Comparing the Effects of Greenhouse Gas Emissions on Global Warming

by

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ABSTRACT

Policies dealing with global warming require a measure of the effects of the emissions of greenhouse gases that create different magnitudes of instantaneous radiative forcing and have different lifetimes. The Global Warming Potential (GWP), a physical index of the total radiative forcing due to an emission of a unit amount of a particular greenhouse gas has been proposed by the Intergovernmental Panel on Climate Change as a such a policy tool. In general, no such physical index will serve this purpose. Adding up physical measures of radiative forcing in different periods resulting from emissions at different times and places is, in an economic and policy sense, like adding apples and oranges. Discounting of radiative forcing in successive periods, as in done in some versions of the GWP, is only an arbitrary weighting.

Reduction of radiative forcing effects in different future periods of greenhouse gas emissions that occur at different times and places can be expected to impose different economic costs. These opportunity cost valuations must be used to weight the effects of a greenhouse gas emission over its lifetime. That leads to the concept of the Emissions Opportunity Cost (EOC) of a greenhouse gas emission. While this is more difficult to measure, it is the essential guide to policy.

I. Introduction

The formulation of policies to deal with global warming requires a measure of the effects of the emissions of greenhouse gases that create different magnitudes of instantaneous radiative forcing and have different lifetimes. The Global Warming Potential (GWP), a physical index of the total radiative forcing due to an emission of a unit amount of a particular greenhouse gas has been proposed by the Intergovernmental Panel on Climate Change as a such a policy tool.[1] According to the IPCC, the GWP would help, "in considering policy options," which, presumably, would include economic evaluations of the consequences of limiting emissions, tax policies, trade in gas emissions "permits" and, perhaps, allocation of international emissions quotas.[2] The GWP is an extension of the concept of Ozone Depletion Potential (ODP) developed in the discussion of controlling the emissions of halocarbons. The ODP became an essential part of the Montreal Protocol agreement for controlling the emissions of these gases.[3] So the concept deserves careful scrutiny and has already generated an extensive discussion of its scientific rationale.[4]

It will be argued here that, in general, no such physical index will serve the purposes suggested by the IPCC. Reduction of radiative forcing effects in different future periods of greenhouse gas emissions that occur at different times and

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[1]J.T. Houghton, G.J. Jenkins and J.J. Ephraums, Climate Change. The IPCC Scientific Assessment, Cambridge U. Press, Cambridge, 1990, p. 58.

[2]J.T. Houghton, G.J. Jenkins and J.J. Ephraums, op.cit., p. 58.

[3]J.T. Houghton, G.J. Jenkins and J.J. Ephraums, op.cit., p. 2; Donald J. Wuebbles, "The Relative Efficiency of A Number of Halocarbons for Destroying Stratospheric Ozone," Lawrence Livermore Laboratory, Jan., 1981 (unpublished).

[4]E.g. Daniel A. Lashof and Dilip R. Ahuja, "Relative contributions of greenhouse gas emissions to global warming," Nature, 344, 5 April, 1990, pp. 529-531, Kirk R. Smith and Dilip R. Ahuja, "Toward A Greenhouse Equivalence Index: The Total Exposure Analogy," Climatic Change, August, 1990, 17:1-7.

places can be expected to impose different economic costs. These cost valuations must be used to weight the effects of a greenhouse gas emission over its lifetime. By not ascribing economic weights to the radiative forcing of a gas emission in successive periods, the GWP, in effect, gives the effects equal economic weight, regardless of the period in which they occur and their sources. This would be true, however, only under very special economic conditions. While some versions of the GWP discount the radiative forcing in successive periods, such discounting, in these circumstances, is an arbitrary weighting that does not resolve the essential economic issue.

II. The Global Warming Potential and the Economic Opportunity Costs of Preventing Global Warming

The Global Warming Potential index integrates the radiative forcing due to a unit of a particular greenhouse gas emission over its residence time in the atmosphere and normalizes that sum by a corresponding integral for carbon dioxide. Using the notation of Lashof and Ahuja, GWP is defined as:

$$GWP = \frac{\int_0^\infty a_i(t)\, c_i(t)\, dt}{\int_0^\infty a_c(t)\, c_c(t)\, dt}, \qquad (1)$$

where $a_i(t)$ is the instantaneous radiative forcing due to a unit increase in the concentration of gas i, and $c_i(t)$ is the fraction of gas i remaining at time t. The corresponding values for CO_2 are in the denominator.[5]

There are a number of issues of atmospheric chemistry in this definition that are the subject of continuing scientific debate, for example, the lifetimes over

[5]op.cit., p. 529.

which the integrals should be defined. These issues will be passed over here as not essential for the points that will be made.

The essential economic concept for policy purposes is that of the opportunity cost of reducing radiative forcing. The "opportunity costs" of emissions reduction are the additional direct and indirect real expenses required, for example, in reducing energy losses or using more expensive, but less polluting electricity generating processes. High opportunity cost producers, by purchasing emissions permits from low opportunity cost emitters, would compensate the latter for assuming the burden of emissions reduction. Or taxes applied to consumers should be designed to reflect the opportunity costs to consumers of foregoing consumption that generate polluting greenhouse gases. These opportunity costs are also known among economists as, "shadow prices," with the word "shadow" reflecting the fact that they are not necessarily the prices that prevail in markets.

The reduction of radiative forcing in some future period imposes opportunity costs in every prior period. However, those opportunity costs can be expected to vary from period to period. The total opportunity costs of an emission in the current period are the sum of the opportunity costs created by radiative forcing in each successive period. The GWP index cannot be used to approximate those opportunity costs by multiplying it by a single price or cost value.

By adding together the successive radiative forcing effects, without valuing these effects, the GWP index implicitly sets equal the current opportunity cost valuations of the radiative forcing in each future period. That would permit them to be factored out of the GWP definition. Yet there is no valid economic reason why these opportunity costs should be equal. It would be true in some kinds of economic steady state, but economic steady states, while a useful theoretical concept, are no more likely to prevail in the future, than in the past. Nor is there any reason to believe that the steady state conditions for different countries would generate the same opportunity cost weights.

William Nordhaus[6] and then Lashof and Ahuja[7] proposed applying a constant discount rate to future radiative forcing in order to, "account for the fact that the damage from warming would differ depending on exactly when the warming occurred."[8] This does recognize the differing economic significance of radiative forcing at different points of time in the future, which must be reflected in present evaluations. Yet, it is an inadequate recognition because there is no reason why the economic evaluations of radiative forcing in successive periods should decline at exactly the rate of discount.

Unfortunately, therefore, the GWP is a concept that cannot, in fact, achieve the goal for which it is intended: "to address policy questions regarding the relative amounts of rational expenditures on different mitigating strategies," and, "develop cost-effective emissions policies at both national and international levels."[9]

In place of the GWP what is needed is a concept in which the radiative forcing in each period is valued by multiplying it by an associated opportunity cost or shadow price. The concept that does this is defined in equation (2) and might be called the Emissions Opportunity Cost (EOC) of a greenhouse gas emission:

$$EOC_i = \int_0^{\infty} v_i(t)\, a_i(t)\, c_i(t)\, dt \quad . \qquad (2)$$

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[6]"Contribution of Different Greenhouse Gases to Global Warming: A New Technique for Measuring Impact," (unpublished), Feb. 11, 1990, p. 3.

[7]op.cit., p. 531.

[8]W. Nordhaus, op.cit., p. 3.

[9]op.cit., p. 531.

In this definition, the a's and the c's have the same meaning as in the definition of GWP in equation (1). The $v_i(t)$'s in this equation represent the current opportunity costs to the economy as a whole, per unit of the gas, of not generating this particular radiative forcing. Thus the EOC concept reflects the instantaneous forcing effects of an emission, the emission's atmospheric lifetime and the opportunity costs of eliminating the radiative forcing. It would be possible to normalize this by relating it to the opportunity cost of not allowing the emission of the same quantity of carbon dioxide to have taken place, but there would be no particular usefulness to doing so.

The only, but very significant, difference between the EOC and GWP concepts are the $v_i(t)$'s, the opportunity cost valuations in the current period of the radiative forcing in each future period. Multiplying the $a_i(t)$ $c_i(t)$ products by a cost converts them into values that can be added up. Adding up physical measures of radiative forcing in different periods resulting from emissions at different times and places is, in an economic and policy sense, like adding apples and oranges. That cannot be done, but adding values of apples and oranges is legitimate.

III. A Simple Model of the Economic Effects of Constraining Greenhouse Gas Emissions

A simple model may help to illustrate the difficulties. It will be formulated as a linear programming problem in order to take advantage of the immediate demonstration that method provides of the valuations of all the relevant variables. This formulation will also provide a connection to the programming models that have been formulated to analyze the economic impacts of emissions constraints.[10]

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[10]See Nordhaus, William, "Economic Growth and Climate: The Carbon Dioxide Problem," American Economic Review, Papers and Proceedings, 67 (1), 341-346; Manne, Alan and Richels, Richard G., "CO2 Emission LImits: An Economic Analysis for the USA," presented at the MIT Workshop on Energy and Environmental Modeling, July 31-Aug. 1, 1989; Blitzer, Charles R.,

The linear programming formulation should not, however, be interpreted as overlooking the many non-linearities in production and consumption, as well as in the generation and accumulation of greenhouse gases, but rather as only an easier way of making a few general points than is possible in a nonlinear dynamic programming formulation.

The representation of the economy can be simplified enormously if it is thought of as if producing only one good, the gross national product. Equivalently, however, the single good may be considered a set of goods, although that would only add detail that is not essential for the present purposes. There will, however, be two greenhouse gases, one of which could be thought of as carbon dioxide, although that, too, is not essential for the demonstration.

The issues that have been raised as to the time over which future effects of emissions should be integrated will be finessed here as not related to the major point being made. The time horizon will be arbitrarily truncated at only three time periods in this model, which are themselves arbitrary and may be considered to be one year, 20 years, roughly the length of a generation, or 100 years. The alternatives would only require different definitions of the parameters to reflect the process of averaging over different periods.[11] It is obvious that this truncation of the future does not capture the long lifetime of some of the greenhouse gases. However, for the present purposes of demonstrating the necessity of considering the economic opportunity costs of emissions, the future need not stretch very far.

Eckaus, Richard S., Lahiri, Supriya and Meeraus, Alex, "A General Equilibrium Analysis of the Effects of Carbon Emissions Restrictions on Economic Growth in A Developing Country," Center for Energy Policy Research, MIT, Cambridge, Mass., July, 1989 (unpublished).

[11]The parametrization of the relation between annual investment and the change in capital stock would be different for one year periods from that for, say, 20 years.

For simplicity the model will represent a closed economy and one without a government sector. Output in each period will depend only on the capital stock available and on intermediate inputs through fixed ratios. Labor requirements will be ignored.

The first constraint of the model states the truism that an economy cannot use more of anything than it has available. The total availabilities from domestic production are X(t) and the uses of output are for: consumption, C(t), investment, I(t), and intermediate inputs, zX(t). Since intermediate requirements are related to output by a parameter, or, for many goods, a matrix of parameters, z, for each period the constraint can be written:

$$C(t) + I(t) + zX(t) \leq X(t).^{12} \tag{3}$$

Since production depends on capital, there is a constraint for each period that requires that production in any period must be less than the productive capacity of the capital stock available at the beginning of the period, K(t). The capital capacity requirements are determined by an capital/output coefficient, b so that:

$$b\,X(t) - K(t) \leq 0 \quad . \tag{4}$$

There is an initial capital endowment $\overline{K(1)}$. After that capital accumulates from investment and depreciation of capital will be neglected. Thus, the capital accumulation processes in the second and third period are:

$$K(2) \leq \overline{K(1)} + I(1) \text{ or } \quad K(2) - I(1) \leq \overline{K(1)} \ . \tag{5}$$

$$K(3) \leq \overline{K(1)} + I(1) + I(2) \text{ or } \quad K(3) - I(1) - I(2) \leq \overline{K(1)} \ . \tag{6}$$

It is also necessary to specify a terminal condition, otherwise there would be no reason for investment in the last period. A convenient way of doing that is

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[12] If the model is interpreted as representing many goods, so each variable presented is really a vector, then some means must be provided of disaggregating each of the uses of output, C(t) and I(t). It will be simply assumed here that could be done, if desired, by a set of linear relations.

simply to require that the last period's investment be enough to provide for growth in the capital stock from the last period to the post-terminal period. Since the capital stock in the last period is $\overline{K(1)} + I(1) + I(2)$, if g is the specified capital stock growth rate,

$$I(3) = g[\ \overline{K(1)} + I(1) + I(2)] \quad . \tag{7}$$

This specification of I(3) can be substituted into the inequality (3) for the third period.

To compute the radiative forcing in a particular period due only to the emission of the two greenhouse gases in that period, it is necessary to multiply the level of the emitting activity, considered here to be the production of the single good, X(t), by the emission rates, e_i, and then apply the instantaneous radiative forcing coefficients, a_i.[13] Both of these rates can be assumed to be constant without damage to the argument. For example, if $R_1(1)$ is the additional radiative forcing in the first period, due to emissions in the same period:

$$R_1(1) = (a_1 e_1 + a_2 e_2) X(1).^{14} \tag{8}$$

The radiative forcing in successive periods due to the greenhouse gas emissions in the first period has to be adjusted to account for the elimination of the gases from the atmosphere. For simplicity it will be assumed that the fractions d_1 and d_2 of the two gases "disappear" in each period and that these fractions are constant over time. Again these assumptions do not affect the main points of the argument. Thus the radiative forcing in period 2 due to the emissions in period 1 is

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[13]This adopts the notation of D.A. Lashof and D.R. Ahuja, op.cit.

[14]This formulation is recognized to be a gross oversimplification of the atmospheric chemistry. However, it is believed that the simplications do not negate the central argument.

$$R_1(2) = [(a_1 e_1)(1-d_1) + (a_2 e_2)(1-d_2)]\, X(1)\,.$$ [15] (9)

Social preferences with respect to climate change will be expressed in a simple way that does not affect the essential point of the illustration. It will be assumed that in each period of the model there is a maximum allowable net addition to radiative forcing, $\overline{R(1)}$, $\overline{R(2)}$ and $\overline{R(3)}$. Thus the constraint on the net addition to the radiative forcing in the first period is

$$R_1(1) - \overline{R(1)} \leq 0\,. \tag{10}$$

There is a similar constraint for each successive period.

A simple linear objective function will be used which is the discounted sum of consumption during the model's time horizon[16]:

$$\sum_t C(t)/(1+w)^{(t-1)} \quad . \tag{11}$$

Although environmental conditions are not included in the objective function but, rather, imposed as a constraint, this does not imply a judgment that there is no utility associated with environmental conditions. This treatment might be rationalized as a means of avoiding the difficulties involved in discovering the relative weights that should be placed on produced consumer goods and environmental quality. Alternatively it can be viewed as an expression of the idea that future generations have an incontrovertible right to a specified level of environmental quality. There could be an objection, which would be correct, that imposition of a constraint on radiative forcing or greenhouse gas accumulation, in effect, gives the specified, maximum allowable addition to

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[15]The a's have the same meaning as in the IPCC and Lashof and Ahuja definitions of the GWP and the (1-d) terms play the same role as the c's in those definitions. The e terms, which generate the total amount of gas associated with a particular production activity, do not appear in the GWP, which is calculated per unit of the gas.

[16]In this formulation, the discount rate, w, represents consumer time preference, not the marginal productivity of capital. It should also be noted that this is quite different from the D.A. Lashof and D.R. Ahuja and W. Nordhaus discounting of radiative forcing.

radiative forcing an infinite weight, since the constraint <u>must</u> be satisfied. The formulation can also be regarded as simply a convenient device with which to map out the consequences of alternative constraint levels.

It should also be noted that there is no feedback in the model from environmental conditions to production conditions. This is certainly a grave oversimplification. To remedy it, however, would take us very far afield and not change the conclusions.

IV. The Value of Additions to Radiative Forcing

The tableau of the model can now be written and is presented in Table 1. The primal problem, which is the maximization of the objective function (11), can be read across the succeeding rows of the tableau. The dual problem, which is the minimization of the cost of using the resources to produce a particular output, generates conditions on the valuations of each of the variables. This dual problem and its corresponding valuations can be read down each of the columns. To avoid the problems created by the arbitrary initial and terminal conditions and to highlight the general lessons provided by the model, it is useful to focus on period 2.

Like the model above, all the valuations are familiar ones, with the exception of those that reflect the constraints on greenhouse gas emissions. Reading down the column for X_2, the dual relationship is:

Value of indirect inputs for X_2	+	Rental of capital to produce X_2	+	Value in period 2 of radioactive forcing generated in producing X_2	+	Value in period 3 of radiative forcing generated producing X_2	-	Value of X(2)	= 0. (12)

If we suppose that a solution to the problem has been found, then both quantities and the dual values associated with each constraint, which are just the

Table 1

MODEL TABLEAU

Period-by-period constraints on increases in radiative forcing by greenhouse gases #1 and #2, with emission rates e_1 and e_2, instantaneous radiative forcing rates a_1 and a_2 and annual decay rates d_1 and d_2

CONSTRAINTS	VARIABLES X(1)	C(1)	I(1)	K(1)	X(2)	C(2)	I(2)	K(2)	X(3)	C(3)	K(3)	
Objective		1				(1+w)				$(1+w)^2$		
Distribution												
Period 1	(z-1)	1	1									
Period 2					(z-1)	1	1					
Perod 3			g				g		(z-1)	1		-gK(1)
Capital Formation												
Period 1				1								$\overline{K(1)}$
Period 2			-1					1				$\overline{K(1)}$
Period 3			-1				-1				1	$\overline{K(1)}$
Capacity												
Period 1	b			-1								
Period 2					b			-1				
Period 3									b		-1	
Radiative Forcing												
Period 1	$a_1e_1+a_2e_2$											$\overline{R(1)}$
Period 2	$a_1e_1(1-d_1)+ a_2e_2(1-d_2)$				$a_1e_1+a_2e_2$							$\overline{R(2)}$
Period 3	$a_1e_1(1-d_1)^2+ a_2e_2(1-d_2)^2$				$a_1e_1(1-d_1)+ a_2e_2(1-d_2)$				$a_1e_1+a_2e_2$			$\overline{R(3)}$

economists' shadow prices, will be known. That permits us to separate unit quantities and prices in the total values in (12). Assuming that, in fact, the emissions constraints are binding, the inequality (12) can be rewritten, with the following shadow prices resulting from the solution:

$v_z(2)$ is the shadow price of the intermediate inputs in period 2;

$v_k(2)$ is the shadow rental of capital in period 2;

$v_{r2}(2)$ is the shadow price of the radiative forcing in period 2 resulting from emissions in period 2;

$v_{r2}(3)$ is the shadow price in period 2 of radiative forcing in period 3 resulting from emissions in period 2;

$v_x(2)$ is the shadow price of output, X(2).

$$v_z(2) + v_k(2) + \{v_{r2}(2)[(a_1 e_1)(1-d_1)] + v_{r2}(2)[(a_2 e_2)(1-d_2)]\}$$

$$+ \{v_{r2}(3)[(a_1 e_1)(1-d_1)] + v_{r2}(3)[(a_2 e_2)(1-d_2)]\} = v_x . \quad (13)$$

The relationship in (13) says that the shadow price of output in period 2 must cover the direct costs of producing output in period 2 plus the opportunity costs of those emissions produced in period 2 <u>in every period subsequent to period 2</u>. The values, $v_{r2}(2)$ and $v_{r2}(3)$ correspond to the v(t)'s which appeared in the expression for EOC above. It is only the arbitrary truncation of the model at the end of the third period that prevents the costs of emissions in periods after period 3 from appearing in the tableau. Since the two gases are generated by the same production process in this model, they have the same shadow price associated with the <u>radiative forcing</u> of each gas. With different amounts of radiative forcing associated with the emissions of each gas, that implies a different price on the <u>emissions</u> of each gas.

For the first type of gas in this discrete, three time period model, the analogue of the GWP used by the IPCC and Lashof and Ahuja would be the sum:

$$[(a_1 e_1)(1-d_1)] + [(a_1\, e_1)(1-d_1)] \quad . \tag{14}$$

However, this sum does not appear in any valuation equation of this illustrative model.

The related sum that does appear in equation (13) is:

$$v_{r2}(2)\,[(a_1\, e_1)(1-d_1)] + v_{r2}(3)\,[(a_1\, e_1)(1-d_1)] \tag{15}$$

This is the discrete, two period analogue of the definition above of the Emissions Opportunity Cost of a particular quantity of radiative forcing, except that this is defined for the total amount of emissions resulting from a particular production activity and, thus, contains the e terms. By comparison, the EOC is defined per unit of a gas.

The existence of a shadow value or opportunity cost of the emissions depends, of course, on the greenhouse gas constraint being binding. When that constraint is binding, it imposes a cost on the emissions in every previous period that contribute to the binding constraint.

In some kind of economic steady state condition $v_{r2}(2)$ and $v_{r2}(3)$ would be equal, and could be factored out of the term in (15). There are many reasons to believe that neither the U.S. economy or any other economy is in a steady state nor will move into a steady state. Nor is there any reason to believe that steady state conditions are a reasonable approximation of those that will actually exist in the U.S. And, finally, the steady state conditions for the U.S., even if they existed or were used as an approximation, would not be the same for other countries, particularly the developing countries with differing levels of income, preferences, endowments and technologies.

In view of the controversy over discounting of future effects it may be noted that there is no discounting of the valuations of the radiative forcing in equation (13) or in the terms of the EOC as measured in (15). Rather than discounting, the EOC requires an evaluation of how much society wants to avoid radiative forcing.

That is not easy to provide, but easiness is not the criterion that should be enforced.

V. Conclusion: The Absence of a Role for Global Warming Potential and the Need for An Emissions Opportunity Cost

The model makes it clear that the Global Warming Potential defined at the outset of the paper is not a satisfactory policy tool. It is possible to construct scenarios in which emissions with the same Global Warming Potential have quite different economic values that are not related by a multiplicative factor. As a simple example, suppose that the constraint on additional radiative forcing was not binding in the first period in the model above. Then, although there would be additions to radiative forcing in the first period, the shadow price on their effects in the first period would be zero. If, however, the constraint on additions to radiative forcing were binding in the second period, the same emissions would have a positive shadow price in the first period related to their radiative forcing originating in the second period.

No easy direct analogies that might help make the point jump to mind. However, with a small stretch of the imagination the essential point can be related to the well-known, "tragedy of the commons."[17] This tragedy is generated by the incentives of individual members of the village that own the commons to increase without limit the number of animals that they graze on the common lands. With increasing density of the animals on the land increases, the ability of the grass to renew itself decreases. The overgrazing leads to the destruction of the commons itself.

To make the analogy with different types of greenhouse gases, suppose that both cattle and sheep are grazed and that, once an animal is put out for grazing

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[17]Garrett Hardin, "The Tragedy of the Commons," Science Dec. 18, 1968, 162, pp. 1243-1248.

on the commons, it stays for its entire lifetime. As is well known, the destructive effects of sheep on pastures is greater than that of cattle as the former shear the grass closer to the ground.

It would be possible to calculate a Grazing Destruction Potential (GDP) that could be measured for a cow which would be the total destructive effect measured over its lifetime. That could be compared with a similar GDP for sheep. The GDP's for cows and sheep would, however, not provide a guide to policy. Correct economic policy requires the equalization of the opportunity costs of adding a cow and sheep to the commons. These opportunity costs depend on the usefulness of the animals to their owners as well as their grazing destruction effects. If one objective of the village was to preserve the commons with least economic cost, and the opportunity costs associated with the grazing destruction by cows and sheep are different, the village could gain, overall, by refraining from adding the type of animal for which the opportunity cost was highest.

It could be expected that these opportunity costs would change over time and that the opportunity costs of cows and sheep would vary from village to village - and from country to country. All of this is intuitively obvious. The analogy is exact, however. Our intuition just does not work so well for greenhouse gas emissions.

It should be noted that the criticisms of the GWP apply equally well to the concept of Ozone Depletion Potential.

It might be objected that argument above makes it more difficult to formulate policy, with valuations of the opportunity costs of radiative forcing being necessary and those valuations changing from one period to the next and from country to country. That objection is both correct and essential. There is no easy way out of confronting the cost to society of reducing radiative forcing.