ELSEVIER

*Energy Policy*. Vol. 24, No. 3, pp. 211–219. 1996

0301-4215/96 $15.00 + 0.00

0301-4215(95)00144-1

# Valuing the impact of $CO_2$ emissions

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**Valuing the impacts of $CO_2$ emissions to the atmosphere has been widely debated, with various studies suggesting very different costs when expressed in units of dollar per tonne of carbon emitted. There are many complex issues involved, and it is often difficult to determine the reasons for the wide range of costs proposed. In this paper, models based on two very different approaches, the PAGE and Intera models, are considered. By applying these models to calculating the marginal impact of $CO_2$ emissions it is shown that what appear initially to be divergent estimates can be reconciled. This process illustrates some of the key issues in this area, and a perspective is provided on which marginal costs are appropriate for different policy decisions.**

*Keywords*: $CO_2$; Greenhouse gases; Carbon tax

There has recently been much debate about the social costs of $CO_2$ emissions to atmosphere and several authors have provided estimates of these costs (Nordhaus, 1991; Cline, 1992; Fankhauser, 1993; Fankhauser, 1994). One way of expressing such costs is in terms of the marginal impact of an extra tonne of carbon emitted into the atmosphere, and a recent review has shown that such estimates generally lie in the range of US$5 to US$25 per tonne of carbon (tC) (Fankhauser and Pearce, 1993). It is often very difficult to determine the reasons for the wide range of costs proposed, as there are many different assertions and assumptions made, some of which are not explicitly stated. In addition, the treatment of uncertainty in this debate has in general been rudimentary.

In this paper, two very different approaches are described and their calculations compared. The first approach will be referred to as the Intera model (Maul and Clement, 1994; Maul, 1994), and the second the PAGE model (Hope *et al*, 1993). Both these models treat uncertainty seriously, but from different viewpoints. By undertaking these detailed comparisons, many of the important issues involved will be illustrated, and a perspective gained on what marginal costs are appropriate in any particular policy debate.

## The Intera approach

Instead of considering the effects of global $CO_2$ emissions over an extended period, as is undertaken in many assessments in this area, the Intera approach considered small perturbations to the global system in order to calculate marginal costs. The calculation of costs for $CO_2$ discharges is then considered in two stages: modelling the environmental effects of discharges, in particular global mean temperature increase, and estimating the impacts of the resulting environmental change. The cost of any given category of impact $C_i$ is expressed as the product of two terms:

$$C_i = E\kappa_i$$

Here $E$ is the appropriate time-integrated environmental impact of unit discharge to the environment (generally the time-integrated increase in global mean temperature) and $\kappa_i$ is the cost impact resulting from unit environmental change (for example the damage caused by a 1°C rise in global mean temperature lasting for one year). The effect of discounting future costs is incorporated by making the environmental impact terms $E$ functions of the discount rate.

*Environmental impact*

Simple linear models of the type employed by Nordhaus are used to calculate the environmental impact terms (Nordhaus, 1991). Models of this type often represent the response of the global system to atmosphere discharges by four key parameters:

(1) the fraction of $CO_2$ which is rapidly removed from the atmosphere;

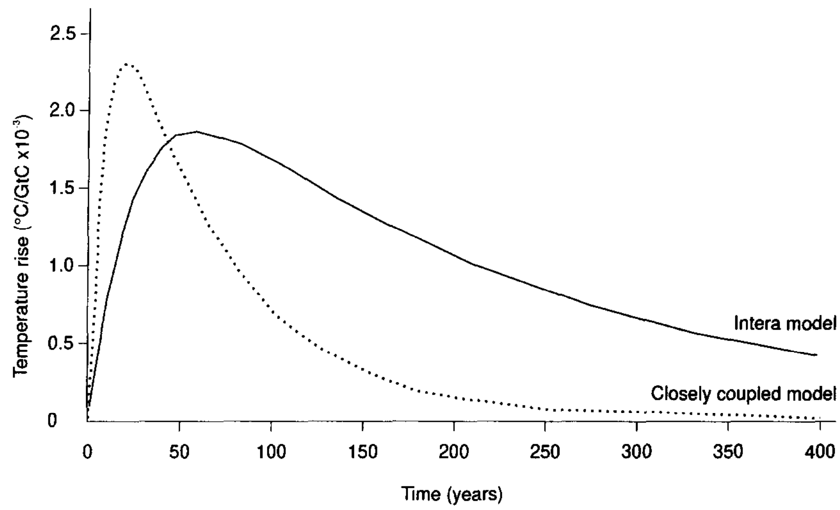


**Figure 1** Model calculations for the global mean temperature rise due to a short-term release

(2) the long-term rate of removal of $CO_2$ from the atmosphere;
(3) the equilibrium global mean temperature rise due to a given increase in atmospheric $CO_2$ levels;
(4) a constant rate for global mean temperature changes in response to changes in atmospheric $CO_2$ levels.

Figure 1 shows how global mean temperatures can be calculated to be affected by a discharge to atmosphere using two different approaches (Maul and Clement, 1994). The 'strongly coupled' model shown is slightly more complex than the simple Intera model, employing an additional term in the governing equations to allow for a fuller description of feedback between the global mean temperature and the atmospheric carbon levels. This model has been shown to be capable of reproducing historical temperature variations very well, and uses a more rapid response rate for the global mean temperature. The detailed differences between these and similar models are in the present context not very significant, as it is the discounted area under the curves in Figure 1 that is relevant to the cost estimates.

Changes in global mean sea level can be modelled in a similar way to global mean temperature changes, by using two parameters: the equilibrium sea level rise for a given increase in global mean temperature; and the rate of response of the system to temperature increases. In this case the response timescales can be very long, of the order of several centuries (Warrick *et al*, 1993).

*Impact costs*

The unit impacts that will be derived by any assessment will depend upon the costing assumptions employed. In the Intera approach, costing assumptions were taken which, as far as possible, are consistent with the conventions employed in the UK nuclear industry for the calculation of long-term liabilities (radioactive waste disposal, reactor decommissioning etc). This approach is used in order to attempt a fair comparison between fossil fuel and nuclear power as means of generating electricity.

Some of the more important assumptions are:

(1) Any international cooperation required to adapt to global warming will take place, so that major social upheavals are not considered.
(2) The cost to the polluter should not vary according to where the damage occurs. In particular, the value of a statistical life (VOSL) is taken to be the same, no matter where the risk of death is incurred.
(3) The discount rate employed is 2% per annum.
(4) No consideration is given to economic growth.

Consistent with the first convention, costs were estimated assuming the need to maintain global living standards at least at present levels, with major social upheavals on a large scale (eg transcontinental refugees) being excluded from consideration. This assumption has not always been employed in other costing studies, so that some authors have suggested very high costs for international refugees and/or major famines and droughts (Ferguson, 1994).

Some costs require a value for human life, and, consistent with the second convention, a single figure of US$3 million was employed. This value for the VOSL has been employed in the UK (CSERGE, 1992), although there is no agreed figure. Other studies generally vary the VOSL according to the country involved. In costing some classes of environmental damage, related costing assumptions have to be addressed. For example, should a polluter pay less for the same type of land damaged in a non-OECD country than in an OECD country? If it is asserted that the polluter should always pay a price which is relevant to the country in which the pollutant is discharged, then the cost assumed should be the same, and this convention was applied in the Intera study.

**Table 1 Global cost estimates for $CO_2$ doubling[a]**

| Impact category | Intera (reference value) | Fankhauser |
|---|---|---|
| Sea level rise | 100 | 41 |
| Agriculture and forestry | 38 | 42 |
| Ecosystems | 50 | 41 |
| Energy requirements | 5 | 23 |
| Extreme weather conditions | 125 | 3 |
| Human health | 250 | 82 |
| Water supply | 25 | 47 |
| Miscellaneous | | 4 |
| Total | 593 | 283 |

[a]All units are US$ billion per year.

### *Cost estimates for $CO_2$ doubling*

Many economic assessments for the effects of global warming take as a reference point the effects of $CO_2$ doubling assumed to correspond to a particular increase in global mean temperature and sea level, typically 2.5°C and 0.5 m respectively. Table 1 compares reference cost estimates for $CO_2$ doubling from the Intera study with those produced by Fankhauser (Fankhauser, 1993). The Intera study values are reference estimates based on a consideration of costs calculated in several studies (including original estimates by Intera), modified where necessary for consistency with the above accounting assumptions. It should be noted that direct comparisons between the impact categories can not always be made, as the scope of impacts included in a given category varies between the studies. Nevertheless, this comparison helps illustrate some of the important characteristics of the Intera calculations.

The table illustrates that the Intera reference values give much higher costs for some impact categories such as extreme meteorological conditions compared with the Fankhauser (and other) calculations. This is partly because of the constant value taken for the VOSL. Major storms have the potential to cause loss of life on a very large scale, particularly in the Third World. Climate change could be giving rise to an increased severity and frequency of storms and floods (Greenpeace, 1992; Chartered Institute of Insurance, 1994), with resulting significant increase in the loss of human life.

The Intera analysis includes both economic and non-economic impacts. Economic impacts include losses (and gains) in activities that are counted in a country's GDP. The non-economic impacts are those which do not appear in GDP measures and are extremely difficult to cost, particularly the importance of ecosystems. Many studies (including Intera's original calculations) have used contingent valuation methods to assess people's willingness to pay to save endangered species, but a number of authors have expressed the view that this does not fully take into account the value of ecosystems because 'life support' functions are not considered. It is also possible that the impact of climate change on biodiversity depends mainly on the rate of change of temperature rather than on the final value reached (Peters and Lovejoy, 1992), which is not incorporated in the Intera approach.

### *The treatment of uncertainty*

In the Intera calculations a nested set approach is used to represent uncertainties. For each choice (such as the selection of a model parameter value) the options are characterized according to how supportable they are. For example, an innermost set could be defined so that all experts would agree that it is possible that a given parameter value could lie in the chosen range. Subsequent, larger sets include choices which are increasingly less supportable, until one reaches a set where all experts would state that the parameter value could not lie outside the set. The algebra of this approach is identical to interval analysis and fuzzy logic (Moore, 1966; Robinson and Cooper, 1995). For example, for a particular result to be in the innermost set it is necessary that all the choices upon which it is based derive from innermost sets.

For the present application, it was judged that the amount of information available for most model parameter values did not justify the use of more than two nested set ranges. These sets have been referred to as inner and outer uncertainty ranges; the inner uncertainty range contains parameter values which it is judged that a majority of experts would consider possible, while the outer uncertainty range contains parameter values which it is judged that at least 5% of experts would consider possible. It is important to bear in mind that people generally tend to underestimate uncertainty ranges (Capen, 1976), so that nested set ranges are often wider than those which would be specified by individual experts. In addition to these two ranges, a reference value is employed from the inner uncertainty range.

Table 2 summarizes the calculated uncertainties for the first stage in the cost calculation, the integrated environmental changes. For temperature rise this quantity represents the discounted area under graphs like those shown in Figure 1, the units deriving from the product of the temperature increase (°C) and time (years) for a given unit emission (GtC). Similarly for sea level rise the units derive from the product of the sea level rise (metres) and time (years) for a given unit emission (GtC). A number of different models were considered in deriving the integrated global

**Table 2 Integrated environmental effects (Intera calculations)**

| Quantity | Outer minimum | Inner minimum | Reference | Inner maximum | Outer maximum |
|---|---|---|---|---|---|
| Discounted integrated temperature rise (°C years per GtC) | 0.01 | 0.07 | 0.1 | 0.12 | 0.3 |
| Discounted integrated sea level rise (metre years per GtC) | 0.0003 | 0.005 | 0.02 | 0.03 | 0.08 |

**Table 3 Impact unit costs (Intera calculations)[a]**

| Impact | Outer minimum | Inner minimum | Reference | Inner maximum | Outer maximum |
|---|---|---|---|---|---|
| Sea level rise | 30 | 50 | 200 | 300 | 1000 |
| Agriculture | 0 | 3 | 15 | 20 | 40 |
| Ecosystems | 5 | 10 | 20 | 60 | 100 |
| Energy | –15 | –6 | 3 | 10 | 15 |
| Extreme weather conditions | 5 | 10 | 50 | 80 | 160 |
| Health | 5 | 10 | 100 | 150 | 300 |
| Water supply | 0 | 2 | 10 | 20 | 30 |

[a]Units are US$ billion per year per °C except for sea level rise (US$ billion per year per metre).

**Table 4 Uncertainties in total discounted costs (Intera calculations)[a]**

| Impact | Outer minimum | Inner minimum | Reference | Inner maximum | Outer maximum |
|---|---|---|---|---|---|
| Sea level rise | 0 | 0.3 | 4 | 9 | 80 |
| Agriculture | 0 | 0.2 | 1.5 | 2.4 | 12 |
| Ecosystems | 0.1 | 0.7 | 2 | 7 | 30 |
| Energy | –0.2 | 0 | 0.3 | 1.2 | 4.5 |
| Extreme weather conditions | 0.1 | 0.7 | 5 | 10 | 48 |
| Health | 0.1 | 0.7 | 10 | 18 | 90 |
| Water supply | 0 | 0.1 | 1 | 2 | 9 |
| Total | 0 | 3 | 24 | 50 | 270 |

[a]Units are US$ per tC.

mean temperature rise and, partly because of the effects of discounting, the inner uncertainty range is surprisingly narrow, representing less than a factor of 2 uncertainty.

Table 3 gives the calculated uncertainties for the second stage of the cost calculation, the unit impact parameters. It should be noted here that the uncertainty ranges include scenarios with and without adaption to climate change, and this question will be referred to later.

The results of combining the two stages of the analysis to give overall costs are shown in Table 4. The reference discounted cost is around US$24 per tC, but the uncertainty ranges are large compared with this value. The bottom ends of the uncertainty ranges are close to zero, consistent with the interpretation that insufficient information is presently available to rule out completely the possibility that costs associated with increased atmospheric levels of $CO_2$ will be small. The top of the inner uncertainty range is US$50 per tC. It can be argued that this is an appropriate value to consider when deciding on the extent to which emissions of $CO_2$ should be penalized. In the Intera approach this value is defined to be as possible as any other value in the inner uncertainty range, and, consistent with the precautionary principle, the top of this range should be used.

## The PAGE model

The PAGE model was developed in 1991 to perform integrated assessments of global warming policies. It calculates both the costs of implementing those policies and the impacts of any global warming that occurs, which is the focus of this paper. The form of the model is shown in Figure 2. It has been described in detail elsewhere (Hope *et al*, 1993), and has recently been applied to nuclear power (Hope, 1994).

PAGE contains equations that cover:

(1) The EU and the whole world. Although PAGE was developed for European Union (EU) policy makers, the greenhouse effect is a global problem. EU emissions of $CO_2$ are only 13% of the world total.
(2) All major greenhouse gases. Global temperature change is calculated not just from the emissions of $CO_2$, but also from the emissions of methane, CFCs and HCFCs.
(3) The impacts of global warming. Changes in global mean temperature are compared to the maximum changes that can be tolerated, and weighting factors are applied to calculate the impacts brought about by global warming in up to ten sectors of the economy (in the application reported in this paper, a single sector was used to represent economic impacts, and a second to capture non-economic, environmental and social impacts).
(4) The effects of uncertainty. The challenge for all greenhouse gas models is to say something useful for policy

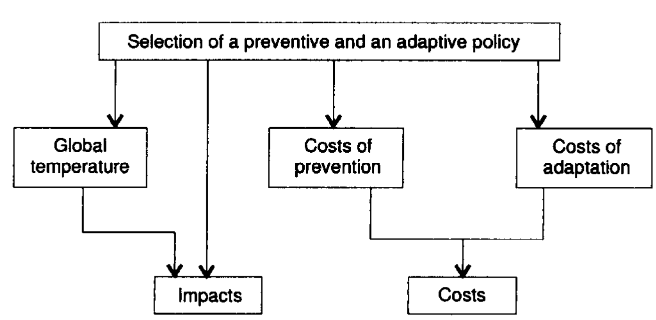


**Figure 2** The form of the PAGE model

makers in a situation of profound uncertainty. The only way to meet that challenge was to incorporate uncertainty into PAGE from the start. More than 80 key input parameters are expressed as probability distributions, and all uncertainties are carried through the calculation so that their effect on any result can be found.

The comprehensive scope of PAGE, combined with the need to make the model accessible to policy makers, implies that the simplest credible functional forms should be used throughout; anything else would lead to an impossibly unwieldy model, and would probably not be justified by the quality of the data available. This caution applies even more strongly to any attempt to calculate global optimum solutions to the global warming problem, and consequently there is no optimization in PAGE; policies are specified by the user, and PAGE calculates their implications.

*Using PAGE to calculate marginal impacts*

By examining the difference in impacts of two policies which vary only in that the second contains an extra 'pulse' of carbon emissions, the marginal impact of the emission pulse can be found. Because PAGE is designed to look at policies that might vary considerably, it is not possible to consider a pulse as small as 1 tonne of carbon. Every 1 billion tonnes (1 GtC, about 15% of annual world emissions), does not make an extra impact that can be detected, and 10 billion tonnes is at the limit of resolution of the model. This is because human emissions of $CO_2$ are small compared to natural cycles, so the pulse needs to be large in human terms before we see a measurable effect. For this experiment, the policies were made to differ by a pulse of

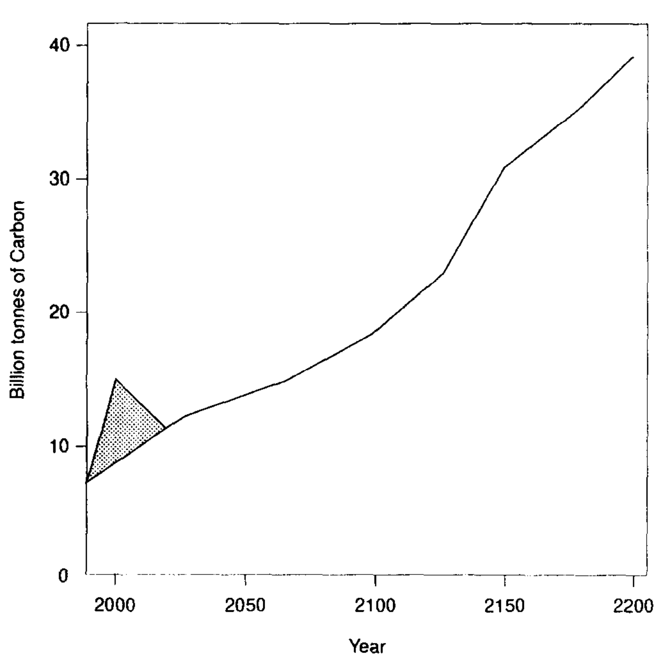


**Figure 3** Emission policies used in the PAGE calculations

100 GtC, emitted over the 30-year period from 1990 to 2020. The extra impact of this pulse is then divided by $10^{11}$ to give a valuation of the impacts per tC.

*PAGE inputs*

Apart from the second policy, the inputs used were those in the most recent version of PAGE. In brief they include:

(1) A horizon of 2200 for calculating impacts to allow for the long time lags in the natural systems. The impacts are aggregated and discounted back to the base year, 1990, at 5% per year; this rate reflects the opportunity cost of capital, although some authors have argued for a lower rate (Cline, 1992).
(2) Business as usual (BAU) emissions of $CO_2$, methane and HFCs based upon IPCC scenario IS92a up to 2100. The second policy adds the pulse of 100 GtC of $CO_2$ emissions on to these BAU emissions. Figure 3 shows the two emission policies, with the emission pulse shaded. To provide some assurance that non-linearities in the model and the size of this pulse did not introduce errors, the extra impact of a pulse of 10 GtC was also calculated; to the resolution of the model, the impact of 10 GtC was one-tenth the impact of 100 GtC.
(3) Non-economic as well as economic impacts. As previously indicated, economic impacts include losses (and gains) in activities that are counted in a country's GDP, such as agriculture, tourism, manufacturing and services. Non-economic impacts are those which do not appear in GDP measures, and include the loss of natural habitats and increased risks to human health. Economic impacts were taken to be somewhere in the range of from US$12.5 billion (0.25% of GDP (Nordhaus, 1991)) to US$80 billion (1.6% of GDP (CRU/ERL, 1992)) per °C per year in the European Union, with a most likely value of US$30 billion (0.6% of GDP (Fankhauser, 1994; Tol, 1994)). Non-economic impacts are taken to be slightly lower than economic impacts to conform to the results found by Nordhaus in a poll of experts that virtually all of the respondents judged that more than half of total impacts would be economic rather than non-economic (Nordhaus, 1994). The actual values used ranged from US$10 billion to US$50 billion per °C per year in the European Union, with a most likely value of US$25 billion. Both economic and non-economic impacts in other regions are taken to be roughly in proportion to the expected size of their economies compared to that of the European Union in the middle of the next century when peak impacts will occur, making global impacts somewhere between 3.25 and 6.35 times as large as those in the EU, with a most likely value of 5.8 times as large.
(4) Large amounts of adaptation in the developed world, such as the building of sea walls and the prevention of development in vulnerable areas, that can eliminate economic impacts altogether for the first 2°C temperature rise, and can reduce the impacts that remain by

**Table 5 Mean temperatures by year and policy (PAGE calculations)[a]**

| | BAU emissions | BAU plus 'pulse' | Difference |
|---|---|---|---|
| 2000 | 0.19 | 0.22 | 0.03 |
| 2020 | 0.73 | 0.84 | 0.11 |
| 2040 | 1.33 | 1.48 | 0.15 |
| 2060 | 1.95 | 2.10 | 0.15 |
| 2080 | 2.57 | 2.71 | 0.14 |
| 2100 | 3.16 | 3.29 | 0.13 |
| 2125 | 3.90 | 4.00 | 0.10 |
| 2150 | 4.62 | 4.70 | 0.08 |
| 2175 | 5.32 | 5.39 | 0.07 |
| 2200 | 6.00 | 6.06 | 0.06 |

[a]All temperatures are °C global mean values above 1990 values.

90% after 50 years; in the developing world, adaptation reduces impacts by 50% after 50 years (CRU/ERL, 1992). Previous PAGE calculations (which also describe in detail how adaptation is included in the model) have shown such adaptation to be highly cost effective. It reduces impacts caused by sea level rise in all economic sectors, and pays for itself 10 or 20 times over (Hope *et al*, 1993). In all regions, adaptation is less effective at reducing non-economic impacts, bringing only a 25% reduction.

(5) An exogenously defined average worldwide growth rate of 2% per year, implying that both economic and non-economic impacts of a 1°C temperature rise also grow at 2% per year before adaptation.

*Initial results*

With these inputs, the extra climatic impact of the pulse of emissions over time can be seen from Table 5, which shows the mean value for the global mean temperature, with BAU emissions only, and with BAU emissions plus the 'pulse'.

Even though the pulse of extra emissions is completed by 2020, the extra impacts continue well into the 22nd century, because of the long atmospheric residence time of $CO_2$, and the long response time of the earth to an increase in radiative forcing.

Table 6 shows how this extra climatic impact translates into total economic plus non-economic impacts. The pulse of emissions raises the mean impact by US\$0.5 × $10^{12}$, from US\$4.7 to US\$5.2 trillion.

Comparing the two policies, and dividing by $10^{11}$ to obtain the marginal impact of a tonne of carbon, the mean value of the extra impacts of the pulse of emissions is US\$5 per tC, with a 90% range from US\$2–7 per tC. The probability distribution is shown in Figure 4. It is not symmetrical;

**Table 6 Net present value of impacts by policy (PAGE calculations)[a]**

| | Minimum | Mean | Maximum |
|---|---|---|---|
| BAU emissions | 2.0 | 4.7 | 8.3 |
| BAU emissions plus pulse | 2.2 | 5.2 | 9.0 |

[a]All values are global costs in units of US\$ trillion. Minimum is the 5% point on the probability distribution of results. Maximum is the 95% point on the probability distribution of results.

the mean value is higher than the value obtained (US\$4 per tC) if the PAGE model is run with modal values, rather than triangular distributions, for all inputs. These calculations do not allow for any levelizing of the source profile resulting from the necessity in PAGE to spread the pulse over a number of years; this question is addressed later.

At first sight these values look lower, and with a smaller range, than those from the Intera method. How is it that methods which are ostensibly addressing the same issue with the same emphasis can come to such different conclusions? A deeper examination reveals four methodological differences and one philosophical difference between the Intera method and the PAGE model that need to be taken into account.

*Discount rate and economic growth rate*

The Intera method uses a 2% discount rate rather than the 5% used in the PAGE model results. The main reason for this lower discount rate is to conform to standard practice in the nuclear industry. The Intera method also assumes no economic growth, and therefore no escalation in unit impacts over time, rather than the 2% escalation assumed in the PAGE results.

The 'effective' discount rate (the difference between the discount rate and the economic growth rate) is thus 2% for the Intera calculations and 3% for the initial PAGE calculations. Recalculating the PAGE results at a 2% discount rate and a zero growth rate for GDP gives a mean valuation of the pulse of emissions of US\$7 per tC, with a 90% range from US\$3–11 per tC.

The question of what discount rate is appropriate for studies involving environmental impacts over very long periods is a contentious issue which will not be discussed in detail here. As stated earlier, the 2% figure used in the Intera study is taken directly from nuclear industry accountancy practice, and the 5% rate used in PAGE comes from consideration of the opportunity cost of capital.

*Timing of the pulse*

As previously indicated, the pulse of emissions in the PAGE model is spread out over a 30-year period peaking in 2000. The structure of the model, designed to look mainly at long-term policies, does not allow a pulse of shorter duration to be investigated. In contrast the Intera method consists of an instantaneous pulse. With a positive discount rate, this will tend to make the PAGE results lower than the Intera ones, and it can be argued that the source term should be levelized at the appropriate discount rate.

If the source terms is a triangle with its peak at time $t = a$ and a base of length $b$, then if the discount rate is $\rho$, the area under the graph has to be modified by a factor $f$ to give the levelized value. The factor $f$ is given by:

$$f = \frac{2}{ab(b-a)\rho^2}\left\{(b-a) - b\exp[-\rho a] + a\exp[-\rho b]\right\}$$

In the PAGE runs $a = 10$ and $b = 30$.

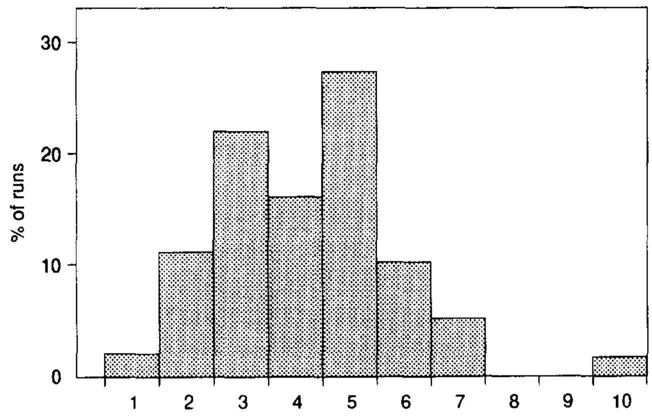


**Figure 4** Probability distribution of results for the initial PAGE calculations

With a discount rate of 2% the factor *f* is 0.77, so that the mean valuation of the pulse of emissions becomes US$9 per tC, with a 90% range from US$4–14 per tC.

*Adaptation*

A third methodological reason for the difference in results could be the large amounts of adaptation included in the PAGE inputs. The reference Intera calculations include much less adaptation on the basis that to be consistent with the 'polluter pays' principle one should not assume that others will make changes to their activities as a result of your operations. As previously noted, however, the Intera uncertainty ranges do include some scenarios with significant adaptation; the possibility of adaptation is effectively included as one source of uncertainty.

A further set of PAGE runs was therefore performed with no adaptation, a 2% discount rate, no economic growth and an allowance for levelizing the source term. This gave a mean impact value of US$19 per tC, with a 90% range of US$8–32 per tC.

*Background emissions*

The fourth methodological difference is that the PAGE results superimpose the pulse of emissions on top of a background of emissions that are expected to occur under business as usual, while the Intera method simply takes a pulse of emissions on its own, with no other emissions either now or in the future, and calculates its impact.

There are two reasons for thinking that this difference might lead to different results, but they work in opposite directions, and so their net effect is not easy to predict from first principles.

The first effect, which would tend to make the impact of a pulse on top of BAU emissions larger than the impact of a pulse on its own, is that the business as usual emissions will in any case lead to an expected rise in temperature of about 2°C by 2060 and 3°C by 2100 at the time when the pulse of emissions is also expected to have its biggest effect (see Table 5). The size and rapidity of this rise make it likely that any robustness that exists in natural systems to tolerate slow or small rises in temperature will have been overcome by the business as usual emissions, and therefore the pulse of extra emissions will be adding to stresses and causing impacts. On the other hand, a pulse of emissions on its own will cause the temperature to rise on top of only a very small and slow background temperature rise caused by whatever pre-base year emissions remain in the atmosphere. Therefore, in some places and at some times, the rise in temperature caused by the pulse of emissions on its own may not move the natural systems outside the range of temperature change that they can tolerate, and so may have very little, or even no, impact.

The second effect, which would tend to make the impact of a pulse on top of BAU emissions smaller than the impact of a pulse on its own, is that the concentration of $CO_2$ in the atmosphere is sufficiently high that the radiative forcing effect, and therefore the eventual temperature rise, is not linear in $CO_2$ concentration, but logarithmic (IPCC, 1990). What this means is that the higher the concentration of $CO_2$ in the atmosphere, the lower the extra temperature rise caused by a given pulse of emissions. Superimposing the pulse on top of substantial business as usual emissions will cause a lower rise in temperature than would occur from the pulse on its own.

To discover which of these effects wins out, a further set of PAGE runs was performed with no adaptation, a 2% discount rate, no economic growth and no emissions of $CO_2$ other than the 100 GtC pulse. The peak mean impact of the pulse rose from the 0.15°C shown in Table 5 to 0.22°C in 2080. With these inputs the PAGE calculations give a discounted integrated temperature rise of 0.1°C years per GtC – exactly equal to the reference value employed in the Intera calculations. The climate models in the two methods are clearly not in major disagreement. The mean impact value, corrected to apply to an instantaneous pulse, becomes US$29 per tC, with a 90% range of US$12–45 per tC. So, with the present assumptions in the PAGE model we find that the mean marginal benefit of removing the last trace of $CO_2$ emissions is about 50% higher than the marginal benefit of removing the first tonne from the business as usual emissions, which we found to be US$19 per tC.

**Table 7 Marginal impacts of $CO_2$ emissions[a]**

| | Minimum | Mean | Maximum |
|---|---|---|---|
| Initial PAGE results | 2 | 5 | 7 |
| As above with 2% discount rate, no economic growth | 3 | 7 | 11 |
| As above with levelized source term | 4 | 9 | 14 |
| As above with no adaptation | 8 | 19 | 32 |
| As above with no other emissions | 12 | 29 | 45 |
| Intera results: Inner uncertainty range | 3 | 24 | 50 |
| Intera results: Outer uncertainty range | 0 | 24 | 270 |

[a]All costs are global values in units of US$ per tC. For the PAGE model: minimum is the 5% point on the probability distribution of results, maximum is the 95% point on the probability distribution of results.

In most situations (and in standard economic textbooks) the opposite is true; the marginal benefit of further cutbacks falls as the cutbacks grow. One implication of our finding is that the economically optimal cutback of $CO_2$ will be much more sensitive to uncertainty than under the standard textbook assumption, as both the marginal benefit and the marginal cost of making cutbacks increase as the cutbacks grow.

*Probabilty versus possibility*

The final results of this investigation of the marginal impacts of $CO_2$ emissions are shown in Table 7. Adjusting for the four methodological differences has brought the PAGE results up considerably, to the extent that the mean value exceeds the Intera reference value with the same assumptions. The range of the PAGE results remains smaller than either of the ranges produced by the Intera method, particularly the outer uncertainty range. The lower end of the PAGE range with adaptation and an instantaneous pulse, US$4 per tC, is very similar to the bottom of the Intera inner uncertainty range. The upper end of the PAGE range at US$45 per tC is also very similar to the upper end of the Intera inner uncertainty range, but remains a factor of six below the top of the Intera outer uncertainty range at US$270 per tC.

We have seen under the discussion of background emissions that the environmental impact components of the two models are very similar. We now need to compare the unit cost impacts employed in the two models. Unlike the PAGE model, the Intera model does not assume a linear relationship between sea level rise and temperature, but if one applies the PAGE assumption that a rise of 1°C corresponds to a sea level rise of 0.25 m, the top of the Intera outer uncertainty range for the unit impacts corresponds to US$895 billion per °C per year. If all the PAGE probability distributions took their maximum values, they would give a valuation of US$500 billion per °C per year for economic impacts and US$320 billion per °C per year for non-economic impacts, a total of US$820 billion per °C per year. So the maximum valuations are remarkably similar as well, and cannot explain the factor of six difference in the maximum values of the results.

The explanation actually involves the philosophical difference between the two methods. The PAGE model is based on the theory of subjective probability. Each of the uncertainty inputs is expressed as a triangular probability distribution which is meant to represent the degree of belief of the person using the model about the values that the parameter can take. In addition, the input distributions are assumed to be uncorrelated, so that a high value for one parameter has no influence on whether another parameter turns out to be at the upper or lower end of its range.

For the valuation in a run of the PAGE model to reach US$820 billion per °C, each of five independent input parameters would have to take values right at the top of their ranges. Probability theory says that the chance of this happening is vanishingly small. Indeed, even for each of the five inputs to be above their median values in the same run is fairly unlikely, only one chance in 32. Since the maximum results from the PAGE model reported here are actually the 95% points on the output probability distribution, the results obtained with input combinations that are unusual and have a vanishingly small probability do not contribute to the ranges reported. The ranges produced by the PAGE model are a delineation of the results that are not unlikely, given the input parameter ranges.

By contrast, the nested set method employed in the Intera approach assumes that any value in a given uncertainty range is just as possible as any other. Under this interpretation, the top of the outer uncertainty range of US$270 per tC is regarded as being just as possible as any other value greater than US$50 per tC in the range, because it is derived from a combination of parameters which is just as possible as the combinations that lead to other costs in the range.

A discussion of the differences between probabilistic and fuzzy approaches to the representation of uncertainty is outside the scope of the present paper. Most people will prefer the approach which they feel best represents the uncertainty in our basic understanding of the physical and economic quantities needed to derive the final costs.

## Discussion and conclusions

The comparison between the Intera and PAGE models has illustrated very clearly how apparently disparate estimates of the impacts of $CO_2$ can be reconciled once a full understanding of the different assumptions employed has been achieved. This emphasizes the need for the conventions and assumptions employed in any such study to be clearly and explicitly stated if the basis of derived values and their range of applicability are to be properly understood.

The results discussed in this paper have an immediate policy relevance. Economists need to know the marginal impact of $CO_2$ emissions if they are to design and set taxes at levels that will approximately internalize the global warming externality. For this purpose, the initial PAGE results provide a useful insight. Ignoring any secondary benefits, money spent on combatting global warming is not available for other productive investments, so a discount rate based on the opportunity cost of capital is appropriate. The mean cost estimate of US$5 per tC is at the lower end of the range of cost estimates produced in other studies and reflects the cost effectiveness of adaptation measures such as building sea walls, improving water resources and controlling development in vulnerable areas.

The taxation would initially be aimed at bringing about a first reduction from business as usual emissions, so the marginal benefit of a 1 tonne reduction from BAU emissions (which is the same as the marginal impact of a tonne of emissions on top of BAU emissions) is the right value. Even the spreading out of the reduction over 30 years, with a peak effect over 10 years, although caused by limitations in the time structure of the model, may not be unreasonable, given the long timescales required for change in many instances, such as the replacement of fuel-burning equipment.

On the other hand, policy makers wishing to take the threat of global warming seriously might also want to know how much to penalize sources of $CO_2$ consistent with the precautionary principle. Here, the Intera figures come into their own. The top of the Intera inner uncertainty range of US$50 per tC is also close to the 95th percentile figure from the PAGE calculations of US$45 per tC. A value in the region of US$45 to 50 per tC would correspond to around 1 p/kWh for electricity generation using conventional coal technology, a significant fraction of generation costs.

## Acknowledgement

The construction of the PAGE model was funded by DG XI of the Commission of the European Communities.

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