiversity, environmental quality and human health. Yet both categories are important and need to be incorporated into global climate cost–benefit analyses. Unfortunately, there is no widely accepted standard for translating global environmental damages into their dollar equivalents.

And there is the issue of discounting. The greenhouse debate is one of intergenerational trade-offs. Many proposals require substantial near-term costs. Benefits (in terms of reduced damages) do not begin to accrue for half a century. Unless one places a high weight on the welfare of future generations, it will be difficult to justify costly near-term actions. Among policy analysts, there is an enormous range of disagreement as to what constitutes an appropriate discount rate.

This paper will not attempt to resolve these issues: costs, benefits, valuation and discounting. Rather, our goal is to provide a sufficiently transparent integrating framework to explore the implications of alternative viewpoints. The framework is called MERGE (model for evaluating regional and global effects of GHG reduction policies). It consists of a series of linked modules representing the major processes of interest. These include: (1) the costs of reducing the emissions of radiatively important gases, (2) natural system disposition and reactions to the emissions of these gases, and (3) the reaction of human and natural systems to changes in the atmospheric/climate system.

We begin with a description of the model's individual components and show how they fit together. We then provide an initial application to illustrate how the framework can be used in the assessment of alternative policy options. Four alternative policies are compared with a business as usual scenario. In each case, we provide estimates of the costs of abatement and the resulting benefits.

This work builds upon the earlier contributions of a number of researchers. The pioneering effort in this area was done by Nordhaus (1991). Peck and Teisberg (1992) followed up the Nordhaus analysis by showing how the optimal global emissions path might change under alternative assumptions about economy-wide costs and the nature of the damage function. Falk and Mendelsohn (1993) developed a global model of carbon control which emphasizes the optimal set of carbon taxes over time. Cline (1992) has also conducted analyses at the global level, reporting cost–benefit ratios for a wide range of scenarios. Other researchers have developed regional models for exploring the pay-offs from various levels of international cooperation: see eg Eykmans *et al* (1992), Dowlatabati and Morgan (1993) and Hope *et al* (1993).

Global 2200

Figure 1 provides an overview of the principal components of MERGE and highlights the major linkages. There are three major submodels: (1) Global 2200; (2) the climate submodel; and (3) the damage assessment submodel. Each is described in turn.

Global 2200 is used to assess the economy-wide costs of alternative emission constraints at the regional and global level. It is an extension of the Global 2100 model of Manne and Richels (1992). Like its predecessor, Global 2200 divides the world into five major geopolitical regions: the USA, other OECD nations (Western Europe, Japan, Canada, Australia and New Zealand), FSU (the former USSR), China and the ROW (rest of world). Unlike Global 2100, Global 2200 is a fully integrated applied general equilibrium model. Each of the regions is viewed as an independent price taking agent, and is subject to an intertemporal budget constraint. At each point in time, supplies and demands are equilibrated through the prices of the internationally traded commodities: oil, gas, coal, carbon emission rights and a numeraire good. This numeraire represents a composite of all items produced outside the energy sector. All prices are expressed in terms of US dollars of constant 1990 purchasing power.

The model is benchmarked with energy and economic statistics for 1990. Global 2200 is based upon look ahead rather than recursive dynamics. This seems particularly important for the evolution of the prices of exhaustible resources such as oil, gas and coal – and for their eventual replacement by backstop technologies.

To facilitate computations, the model employs time intervals of unequal length. There are 10 year time steps from 1990 to 2050, and 25 year steps during the following century and a half. For purposes of current decision making, it is important to provide details on the near future but sufficient to take a more aggregate view of future events.

Intertemporal optimization

For each region, there is a single representative producer–consumer. Savings decisions are modeled by choosing each region's consumption sequence so as to maximize the sum of the discounted 'utility' of consumption. That is,

$$\operatorname*{Max} \sum_{t=1}^{T} U(c(t))(1+\rho)^{-t} \tag{1}$$

where U is the single period level of utility or social well-being, $c(t)$ is the flow of consumption at time t, and ρ is the rate of time preference for utility.

For optimizing the pattern of investment and consumption over successive time periods, we take the special case where the utility function is the logarithm of consumption. That is

$$\operatorname*{Max} \sum_{t=1}^{T} \log c(t)(1+\rho)^{-t} \tag{2}$$

This implies that marginal utility is always positive, but is a diminishing function of the aggregate level of consumption. There is a unitary elasticity of substitution between consumption in each time period.

It is important to distinguish between the rate of time preference for utility and the marginal productivity of capital. The former applies to the discounting of the utility of different generations, the latter to the discounting of goods and services. For the logarithmic form of the utility function, the following equation will hold along an optimal steady-state growth path:

$$r = g + \rho \tag{3}$$

where r is the marginal productivity of capital and g is the annual growth rate. For a proof of this proposition, see Chakravarty (1969, p 65). Our approach has been to choose a value of ρ such that the marginal productivity of capital will remain close to its current level over the

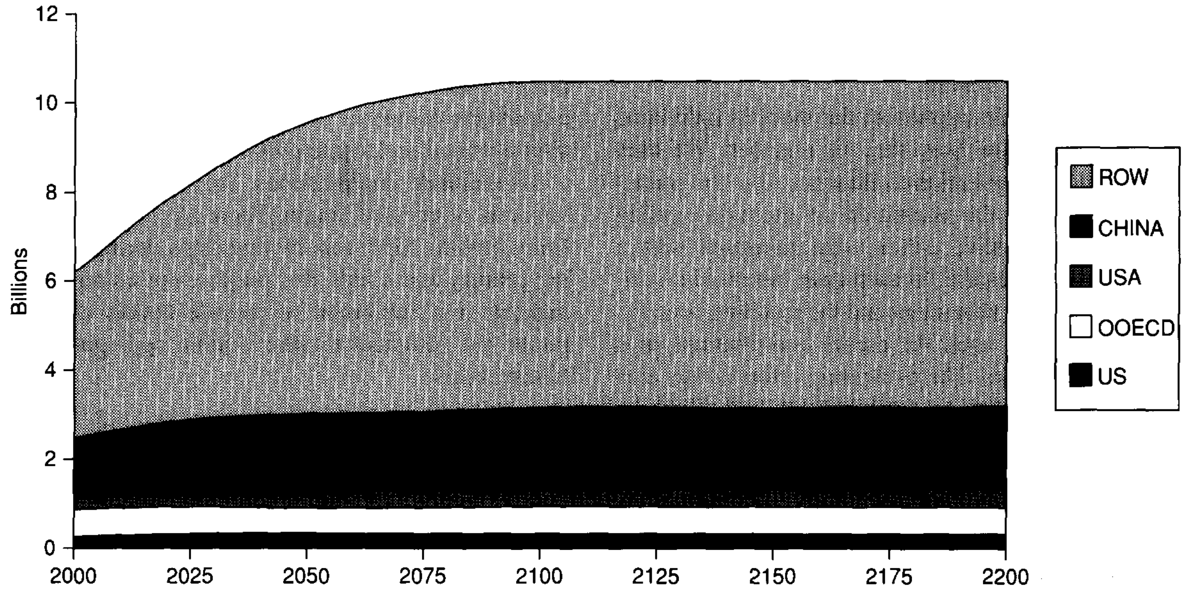

Figure 2 Population projections

entire planning horizon. For example, in order to simulate an economy in which the growth rate $g = 2\%$, and r is 5%, we set ρ at 3%.

Note that a lower or a zero rate of utility time preference would not provide a good description of the collective outcome of individual choices. It would also imply an unrealistically rapid increase in the near-term rate of investment and capital formation (see eg the numerical results reported in Manne (1992)). In that report, see also the implications of choosing a more general isoelastic utility function rather than the logarithmic form.

The model is benchmarked, and the utility discount rates are chosen so that – when expressed in terms of the international numeraire good – the net real rates of return on capital are identical (5% per year) in all regions. At first glance, this simplification appears unrealistic. For practical purposes, however, this seemed preferable to incorporating the complexities required to define the rate of change of each region's real foreign exchange rate relative to the US dollar.

Production and consumption

In order to focus upon the long-run issues of energy–economy interactions, resource exhaustion and the introduction of new technologies, each region is described in highly aggregated terms. Outside the energy sector, all economic activity is represented in terms of dollars of real purchasing power. Within the energy sector, only two end products are distinguished: electric and non-electric energy.

Electric and non-electric energy are supplied by the energy sector to the rest of the economy. Like the material balance equations of an input-output model, aggregate economic output (Y) is allocated between interindustry payments for energy costs (EC) and 'final demand' for current consumption (C) and investment (I). Thus:

$$Y = C + I + EC \tag{4}$$

For the economy-wide production function in each region, we assume that gross output (Y) depends upon four inputs: K, L, E, N – capital, labor, electric and non-electric energy. To minimize the number of parameters that require either calibration or econometric estimation, the long-run static production function is described by a nested non-linear form:

$$Y = [a(K^{\alpha}L^{1-\alpha})^{\gamma} + b(E^{\beta}N^{1-\beta})^{\gamma}]^{1/\gamma} \tag{5}$$

where $\gamma = (\sigma - 1)/\sigma$ for $\sigma \neq (0,1,\infty)$.

Equation (5) is based on the following assumptions:

- there are constant returns to scale in terms of these four inputs;
- there is a unit elasticity of substitution between one pair of inputs – capital and labor – with α being the optimal value share of capital within the pair;
- there is a unit elasticity of substitution between the other pair of inputs – electric and non-electric energy – with β being the optimal value share of electricity within the pair;
- there is a constant elasticity of substitution between these two pairs of inputs – the constant being denoted by σ (also known as ESUB);
- the scaling factors a and b are determined so that the energy demands in the base year are consistent

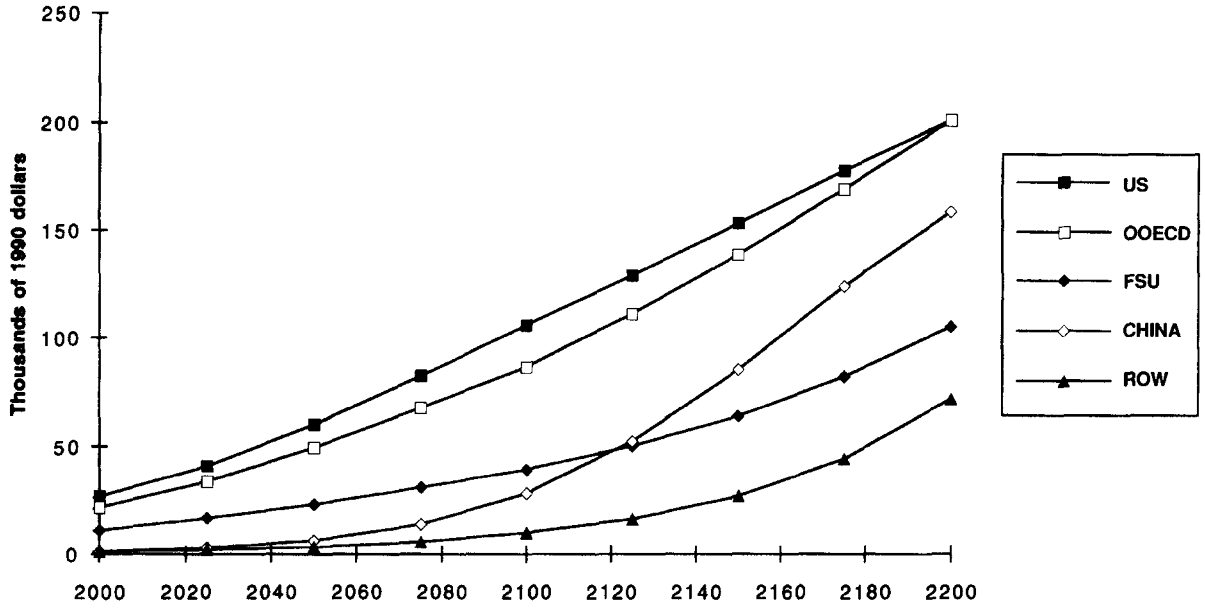

Figure 3 Per capita GDP

with the 'reference price' for non-electric energy; and

- there are autonomous energy-efficiency improvements (AEEI) that are summarized by the scaling factor *b*.

Key demand-side parameters

The rate of GDP growth is a key determinant of energy demands. The rate depends on both population and per capita productivity trends. Figure 2 shows our estimates of the projected population. For the 21st century, these are taken from Zachariah and Vu (1988). It is assumed that the population will stabilize in all regions during the 22nd century. At that time, 88% of the world's population will be located in the regions currently described as developing countries: China and the ROW.

Figure 3 presents our per capita GDP projections. These are termed 'potential' because they are based upon constant energy prices. Up to 2100, these rates represent the average of the higher and lower growth cases adopted by the IPCC's Working Group III (1990). From 2100 onward, it is assumed that per capita growth rates will decline over time, but that the gap between the industrialized countries and the ROW will continue to be substantial. If we follow the IPCC's projections through to 2100, it is difficult to believe that the ROW's growth rate will accelerate rapidly enough so that its per capita incomes will converge to those of the other regions between 2100 and 2200.

Because of energy–economy interactions, the potential GDP growth rates do not uniquely determine the realized rates. Energy costs represent just one of the claims on the economy's output. Tighter environmental standards and/or an increase in energy costs will reduce the net amount of output available for meeting current consumption and investment demands. The realized GDP will then fall short of the potential.

Energy consumption need not grow at the same rate as the GDP. Over the long run, they may be decoupled. In Global 2200, these conservation possibilities are summarized through two macroeconomic parameters: ESUB (the elasticity of price induced substitution) and AEEI (autonomous energy-efficiency improvements).

If there is sufficient time for the adaptation of capital stocks, most analysts would agree that there is a good deal of possible substitutability between the inputs of capital, labor and energy. The degree of substitutability will affect the economic losses from energy scarcities and from price increases. The ease or difficulty of these trade offs is summarized by the elasticity of price induced substitution (ESUB). The higher its value, the less expensive it is to decouple energy consumption from GDP growth during a period of rising energy prices.

When energy costs are a small fraction of total output, ESUB is approximately equal to the absolute value of the price elasticity of demand. In Global 2200, this parameter is measured at the point of secondary energy production: electricity at the busbar, crude oil and synthetic fuels at the refinery gate. On the basis of a 'backcasting' experiment for the USA, the reference case values for ESUB have been set at 0.40 both for the USA and for the other OECD nations. These countries have already demonstrated their ability to use the price mechanism for decoupling energy from GDP growth.

Table 1 Identification of electricity generation technologies

	Identification		
Existing technologies			
HYDRO	Hydroelectric, geothermal, and other renewables		
GAS-R	Remaining initial gas fired		
OIL-R	Remaining initial oil fired		
COAL-R	Remaining coal fired		
NUC-R	Remaining initial nuclear		
		Earliest possible introduction date[a]	**Estimated US cost**[b] **(mills/kWh)**
New technologies			
GAS-N	Advanced combined cycle, gas fired	1995	34.3[c]
COAL-N	New coal fired	1990	51.0[d]
ADV-HC	High cost carbon free	2010	75.0
ADV-LC	Low cost carbon free	2020	50.0

[a] Estimated year when the technology could provide 0.1 trillion kWh (approximately 20 GW of installed capacity at 60% capacity factor). For the other OECD region, we assume that the technology could provide 0.2 trillion kWh by this date.
[b] Based on 1990 dollars.
[c] Based on price of gas in 1990. Gas prices are projected to rise over time.
[d] Estimated costs are assumed to be 10 mills/kWh higher in the other OECD region due to higher fuel costs.

In other regions of the world, price induced conservation is more problematic. It depends on long-term structural changes in the political and economic system. We have therefore set ESUB at 0.30 for these other three regions.

Along with the reductions in energy demand induced by rising energy prices, there is also the impact of autonomous energy-efficiency improvements (AEEI). Non-price efficiency improvements may be brought about by deliberate changes in public policy eg speed limits for automobiles. Energy consumption may also decline as a result of shifts in the basic economic mix away from manufactured goods and toward more services. Thus, the AEEI summarizes all sources of reductions in the economy-wide energy intensity per unit of output.

For most regions and time periods, we have assumed that the AEEI will be 0.5% per year. That is, regardless of whether the GDP growth is 2.5% or 1.0% per year, total primary energy consumption will grow at a rate that is 0.5% lower than that of the GDP.

The numerical value of the AEEI is highly controversial. Clearly the cost of emissions abatement is sensitive to the value of this parameter. Suppose, for example, that one were quite optimistic and projected the AEEI at 1.5% per year. By the year 2100, the economy would then consume only 20% of the amount of energy required with an AEEI of zero. This is entirely apart from the conservation induced by rising energy prices in response to the depletion of conventional oil and gas resources.

In addition to the ESUB and AEEI, one other numerical parameter affects the decoupling between energy consumption and economic growth. The reference price of non-electric energy, PNREF, is employed in benchmarking the aggregate production function. Its numerical value is chosen so as to allow for differences in the extent to which domestic policies have insulated consumers from international energy price movements.

As a consequence, the economies of some regions may not have completed the long-term adjustment to the oil price shocks of the 1970s. If PNREF is less than the actual 1990 base year oil price of $3.70 per gigajoule ($22 per barrel), there will be some near-future price induced conservation in addition to that determined by the AEEI factor. The importance of this effect will depend upon what is assumed with respect to the persistence of tax and subsidy wedges between domestic and international prices.

In calculating these once and for all efficiency gains, the value of PNREF is taken to be $3.00 per gigajoule in the USA, $7.70 (including taxes of $4.00) in the other OECD region, $1.00 in the former USSR and $2.00 both in China and the ROW. For purposes of the simulations reported here, domestic taxes are maintained at the 1990 level within the other OECD region, but subsidies are eliminated at a rapid pace elsewhere.

Key supply-side parameters

Table 1 identifies the alternative sources of electricity supply. The first five technologies represent existing sources: hydroelectric and other renewables, gas, oil and coal fired units, and nuclear power plants. The second group of technologies includes the new electricity generation options that are likely to become available during the coming decades. They differ in terms of their projected costs, carbon emission rates, and dates of

Table 2 Non-electric energy supplies

Technology name	Description	Carbon emission coefficient (tons of carbon per GJ of crude oil equivalent)	Unit US cost per GJ of crude oil equivalent (1990 dollars)
OIL-MX	Oil imports or exports	0.0199	3.70 in 1990 rising over time
CLDU	Coal – direct uses	0.0241	2.00
OIL-LC	Oil – low cost	0.0199	2.50
GAS-LC	Natural gas – low cost	0.0137	2.75[a]
OIL-HC	Oil – high cost	0.0199	3,00
GAS-HC	Natural gas – high cost	0.0137	4.25[a]
RNEW	Renewables	0.0000	6.00
SYNF	Synthetic fuels	0.0400	8.33
NE-BAK	Nonelectric backstop	0.0000	16.67

[a] To allow for gas distribution costs, $1.25 per GJ is added to the wellhead price.

Source: The source of most of these carbon emission and cost coefficients is Energy Modeling Forum 12 (1993).

introduction. The introduction date for a new technology is defined as the earliest year in which the technology could provide 0.1 trillion kWh in each region (approximately 20 GW of installed capacity at a 60% capacity factor).

ADV-HC and ADV-LC, respectively, refer to advanced high- and low-cost carbon free electricity generation. Any of a number of technologies could be included in these categories: solar, wind, nuclear, biomass and others. Given the enormous disagreement as to which of these will ultimately win out in terms of economic attractiveness and public acceptability, we have chosen to refer to them generically.

Table 2 identifies the nine alternative sources of non-electric energy within Global 2200. In the absence of a carbon constraint or a limit on coal resources, the SYNF technology (coal or shale based synthetic liquid fuels) places an upper bound on the future cost of non-electric energy. Table 2 includes two broad categories of carbon free alternatives: RNEW (low-cost renewables such as ethanol from biomass) and NE-BAK (high-cost backstops such as hydrogen produced through photovoltaics and electrolysis). The key distinction is that RNEW is in limited supply, but NE-BAK is available in unlimited quantities at a constant but considerably higher cost.

Upper bounds are imposed upon the contribution of each of these supply technologies during each time period. There are also constraints that limit the rate of expansion from one period to the next. As a result of these constraints, there may be an erratic time path for the prices of alternative forms of energy. There may be a temporary phase during which prices overshoot their long-term backstop equilibrium levels.

Oil, gas and coal are viewed as exhaustible resources. Proved reserves are depleted by current production and augmented by new discoveries out of the remaining stock of undiscovered resources. At any one time, production is a fixed fraction of remaining reserves. New discoveries may not exceed a fixed fraction of the remaining undiscovered resources. Thus, Global 2200 combines some of the desirable economic attributes of Hotelling's model of depletable resources and the geological attributes of Hubbert's model. Under our standard assumptions, it turns out that conventional oil and gas resources are largely depleted by 2050, but that the world's coal supplies could provide for an additional century's worth of synthetic fuels.

Global 2200 is written in the GAMS language (see Brooke *et al*, 1988). In order to solve this computable general equilibrium model, we used the sequential joint maximization technique originated by Rutherford (1992). There are 2800 linear and non-linear constraints, and there are 3800 variables – many of them subject to individual upper bounds. On an IBM RS/6000-375 work station, the solution time is about half an hour per case.

Climate submodel

In MERGE, we focus on three of the most important anthropogenic greenhouse gases: carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O). The concentrations of these gases in the earth's atmosphere have been increasing since the industrial revolution – primarily as a result of human activities. In this section, we describe the relationship between man-made emissions and atmospheric concentrations and the resulting impact on temperature.

The emissions of each gas are divided into two categories: energy and non-energy. Global 2200 projects energy related emissions of CO_2, CH_4 and N_2O by fuel type for each period up to 2200. Emissions from other sources are exogenous inputs into MERGE. Table 3 presents a summary of key assumptions.

Without the withdrawal of carbon from the atmosphere, observed atmospheric concentrations of CO_2 would have risen much more rapidly than indicated by

Table 3 Summary of assumptions regarding key greenhouse gases

Trace gas	CO_2	CH_4	N_2O
Atmospheric concentration			
Pre-industrial (ppmv)	280	0.8	0.288
1990 (ppmv)	353	1.72	0.310
Energy related emissions			
1990 (billion tons)	6.0	0.08	0.0001
Growth rate, post-1990		(determined endogenously)	
Non-energy related emissions			
1990 (billion tons)	0.2	0.454	0.0139
Growth rate, post-1990	0	0.8	0.2

Sources: IPCC (1990; 1992).

the quantity of carbon emissions. In recent history, approximately 50% of the industrial emissions of CO_2 appeared to have been absorbed. Most of this absorption is by the oceans but not all of the withdrawals can be explained in this way. We assume that prior to the industrial revolution, natural additions were offset exactly by natural removal. That is, the stock of carbon was in steady state.

Future atmospheric CO_2 concentrations are modeled using a reduced form carbon cycle model developed by Maier-Reimer and Hasselmann (1987). Carbon emissions are divided into five classes, each with different atmospheric lifetimes. Specifically, $G(t)$, the impulse response function to an instantaneous injection of CO_2 to the atmosphere, is expressed as a weighted sum of the exponentials

$$G(t) = \sum_{i=1}^{5} a_i \exp(-t/\tau_i) \tag{6}$$

where a_i are scaling factors; $\sum a_i = 1$; and τ_i are decay constants. The above linear response expression was fitted by least squares to the computed response of a full scale ocean carbon cycle model (Maier-Reimer and Hasselmann, 1982).

For CH_4 and N_2O, the atmospheric stock in year $t + 1$ equals the fraction of the stock in year t remaining in the atmosphere plus new emissions. That is,

$$S_{G,t+1} = k_G * S_{G,t} + E_{G,t} \tag{7}$$

where $S_{G,t}$ is the stock of gas G in year t; k_G is the retention factor for gas G ($k_{CH_4} = 0.9$ and $k_{N_2O} = 0.9933$); and $E_{G,t}$ are the emissions of gas G in year t.

The next step is to assess the impact of future concentrations of greenhouse gases on the earth's radiative forcing balance, that is, the balance between the energy absorbed by the earth and that emitted by it in the form of infrared radiation.

According to the IPCC (1990), atmospheric concentrations of CO_2, CH_4 and N_2O have the following impacts on radiative forcing relative to their 1990 levels (respectively indicated by CO_{2_0}, CH_{4_0} and N_2O_0):

$$\Delta F_{CO_2} = 6.3 \ln (CO_2/CO_{2_0}) \tag{8}$$

$$\Delta F_{CH_4} = 0.036 (CH_4^{0.5} - CH_{4_0}^{0.5}) - f(CH_4, N_2O_0) + f(CH_{4_0}, N_2O_0) \tag{9}$$

$$\Delta F_{N_2O} = 0.14 (N_2O^{0.5} - N_2O_0^{0.5}) - f(CH_{4_0}, N_2O) + f(CH_{4_0}, N_2O_0) \tag{10}$$

where ΔF_G is the change in net flux (W/m^2) corresponding to a volumetric concentration change for gas G relative to the 1990 level and the CH_4–N_2O interaction term $f(CH_4, N_2O) = 0.47 \ln[1 + 2.01*10^{-5}*(CH_4*N_2O)^{0.75} + 5.31*10^{-15}*CH_4*(CH_4*N_2O)^{1.52}]$.

The aggregate effect is obtained by summing the radiative forcing effect of each gas. Aggregate radiative forcing is assumed to have the following impact on the change in global potential surface temperature, ΔPT:

$$\Delta PT = d*\Delta F \tag{11}$$

where the potential temperature is the long-run temperature which will occur if a specific level of forcing is maintained indefinitely; ΔPT is measured relative to 1990 temperature; $d = 0.555$ °C/W/m^2; and $\Delta F = \Delta F_{CO_2} + \Delta F_{CH_4} + \Delta F_{N_2O}$.

Since oceans take a long time to warm up, the actual temperature, AT, will lag behind the potential temperature. We model this lag process as follows:

$$\Delta AT_{t+1} - \Delta AT_t = c_1 * (\Delta PT_t - \Delta AT_t) \tag{12}$$

where $c_1 = 0.05$ represents a 20 year mean lag, and ΔAT_t measures the actual change in temperature in year t relative to 1990.

According to global circulation model analyses, temperatures will increase more rapidly as one moves toward the poles. We assume that the temperature

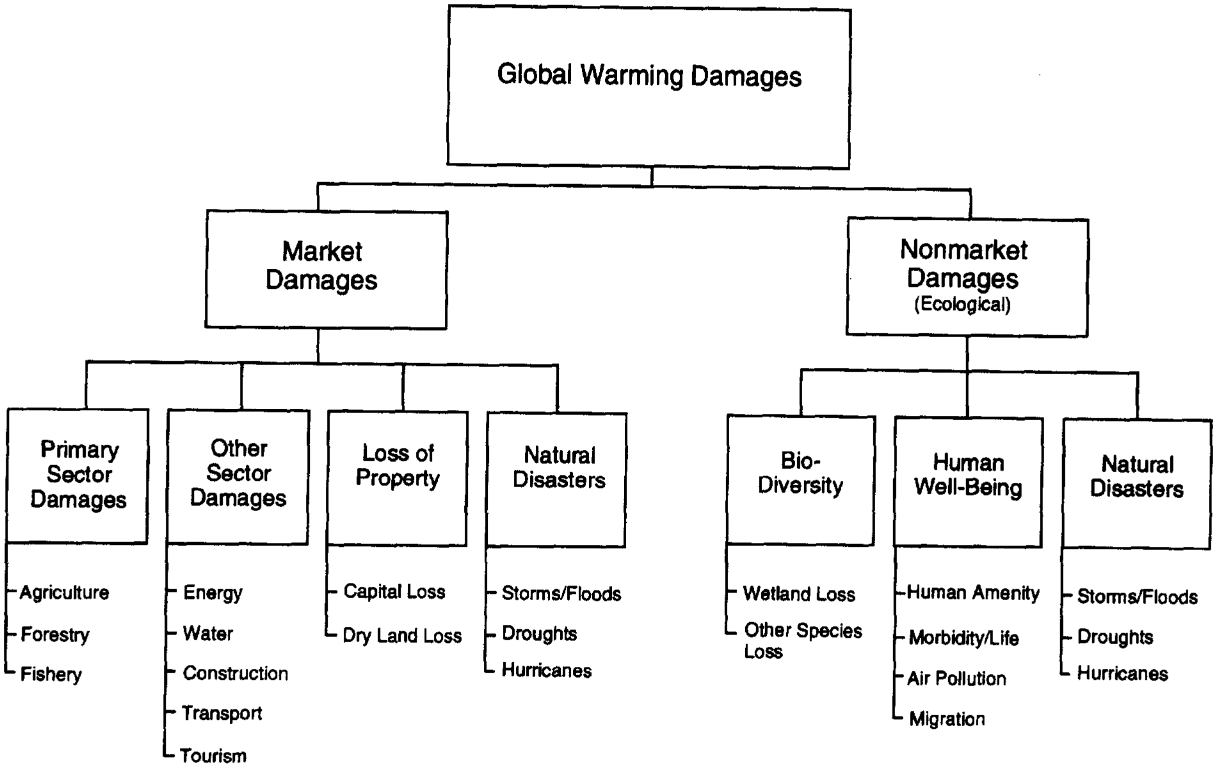

Figure 4 Overview on global warming impacts

change in temperate countries is the global mean and that the change in tropical countries is half the global mean.

Damage assessment submodel

In a critique of attempts to quantify the impacts of climate change, Grubb (1993) identifies the question that analysts need to address: 'What may be the impact of increasing greenhouse gas concentrations on the overall welfare of future generations globally, expressed in terms of present day monetary equivalence?' It is easy to pose this question in qualitative terms, but difficult to arrive at a consensus on the quantitative impacts.

Part of the problem is what to include in the evaluation. It is far easier to quantify effects on goods sold in markets such as food and energy than on services such as biodiversity, environmental quality and human health which have no market values. Both categories are important and need to be incorporated into global climate cost–benefit analyses.

Figure 4 (adapted from Fankhauser (1993)) presents a classification of climate change impact categories. Market effects reflect categories that are included in conventionally measured national income and can be valued using prices and observed demand and supply functions. Non-market effects have no observable prices, and so they must be valued using alternative revealed preference or attitudinal methods.

Consistent with Figure 4, we divide damages into two categories: market and non-market. $D_{t,n}$, market damages for period t in region n, are defined by the following relationship:

$$D_{t,n} = d_{1,n} * \Delta AT_{t,n}^{d_{2,n}} * GDP_{t,n} \qquad (13)$$

Much of the discussion has focused on damages at a single point in time – when temperature increases by 2.5 °C above 1990 levels. It is also important to specify what happens before and after this date. There has been considerable speculation about the shape of the damage function (see, eg, Peck and Teisberg (1992)). For the present analysis, we adopt the assumption of Nordhaus (1992) that damages rise quadratically with temperature change. That is, in Equation (13), $d_{2,n} = 2$.

Next we turn to non-market damages. Few issues in the greenhouse debate are more challenging or have engendered more controversy. What value does society place on biodiversity? Environmental quality? Human health? Many cost–benefit calculations ignore the issue altogether and confine their analyses to economically measurable consequences only. As noted by Dorfman and Dorfman (1976), 'there is discretion in declining to attempt the nearly impossible, but there is also danger

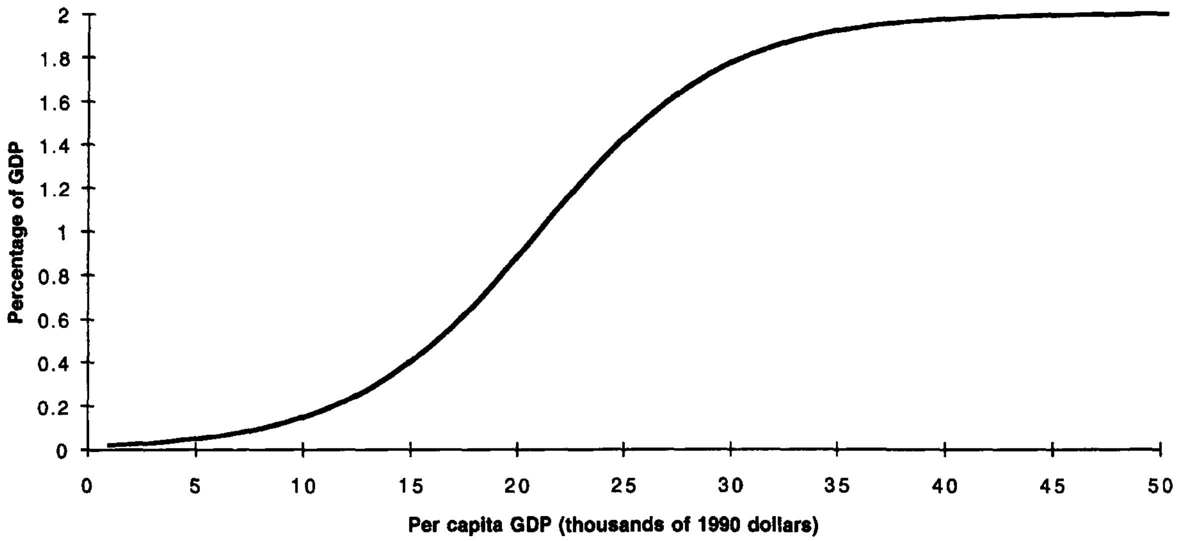

Figure 5 Willingness to pay to avoid 2.5 °C change in temperature: non-market (ecological) damages

since effects omitted from the benefit-cost calculation tend to be given insufficient weight in making decisions based upon the calculation'.

In this paper, we take an approach based on willingness to pay (WTP). The issue is framed in the context of how much consumers in each region would be willing to pay to avoid ecological damages. The fraction depends both on temperature change and GDP per capita:

$$WTP_{t,n} = d_{3,n} * \Delta AT_{t,n}^{\;d_{4,n}} / (1+100 * \exp(-0.23*GDP_{t,n}/POP_{t,n}) \quad (14)$$

The relationship between *WTP* for non-market goods and per capita income is assumed to be S-shaped, and is calibrated so that it does not exceed 100% of GDP. At low incomes, people are not willing to pay much to avoid non-market effects. However, as incomes climb, *WTP* increases rapidly and then plateaus at a constant proportion of income. For example, Figure 5 shows the WTP function for $d_{3,n} = 0.0032$ and $d_{4,n} = 2$. This means that when per capita incomes approach 40 (thousands of 1990 dollars), consumers are willing to pay 2% of GDP to avoid a 2.5 °C increase in temperature, and 8% of GDP to avoid a 5 °C increase.

According to Equation (14), each region values ecological damages independently of where such damage occurs. That is, consumers in a particular region place the same value on wetland losses whether they occur within or outside their own boundaries. The same is true for human health and wildlife. The S-shaped function implies, however, that lower income regions will place a lower value on such losses than higher income regions. As a result, non-market damages will be higher for developed countries.

Rather than advocate any particular set of numbers, we will explore the implications of alternative valuations. We seek to address the following question: how much must an informed global community be willing to pay to avoid ecological damages in order for a particular policy to make sense?

Emissions, concentrations and temperature change under five alternative policy scenarios

Numerous proposals have been put forward for controlling greenhouse gas emissions. These have ranged from a modest slowing in the rate of growth to drastic reductions below present levels. To illustrate how MERGE can be used for integrated cost–benefit analysis, we will apply it to a representative menu of policy choices. These include:

- business as usual;
- a tax on carbon emissions starting at $1/tonne in 2000 and increasing at 5%/year;
- a tax on carbon emissions starting at $5/tonne in 2000 and increasing at 5%/year;
- stabilizing global CO_2 emissions at 1990 levels; and
- stabilizing concentrations of CO_2 in the atmosphere at near current levels.

The difference between the two tax policies is primarily one of timing. The tax beginning at one dollar per ton rises to five dollars per ton by about 2030. If we ignore the relatively small deadweight losses incurred prior to this date, it is equivalent to delaying the imposition of the five dollars per ton tax by 30 years. For short hand, we will refer to this as the delayed tax alternative.

There is no unique formula for achieving stabilization – either of emissions or concentrations. Each involves

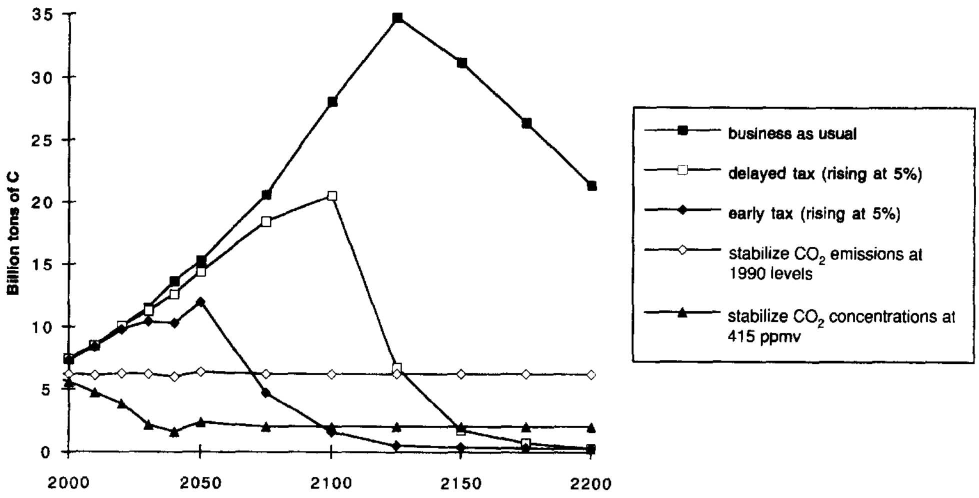

Figure 6 Global CO_2 emissions

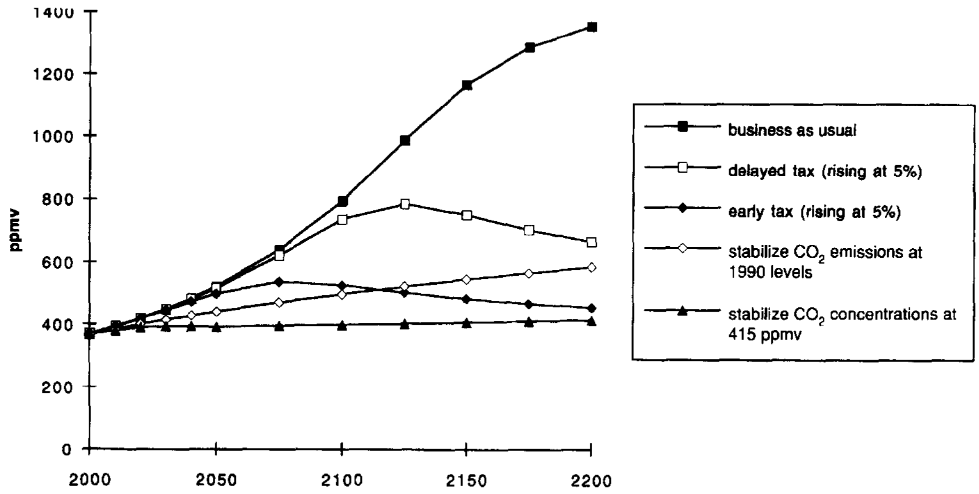

Figure 7 CO_2 concentrations

the difficult issue of the allocation of emission rights among regions. In this paper, we explore one widely discussed proposal, a gradual transition to equal per capita emission rights. We assume that carbon rights are initially distributed among regions in proportion to their 1990 level of emissions. Over time, the shares change gradually. By 2030, carbon rights are distributed in proportion to 1990 population levels. Note that the 1990 population base penalizes nations that fail to control their rate of population growth.

The IPCC (1990) estimates that emissions would have to be reduced immediately to 30% of 1990 levels in order to keep atmospheric CO_2 concentrations constant. Given that fossil fuels provide more than 90% of the world's commercial energy, this seems unrealistic. For our stabilization scenario, we assume that emissions are reduced gradually to 30% of 1990 levels by 2030. This results in stabilization of atmospheric concentrations at 415 ppmv – approximately 50% higher than pre-industrial levels.

Figure 6 compares carbon emissions for the five alternatives. Under business as usual, emissions continue to rise into the 22nd century. The growth reflects the increasing dependence on coal in the non-electric sector. With the eventual exhaustion of low-cost oil and gas resources, coal based synthetic fuels are apt to become the marginal source of non-electric energy supply. Unfortunately, the synthetics emit twice as much CO_2 per unit of energy as conventional oil.

In the longer term, CO_2 emissions will begin to decline – even under business as usual. Coal, like other fossil fuels, is in limited supply. As economically recoverable resources are exhausted, coal too will be replaced by other alternatives. Even in the absence of CO_2 considerations, the world's dependence on fossil fuels is likely to decline sharply towards the end of the 22nd century.

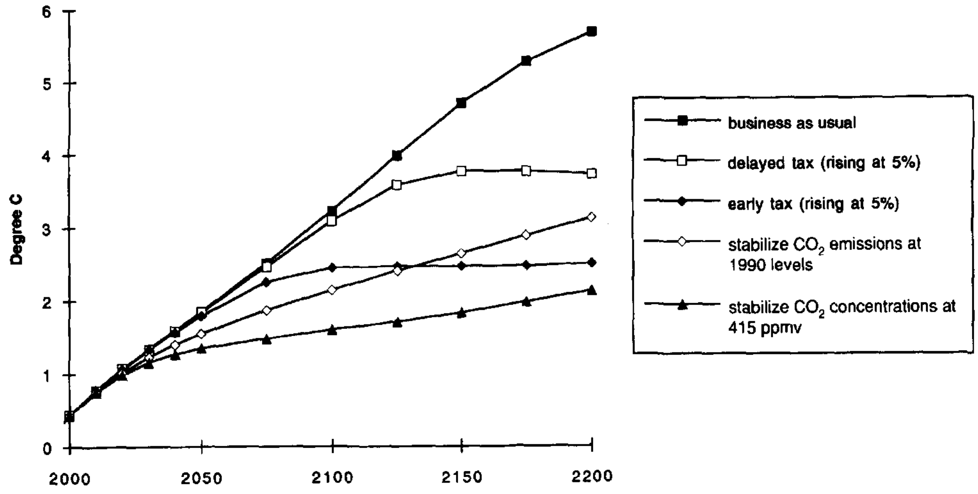

Figure 8 Mean global temperature change from 1990

The effect of the tax policies is to hasten the end of the synthetic fuels era. When the tax on carbon rises above $200 per tonne, the carbon free non-electric backstop becomes the technology of choice. With the delayed tax, this happens shortly after the year 2100. This explains the rapid fall off in carbon emissions as we move into the 22nd century. With the early tax, the $200 threshold is reached 30 years earlier. The synthetic fuels era is shortened accordingly.

Using the carbon cycle model, it is straightforward to convert emissions into atmospheric concentrations. Figure 7 compares results for the five alternatives. Under business as usual, concentrations are twice pre-industrial levels in the middle of the next century, and they double again by 2200.

The tax policies initially stabilize concentrations, and eventually lead to their decline. In the case of the delayed tax, concentrations approach 800 parts per million by volume (ppmv) and then return to 650 ppmv. For the early tax policy, they peak at 550 ppmv, then return to 450 ppmv.

By stabilizing emissions at 1990 levels, we do not halt the rise in atmospheric CO_2 concentrations. By 2200, concentrations approach 600 ppmv, and they continue to rise. The most stringent policy is designed specifically to achieve stabilization of concentrations. This happens at approximately 415 ppmv.

Figure 8 compares the impact on mean global temperature. Under business as usual, temperature increases by 2.5 °C (above the 1990 level) by 2075 and by nearly 6 °C by 2200. Not surprisingly, the delayed tax is the least effective in reducing temperature change. It does, however, serve to limit the long-term temperature rise to 4 °C.

By accelerating the imposition of the tax, there is a substantial impact on temperature change. The increase is now limited to 2.5 °C. Note also that over the longer term (post-2075), the early tax turns out to be more effective than the emissions stabilization policy (in terms of limiting temperature change).

Up to 2200, the policy with the greatest impact on global warming is one in which concentrations would be stabilized near current levels. Note, however, that stabilizing CO_2 concentrations does not cap the temperature rise. There are continuing emissions of the other greenhouse gases.

Benefits and costs

In the previous section, the effectiveness of the policy options were measured in physical terms – emissions, concentrations and mean temperature change. Although the exercise yielded some useful insights, it is a limited guide to greenhouse decision making. Sensible greenhouse policy requires a careful balancing of both benefits and costs. The next step in an integrated assessment is to translate temperature changes into market and non-market damages. To do this, we must first calibrate the regional damage functions.

In his original work on the impacts of climate change, Nordhaus (1991) focused primarily on market damages to the USA from a doubling of atmospheric CO_2 levels ($2 \times CO_2$). Noting that only 3% of US national output originates in climate sensitive sectors and another 10% in sectors that are modestly sensitive to climate change, he estimated that the net economic damages from a $2 \times CO_2$ scenario are likely to be of the order of 0.25% of national income.

Nordhaus acknowledged, however, that many valuable goods and services are excluded from conventional national income accounts. Correcting for these omissions and extending to the world, his best guess of the costs imposed by a doubling in atmospheric CO_2 concentrations was 1% of global GDP, with a range of 0.25–2%.

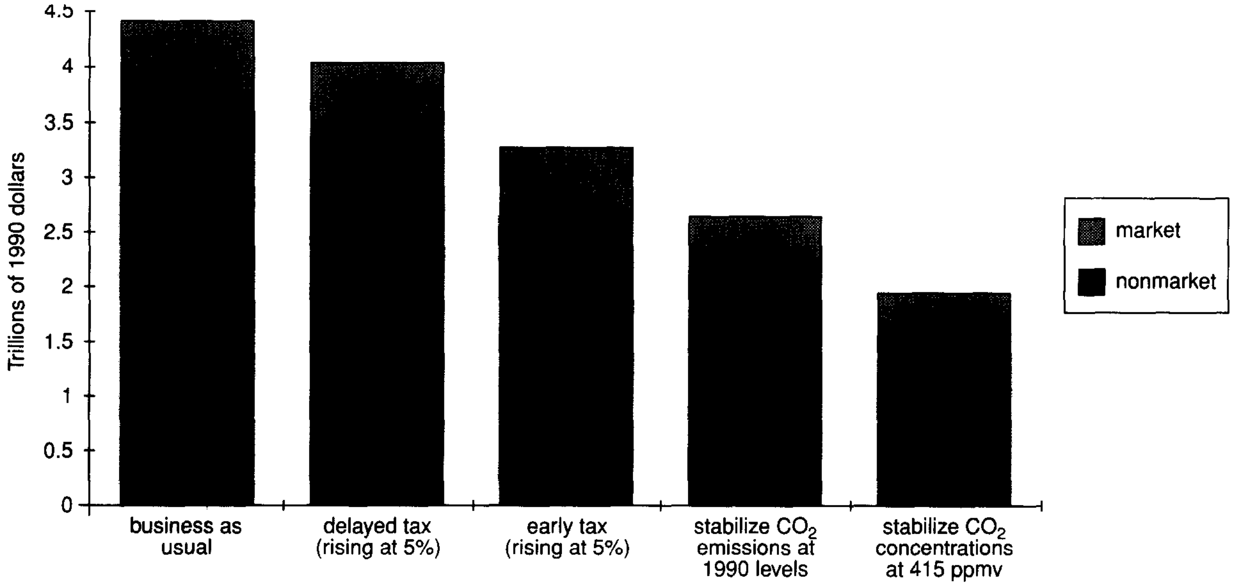

Figure 9 Global damages discounted to 1990 at 5%

Subsequent studies have attempted more comprehensive analyses for the USA with surprisingly similar results. Cline (1992) and Fankhauser (1993) estimate losses of the order of 1.1% and 1.3%, respectively, for a $2 \times CO_2$ scenario. When Cline adjusts for output composition in different countries, he projects total losses to the global economy of 1.3%. Similarly, Fankhauser suggests that the damage related to a doubling of atmospheric concentration may be of the order of 1–1.5% of GDP worldwide.

Although there appears to be some convergence in the GDP estimates, it is important to note that climate impact assessment is still in a rudimentary stage. Investigators are quick to stress the preliminary nature of their findings and the need for additional work. The present analysis makes no attempt to narrow the range of uncertainty surrounding damages, nor do we endorse a particular set of estimates. Rather, our goal is to demonstrate how damage projections should fit into the overall assessment of climate change. In doing so, we hope to shed some light on the sensitivity of greenhouse policy to alternative assumptions about the shape and nature of the damage function.

With these caveats in mind, we now describe the assumptions used to estimate the regional loss functions. If damages change quadratically with temperature, the calibration requires only a single point on each function.

For developed regions, we assume that a 2.5 °C increase in temperature (above 1990 levels) would result in market damages of 0.25% of GDP. This is consistent with Nordhaus' estimates of market losses to the USA for a $2 \times CO_2$ scenario.

For other regions, the assessment is more difficult. Relatively little attention has been devoted to estimating market damages outside of the OECD. Developing countries tend to have a larger share of their economies concentrated in climate sensitive sectors, particularly in agriculture. This vulnerability, however, is apt to shrink over time as these countries take on more of the characteristics of their industrialized counterparts. Moreover, they are more likely to be in equatorial regions where temperature changes are less severe than in polar latitudes. Nevertheless, many believe that market damages are apt to be a higher percentage of GDP for developing countries. For the present analysis, we assume a multiple of two.

For non-market damages, we begin with the willingness-to-pay function described in Figure 5. It is based on the assumption that consumers in high income countries would be willing to pay 2% of GDP to avoid the ecological damages associated with a 2.5 °C increase in temperature. As a point of reference, the USA currently devotes approximately 2% of its gross domestic product to all forms of environmental protection. This compares with 2.7% for research and development and 5.5% for national defense (Council of Economic Advisors, 1993). Given the highly subjective nature of the willingness to pay assumption, we will subject it to extensive sensitivity analysis.

We are now ready to conduct the next step in an integrated assessment – the estimation of market and non-market damages. Figure 9 summarizes the results in present value terms. For the business as usual alternative, the losses approach $4.4 trillion (discounted to 1990 at 5% per year). Consistent with the earlier studies,

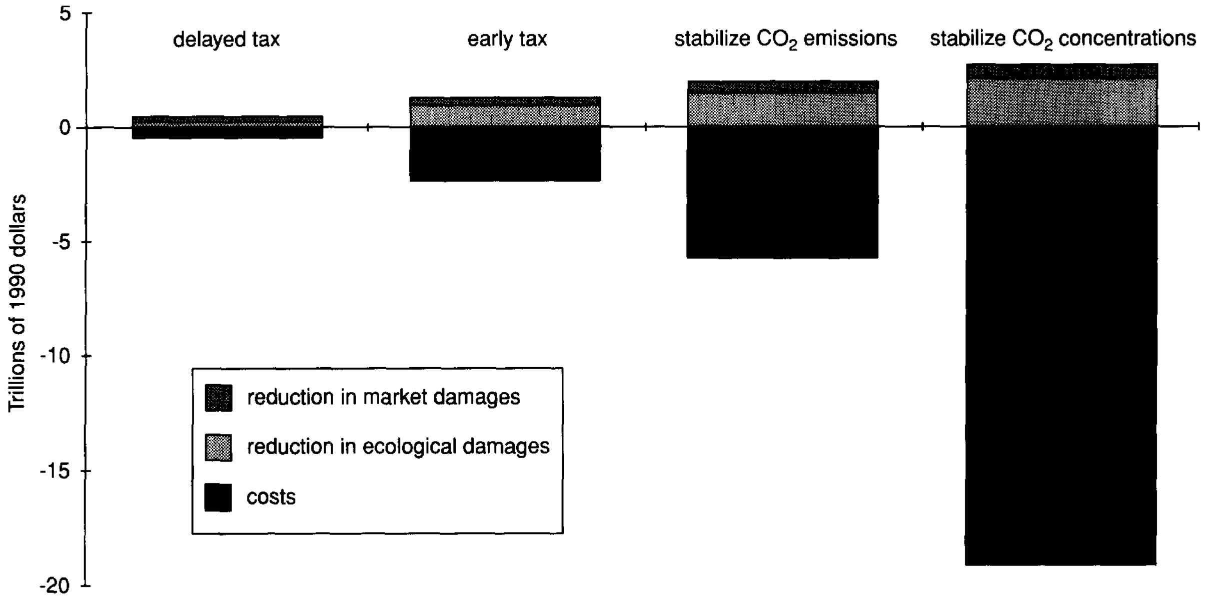

Figure 10 Global benefits and costs discounted to 1990 at 5%

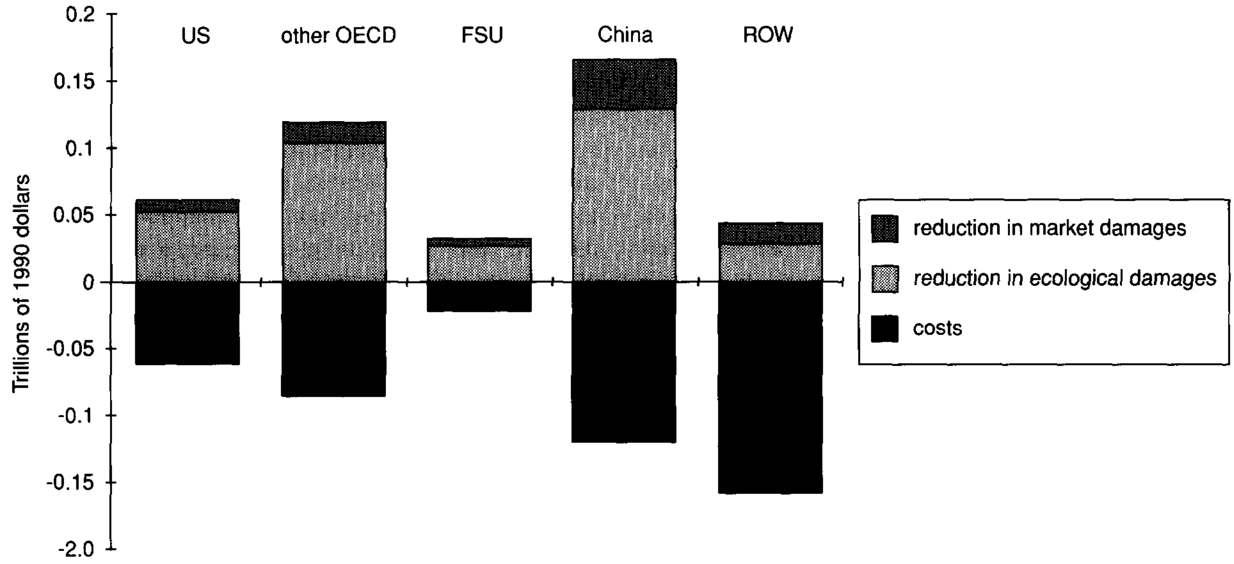

Figure 11 Regional benefits and costs from delayed tax policy (discounted to 1990 at 5%)

the bulk of the damages are in non-market categories. As a point of comparison, the projected losses for a 2.5 °C change in temperature amount to 1.4% of discounted worldwide GDP. This is also well within the range of the earlier estimates.

The economic benefits of an alternative policy may be measured in terms of the reduction in damages relative to business as usual. Total damages are reduced the most when CO_2 concentrations are stabilized at 415 ppmv. In this case, the benefits are nearly $2.5 trillion. By contrast, the benefits from the delayed tax policy are less than $0.5 trillion.

The desirability of a policy depends upon both benefits and costs. Using Global 2200, we calculate the economy-wide costs of each abatement alternative. The results are summarized in Figure 10. Although stabilizing concentrations buys the most – in terms of reduced market and non-market damages – it also carries the highest price tag. Costs outweigh benefits by almost eight to one. From a purely benefit-cost perspective, the only policy that appears attractive is the delayed tax. Both benefits and costs are of the order of $0.4 trillion.

MERGE also allows us to examine the distribution of

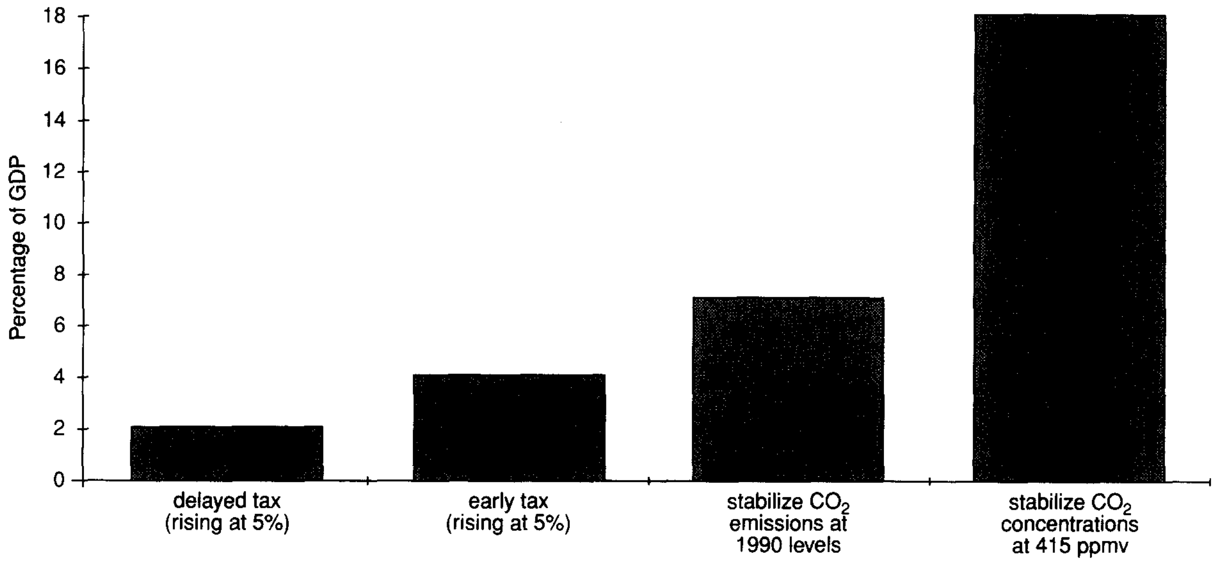

Figure 12 Break-even willingness to pay: 5% return on capital

benefits and costs across regions. Figure 11 shows such a breakdown for the delayed tax policy. Note that all regions are winners except ROW. There are two reasons for this. First, the temperature increase for the tropics is half of the global mean increase and most of ROW is in the tropics. Hence, it experiences less damage than the other regions. Secondly, because of its relatively low per capita income, it values nonmarket damages less than its more wealthy counterparts. In order to induce ROW to join into an agreement with the other four regions, there would have to be additional side payments.

Some sensitivity analyses

Like all quantitative analyses, the results are driven by the numerical inputs. In this section, we explore the sensitivity of the results to three key sets of assumptions: the willingness-to-pay to avoid ecological damages, the cost of alternative emission control policies, and the discount rate.

Given the highly subjective nature of the willingness to pay function, limited insight is gained from any particular set of estimates. It is more instructive to ask how much consumers must be willing to pay to avoid ecological damages in order for a particular policy to make sense from an economic cost–benefit perspective.

Figure 12 shows the break-even points for our four alternatives to business as usual. The delayed tax is justified when high-income consumers are willing to pay 2% of GDP to avoid a 2.5 °C increase in temperature. For a stringent emissions policy to be attractive, there must be a high willingness to pay. For the most costly policy, (stabilization of emissions at 415 ppmv), high-income consumers must be willing to pay approximately 17% of GDP to avoid a 2.5 °C increase in temperature. This is the point at which the benefits just break even with the costs.

Next, we look at how the break-even willingness to pay depends upon the costs of the emission control policies. Our reference case Global 2200 assumptions were described above. We now adopt more optimistic assumptions regarding two critical parameters: the elasticity of price induced conservation and the cost of the carbon free non-electric backstop (NE-BAK).

The degree of substitutability between the inputs of capital, labor and energy will affect the economic losses from energy price increases. Our earlier substitution elasticities were based on a backcasting exercise, and they best explain the US historical record (Manne and Richels, 1992). For the sensitivity analysis, we assume that the elasticities are 50% higher.

Similarly, we adopt considerably more optimistic assumptions about the cost of the non-electric backstop. For the sensitivity analysis, we assume that NE-BAK is only slightly more expensive than coal based synthetic fuels – \$55 as opposed to \$50 per barrel.

Figure 13 shows the impact of these optimistic abatement cost assumptions on the break-even willingness to pay. The effect is to lower the cost of the policy. This automatically lowers the value we must assign to ecological damages for control policies to be economically justifiable.

Finally, we turn to the issue of the discount rate ie the rate at which we discount goods and services from the

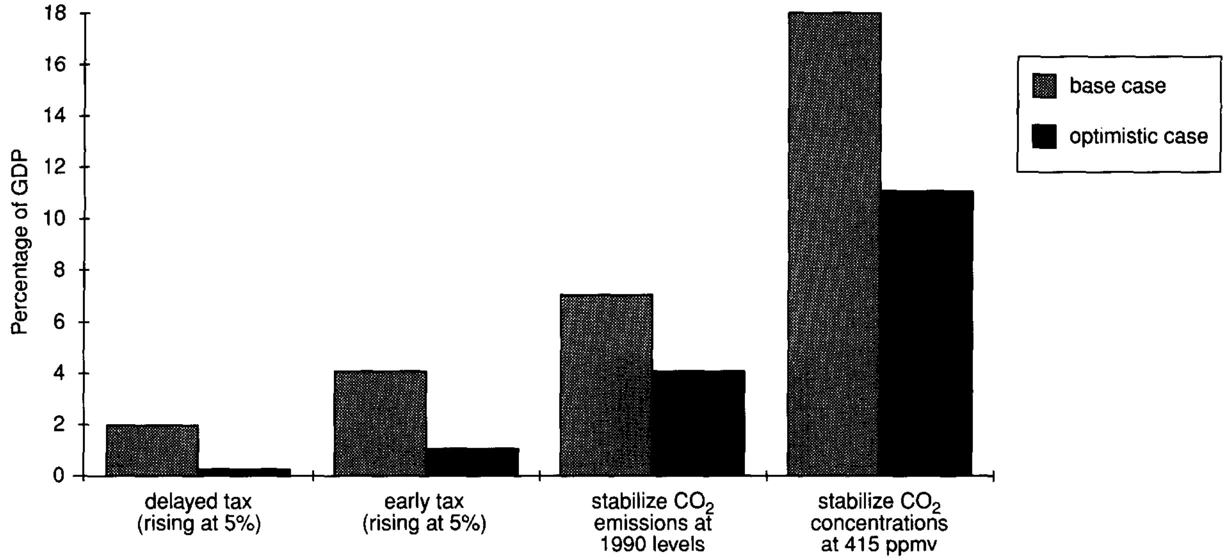

Figure 13 Break even willingness to pay: sensitivity to abatement costs

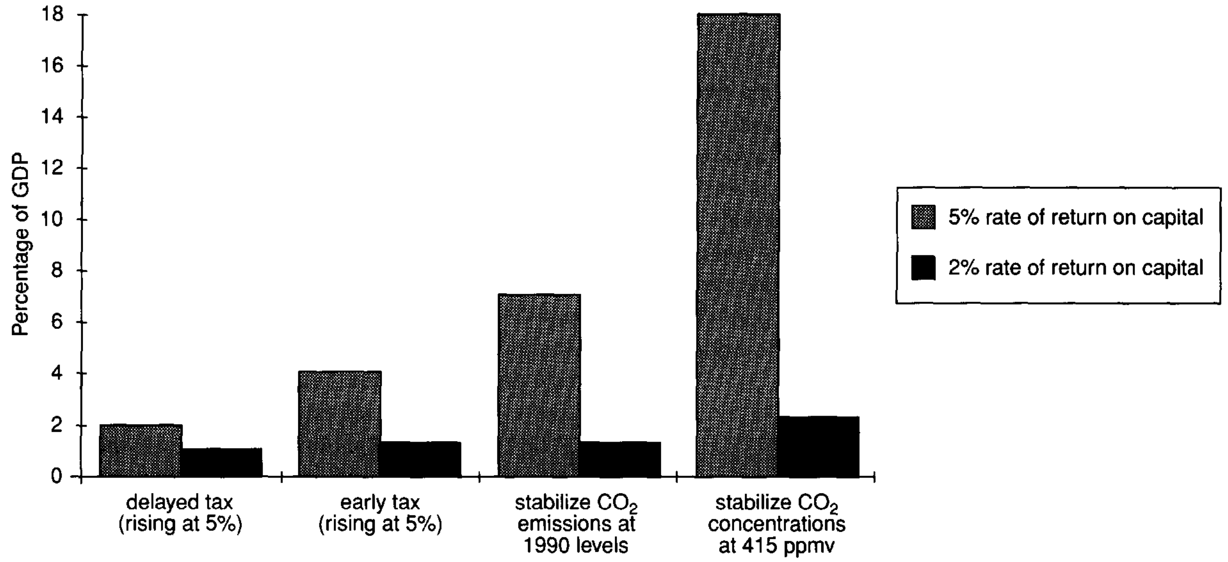

Figure 14 Break even willingness to pay: 5% versus 2% rate of retuun on capital

future to the present. Costs and benefits are both discounted at the same rate as investment opportunities elsewhere in the economy. From Equation (3), recall that in an economy growing at 2% per year, a 5% marginal productivity of capital is consistent with a 3% pure rate of utility time preference. If one adopts a prescriptive rather than a descriptive approach, one might assume a lower rate of utility time preference. This is a logically consistent scenario, but would require an unrealistically rapid increase in investment in the early years. The result would be to drive down the marginal productivity of capital to some much lower value than its current level of 5%. For example, Cline (1992) suggests that the appropriate number is closer to 2%. MERGE is designed so that such differences in viewpoints can be incorporated easily and their significance assessed.

Figure 14 shows the impact of the lower discount rate on the break-even willingness-to-pay. Increased weight is placed on future impacts. Hence, damages do not have to be as high in the future in order to justify action. As a result, the break-even point is lower.

Some final comments

MERGE provides a framework for thinking about climate change policy proposals. The model is designed to be sufficiently flexible and transparent so that it can be used to explore alternative views on a wide range of contentious issues eg costs, damages, non-market valuation and discounting.

Given the level of uncertainty which pervades the climate debate, it would be unrealistic to expect cost–benefit analysis to lead to consensus on a bottom line – at least in the immediate future. Rather, models such as MERGE should be viewed as research tools capable of providing insights into which aspects of the debate may be most important. In this way, they can help focus the discussion and identify the areas where additional research may have the highest pay off.

The present analysis has indeed identified a number of issues for further investigation. The evaluation of damages – particularly ecological damages – deserves a great deal more attention. The conventional wisdom, that losses will be higher for developing countries, needs to be re-examined. True, developing countries tend to derive a larger share of their economic output from climate sensitive sectors. But market damages may turn out to be a relatively minor part of the story.

The more important issue may be how we allocate and value ecological losses. Unfortunately, the accounting is far from straightforward. For the present analysis, we assumed that inhabitants of a particular region place the same value on global ecological losses regardless of their geographical location. The losses are then evaluated in terms of willingness to pay. This means that low income countries have lower ability to pay, and therefore lower losses than high income countries.

Given the importance of ecological factors to the overall climate cost–benefit calculus, more attention needs to be devoted to their valuation. 'Non'-market damages do not lend themselves easily to monetary valuation. Yet there is little alternative but to try. The best course of action may be to frame the issue in terms of a break-even willingness to pay. The various parties can then debate whether the benefits of a policy outweigh the costs.

The analytical framework itself needs further attention. Perhaps the most serious limitation is the treatment of uncertainty. The climate issue entails high stakes. Waiting leads to the risk of irreversible damages. Immediate action leads to the risk that large costs will be incurred in the near future, and there is considerable disagreement on how these actions will eventually affect the world's climate. Policy makers need help in identifying hedging strategies which balance the costs of delay against those of premature action.

To be a more effective policy tool, MERGE needs to deal more explicitly with critical climate-related risks. We need to provide the capability to replace point estimates with probability distributions reflecting the full range of possible outcomes. Much of the greenhouse debate centers around low probability but high consequence events. These concerns must be included in the analytical process.

We must also do a better job of capturing the true nature of policy making. Greenhouse decision making is apt to be a sequential process with many opportunities for learning and midcourse corrections. The issue is not deciding what to do about greenhouse emissions over the next century. It is deciding what to do over the next decade in the light of alternative consequences over the next century.

Policy frameworks are needed which reflect this 'act – then learn' character of the decision process. With the help of such tools, we will be better able to address two central issues. Which of the many climate related uncertainties are most important to today's decisions? And which strategies provide the best hedge against greenhouse related risks?

Acknowledgements

This research was funded by the Electric Power Research Institute (EPRI). The authors are much indebted to Tim Olsen and Susan Swinehart for research assistance. We have benefited from discussions with William Cline, Jae Edmonds, Sam Fankhauser, Larry Goulder, Erik Haites, William Nordhaus, Stephen Peck, Stephen Schneider and Thomas Teisberg. The views presented here are solely those of the individual authors, and do not necessarily represent the views of EPRI or its members.

References

Brooke, A, Kendrick, D and Meeraus, A (1988) *GAMS: A User's Guide* Scientific Press, Redwood City, CA

Chakravarty, S (1969) *Capital and Development Planning* MIT Press, Cambridge, MA

Cline, W (1992) *The Economics of Global Warming* Institute for International Economics, Washington, DC

Council of Economic Advisors (1993) *Economic Report of the President* US Government Printing Office, Washington, DC

Dorfman, R and Dorfman, N (1976) *Economics of the Environment* W W Norton, New York

Dowlatabati, H and Morgan, G (1993) 'A model framework for integrated studies of the climate problem' *Energy Policy* **21** (3)

Energy Modeling Forum (1993) *Reducing Global Carbon Emissions: Costs and Policy Options* EMF-12, Stanford University, Stanford, CA

Eykmans, J, Proost, S and Schokkaert, E (1992) *Efficiency and Distribution in Greenhouse Negotiations* Draft, Katholieke Universiteit Leuven, Leuven

Falk, I and Mendelsohn, R (1993) 'The economics of controlling stock pollution: an efficient strategy for greenhouse gases' *Journal of Environmental Economics and Management* **25** 76–88

Fankhauser, S (1993) 'The economic costs of global warming' in *Costs, Impacts, and Benefits of CO_2 Mitigation* International Institute for Applied Systems Analysis, Laxenburg, Austria

Grubb, M (1993) 'The costs of climate change: critical elements' in Kaya, Y, Nakicenovic, N and Toth, F (eds) *Costs, Impacts, and Benefits of CO_2 Mitigation* International Institute for Applied Systems Analysis, Laxenburg, Austria

Hope, C, Anderson, J and Wenman, P (1993) 'Policy analysis of the greenhouse effect' *Energy Policy* **21** (3)

IPCC (1990) *Climate Change: The IPCC Scientific Assessment* Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge

IPCC (1992) *Climate Change 1992: The Supplementary Report to the IPCC Scientific Assessment* Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, UK

Maier-Reimer, E and Hasselmann, K (1982) *An Ocean Circulation Model for Climate Studies* Technical Report, Max-Planck-Institute, Hamburg

Maier-Reimer, E and Hasselmann, K (1987) 'Transport and storage of carbon dioxide in the ocean: an inorganic ocean-circulation carbon cycle model' *Climate Dynamics* **2**

Manne, A and Richels, R (1992) *Buying Greenhouse Insurance: The Economic Costs of Carbon Dioxide Emission Limits* MIT Press, Cambridge, MA

Manne, A (1992) *The Rate of Time Preference: Implications for the Greenhouse Debate* Working paper, Stanford University, CA

Nordhaus, W (1991) 'To slow or not to slow: the economics of the greenhouse effect' *Economic Journal* **101** 407

Peck, S and Teisberg, T (1992) 'CETA: a model for carbon emissions trajectory assessment' *Energy Journal* **13** (1)

Rutherford, T (1992) *Sequential Joint Maximization* Working paper, University of Colorado, CO

Working Group III (1990) *Formulation of Response Strategies* Intergovernmental Panel on Climate Change, Washington, DC

Zachariah, K and Vu, M (1988) *World Population Projections, 1987–1988 Edition* World Bank, Johns Hopkins University Press, Baltimore, MD