

THE COST OF USING GLOBAL WARMING POTENTIALS: ANALYSING THE TRADE OFF BETWEEN CO₂, CH₄ AND N₂O

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Abstract. The metric governing the trade-off between different greenhouse gases in the Kyoto Protocol, the Global Warming Potentials (GWPs), has received ample critique from both scientific and economic points of view. Here we use an integrated climate-economic optimization model to estimate the cost-effective trade-off between CO₂, CH₄ and N₂O when meeting a temperature stabilization target. We then estimate the increased cost from using GWPs when meeting the same temperature target. Although the efficient valuation of the gases differs significantly from their respective GWPs, the potential economic benefit of valuing them in a more correct way amounts to 3.8 percent of the overall costs of meeting the temperature stabilization target in the base case. In absolute value, this corresponds to an additional net present value cost of US\$₂₀₀₀ 100 billion. To corroborate our findings we perform a Monte Carlo-analysis where several key parameters are randomly varied simultaneously. The result from this exercise shows that our main result is robust to a wide range of changes in the key parameter values, giving a median economic loss from using GWPs of 4.2 percent.

1. Introduction

The basket approach of the Kyoto protocol allows countries to meet their emission targets by reducing six different greenhouse gases (CO₂, CH₄, N₂O, HFCs, PFCs, and SF₆). The possibility to use a multi-gas approach to meet climate targets has substantial economic advantages. Several studies (Hayhoe et al., 1999; Reilly et al., 1999, 2002) have shown that the cost of meeting the targets in the Kyoto protocol or more long-term climate targets can be substantially reduced (more than 50 percent) if a multi-gas approach is used instead of a CO₂ only approach.¹

The trade-off between the different greenhouse gases in the Kyoto protocol is governed by global warming potentials (GWPs), estimated by the Intergovernmental Panel on Climate Change (Ramaswamy et al., 2001). The GWP metric in its current formulation was put forward in the first IPCC assessment (Shine et al., 1990), based on work by Lashof and Ahuja (1990) and Rodhe (1990). The idea behind the GWPs is to integrate the radiative forcing of an additional emission pulse of one kg of a greenhouse gas over a specified time period (in Kyoto a time horizon of 100 years is chosen) and compare this with the integrated effect over the same time period of an additional emission pulse of a reference gas, i.e. CO₂ (Ramaswamy et al., 2001).

However, several studies have pointed to limitations of the GWP metric, both from a scientific and an economic perspective (see e.g., Fuglestvedt et al., 2003, or O'Neill, 2000, for a good overview of the critique). The economic critique has mainly focused on the fact that GWPs do not consider the expected damages from climate change, what policy target should be met or abatement costs, and that the GWP values are sensitive to an arbitrarily chosen time horizon (O'Neill, 2003; Reilly and Richards, 1993; Schmalensee, 1993; Eckaus, 1992). The scientific critique has pointed to the choice of indicator (i.e. radiative forcing rather than temperature response), the fact that a constant background atmosphere is used (thereby overlooking feedbacks on lifetime and radiative forcing of the gases), the use of an impulse emission rather than a sustained or finite step emission change, and that equal emissions, weighted by GWP, can give very different climate impacts, depending on the mix of gases² (Smith, 2003; O'Neill, 2000; Smith and Wigley, 2000a,b; Fuglestvedt et al., 2000; Reilly et al., 1999).

Several alternative metrics have also been proposed (Reilly and Richards, 1993; Hammitt et al., 1996; Kandlikar, 1996; Manne and Richels, 2001; Fuglestvedt et al., 2003; Shine et al., 2005), both purely physical based metrics and metrics taking into account both physical and economical aspects. Still, none has gained political or scientific acceptance. If a process is to be started with the aim of replacing the current GWP metric with a better formulation, it is important to assess the possible economic gains of adopting an alternative metric, as such a process could be politically and scientifically controversial.

In this paper we seek to do just that, i.e., to estimate the economic loss of using GWPs, compared to the case where a cost-effective trade-off between different greenhouse gases is made. It has been shown earlier (Manne and Richels, 2001) that the economically efficient trade-off ratios between CO₂, CH₄ and N₂O differ substantially from their GWPs and that these trade-off ratios change over time. Here, we take this analysis one step further and estimate not only the economically efficient trade off between the gases, but also the incremental cost of making an inefficient trade-off (i.e., using today's GWP). This question has been addressed in a preliminary analysis by O'Neill (2003) and in a working paper by Aaheim et al. (2004).³ Both studies suggest that the additional cost of using GWPs is rather low compared to the overall cost of meeting a climate stabilization target.

Our work differs from that of O'Neill (2003) and Aaheim et al. (2004) in several aspects. In Aaheim et al. (2004) emissions are (partly) endogenously derived from energy use in a Ramsey growth model, while we prescribe a baseline emission scenario exogenously, as do O'Neill. We adopt a more advanced climate model than both Aaheim et al. and O'Neill, looking at temperature constraints rather than radiative forcing constraints. The reason for this is that the inertia in the temperature response affects the trade-off between long-lived (CO₂, N₂O) and short-lived (CH₄) greenhouse gases, and thus the cost of using GWPs. We also use a more accurate carbon cycle representation than Aaheim et al., albeit somewhat less advanced than that of O'Neill. We also include the feedback effect of methane concentration on its

own lifetime and the indirect effect of methane on tropospheric ozone concentration and stratospheric water vapor.

Finally, and most importantly, we corroborate our findings with an extensive Monte Carlo analysis, varying the climate sensitivity, baseline emissions and marginal costs of abatement. We also run the model with different discount rates, with a decadal temperature constraint and in a cost-benefit setting to further examine the robustness of the results. In addition, we also offer an intuitive economic explanation as to why the costs of using GWPs are relatively small.

The method and model is described in Section 2. The results for the base case, giving insights into the dynamics of the model, are presented in Section 3.1, while the results from the sensitivity analysis are presented in Section 3.2. In Section 4 we discuss the results and conclude.

2. Method and Model

To analyze the economic losses from using GWPs when making trade-offs between abatement of different greenhouse gases, we have developed an integrated climate-economic model called MiMiC (Multi-gas Mitigation Climate model). The model minimizes the net present value cost of stabilizing the temperature at a predefined level. In order to calculate the economic cost of using current GWPs, the model is first run with the constraint that the ratios of the marginal cost of abatement between the gases shall equal today's GWP-indices, i.e. 23 for CH₄ and 296 for N₂O (Ramaswamy et al., 2001), and then without this constraint to allow for an optimal trade-off between the three gases. The cost of using today's GWPs is calculated as the increased net present value cost of abatement compared to the case where an efficient trade-off between the gases is made. To test the robustness of our results, we perform an extensive Monte-Carlo analysis (see Section 2.7 below), reflecting the many uncertainties in model parameters. We also calculate the potential economic gains from a multi-gas strategy by running the model without the possibility for CH₄ and N₂O abatement.

For the climate stabilization target, we adopt a ceiling of 2 °C increase in global average surface temperature above pre-industrial levels, a target proposed by several authors (e.g., Azar and Rodhe, 1997; Graßl et al., 2003). The model runs between the years 1990–2200, however abatement is only allowed for 2000 onwards. The model runs with a decadal time-step, though for processes on shorter time-scale than ten years (e.g., removal of CH₄ from the atmosphere, and the transient response of the temperature model) yearly values are calculated. In the base case the discount rate is set to 5 percent/year and the climate sensitivity to 3 °C for a doubling of the pre-industrial atmospheric CO₂ concentration.

Below, the model is described in more detail, starting with emissions of CO₂, CH₄, N₂O,⁴ and sulfur⁵ (see Section 2.1), calculations of subsequent changes in concentrations of the GHGs (2.2), perturbations of radiative forcing (2.3), and

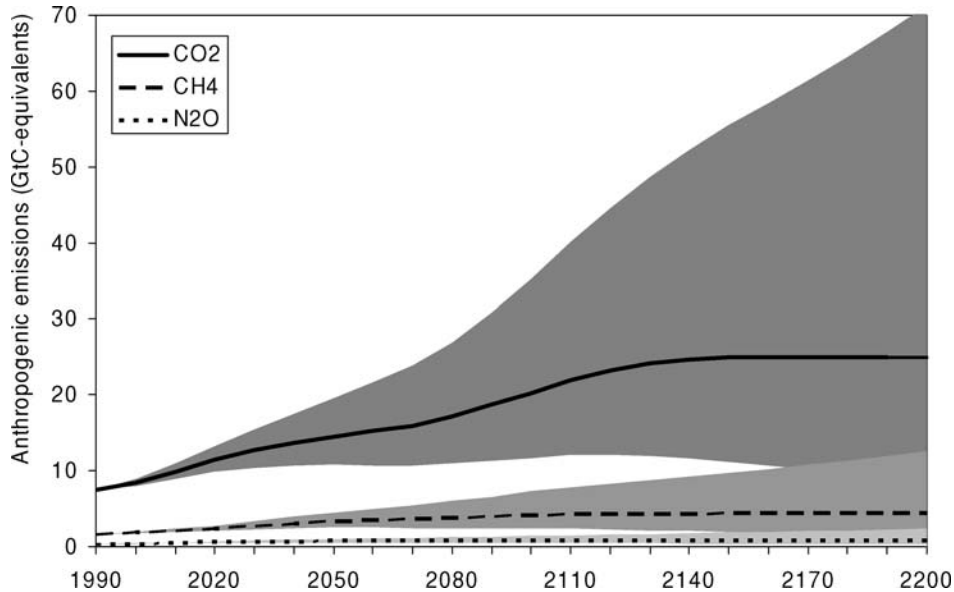


Figure 1. The baseline emissions as given by the IPCC IS92a scenario (2000–2100) for CO₂ (solid line), CH₄ (dashed line) and N₂O (dotted line), the latter two converted to GtC-equivalents using 100-year GWPs taken from TAR (Houghton et al., 2001). The emissions after 2100 are assumed to follow a decreasing path, see text. The span over which the emission scenarios are varied in the Monte Carlo analysis is also shown in shading.

changes in surface and ocean temperatures (2.4). It is then described how the climate module is initialized by calibrating it to historical data (2.5). Finally, the marginal abatement costs curves for the different gases are presented (2.6).

2.1. BASELINE EMISSIONS

Between year 2000 and 2100 the baseline emissions for the GHGs are taken from the IPCC IS92a scenario (IPCC, 1992), being a business-as-usual scenario. The radiative forcing for sulfur, being a proxy of anthropogenic radiative forcing not considered explicitly in the model, is assumed to decrease by one percent per annum over the entire time period. Anthropogenic emissions of the well-mixed GHGs after 2100 are assumed to follow a path towards stabilization of the annual emissions in the year 2150 at the level of 25 GtC for CO₂, 700 MtCH₄ for anthropogenic methane emissions and 6.5 MtN for anthropogenic nitrous oxide emissions (see Figure 1). These somewhat arbitrary assumptions regarding post-2100 baseline emissions are of course highly uncertain (as are the emissions in 2000–2100), and they are therefore varied in a large span in the Monte Carlo analysis (see Figure 1).

2.2. ATMOSPHERIC CONCENTRATIONS OF GHGS

CO₂ concentrations are modeled by the four box, linear pulse representation of the Bern carbon cycle model used in the IPCC's Third Assessment Report (hereafter TAR) (Houghton et al., 2001). CH₄ and N₂O concentrations are modeled using the global mean mass-balance equations given in TAR (Prather et al., 2001). The lifetime of CH₄ is thus a compound of the different lifetimes for the three main sinks: stratosphere (120 years), soils (160 years), and atmospheric OH (9.6 years for a CH₄ abundance of 1745 ppb). The latter is also adjusted upwards by 0.28 percent for each percent increase in CH₄ concentration, to take into account the feedback effect CH₄ has on its own atmospheric lifetime (Prather et al., 2001).

2.3. RADIATIVE FORCING

The equations for radiative forcing are the simplified expressions given in TAR (Ramaswamy et al., 2001), accounting for the overlapping absorption bands of CH₄ and N₂O. The indirect effect of methane on atmospheric chemistry, raising (global) tropospheric ozone concentrations and increasing stratospheric water vapour content, is also accounted for, with functional forms taken from Wigley et al. (2002), for the former, and Harvey et al. (1997), for the latter.

Sulfur emissions are used as a proxy for the net negative radiative forcing of forcings not included in the model, partly to calibrate the climate model (see below). Here, we assume a linear relationship between emissions and radiative forcing, following the direct effect of sulfate aerosols in Harvey et al., (1997). Natural forcings (i.e. changes in solar irradiance and stratospheric aerosols, due to volcanic eruptions) are also included in the model. For the calibration (see below) historical data is used, while future forcing is simply assumed to be equal to the average forcing for the historical record. This assumption is made because of the difficulties in predicting future changes in these forcings.

2.4. TEMPERATURE MODEL

The temperature is modeled by the two-box model developed by Schneider and Thompson (1981), consisting of an atmosphere-upper ocean and a deep ocean reservoir, but with parameter values taken from Nordhaus (1994), except for the value of the climate sensitivity and the inverse heat capacity of the upper box (atmosphere-upper ocean layer). Since the latter parameter largely determines the transient response of the temperature model, the value is set so that our model matches the transient response of 15 Atmosphere Ocean General Circulation Models (AOGCMs) presented in TAR (Cubasch et al., 2001), as measured by the CMIP2 experiment.⁶ For each model comparison we set the climate sensitivity of our model to that reported for the AOGCM in question. We then fit the transient response of our

model to that of the AOGCMs by means of a least squares fit. The resulting inverse heat capacity parameter is $0.0372\text{ }^{\circ}\text{C per W/m}^2$ and year, compared to Nordhaus' value of $0.0226\text{ }^{\circ}\text{C per W/m}^2$ and year, implying a somewhat faster response to forcing perturbations in our model.

2.5. CALIBRATING THE TEMPERATURE MODEL

We calibrate the temperature model by adjusting the radiative forcing contribution of aerosols so as to replicate the historical temperature record, from 1860–2000. The historical data for concentration of the well-mixed GHGs is taken from the NASA GISS global circulation model (Hansen and Sato, 2004; supporting material). Global emissions of sulfur are taken from Stern (2005). Natural forcings are also taken from the NASA GISS model (NASA GISS, 2005). These are updated values for variability in solar irradiance, based on Lean et al. (1995), and for stratospheric aerosols from volcanic eruptions, based on Sato et al. (1993). The temperature series used to calibrate the model is taken from Met-Office (2005), based on Folland et al. (2001), Jones et al. (2001), and Jones and Moberg (2003).

The result of the temperature calibration, together with the resulting temperature path from following the baseline emissions in our model, is displayed in Figure 2. As can be seen, the historical temperature recorded is reproduced with relatively high accuracy, although of course our model leaves out many aspects of the climate system (e.g. internal variability). The sum of the direct and indirect affect of sulfur aerosol forcing obtained from the calibration is -0.79 W/m^2 in year 2000, for the base case climate sensitivity of $3\text{ }^{\circ}\text{C}$. The temperature change for the baseline emission scenario, reaching $2.7\text{ }^{\circ}\text{C}$ above the 1961–1990 average in year 2100, is somewhat higher than the simple climate model results reported for the IS92a scenario in IPCC's second assessment report (Kattenberg et al., 1996). This is largely due to the fact that we assume a much lower sulfur emission trajectory.

2.6. MARGINAL ABATEMENT COST CURVES

The marginal cost of CO_2 abatement is in the form of a second degree polynomial,

$$\text{MC}_{\text{CO}_2}(\$/tC) = \alpha \cdot x + \beta \cdot x^2,$$

where α and β are constants, and x is abatement as a share of total baseline emissions (in percent). The numerical values of α and β are taken from Ellerman and Decaux (1998). However, since their cost estimate is for the Kyoto-period only and we run the model for a much longer time-span, we adjust the marginal abatement cost curve (MAC) downwards (giving a cost of US\$800/tC for 100 percent abatement). The shift in the CO_2 MAC also reflects the inclusion of biomass energy with carbon capture and storage (Obersteiner et al., 2001; Azar et al., 2005) as an abatement option. This implies that CO_2 abatement can actually be higher

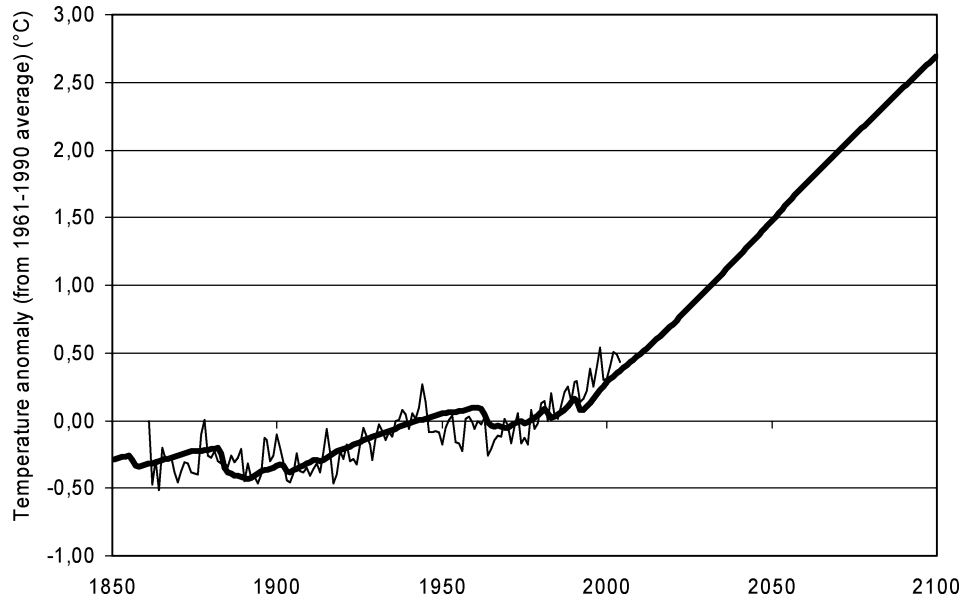


Figure 2. The modeled temperature change in the period 1850–2100 (*thick line*), based on historical forcings (CO_2 , CH_4 , N_2O , aerosols, solar irradiation and volcanic eruptions) in the period 1850–2000, and IS92a emissions of GHGs, together with average natural forcings and decreasing aerosol emissions, in the period 2000–2100. The model is calibrated as to match the historical temperature record in the period 1850–2000 (*thin line*).

than baseline emissions, resulting in global emissions being negative. This means that the MAC extends beyond 100 percent abatement. The resulting values for the constants are given in Table I, and the resulting MAC can be seen in Figure 3.

The CH_4 and N_2O marginal abatement costs are represented by an exponential function,

$$\text{MC}_{\text{Non-CO}_2} (\$/\text{tC-eq.}) = \alpha \cdot (e^{\beta x} - 1),$$

TABLE I

The numerical values for the constants in the marginal abatement cost formulations used in the model (see text). Numbers in parentheses are the span in which the parameters are varied in the Monte Carlo analysis. Marginal costs are given in US\$₂₀₀₀ per tC-equivalent, using the GWP values from IPCC's third assessment report (Ramaswamy et al., 2001)

	CO_2	CH_4	N_2O
α	0.63 (0.32–0.95)	5.48 (2.74–8.22)	1.57 (0.79–2.36)
β	0.07 (0.04–0.11)	0.10 (0.05–0.15)	0.16 (0.08–0.24)

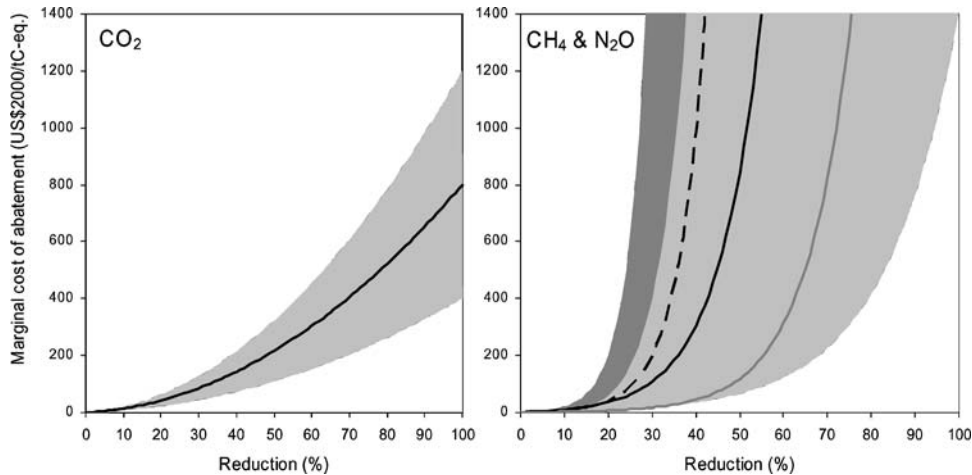


Figure 3. The marginal cost of abatement for CO₂ (left), methane (right, solid line) and nitrous oxide (right, dashed line) for the base case. The span within which the marginal cost is varied in the Monte Carlo analysis is also shown for CO₂, CH₄ (light shading), and N₂O (dark shading, lower bound indicated by the grey line).

where again α and β are constants, and x is abatement in percent. The added minus-one term implies that the marginal cost for zero abatement is zero. The numerical values of α and β for CH₄, displayed in Table I, are based on DeAngelo (2003) (for CH₄ emissions from rice cultivation and enteric fermentation) and US EPA (2004) (for all other CH₄ emission sources). The numerical values for N₂O abatement are taken from Reilly et al. (2002), and displayed in Table I. The resulting MAC curves can be seen in Figure 3.

2.7. MONTE CARLO ANALYSIS AND FURTHER SENSITIVITY ANALYSIS

To test the robustness of our results a Monte Carlo simulation is carried out by calculating the economic loss of using GWPs in 1000 samples, where climate sensitivity, MACs and baseline emissions are varied randomly in large spans, so as to capture a wide range of assumptions and combinations of them.

Starting with the climate sensitivity, a number of recent studies have indicated that the probability function for that parameter has positive skew, i.e., with a long tail of high sensitivities with low probabilities (Forest et al., 2002; Murphy et al., 2004; Stainforth et al., 2005). Following this, we let the uncertainty in climate sensitivity be represented by a log-normal distribution, with a 5–95 percent probability range of 1.9 °C–5.3 °C per CO₂ equivalent doubling⁷ (Murphy et al., 2004). For each run in the Monte Carlo analysis, having a different climate sensitivity, the temperature model is recalibrated to fit historical data as described above, giving a new value for the strength of the sulfur forcing.

The baseline emissions and the marginal cost of abatement for each gas vary as illustrated in Figures 1 and 3, respectively. See also Table I for the MAC spans. We assume a wider span in the uncertainty for the marginal abatement costs curves for methane and nitrous oxide as compared to carbon dioxide, since abatement options for these gases are less studied and since substitution effects, for example from consumption of livestock meat to non-ruminant meat, are not included in the estimates of these cost curves. We also run the Monte Carlo analysis for two alternative discount rates, a low rate of 3 percent, and a high rate of 7 percent, to reflect the uncertainty, as well as value judgments, about the appropriate discount rate.

To further test the robustness of our results we also run the model with a constraint on the rate of temperature change, set at 0.2 °C per decade. Finally, we run the model as a cost-benefit model, where the sum of net present value of the abatement and climate change damage costs are minimized. However, there are several good reasons why one should be skeptical of cost-benefit analyses in the case of global climatic change (see Azar, 1998 and Van den Bergh, 2004, for arguments). In the cost-benefit case, the damage cost for climate related impacts is taken from Nordhaus (1994),

$$D = \gamma \cdot Y \cdot (T/3)^\varepsilon,$$

where D is damage in monetary terms, Y global output (taken from IS92a, with the linear trend in 2050–2100 extended up to 2200), T is surface temperature change and γ and ε are parameters. We let the exponent in the damage function (ε) vary uniformly between 1 and 3, while we assume that the damage cost of a temperature increase of 3 °C (γ) vary uniformly between 0.665 percent and 2.66 percent of global GDP, i.e. half and twice the values that Nordhaus use.

3. Results

3.1. BASE CASE

Figure 4 displays the shadow price ratios (SPRs), i.e. the ratio between the marginal abatement cost of CH₄ and N₂O, and of CO₂, respectively, at each point in time for the base case run. The most conspicuous effect in the cost-effective trade-off case is that the relative value of methane rises as one approaches the temperature stabilization target, while the relative value for nitrous oxide rises up to about 2050 and then gradually levels off and falls. These results are in line with Manne and Richels (2001).

The short atmospheric life-time of CH₄ implies that early abatement of this gas has a small effect on the climate at the time when the temperature is stabilized, and therefore the value is low in the beginning of the period. Note, however, that CH₄ still is valued nearly five times as high as CO₂, reflecting the strength of CH₄ as a greenhouse gas in combination with the inertia of the climate system, meaning that a radiative forcing perturbation has a (diminishing) effect on the temperature from

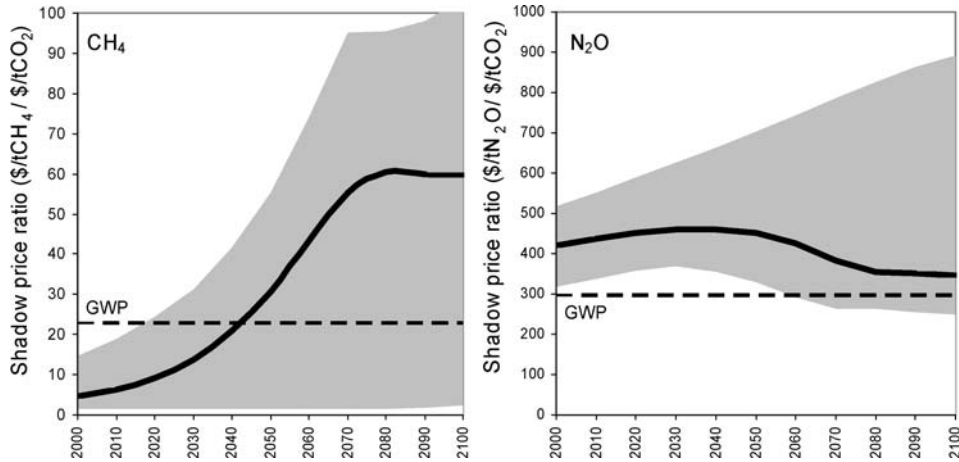


Figure 4. Shadow price ratio between CH₄ (left) and N₂O (right), and CO₂, respectively and their GWP values (dashed lines) calculated over 100 years. The shaded areas show the span over which the shadow price ratio varies in the Monte Carlo-analysis.

years to centuries (depending on climate sensitivity and effective heat capacity of the oceans).

O'Neill (2003) and Aaheim et al. (2004) also find increasing SPRs over time for methane although their initial value is much lower (close to zero), in the case of Aaheim et al. for several decades. This seems to be caused by the fact they do not model the global temperature, and therefore do not capture the inertia effect explained above.

For N₂O, the shadow price ratio is closer to its GWP value since the lifetime dynamics of the gas is more similar to that of CO₂. However, the valuation of N₂O is higher than its current GWP value (296). This is mainly due to the fact that the GWP is calculated with a constant background concentration, while in our model the concentrations of both CO₂ and N₂O increase. Since the marginal radiative forcing of CO₂ decreases faster than that of N₂O (logarithmic versus square root dependence), this implies that N₂O is valued higher in our model.

Although our analysis suggests that the economically correct valuation of the gases is significantly different from their respective GWP₁₀₀, the potential economic benefit of valuing them in this more correct way is relatively small. In the base case the benefit amounts to about US\$100 billion (net present value at year 2000), or merely 3.8 percent of the overall cost of US\$2.6 trillion to meet the temperature stabilization target.⁸ It is useful to compare this with the extra cost of adopting a CO₂ only strategy, which in our model is about 45 percent more costly than the multi-gas strategy. The cost of using GWPs found here is in line with the results from the other studies mentioned in the introductory section of this paper (O'Neill, 2003; Aaheim et al., 2004). A heuristic explanation as to why the economic losses from using GWPs are so low, is offered in Appendix A.

The annual cost of using the wrong metric is also small. This implies that no large future costs of using the wrong metric are “discounted away” in net present value calculations. This could otherwise have implications for the intergenerational equity aspect of choosing a suitable metric.

3.2. MONTE CARLO-ANALYSIS

The Monte Carlo simulation shows that the low cost of using the wrong metric is rather insensitive to large changes in the parameter values, and combinations thereof, see Figure 5 and Table II. As can also be seen in Table II, the cost of using GWPs increase with increasing discount rate. The reasons is that the relative cost of using GWPs are lower the higher the abatement level, as explained in Appendix A. With a high discount rate costs early in the model, when abatement levels are generally lower, are weighted higher, and thus the NPV cost of using GWPs becomes higher. Similarly, the cost decrease with increasing climate sensitivity, since higher climate sensitivity implies higher abatement levels.

Adding the decadal time constraint, does not affect the overall cost of using the wrong metric considerably, as seen in Table II. In Table II, the results from the cost-benefit approach are also presented. These result indicate that the losses are even lower when using this approach as compared to using a cost-effectiveness approach. The explanation is that the shadow price ratio of CH₄ to CO₂ is now

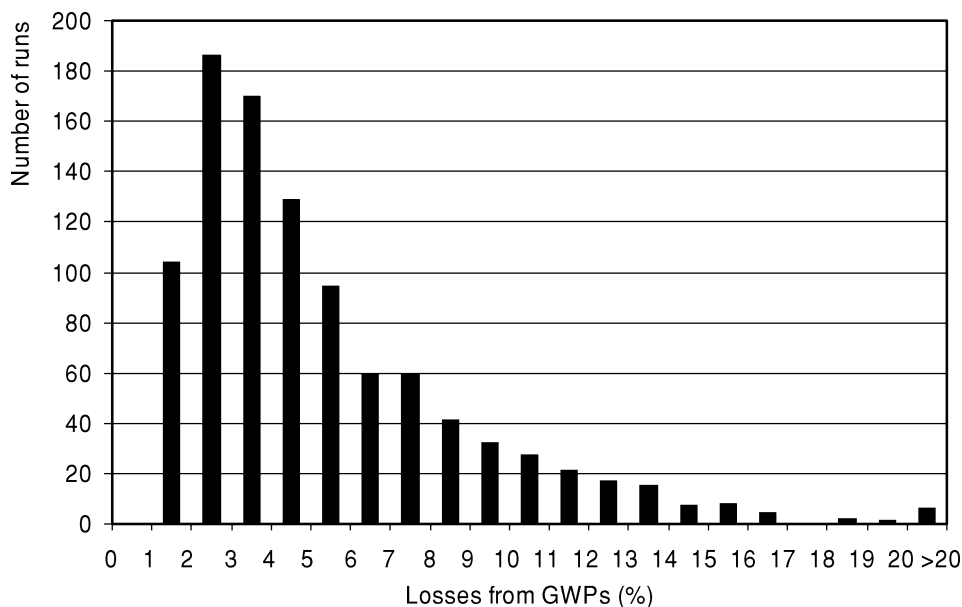


Figure 5. Histogram of the relative economic loss of using GWP as compared to the optimal trade off between the gases.

TABLE II

The mean, median and standard deviation from Monte Carlo analysis is presented as the percentage extra cost of using GWP instead of the optimal trade off ratios

Method	Mean (%)	Median (%)	Standard deviation (%)
Cost effect. 2 °C	5.3	4.2	3.6
-3% discount rate	3.6	2.7	3.2
-7% discount rate	7.0	5.8	4.0
Cost effect. 2 °C and 0.2 °C /decade	5.4	4.5	3.2
Cost Benefit	2.3	1.4	2.9

relatively closer to its GWP value over the whole modeling time period (since the short term temperature response is now valued higher), compared to the cost-effectiveness case.

Although the economic losses do not change to any great extent in the Monte Carlo analysis, this is not the case for the cost-effective valuation of the gases, displayed in Figure 4. The shadow price ratio of CH₄ to CO₂ varies by a factor of nine already at the year 2000 and increases up to a factor of 60 or more at the end of the century. This variation is mainly explained by decreasing marginal radiative forcing to increasing concentrations and the fact that the marginal radiative forcing decreases faster for CO₂ than for CH₄ and N₂O. The concentrations, and thereby the shadow price ratios, are in turn determined by the climate sensitivity, baseline emission scenarios and abatement costs for the different gases, all of which are being varied in the Monte Carlo analysis.

Also, letting the discount rate vary (between 3 and 7 percent), increases the span of the shadow price ratio for CH₄ somewhat, since changing the discount rate can partly be seen as equivalent to changing the time horizon used in traditional GWP calculations. But more importantly, taking the rate of temperature change into account through a decadal temperature constraint of 0.2 °C, changes the efficient valuation of CH₄ very much, with the shadow price ratio exceeding 40 throughout the modeling time horizon in most cases (cf Manne and Richels, 2001). This since the short term radiative effect of CH₄ is important from year 2000 onwards, compared to the base case when the short term response is important close to, or when, the temperature target is reached. Consequently, the shadow price ratio of N₂O, because of its long lifetime, do not change to any large extent when adding the decadal temperature constraint.

4. Discussion and Conclusion

Our analysis has shown that the economic cost of using today's GWPs, being an inefficient metric from an economic perspective, amounts to a few percent of the overall cost of meeting a temperature stabilization target. Still, even if the global

net losses are small in relative terms, the absolute losses are not unsubstantial. Further, the value of the metric could have important national and regional economic consequences, since emissions of the gases are not equally distributed across countries. In general, non-CO₂ greenhouse gases take a larger share in many developing countries' national greenhouse gas budgets compared for example to many OECD countries. But if a different metric is chosen, it is likely that governments would negotiate targets that are different from what they would have chosen to accept otherwise, so that the overall costs for each country remain roughly the same (cf. Godal and Fuglestedt, 2002).

In any case, the problems with GWPs have to be evaluated in relation to the political cost of changing the metric (Skodvin and Fuglestedt, 1997). Most alternative metrics proposed are dependent on the choice of uncertain and politically controversial assumptions, e.g. climate damage costs or policy goal, marginal abatement costs, climate sensitivity, discount rates, etc.

As can be seen in the Figure 4, the span in which the cost-effective trade-off varies when parameters are varied in the Monte Carlo analysis is very large. And this is the case even without introducing a rate of temperature change constraint or changing the discount rate, something that would imply a larger span, especially for methane. Thus, choosing an alternative metric to the GWP based on so many uncertain and contentious assumptions is likely to lead to political and scientific controversies and hence large transaction costs, in the form of complicated negotiations that would steal time from other, perhaps more pressings, concerns.

Finally, just as many other models before ours, this study clearly shows the potentially large economic gains from a multi-gas approach to climate change, as compared to a CO₂-only approach. However, most economic analyses of the multi-gas issue has failed to address the issue of how to control the inherently uncertain and site specific (non-point source) emissions of CH₄ and N₂O emissions, especially those from the agricultural sector. The monitoring and verification problems for these emissions could potentially be so large that what is normally seen as more blunt and less efficient policy instruments, like technology or management regulations or payment schemes, could be the policy instruments of choice (Johansson and Persson, 2005). Consequently, the economic gains of a multigas approach could be lower than indicated by this and other studies. This aspect is probably a more important aspect, both economically and politically, than the metric issue, and deserves more attention than what it has previously received.

Appendix A: A Heuristic Explanation of the Economic Losses from the use of GWPs

To understand why the relative loss of using GWP₁₀₀ is so small we offer a heuristic explanation for the case of the trade-off between CO₂ and CH₄. Figure 6 displays this trade-off for two instances in our model, year 2010, and year 2100. In the

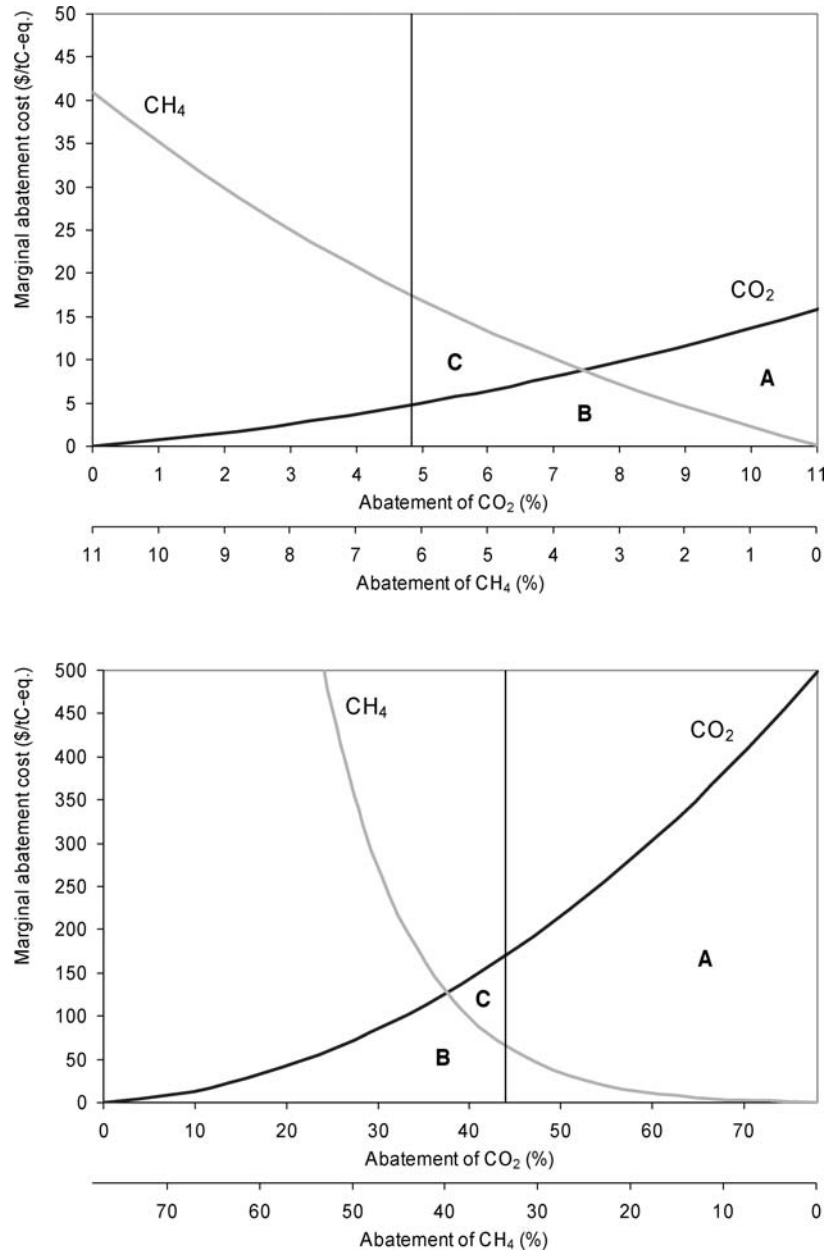


Figure 6. Graphs displaying the MAC curves for CO₂ and CH₄ for two representative years in our model, 2000 (upper) and 2100 (lower), used to give an intuitive explanation as to why the cost of using GWPs is relatively low (for explanation, see text).

year 2010, aggregate abatement for these two gases in the model is 11 percent of emissions in carbon dioxide-equivalents, calculated using the *optimal valuation of CH₄* (i.e. the SPR discussed above), which is 6.3 for this time period. The marginal abatement costs shown in the figure are also expressed in US\$/tC-equivalent, again using the *optimal valuation for CH₄*. To begin with, the total abatement cost, if abatement is targeted on CO₂ only, is the area below the CO₂ MAC (area A plus B). In the cost-effective trade-off case, however, CO₂ abatement is reduced to about 7.5 percent and the total abatement cost is given by area B only. Thus, the figure clearly shows the economic gains of a multi-gas approach, corresponding to area A.

Consider now the case when the model is forced to deviate from the cost-effective trade-off, by imposing that the ratio between CH₄ and CO₂ marginal abatement costs should equal the GWP₁₀₀ value of CH₄. If total abatement is held fixed, this implies more CH₄ abatement and less CO₂ abatement, since the GWP is higher than the efficient valuation (6.3). This trade-off is indicated by the thin vertical line in the figure, where total abatement costs now are given by area B plus C. Thus, the economic loss of using GWP corresponds to area C in the graph. The case is similar for the year 2100 but since the efficient valuation of CH₄ here (60) is higher than the GWP value, the GWP constraint implies less CH₄ abatement and more CO₂ abatement than in the cost-effective case. Again this is represented by the thin vertical line and the economic loss from GWP corresponds to area C.

Some things are worth noting. First, the economic losses in both cases are relatively small (compared to total costs in the cost-effective case, B), which is in line with the results obtained in the numerical model. However, the heuristic explanation given here have only considered a static case, while our numerical model is dynamic. This implies that the losses are in fact lower than what is indicated in Figure 6, since abatement in the GWP case will be shifted in time to minimize abatement costs.⁹ Secondly, the relative loss seems to be higher in 2010 than in 2100 when the level of abatement is higher. This should imply that for higher climate sensitivities, when a higher level of abatement is needed, the relative loss should be smaller. This is what we find in the Monte Carlo analysis.

Finally, the exponential shape of the non-CO₂ gases' MACs imply that after a certain level, relatively small changes in abatement effort gives large changes in the marginal cost of abatement. What this means is that for high levels of abatement, although the valuation in the cost-effectiveness case deviates quite a lot from the GWP value, the emission path do not differ substantially from the GWP case. This contributes to a lower loss of using GWP.

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Notes

¹However, one should note that these studies have assumed that abatement of these emissions is undertaken in a cost-effective manner. This is not very likely, due to the diffuse character of a large share of these emissions, which means that cost-effective policies are difficult to implement (Johansson and Persson, 2005) and problems with monitoring and verification of emissions changes may arise (Victor, 2001; Johansson and Azar, 2003).

²However, note that the last problem remains for all weighting schemes, due to the different lifetime characteristics of the gases.

³A related study, looking at national compliance costs when using GWPs for different time-horizons has been made by Godal and Fuglestad (2002).

⁴The other gases in the Kyoto protocol are not included in the model since they do not significantly contribute to the radiative forcing change now and is not expected to do so over the coming centuries.

⁵Sulfur is used as a proxy for all other anthropogenic forces not considered directly. However, the direct and indirect effects of sulphur emissions are most likely the dominating factors in this parameter.

⁶In the CMIP2 simulation the climate model is run with a forcing corresponding to a 1 percent increase in CO₂ concentration per year, and the transient response is estimated as the average global mean temperature response in the years 61–80, i.e. at the time for CO₂-doubling plus/minus ten years (Cubasch and Meehl, et al., 2001). The transient response for the models presented in TAR range from 1.1 °C to 3.1 °C, but note that this is from models with climate sensitivities ranging from 2.1 °C to 5.1 °C for a CO₂ doubling. For the base case climate sensitivity of 3 °C, the transient response of MiMiC, as measured by the CMIP2 experiment, is 1.75 °C.

⁷Since the probability density function (PDF) reported by Murphy et al. (2004) is based on an ensemble of models, and not on a standard mathematical PDF, our log-normal representation is not identical to their results. Therefore, basing our PDF on the 5–95 percent probability range reported by Murphy et al. (unweighted case), gives a slightly higher median climate sensitivity, of 3.1 °C per CO₂ equivalent doubling, as compared to Murphy et al's 2.9 °C.

⁸The total discounted abatement cost of US\$2.6 trillion in the base case (and the mean cost of US\$2.7 trillion in the Monte Carlo analysis) is in line with results in the existing literature (although studies reporting abatement costs for temperature stabilization including non-CO₂ GHGs are rare). In TAR (Hourcade et al., 2001), the cost of stabilizing the atmospheric CO₂ concentration at 450, 550 and 650 ppm is estimated to be in the range of US\$2.5–18 trillion, US\$1–8 trillion and US\$0.5–2 trillion, respectively. Although not directly comparable to our results, these figures indicate that our model is consistent with well established results in the literature.

⁹Investigations by using our numerical model indicate that the economic loss in the static case is reduced by 10–30 percent by changing the total abatement of the three gases in each time step (i.e. optimizing abatement over time, subject to the GWP constraint).

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