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THE MARGINAL IMPACTS OF CO_2, CH_4 AND SF_6 EMISSIONS

C Hope

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The Judge Institute of Management
University of Cambridge
Trumpington Street
Cambridge CB2 1AG, UK
www.jims.cam.ac.uk

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Dr Chris Hope
Judge Institute of Management
University of Cambridge
Tel: +44 (0) 1223 338194
Fax: +44 (0) 1223 339701
Email: chris.hope@jims.cam.ac.uk

Please address enquiries about the series to:

Research Support Manager
Judge Institute of Management
Trumpington Street
Cambridge CB2 1AG, UK
Tel: 01223 339611 Fax: 01223 339701
E-mail: research-support@jims.cam.ac.uk

The marginal impacts of CO_2, CH_4 and SF_6 emissions

Chris Hope
Judge Institute of Management
University of Cambridge
chris.hope@jims.cam.ac.uk

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Executive summary

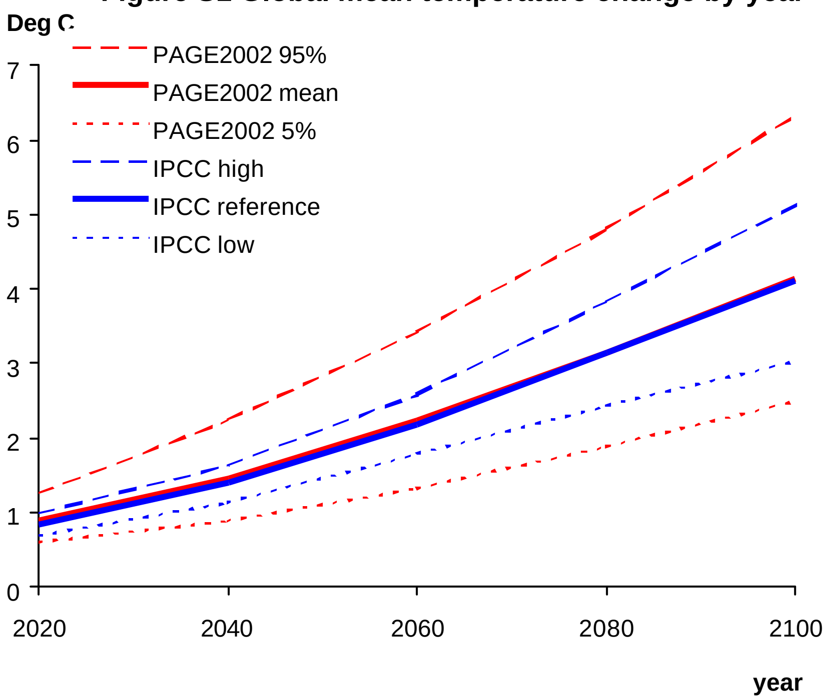
A new version of the PAGE model, PAGE2002, has been developed and used to calculate the marginal impacts of CO2, CH4 and SF6 emissions. The main structural changes in PAGE2002 are the introduction of a third greenhouse gas and the incorporation of possible future large-scale discontinuities.

The PAGE2002 model uses relatively simple equations to capture complex climatic and economic phenomena. This is justified because the results approximate those of the most complex climate simulations, and because all aspects of climate change are subject to profound uncertainty. To express the model results in terms of a single 'best guess' could be dangerously misleading. Instead, a range of possible outcomes should inform policy. PAGE2002 builds up probability distributions of results by representing 31 key inputs to the marginal impact calculations by probability distributions.

In this investigation, PAGE2002 is run with global emissions of greenhouse gases from Scenario A2 of the IPCC. This scenario represents a heterogeneous world, with an underlying theme of self-reliance and preservation of local identities. As with all the IPCC illustrative scenarios, it assumes no active intervention to control emissions.

The PAGE2002 mean results track the IPCC climate results very well, as figure S1 below shows. The range of results from the PAGE2002 model is larger than the range reported in the IPCC TAR. This is to be expected, as the IPCC results are simply the highest and lowest best guess results from the seven General Circulation Models considered by the IPCC, and not a true probability distribution.

Figure S1 Global mean temperature change by year



Source: PAGE2002 model runs and IPCC

PAGE2002 gives the mean climate change impacts of scenario A2 over the next two centuries from 2000 to 2200 as US$26.3 trillion in year 2000 dollars, discounted back to 2000 at a pure time preference rate of 3% per year. The 5% and 95% points on the distribution are US$6.3 trillion and US$66.9 trillion.

The marginal impact of each of the three gases, CO2, CH4 and SF6 is calculated by reducing the emissions of the gas by a small amount in the first analysis year, 2001, and finding the difference in impacts that this creates. The structure of the PAGE2002 model allows a probability distribution for the difference in impacts to be calculated.

Table S1 shows the marginal impact results. The mean value for CO2 is US$19 per tonne of Carbon (or about US$5 per tonne of CO2), for methane it is US$105 per tonne, and for SF6, US$200 000 per tonne. Using the mean values, each tonne of methane has 21 times the impact of a tonne of CO2, and each tonne of SF6 has about 40 000 times the impact of a tonne of CO2. For each gas, the range between the 5% and 95% points is about an order of magnitude. For comparison, the IPCC gives 100-year Global Warming Potentials on a mass basis of 23 for methane and 22 200 for SF6.

Table S1 Marginal impacts by gas

2000 - 2200 *US$(2000) per tonne*

	5%	**mean**	**95%**
C as CO2	4	19	51
Methane	25	105	263
SF6	45 000	200 000	450 000

Source: PAGE2002 model runs

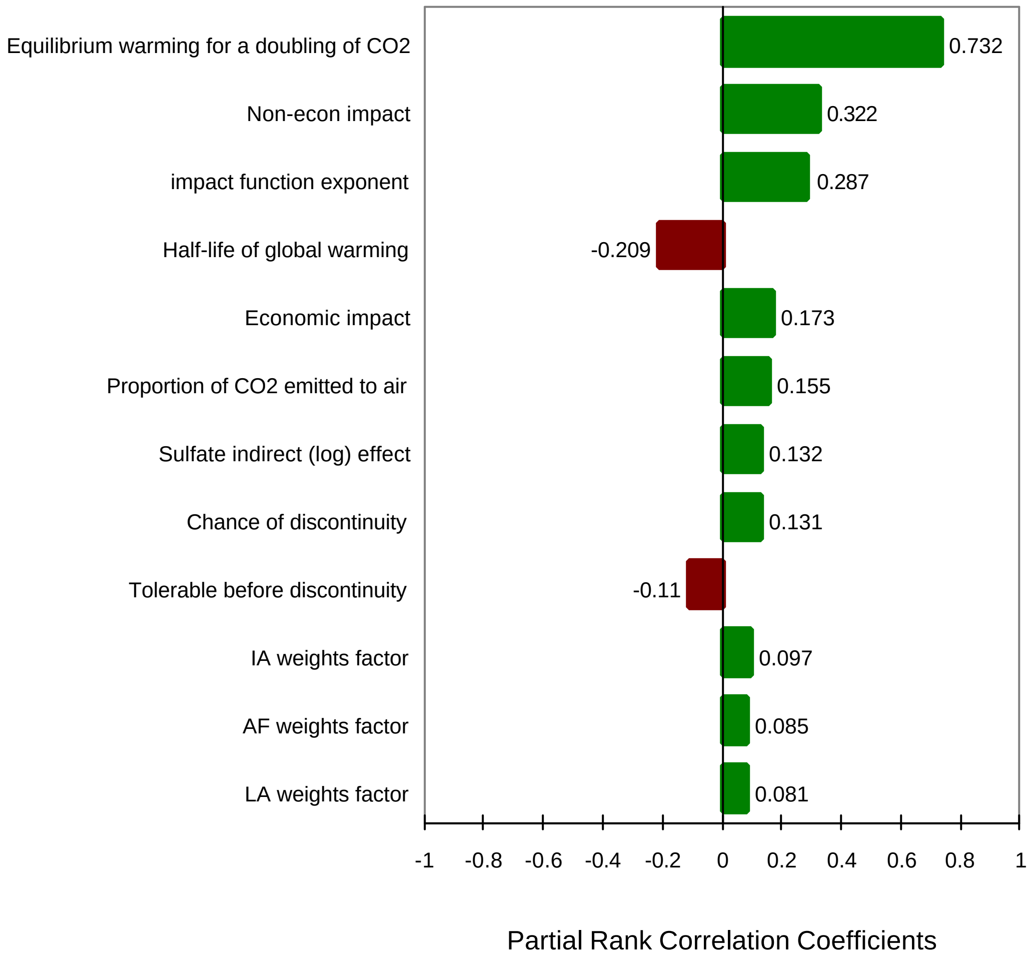
Market prices are about US$160 per tonne for methane and about US$25 000 per tonne for SF6. The climate change impacts of methane are a significant proportion of its market price. So a pipeline replacement to decrease losses could be justified if the Net Present Cost were less than about US$265 per tonne saved in 2000 US dollars - made up of not just US$160 from having the gas available to sell, but also US$105 from the reduction in climate change impacts.

For SF6 the climate change impacts are much larger than the market price. The economics of schemes to reduce the leakage of SF6 are transformed once the climate change impacts are properly counted.

Figure S2 shows the most important influences on the marginal impact of a tonne of SF6. The largest correlation, +0.732, is with the equilibrium warming for a doubling of CO2 concentration. The sign of the correlation coefficient shows that a larger value for the input gives a larger value for the marginal impact, as we would expect.

All of the influences in figure S2 are of the correct sign. That the top four influences divide into two scientific and two economic parameters is a strong argument for the building of Integrated Assessment models such as PAGE2002. Models that are exclusively scientific, or exclusively economic, would omit parts of the climate change problem which still contain profound uncertainties.

Figure S2 Correlations with marginal impact of SF6



The marginal impact estimates given in this paper have been calculated for only a single IPCC scenario, A2. Although earlier work has shown the results to be fairly insensitive to the scenario used, it would probably be worthwhile to repeat the calculations at least for one other of the IPCC scenarios, scenarioB2. This is not because the different emissions in scenario B2 would change the results, so much as the different GDP and population growth assumptions, which imply different discount rates, which are known to affect the results strongly.

Finally, the calculations reported here should be repeated regularly as new information is constantly becoming available in this area. Keeping the calculations up to date will ensure that policy is not being informed by outdated science and economics

The PAGE2002 model

PAGE2002 is an updated version of the PAGE95 integrated assessment model (Plambeck, Hope and Anderson, 1997, Plambeck and Hope, 1995 and Plambeck and Hope, 1996). The main structural changes in PAGE2002 are the introduction of a third greenhouse gas and the incorporation of possible future large-scale discontinuities into the impact calculations of the model (IPCC, 2001a, p5). Default parameter values have also been updated to reflect changes since the IPCC Second Assessment Report in 1995.

PAGE2002 contains equations that model:

* Emissions of the primary greenhouse gases, CO2 and methane, and a third gas, SF6 in this investigation. PAGE2002 models other greenhouse gases such as N_2O and (H)CFCs as a time-varying addition to background radiative forcing.

* The greenhouse effect. Anthropogenic emissions of greenhouse gases exceed the rate of removal by chemical and biological processes and accumulate in the atmosphere. The greenhouse gases trap heat in the atmosphere so that less of the incoming solar radiation is re-radiated to space. This increases radiative forcing, the net flux of energy to Earth. The Earth's temperature rises very slowly as excess heat is transferred from the atmosphere to land and ocean.

* Cooling from sulphate aerosols. Sulphate aerosols result from fossil fuel combustion and are commonly known as the cause of acid rain. They also backscatter incoming solar radiation and interfere with cloud formation, producing a direct and indirect reduction in radiative forcing. This counteracts the greenhouse effect.

* Regional temperature effects. Unlike greenhouse gases which remain in the atmosphere for decades and are globally mixed, sulphate aerosols have a very short atmospheric lifetime (about 6 days) and so tend to remain in the source region. Therefore sulphate aerosol cooling is a regional phenomenon. For the eight world regions in PAGE2002, temperature rise is computed from the difference between global warming and regional sulphate aerosol cooling. Sulphate cooling is greatest in the more industrialised regions, and tends to decrease over time due to sulphur controls to prevent acid rain and negative health effects.

* Nonlinearity and transience in the damage caused by global warming. Climatic change impacts in each analysis year are a polynomial function of the regional temperature increase in that year above a time-varying tolerable level of temperature change, $(T-T_{tol})^n$, where n is an uncertain input parameter. If the temperature rises beyond another threshold, there is a chance that a large-scale climate discontinuity will occur with very serious effects; the more the temperature rises beyond the threshold, the larger the chance of the discontinuity occurring.

* Regional economic growth. Impacts are evaluated in terms of an annual percentage loss of GDP in each region, for a maximum of two sectors- in this

application defined as economic impacts and non-economic (environmental and social) impacts.

* Adaptation to climate change. Investment in adaptive measures (e.g. the building of sea walls; development of drought resistant crops) can increase the tolerable level of temperature change (T_{tol}) before economic losses occur and also reduce the intensity of both noneconomic and economic impacts.

The PAGE2002 model uses relatively simple equations to capture complex climatic and economic phenomena. This is justified because the results approximate those of the most complex climate simulations, as shown below, and because all aspects of climate change are subject to profound uncertainty. To express the model results in terms of a single 'best guess' could be dangerously misleading. Instead, a range of possible outcomes should inform policy. PAGE2002 builds up probability distributions of results by representing 31 key inputs to the marginal impact calculations by probability distributions.

The full set of equations and default parameter values in PAGE2002 are included as appendices to this report. Most parameter values are taken directly from the IPCC Third Assessment Report (IPCC, 2001b). Some of the more important parameters are discussed in the next section.

Parameter values in PAGE2002

Climate parameters

The model assumes that only a proportion of the anthropogenic emissions of CO2 ever gets into the atmosphere. The main use for this is to simulate the very rapid initial decay of CO2 in the atmosphere, before it settles down to something closer to an exponential decline. The concentration excess of CO2 does not decline to zero; after a long time a new equilibrium partitioning between atmosphere and ocean will be reached, with a significant fraction of cumulative emissions continuing to reside in the atmosphere. Natural emissions of CO2 can also be stimulated by increasing global mean temperature, either directly or through the suppression of sinks.

Table 1 shows the carbon cycle parameter values used in this investigation. In this and other tables, all probabilistic values are triangular distributions with the minimum, mode and maximum values shown. All deterministic values are shown in the mean column only.

Table 1	Mean	Min	Mode	Max	Source
CO2 emitted to air (%)	60	46	60	74	IPCC, 2001b, p190[a]
CO2 remain in air (%)	35				IPCC, 2001b, p187[b]
CO2 stimulation (GT/degC)	7	3.5	7	10.5	IPCC, 2001b, p218[c]

Notes:

a. Source gives average fluxes to land and to the ocean of 3.8 GtC per year, with uncertainties of about +/- 1 GtC per year. Gives a parameter value of about 52% +/- 14%, but this mechanism is expected to be less effective at removing higher levels of CO2 (at least as a proportion of emissions, if not absolutely) (IPCC, 2001b, p 197), so set the mode at 60%.
b. Source gives 25% of emissions, but this parameter is % of emissions to air so divide by 0.6.
c. Temperature rise makes the ocean and land in particular less good at the quick absorption of CO2. Source shows that the drop is about 4 GtC/yr for land, and 1 GtC per year for the oceans, giving a total of 5 GtC, or 18 Gt CO2 per year. Dividing by 2.5 degC temperature rise by 2100 from scenario IS92a, gives a mean value of about 7 Gt CO2 per deg C. From the diagram, the range is perhaps 0.5 to 1.5 times.

The concentration of CO2 in the atmosphere is high enough (hundreds of parts per million) that the extra radiative forcing is a logarithmic function of concentration. The concentration of methane is such (about 1 part per million) that the radiative forcing is proportional to the square root of the concentration plus a small negative term to allow for the overlap with nitrous oxide, and the concentration of SF6 is low enough (less than 1 ppb) that the radiative forcing is linear in the concentration. The extra radiative forcing from human emissions of greenhouse gases is the sum of the extra forcing from CO2 methane and SF6, plus a small contribution to forcing from other greenhouse gases such as nitrous oxide that are not explicitly modelled. Table 2 shows the lifetime and forcing parameters used in this investigation.

Table 2	Mean	Minimum	Mode	Maximum	Source
CO2 half-life (years)	123	100	120	150	As in PAGE95
CH4 half-life (years)	10.5				IPCC, 2001b, p251[a]
SF6 half-life (years)	3200				IPCC, 2001b, p389
CO2 slope of forcing equation	5.35				IPCC, 2001b, p358
CH4 slope of forcing equation	0.04				IPCC, 2001b, p818[a]
SF6 slope of forcing equation	0.52				IPCC, 2001b, p389

Note:

a. Gives a good simulation of the concentration and forcing for scenario A2 augmented by indirect effects.

The negative radiative forcing effect of sulphate aerosols has a linear component of backscattering (the direct effect) and a logarithmic component from cloud interactions (the indirect effect). Table 3 shows the sulphate forcing parameter values used in this investigation.

Table 3	Mean	Min	Mode	Max	Source
Sulfate direct (linear) effect (Mwyr/kgS)	-0.7	-1.2	-0.6	-0.3	IPCC, 2001b, p8-9[a]
Sulfate indirect (log) effect (W/m2)	-0.4	-0.8	-0.4	0	IPCC, 2001b, p8-9[b]

Notes:

a. Base year global mean forcing of -0.2 to -0.8 W/m2, with a most likely value of -0.4 W/m2
b. Base year global mean forcing of 0 to -2 W/m2, with a most likely value of -1 W/m2

Over the range of extra forcing that is likely before 2200, the equilibrium temperature can be taken to be a linear function of the net extra radiative forcing. The slope is given by the equilibrium temperature rise for a doubling of CO2. Each region is assumed to warm towards its equilibrium temperature at a rate proportional to the difference between the equilibrium temperature and the realised temperature in the previous model year. Table 4 shows the global warming parameter values used in this investigation.

Table 4	Mean	Min	Mode	Max	Source
Equilibrium warming for 2xCO2 (degC)	3	1.5	2.5	5	IPCC, 2001b, p67
Half-life of global warming (years)	50	25	50	75	IPCC, 2001b, p561

Impact parameters

PAGE2002 models two damage sectors: economic and noneconomic. Impacts are assumed to occur only for temperature rise in excess of some tolerable rate of change, or that has a magnitude above the tolerable plateau. Adaptation can increase the tolerable temperature change or reduce the impact if the tolerable temperature change is exceeded.

Weights are used to monetise the impacts to allow for comparison and aggregation across economic and noneconomic sectors. The weights express the percentage of GDP lost for benchmark warming of 2.5 degC above the tolerable level in each impact sector in the EU, with regional multipliers for other regions. Note that weights may be negative, representing a gain, as in the case of Eastern Europe and the former Soviet Union. Impacts are computed for each region, sector, and analysis period as a power function of regional temperature increase above the tolerable level. Table 5 shows the weights used in this investigation.

Table 5	Mean	Min	Mode	Max	Source
Econ impact in EU(%GDP for 2.5 degC)	0.5	-0.1	0.6	1	IPCC, 2001a, p940, 943
Non-econ imp EU (%GDP for 2.5 degC)	0.73	0	0.7	1.5	IPCC, 2001a, p940, 943
Impact function exponent	1.76	1	1.3	3	As in PAGE95
Eastern Europe & FSU weights factor	-0.35	-1	-0.25	0.2	IPCC, 2001a, p940
USA weights factor	0.25	0	0.25	0.5	IPCC, 2001a, p940
China weights factor	0.2	0	0.1	0.5	IPCC, 2001a, p940
India weights factor	2.5	1.5	2	4	IPCC, 2001a, p940
Africa weights factor	1.83	1	1.5	3	IPCC, 2001a, p940
Latin America weights factor	1.83	1	1.5	3	IPCC, 2001a, p940
Other OECD weights factor	0.25	0	0.25	0.5	IPCC, 2001a, p940
Tolerable temp OECD economic (degC)	2				As in PAGE95[a]
Drop in econ impact OECD (%)	90				As in PAGE95[a]
Drop in econ impact RoW (%)	50				As in PAGE95[a]
Drop in non-econ impact (%)	25				As in PAGE95[a]

Note:
a. Tolerable temperature rises and drops in impact come from aggressive adaptation efforts.

The parameters for the risk of a possible future large-scale discontinuity are shown in Table 6. These are little more than guesses at present. IPCC, 2001a, p947 says the impact may exceed ordinary disasters by orders of magnitude.

Table 6	Mean	Min	Mode	Max	Source
Tolerable before discontinuity (degC)	5	2	5	8	IPCC, 2001a, p5
Chance of discontinuity (% per degC)	10.33	1	10	20	
Loss if discontinuity occurs, EU (%GDP)	11.66	5	10	20	IPCC, 2001a, p947

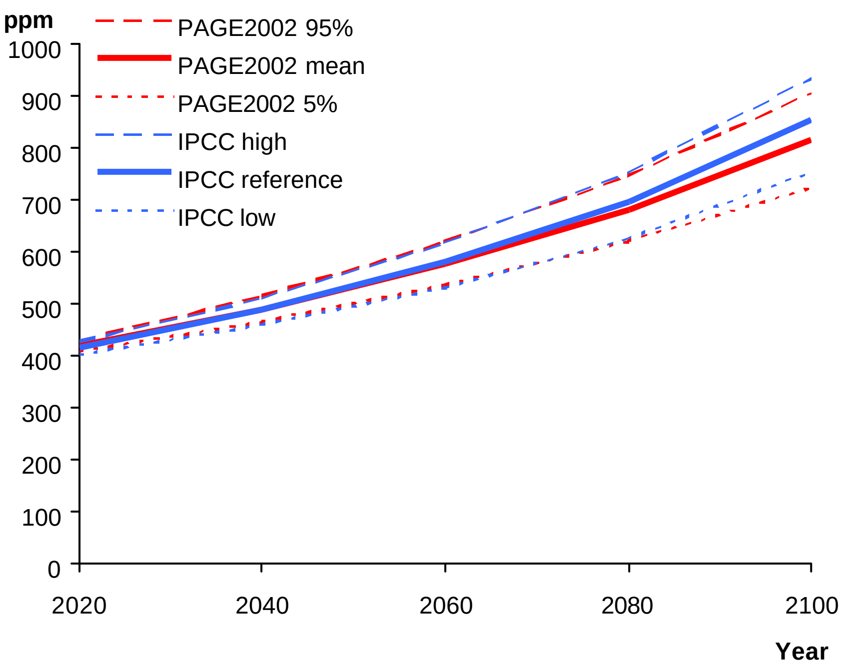
Climate Results from PAGE2002 compared to the IPCC

In this investigation, PAGE2002 is run with global emissions of greenhouse gases from Scenario A2 of the IPCC (IPCC, 2001b, p64). This is one of a family of six illustrative scenarios produced by the IPCC, and one of two investigated in sufficient depth in the Third Assessment Report to allow detailed comparisons with the PAGE2002 results (IPCC, 2001b, p531). It represents a very heterogeneous world, with an underlying theme of self-reliance and preservation of local identities (IPCC, 2001b, p63). As with all the IPCC illustrative scenarios, it assumes no active intervention to control emissions. Because the model continues to calculate impacts to 2200, emissions are assumed to remain constant after 2100, the end point of the A2 scenario.

The other scenario investigated in depth by the IPCC, scenario B2, is oriented towards environmental protection and social equity and leads to somewhat lower emissions (IPCC, 2001b, p63).

Figure 1 shows the CO2 concentrations from PAGE2002 and from the IPCC for scenario A2 from 2020 to 2100.

Figure 1 CO2 concentration by year

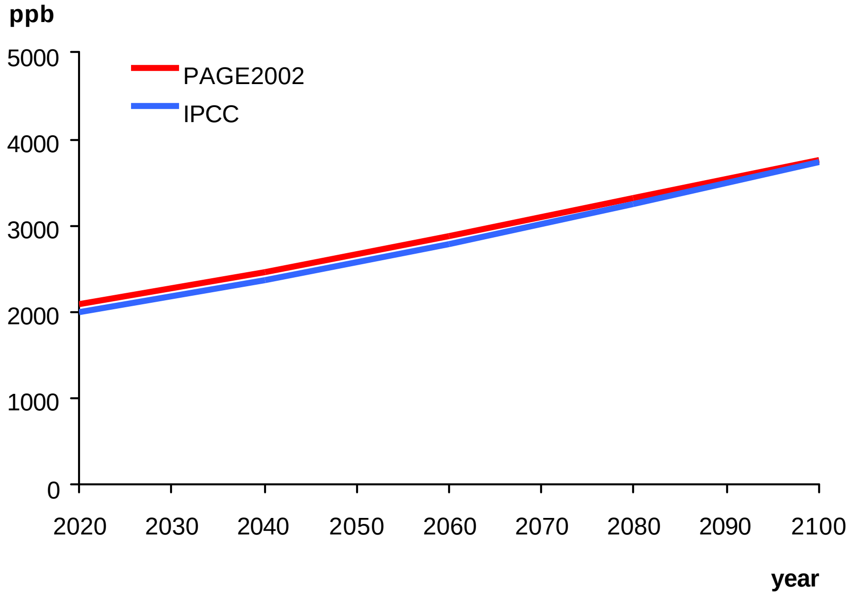


Source: PAGE2002 model runs and IPCC, 2001b, p808

The PAGE2002 mean results track the IPCC reference results very well to 2080, falling about 40 ppm short in 2100. The 5% and 95% lines from PAGE2002 are also close to the IPCC low and high results. Although the IPCC results do not have probabilities attached, they are clearly designed to be close to the plausible extremes. They are described as 'climate sensitivity 1.5 degC and maximal CO_2 uptake by oceans and land' and 'climate sensitivity 4.5 degC and minimal CO_2 uptake by oceans and land' respectively (IPCC, 2001b, p808).

Figure 2 shows the methane concentrations from PAGE2002 and from the IPCC for scenario A2 from 2020 to 2100. PAGE2002 does not calculate this probabilistically, so only a single line is shown. The correspondence with the IPCC results is very good.

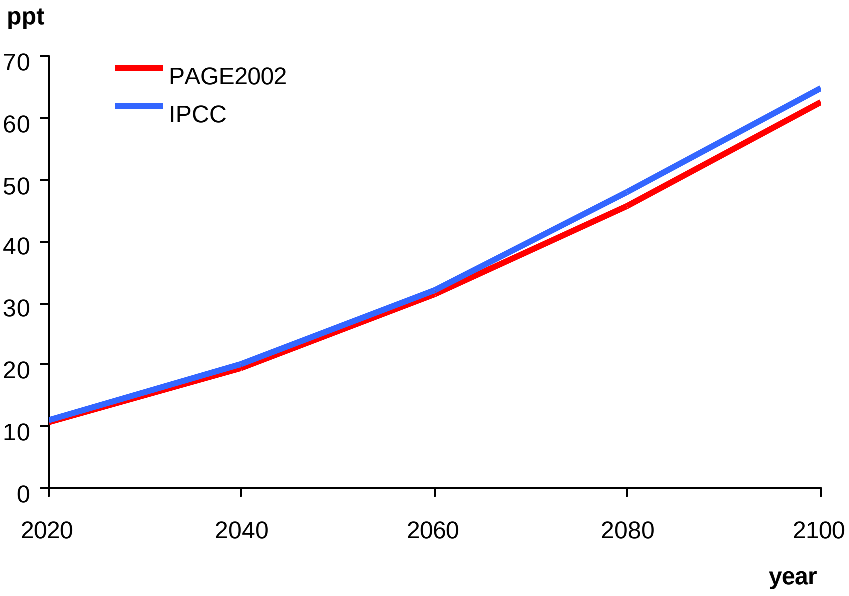
Figure 2 CH4 concentration by year



Source: PAGE2002 model runs and IPCC, 2001b, p809

Figure 3 shows the SF6 concentrations from PAGE2002 and from the IPCC for scenario A2 from 2020 to 2100. PAGE2002 does not calculate this probabilistically, so only a single line is shown. The correspondence with the IPCC results is again very good.

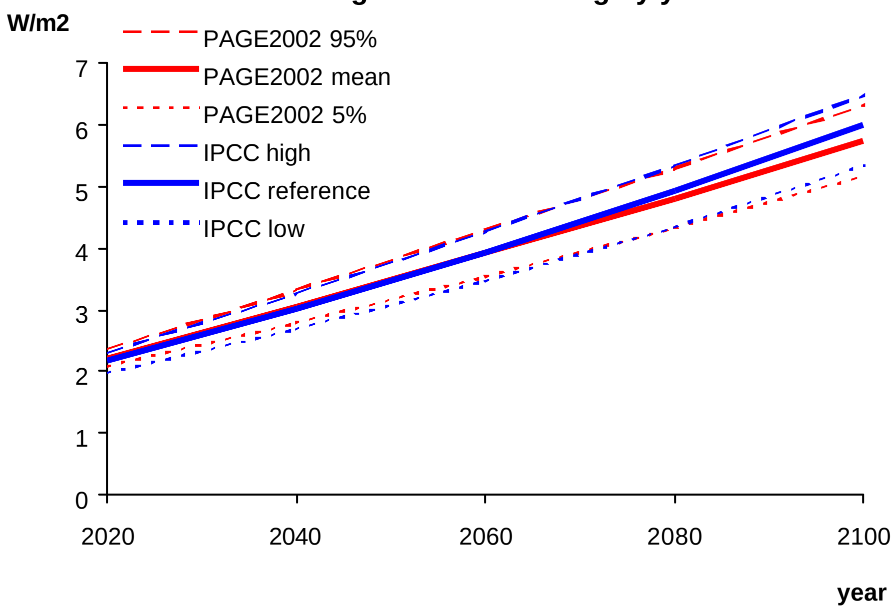
Figure 3 SF6 concentration by year



Source: PAGE2002 model runs and IPCC, 2001b, p811

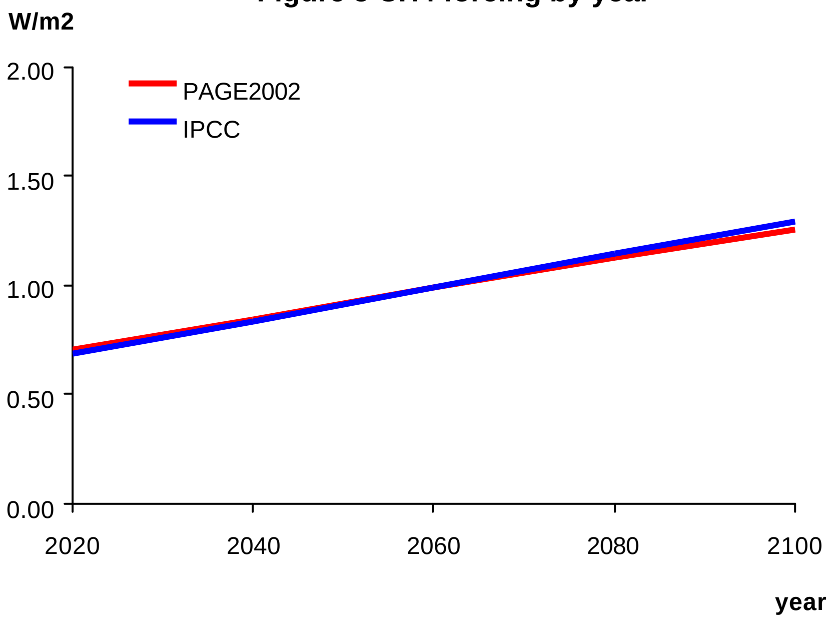
Figures 4 to 6 show the radiative forcing from CO2, methane and SF6 from PAGE2002 and the IPCC respectively. For the methane comparison, the IPCC values have been increased by the same factor as in the base year of 2000 (1.19) to account for the indirect effects (IPCC, 2001b, p365). As can be seen from the figures, the correpondence between the PAGE2002 results and the IPCC values is very good.

Figure 4 CO2 forcing by year



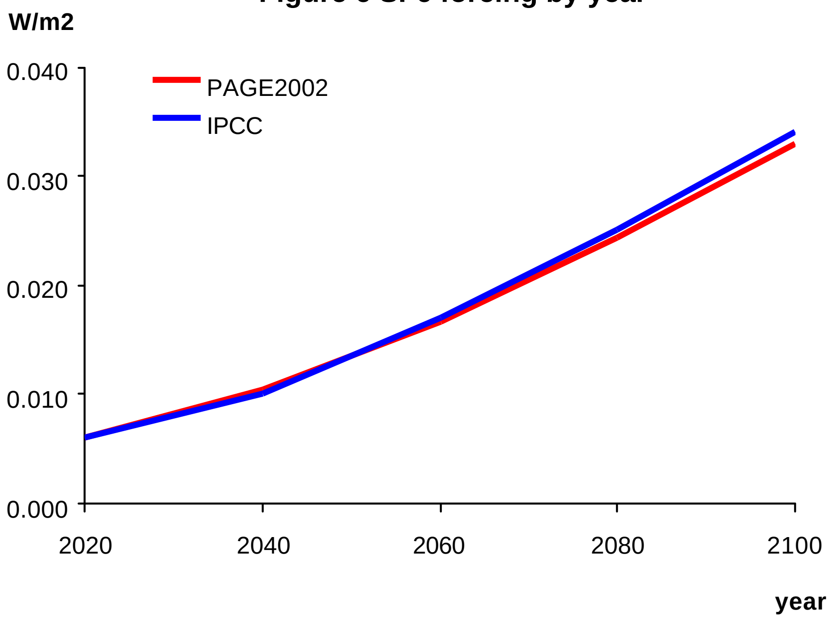
Source: PAGE2002 model runs and IPCC, 2001b, p817

Figure 5 CH4 forcing by year



Source: PAGE2002 model runs and IPCC, 2001b, p818

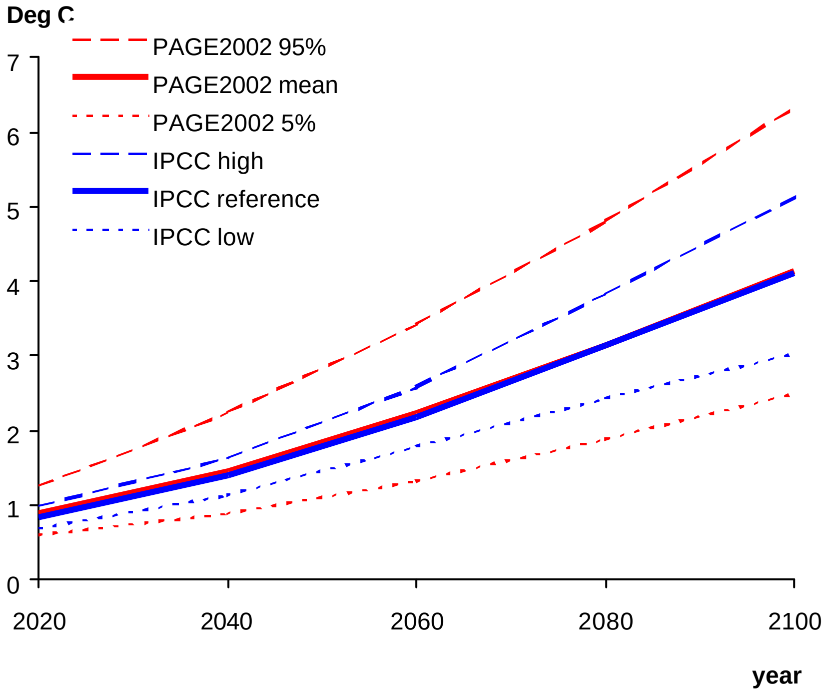
Figure 6 SF6 forcing by year



Source: PAGE2002 model runs and IPCC, 2001b, p819

Figure 7 shows the final comparison between PAGE2002 and IPCC results, for global mean temperature change since pre-industrial times.

Figure 7 Global mean temperature change by year



Source: PAGE2002 model runs and IPCC, 2001b, p824, 556

Once again the agreement between the PAGE2002 mean results and the IPCC reference results is excellent – the two lines on the figure essentially coincide.

The range of results from the PAGE2002 model is larger than the range reported in the IPCC TAR, but this is to be expected, as the IPCC results are simply the highest and lowest best guess results from the seven General Circulation Models considered by the IPCC. As the IPCC states 'This is not the extreme range of possibilities, for two reasons. First, forcing uncertainties have not been considered. Second, some AOGCMs have effective climate sensitivities outside the range considered.' (IPCC, 2001b, p555). The PAGE2002 results do include uncertainties in forcing, particularly for sulphates, and the full range of climate sensitivities up to 5 degC for a doubling of CO2.

Marginal impact calculations

PAGE2002 gives the mean climate change impacts of scenario A2 over the next two centuries from 2000 to 2200 as US$26.3 trillion in year 2000 dollars, discounted back to 2000 at a pure time preference rate of 3% per year. The 5% and 95% points on the distribution are US$6.3 trillion and US$66.9 trillion.

The marginal impact of each of the three gases, CO2, CH4 and SF6 is calculated by reducing the emissions of the gas by a small amount in the first analysis year, 2001, and finding the difference in impacts that this creates. The structure of the PAGE2002 model allows a probability distribution for the difference in impacts to be calculated.

The small amount chosen was 10% of the year 2000 emissions. The difference in impacts was divided by the number of tonnes of the gas that this represents (800 Mt C as CO2, 32.3 Mt for CH4 and 600 tonnes for SF6) to get the marginal impact per tonne. The calculation was repeated with a 20% drop in emissions to check that rounding errors were not significant.

Table 7 shows the marginal impact results. The mean value for CO2 is US$19 per tonne of Carbon (or about US$5 per tonne of CO2), for methane it is US$105 per tonne, and for SF6, US$200 000 per tonne. Using the mean values, each tonne of methane has 21 times the impact of a tonne of CO2, and each tonne of SF6 has about 40 000 times the impact of a tonne of CO2. For each gas, the range between the 5% and 95% points is about an order of magnitude.

Table 7 Drop in impacts and marginal impacts by gas

2000 - 2200 *US$(2000) billion for a 10% drop*

	5%	mean	95%
C as CO2	3.6	15.5	40.8
Methane	0.8	3.4	8.5
SF6	0.03	0.12	0.28

2000 - 2200 *US$(2000) per tonne*

	5%	mean	95%
C as CO2	4	19	51
Methane	25	105	263
SF6	45 000	200 000	450 000

Source: PAGE2002 model runs

For comparison, the IPCC gives 100-year Global Warming Potentials (GWPs) on a mass basis of 23 for methane and 22 200 for SF6 (IPCC, 2001b, p388).

GWPs have at least three obvious drawbacks: they are very sensitive to the arbitrary time horizon chosen. They do not allow impacts that occur soon to be valued more highly than those that occur in the distant future, and they are relative, rather than absolute, measures. Knowing the GWP of a gas does not necessarily help very much in deciding how much effort, if any, should be devoted to reducing the emissions of it.

By contrast, the marginal impact calculated here is an absolute measure. It does not require the assumption of an arbitrary time horizon. It allows near-term impacts to be valued more highly. It can also be compared with estimated costs for abating emissions of the gas.

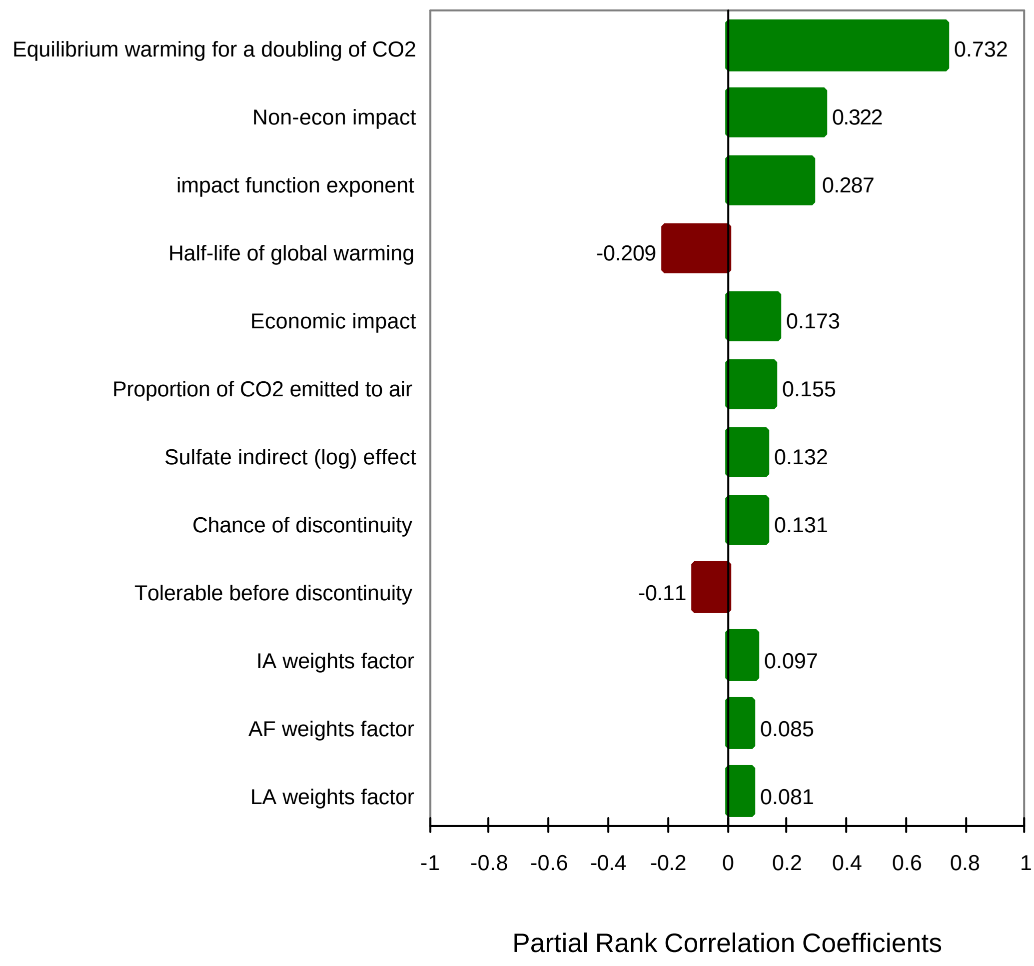
Market prices are about US$160 per tonne for methane (BP, 2002), and about US$25 000 per tonne for SF6. The climate change impacts of methane are a significant proportion of its market price. So a pipeline replacement to decrease losses could be justified if the Net Present Cost were less than about US$265 per tonne saved in 2000 US dollars - made up of not just US$160 from having the gas available to sell, but also US$105 from the reduction in climate change impacts.

For SF6 the climate change impacts are much larger than the market price. The economics of schemes to reduce the leakage of SF6 are transformed once the climate change impacts are properly counted.

Sensitivity of SF6 marginal impact

As the focus of this work is on SF6, figure 8 shows the most important influences on the marginal impact of a tonne of SF6. The largest correlation, +0.732, is with the equilibrium warming for a doubling of CO2 concentration. The sign of the correlation coefficient shows that a larger value for the input gives a larger value for the marginal impact, as we would expect.

Figure 8 Correlations with marginal impact of SF6



The next two most important influences are the non-economic impact of a 2.5 degC temperature rise, and the value of n in the expression $(T-T_{tol})^n$, which defines the impacts for other temperatures.

Next comes another scientific parameter, the half-life of global warming. This time the correlation is negative, showing that a lower value for the input gives a larger value for the marginal impact. This again is in the direction we would expect, as a lower value for the half-life means that the Earth responds more quickly to the increased forcing, giving earlier impacts which have a larger net present value.

All of the influences in figure 8 are of the correct sign. Two of the top 12 influences shown in the figure refer to the possible future large-scale discontinuities, even though the discontinuities are unlikely to occur for at least the next 50 years.

That the top four influences divide into two scientific and two economic parameters is a strong argument for the building of Integrated Assessment models such as PAGE2002. Models that are exclusively scientific, or exclusively economic, would omit parts of the climate change problem which still contain profound uncertainties.

Comparison with earlier work

An earlier version of the PAGE model, PAGE95, has been used previously to produce marginal impact estimates for CO2 and methane. These previous estimates were in US$1990, discounted at a pure time preference rate of 3% back to 1990, and are shown in table 8.

Table 8 Marginal impacts by gas from PAGE95

1990 - 2200 *US$(1990) per tonne*

	5%	**mean**	**95%**
C as CO2	10	21	48
Methane	30	110	260

Source: PAGE95 runs reported in Plambeck and Hope, 1996; Hope, 2001.

Comparing table 8 with table 7 shows that the mean results for the marginal impacts have hardly changed, although the lower end of the range has dropped by a factor of two. The previous mean estimate for CO2 of US$21 per tonne of Carbon has become US$19 per tonne of Carbon. But this gives rather a misleading impression of stability and precision. In fact the mean values have hardly changed because several quite significant changes have approximately cancelled each other out, as shown in Table 9 for CO2.

The first three rows show the effects of each structural change to the model. Including large-scale discontinuities increases the mean impact of a tonne of CO2 by 16%. Even though the discontinuity occurs in the 22nd century, if at all, it still has an effect on marginal impacts now as the lifetime of CO2 emissions is so long.

Rebasing the model to 2000 rather than 1990 increases the impacts by 24%, because a US$1990 is worth 24% more than a US$2000. Allowing the change in emissions to occur in a single year, rather than spread over 15 years as in PAGE95, increases the marginal impact by 22%.

Table 9 The effect of updates to PAGE on the mean marginal impact of CO2

Structural changes:	**Change in mean CO2 impact**
Large-scale discontinuities	+ 16%
Base year 2000	+ 24%
Change in emissions in single year	+ 22%
Parameter changes:	
Higher base year GDP	+ 82%
Higher GDP growth	+ 78%
Higher population growth	+ 21%
Lower sulphate effects	+ 15%
Lower economic effects in EU	- 42%
Lower economic effects in LDCs	- 55%
Carbon cycle changes	- 39%
Methane chemistry changes	- 29%

Source: PAGE2002 model runs

The effect of each parameter change is measured by running the model twice, once with all the changes implemented, and again with all the changes implemented except the one whose effect is being measured, which is left at its PAGE95 level, and noting the increase in mean impact in the first run compared to the second.

Using the year 2000 GDP from PAGE95, which totals US$33.3 trillion in US$2000, rather than the US$43.6 trillion in PAGE2002, gives a mean drop in impacts of 8.5 instead of US$15.5 billion, for an 82% rise from using the new higher base year GDP. This is more than 43.6/33.3 because the economic growth has been faster than expected mainly in the developing countries, which bear the brunt of any impacts. Using the GDP growth rates from PAGE95 gives a mean drop in impacts of 8.7 instead of US$15.5 billion. Using the discount rates from PAGE95 (which reflect the lower population growth forecasts in PAGE95, since both versions are using a 3% pure time preference rate) gives a mean drop in impacts of 12.8 instead of US$15.5 billion.

The effects of sulphates are slightly smaller in PAGE2002 than in PAGE95. Since sulphates have a cooling effect, this increases the marginal impacts.

Putting the focus region weights back to their PAGE95 values gives a mean drop in impacts of 26.7 instead of US$15.5 billion for CO2. Putting the regional weight factors back to their PAGE95 values gives a mean drop in impacts of 34.2 instead of US$15.5 billion for CO2. Both of these changes reflect the consensus that has developed since the IPCC SAR that very high impacts are implausible for modest temperature changes.

The carbon cycle changes include lower values for the climate sensitivity and the proportion of emissions which get into the atmosphere, and a positive rather than negative mean value for the effect of temperature rises on the stimulation of natural emissions, now reflecting the lower ability of oceans to remove CO2 at higher temperatures (IPCC, 2001b, p218) as well as the enhanced plant growth which was the dominant factor in PAGE95. The methane chemistry changes involve small adjustments to the CH4 pre-industrial concentration, half-life, base year forcing and slope of the forcing equation.

The net effect of all these changes is to leave the mean marginal impact estimate for CO2 almost unchanged, although now expressed in year 2000 dollars not year 1990 ones.

Future work

The marginal impact estimates given in this paper have been calculated for only a single IPCC scenario, A2. Although earlier work has shown the results to be fairly insensitive to the scenario used, it would probably be worthwhile to repeat the calculations at least for one other of the IPCC scenarios, scenarioB2. This is not because the different emissions in scenario B2 would change the results, so much as the different GDP and population growth assumptions, which imply different discount rates, which are known to affect the results strongly (Hope, 2001).

The PAGE2002 model allows the marginal impacts of any gas to be found, provided only that its concentration is low enough that its radiative forcing effect is linear in its concentration (CO2 and CH4 are special cases, which have their own special equation forms). Using this feature to find the marginal impacts of a range of other gases would contribute to policy discussions about the balance of effort in greenhouse gas reductions.

Finally, the calculations reported here should be repeated regularly as new information is constantly becoming available in this area. The new, more flexible, form of PAGE can incorporate new forms for probability distributions, and allow new parameters to be made uncertain. Keeping the calculations up to date will ensure that policy is not being informed by outdated science and economics.

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References

BP, 2002, Statistical Review of World Energy, http://www.bp.com/centres/energy2002/gas/prices.asp, accessed December 2002.

Hope C, 2001, *The Climate Change Benefits of Reducing Methane Emissions*, Judge Institute of Management WP 13/01, submitted to Climatic Change.

IPCC, 2001a, *Climate change 2001, Impacts, Valuation and Vulnerability*, Contribution of Working Group II to the Third Assessment Report of the Intergovernmental panel on Climate Change, Cambridge University Press.

IPCC, 2001b, *Climate change 2001, The Scientific Basis*, Contribution of Working Group I to the Third Assessment Report of the Intergovernmental panel on Climate Change, Cambridge University Press.

Plambeck E L and Hope C W (1995), 'Validation and initial results for the updated PAGE model', Research Papers in Management Studies 1994-1995 no 15, University of Cambridge, UK.

Plambeck E L and Hope C W (1996), 'PAGE95. An updated valuation of the impacts of global warming', *Energy Policy*, *24*, 9, 783-794.

Plambeck E L, Hope C W and Anderson J (1997), 'The PAGE95 model: integrating the science and economics of global warming', *Energy Economics, 19, 77-101*.