MULTI-GAS EMISSION REDUCTION FOR CLIMATE CHANGE POLICY: AN APPLICATION OF *FUND*

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Abstract

The costs of greenhouse gas emission reduction are investigated with abatement of carbon dioxide, methane, and nitrous oxide using the *FUND* model. The central policy scenario keeps anthropogenic radiative forcing below 4.5 Wm^{-2}. If CO_2 emission reduction were the only possibility to meet this target, the net present value of consumption losses would be $45 trillion; with abatement of the other gases added, costs fall to $33 trillion. The bulk of these costs savings can be ascribed to nitrous oxide. Because nitrous oxide is so much more important than methane, the choice of equivalence metric between the greenhouse gases does not matter much. Sensitivity analyses show that the shape of the cost curves for CH_4 and N_2O emission reduction matters, and that the inclusion of SO_2 and sulphate aerosols make policy targets substantially harder to achieve. The costs of emission reduction vary greatly with the choice of stabilisation target. A target of 4.5 Wm^{-2} is not justified by our current knowledge of the damage costs of climate change.

Key words

Climate change, emission reduction, carbon dioxide, methane, nitrous oxide

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1. Introduction

International climate policy has stalled. One of the reasons are the (perceived) high costs of implementation something like the Kyoto Protocol and the UNFCCC's ultimate aim of stabilising atmospheric concentrations of greenhouse gases. Options to reduce the costs of emission reduction are therefore worth investigating. Particularly, as oil prices are so high at the moment, options to reduce emissions without raising the price of petrol would increase the political feasibility of emission abatement. Reducing the emissions of methane (CH_4) and nitrous oxide (N_2O) are such options. Previous discussions have focussed on "where" flexibility (that is, the ability to shift emission reduction between countries) and on "when" flexibility (that is, the ability to shift emission reduction between periods). The ability to shift emission reduction between gases may be referred to as "how" flexibility (Manne and Richels, 2000).

The economic literature on the costs of greenhouse gas emission reduction has focussed on carbon dioxide from industry and electricity (Hourcade *et al.*, 1996a,b, 2001). This is the largest single source of greenhouse gases. However, other sources are important too. Perhaps the explanation for the paucity of studies is that these other sources are hard to include into models that emphasize energy economics. Methane is emitted by coal mining and leakage from gas transport, but also by agriculture. Nitrous oxide originates from agriculture and a range of industrial processes. Another explanation is the lack of data on engineering solutions to CH_4 and N_2O emissions and their costs. Although there are a fair number of older of partial studies on emissions, options and costs (van Amstel, 1993; van Amstel *et al.*, 1993; EPA, 1993a,b,c, 1999; de Jager and Blok, 1993; van Ham, 1994, 2002; Kroeze, 1994; de Jager *et al.*, 1996a,b; AEAT, 1998; IEA GHG, 1998; Kruger *et al.*, 1998; Bates, 2000; Bates and Haworth, 2000), Tol (1999) and Tol *et al.* (2003)[1] had to extrapolate methane emission reduction costs curves from the Netherlands to the rest of the world. Reilly *et al.* (1999) were the first to report, albeit only graphically, an internally consistent, region specific set of cost curves. Things are changing rapidly now, particularly with the solid input from US EPA (2003). This new information is now being taken up by the models used for climate policy analysis. This study contributes to that.

A few previous studies have looked at multi-gas emission reduction. Tol (1999) looks at carbon dioxide and methane, finding that "how" flexibility is as important as "where" flexibility, with cost savings of up to 70%. Reilly *et al.* (1999) study emission reduction for all greenhouse gases, finding annual cost reductions of about 50%. They emphasize that emission reduction targets, if expressed relative to a base year, are sensitive to the gases included. The analysis of Manne and Richels (2000) is restricted to CO_2, CH_4 and N_2O. Their annual cost savings in 2010 are 20-50%, smaller than in Reilly *et al.* (1999). Jensen and Thelle (2001) include all Kyoto gases in a medium-term model; their welfare costs in the OECD fall by 20-35% due to the inclusion of other gases, but the countries of the former Soviet Union lose substantial revenue in the emission permit trade. The study by Tol *et al.* (2003) is restricted to carbon dioxide and methane. In contrast to the other multi-gas studies (including this one), it emphasizes the differences in the dynamics of the two gases in the economy, a factor that complicates the optimal trade-off between respective emission reductions. Tol *et al.* (2003) report cost savings of up to 70% by including methane only. Aaheim *et al.* (2004) use a simpler model than the previous studies. Their cost savings due to including the other gases is much smaller, only 10%, but their emission reduction target is much stricter. They also show that relative cost savings fall as the target gets stricter.

The current study differs from previous papers in using a different set of scenarios and sensitivity analyses, and using more reliable data on the costs of emission reduction. Nonetheless, new qualitative insights emerge as well. Section 2 presents the model used, *FUND*2.7. Section 3 shows the basic results and sensitivity analyses. Section 4 concludes.

2. The model

The model used is version 2.7 of the *Climate Framework for Uncertainty, Negotiation and Distribution (FUND)*. Version 2.7 of *FUND* corresponds to version 1.6, described and applied

[1] Both studies were in fact done in 1998.

by Tol (1999a-e, 2001, 2002a), except for the impact module, which is described by Tol (2002b,c) and updated by Tol (2002d). A further difference is that the current version of the model distinguishes 16 instead of 9 regions. The current version of the model also includes emission reduction for nitrous oxide (N_2O), not incorporated in earlier versions of *FUND*, as well as a new formulation of methane (CH_4) emission reduction.

Essentially, FUND consists of a set of exogenous scenarios and endogenous perturbations. The model distinguishes 16 major regions of the world, viz. the United States of America, Canada, Western Europe, Japan and South Korea, Australia and New Zealand, Central and Eastern Europe, the former Soviet Union, the Middle East, Central America, South America, South Asia, Southeast Asia, China, North Africa, Sub-Saharan Africa, and Small Island States. The model runs from 1950 to 2200 in time steps of one year. The prime reason for starting in 1950 is to initialize the climate change impact module. In *FUND*, the impacts of climate change are assumed to depend on the impact of the previous year, this way reflecting the process of adjustment to climate change. Because the initial values to be used for the year 1950 cannot be approximated very well, both physical and monetized impacts of climate change tend to be misrepresented in the first few decades of the model runs. The 22nd century is included to make sure that climate policies aimed at stabilizing concentrations indeed achieve that goal.

The period of 1950-1990 is used for the calibration of the model which is based on the *IMAGE* 100-year database (Batjes & Goldewijk, 1994). The climate scenarios for the period 2010-2200 are based on the EMF14 Standardized Scenario, which lies somewhere in between IS92a and IS92f (Leggett *et al.*, 1992).

The scenarios concern the rate of population growth, economic growth, autonomous energy efficiency improvements, the rate of decarbonization of the energy use (autonomous carbon efficiency improvements), and emissions of carbon dioxide from land use change, methane and nitrous oxide.

The scenarios of economic and population growth are perturbed by the impact of climatic change. Population decreases with increasing climate change related deaths that result from changes in heat stress, cold stress, malaria, and tropical cyclones. Heat and cold stress are assumed to have an effect only on the elderly, non-reproductive population. In contrast, the other sources of mortality also affect the number of births. Heat stress only affects the urban population. The share of the urban population among the total population is based on the World Resources Databases (WRI, 2000). It is extrapolated based on the statistical relationship between urbanization and per-capita income which are estimated from a cross-section of countries in 1995. Climate-induced migration between the regions of the world also cause the population sizes to change. Immigrants are assumed to assimilate immediately and completely with the respective host population.

The tangible impacts are dead-weight losses to the economy. Consumption and investment are reduced without changing the savings rate. Thus, climate change reduces the long-term economic growth, although for the short term the consumption is particularly affected. Economic growth is also reduced by carbon dioxide abatement measures.

The energy intensity of the economy and the carbon intensity of the energy supply autonomously decrease over time. This process can be accelerated by abatement policies.

The endogenous parts of *FUND* consist of the atmospheric concentrations of carbon dioxide, methane and nitrous oxide, the global mean temperature, the impact of carbon dioxide emission reductions on the economy and on emissions, and the impact of the damages to the economy and the population caused by climate change.

Methane and nitrous oxide are taken up in the atmosphere, and then geometrically depleted:

(1) $C_t = C_{t-1} + \alpha E_t - \beta\left(C_{t-1} - C_{pre}\right)$

where *C* denotes the concentration, *E* the emissions, *t* the year, and *pre* the pre-industrial concentration. Table 1 lists the parameters for both gases.

The atmospheric concentration of carbon dioxide, measured in parts per million by volume, is derived from a five-box model:

(2a) $Box_{i,t} = \rho_i Box_{i,t} + 0.000471\alpha_i E_t$

where

(2b) $C_t = \sum_{i=1}^{5} \alpha_i Box_{i,t}$

Here α_i denotes the fraction of emissions *E* (in million metric tons of carbon) that is allocated to box *i* (0.13, 0.20, 0.32, 0.25 and 0.10 respectively) and ρ the rate of decay of the boxes (ρ = exp (- 1 / life time). The life times in the boxes are ∞, 363, 74, 17, and 2 years respectively. This model is based on Maier-Reimer and Hasselmann (1987). Its parameters are taken from Hammitt *et al*. (1992). According to this model, 13 per cent of total emissions remain in the atmosphere indefinitely, while 10 per cent are removed within an average time period of two years.

The radiative forcing of carbon dioxide, methane and nitrous oxide is determined based on Shine *et al*. (1990). The global mean temperature *T* is governed by a geometric build-up to its equilibrium (determined by the radiative forcing *RF*), with a half-life of 50 years. In the base case, the global mean temperature rises in equilibrium by 2.5°C for a doubling of carbon dioxide equivalents, so:

(3) $T_t = \left(1 - \frac{1}{50}\right) T_{t-1} + \frac{1}{50} \frac{2.5}{6.3 \ln(2)} RF_t$

Regional temperature follows from multiplying the global mean temperature by a fixed factor, which corresponds to the spatial climate change pattern averaged over 14 GCMs (Mendelsohn *et al*., 2000). The global mean sea level is also geometric, with its equilibrium level determined by the temperature and a half-life of 50 years. Both temperature and sea level are calibrated to correspond to the best guess temperature and sea level for the IS92a scenario of Kattenberg *et al.* (1996).

The climate impact module is based on Tol (2002b,c). The following impact categories of climate change are considered: agriculture, forestry, sea level rise, cardiovascular and respiratory disorders related to cold and heat stress, malaria, dengue fever, schistosomiasis, diarrhea, energy consumption, water resources, and unmanaged ecosystems.

People can die prematurely due to temperature stress or vector-borne diseases, or they can migrate because of sea level rise. Like all impacts of climate change, these effects are monetized. The value of a statistical life is set to be 200 times the annual per capita income. The resulting value of a statistical life lies in the middle of the observed range of values in the literature (cf. Cline, 1992). The value of emigration is set to be 3 times the per capita income (Tol, 1995, 1996), the value of immigration is 40 per cent of the per capita income in the host region (Cline, 1992). Losses of dryland and wetlands due to sea level rise are modeled explicitly. The monetary value of a loss of one square kilometer of dryland was on average $4 million in OECD countries in 1990 (cf. Fankhauser, 1994). Dryland value is assumed to be proportional to GDP per square kilometer. Wetland losses are valued at $2 million per square kilometer on average in the OECD in 1990 (cf. Fankhauser, 1994). The wetland value is assumed to have logistic relation to per capita income. Coastal protection is based on cost-benefit analysis, including the value of additional wetland lost due to the construction of dikes and subsequent coastal squeeze.

Other impact categories, such as agriculture, forestry, energy, water, and ecosystems, are directly expressed in monetary values without an intermediate layer of impacts measured in their 'natural' units (cf. Tol, 2002b).

Climate change related damages can be attributed to either the rate of change (benchmarked at 0.04°C/yr) or the level of change (benchmarked at 1.0°C). Damages from the rate of temperature change slowly fade, reflecting adaptation (cf. Tol, 2002c).

Impacts of climate change on energy consumption, agriculture, and cardiovascular and respiratory diseases explicitly recognize that there is a climatic optimum which is determined by a variety of factors, including plant physiology and the behavior of farmers. Impacts are positive or negative depending on whether the actual climate conditions are moving closer to or away from that optimum climate. Impacts are larger if the initial climate conditions are further away from the optimum climate. The optimum climate is of importance with regard to the potential impacts. The actual impacts lag behind the potential impacts, depending on the speed of adaptation. The impacts of not being fully adapted to new climate conditions are always negative (cf. Tol, 2002c).

The impacts of climate change on coastal zones, forestry, unmanaged ecosystems, water resources, malaria, dengue fever, and schistosomiasis are modeled as simple power functions. Impacts are either negative or positive, and do not change sign (cf. Tol, 2002c).

Vulnerability to climate change changes with population growth, economic growth, and technological progress. Some systems are expected to become more vulnerable, such as water resources (with population growth), heat-related disorders (with urbanization), and ecosystems and health (with higher per capita incomes). Other systems are projected to become less vulnerable, such as energy consumption (with technological progress), agriculture (with economic growth) and vector- and water-borne diseases (with improved health care) (cf. Tol, 2002c).

Carbon dioxide emissions are calculated on the basis of the Kaya identity:

$$(4) \qquad M_{r,t} = \frac{M_{r,t}}{E_{r,t}} \frac{E_{r,t}}{Y_{r,t}} \frac{Y_{r,t}}{P_{r,t}} P_{r,t} =: \psi_{r,t} \varphi_{r,t} Y_{r,t}$$

where M denotes emissions, E denote energy use, Y denotes GPD and P denotes population; t is the index for time, r for region. The carbon intensity of energy use, and the energy intensity of production follow from:

$$(5) \qquad \psi_{r,t} = g^{\psi}_{r,t-1} \psi_{r,t-1} - \alpha \tau^{\psi}_{r,t-1}$$

and

$$(6) \qquad \varphi_{r,t} = g^{\varphi}_{r,t-1} \varphi_{r,t-1} - \alpha \tau^{\varphi}_{r,t-1}$$

where τ is policy intervention and α is a parameter. Policy also affects emissions via

$$(4') \qquad M_{r,t} = \left(\psi_{r,t} - \chi^{\psi}_{r,t}\right)\left(\varphi_{r,t} - \chi^{\varphi}_{r,t}\right) Y_{r,t}$$

$$(7) \qquad \chi^{\psi}_{r,t} = \kappa_{\psi} \chi_{r,t-1} + (1-\alpha) \tau^{\psi}_{r,t-1}$$

and

(8) $\chi^{\varphi}_{r,t} = \kappa_{\varphi}\chi_{r,t-1} + (1-\alpha)\tau^{\varphi}_{r,t-1}$

Thus, the parameter $0<\alpha<1$ governs which part of emission reduction is *permanent* (reducing carbon and energy intensities at all future times) and which part of emission reduction is *temporary* (reducing current energy consumptions and carbon emissions), fading at a rate of $0<\kappa<1$. In the base case, α=0.5, $\kappa_{\psi}=\kappa_{\varphi}$=0.9. Alternatively, one may interpret the difference between permanent and temporary emission reduction as affecting commercial technologies and capital stocks, respectively. The behaviour of the emission reduction module is similar to that of the models of Grubb *et al.* (1995), Ha-Duong *et al.* (1997) and Hasselmann *et al.* (1997). It is a reduced form way of modelling that part of the emission reduction fades away after the policy intervention is reversed, but that another part remains through technological lock-in. Learning effects are described below.

The costs of emission reduction C are given by

(9) $$\frac{C_{r,t}}{Y_{r,t}} = \frac{\beta_{r,t}\tau^2_{r,t}}{H_{r,t}H^g_t}$$

H denotes the stock of knowledge. Equation (9) gives the costs of emission reduction in a particular year for emission reduction in that year. In combination with Equations (5)-(8), emission reduction is cheaper if smeared out over a longer time period. The parameter β follows from

(10) $$\beta_{r,t} = 1.57 - 0.17\sqrt{\frac{M_{r,t}}{Y_{r,t}} - \min_s \frac{M_{s,t}}{Y_{s,t}}}$$

That is, emission reduction is relatively expensive for the region that has the lowest emission intensity.[2] The calibration is such that a 10% emission reduction cut in 2003 would cost 1.57% (1.38%) of GDP of the least (most) carbon-intensive region, and a 80% (85%) emission reduction would completely ruin its economy; later emission reductions are cheaper by Equations (10) and (11). Emission reduction is relatively cheap for regions with high emission intensities. The thought is that emission reduction is cheap in countries that use a lot of energy and rely heavily on fossil fuels, while other countries use less energy and less fossil fuels and are therefore closer to the technological frontier of emission abatement.[3] The model has been calibrated to the results reported in Hourcade *et al.* (1996); for relatively small emission reduction, the costs in *FUND* correspond closely to those reported by other top-down models, but for higher emission reduction, *FUND* finds higher costs, because *FUND* does not include backstop technologies, that is, a carbon-free energy supply that is available in unlimited quantities at fixed average costs.

The regional and global knowledge stocks follow from

(11) $$H_{r,t} = H_{r,t-1}\sqrt{1+\gamma_R\tau_{r,t-1}}$$

and

(12) $$H^G_t = H^G_{t-1}\sqrt{1+\gamma_G\tau_{r,t}}$$

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[2] The model disregards potential advantages of leading in technology, e.g., through exports and patents.

[3] Note that “cheap” should read “cheap per unit of emission reduction”; the total costs of emission reduction, of course, depend on the costs per unit as well as the total emission reduction obligation. The USA (EU) has high (low) costs under the Kyoto Protocol not because its emission reduction is expensive (cheap) but because its emission reduction target is high (low).

Knowledge accumulates with emission abatement. More knowledge implies lower emission reduction costs. Equations (9) and (11) together constitute learning by doing. The parameters γ determines which part of the knowledge is kept within the region, and which part spills over to other regions as well. In the base case, γ_R=0.9 and γ_G=0.1. The model is similar in structure and numbers to that of Goulder and Schneider (1999) and Goulder and Mathai (2000). Note that, although there is learning by doing – Equations (11) and (12) – technology diffusion – Equation (10) – as well as permanent effects of emission reduction on the growth path of the economy – Equations (7) and (8) – the model does assume that policy interventions are always costly, and that larger interventions are more costly.

The costs of methane and nitrous oxide emission reduction are based on the analysis of the USEPA (2003). They report supply curves of emission reduction, stating how much can be abatement at a certain price. First, these supply curves were shifted to exclude negative costs. Note that this increases costs. Second, emission reductions were expressed as fractions of baseline emissions. Third, total emission reduction costs (the area under the supply curve) was calculated, and expressed as a fraction of GDP. Fourth, the regional results of the EPA analysis was attributed to the *FUND* regions. Fifth, the bottom-up curve was approximated with a smooth exponential function. Sixth, the exponential curve was approximated with a quadratic curve. Note that this decreases costs. Table 2 shows the parameters for methane, Table 3 for nitrous oxide. Initially, the quadratic cost curve was supposed to function as sensitivity analysis. However, the quadratic cost curve has the advantage that both costs and marginal costs are zero at zero emission reduction. The exponential cost curve has total costs equal to zero at zero emission reduction, but marginal costs are greater than zero. This implies that, for a low carbon price, methane and nitrous oxide emission reduction are zero, while carbon dioxide emission reduction is not. On the other hand, large emission reduction is cheaper with the quadratic specification than with the exponential one. Nonetheless, we prefer the quadratic specification over the exponential one.

Another change in the model is the addition of sulphur dioxide (SO_2) emissions and sulphate aerosols concentrations. SO2 emissions are calibrated to the IMAGE 2.2 model (IMAGE Team, 2001). SO2 emissions are proportional to the amount of fossil fuel used and fall with per capita income, using an income elasticity of 0.45. Direct radiative forcing of sulphate aerosols is assumed to be linear in SO2 emissions. Indirect radiative forcing is assumed to be logarithmic in emissions. The exact specification is

$$RF(SO_2) = \frac{0.3}{14.6} SO_2 + 0.8 \frac{\ln\left(1 + SO_2/34.4\right)}{\ln\left(1 + 14.6/34.4\right)} \qquad \text{(x)}$$

where 14.6 TgS are the anthropogenic emissions in 1950 and 34.4 TgS are the natural emissions, which are kept constant. The climate module is recalibrated so that the global mean temperature in the period 1950-2000 roughly matches observations.

3. Results

3.1. Emission reduction with 1, 2 and 3 gases

The central policy scenario aims to keep additional radiative forcing below 4.5 Wm^{-2}. We compare the result if this goal is met with only carbon dioxide emission reduction, with all three greenhouse gases, and with CO_2 plus one of the others. Figure 1 shows the atmospheric concentrations of carbon dioxide in case with CO_2 only and with the three gases; Figure 1 also includes the business as usual scenario. As expected, with the other two gases added, the cuts in CO_2 emissions are less; however, the difference is not that large, as the target of 4.5 Wm^{-2} is fairly strict. Figure 2 shows the atmospheric concentrations of methane. Concentrations would be cut substantially, particularly towards the end of the century, and even more so if nitrous oxide emission reduction is excluded. Figure 3 shows the atmospheric concentrations of nitrous oxide. Compared to methane, emission reduction is spread more smoothly over the century, while the omission of methane emission reduction has little effect.

Figure 4 shows the net present value of the loss of consumption due to emission reduction in the OECD, Eastern Europe and the former Soviet Union, and developing countries. With all three gases, meeting the target of 4.5 Wm^{-2} would cost \$32.9 trillion. This number is so high because the target is so strict. With CO_2 emission reduction only, the costs would rise to \$44.6 trillion. Methane and nitrous oxide emission reduction thus reduce costs by some 26%, substantially less than reported elsewhere (see Section 1). Most of the cost saving is due to nitrous oxide. Without N_2O, the costs would be \$41.4 trillion. Without CH_4, the costs would be \$33.3 trillion.

Figure 5 shows the consumption losses over time, which reach about 9% in 2100 with all three gases and exceed 10% with CO_2 only; a 10% loss of consumption from baseline in a century represents a loss of 5 years of growth. Figure 5 also shows the cost savings due to the other greenhouse gases. In the earlier years, cost savings exceed 50% but this falls to 15% by 2100. The reason is that methane and nitrous oxide emission reductions are cheap compared to carbon dioxide emission reduction, but are only limited in scope: substantial greenhouse gas emission reduction requires substantial carbon dioxide emission reduction. The cost savings in the earlier years correspond much better to the previous literature.

3.2. Sulphur dioxide

Sulphur dioxide was not considered in previous versions of the *FUND* model, but it is in this one. Sulphur dioxide emissions are turned into sulphate aerosols which have only a short life time in the atmosphere, but have a substantial cooling effect nonetheless. Sulphur dioxide originates from fossil fuel burning, just like carbon dioxide does. Sulphur dioxide emissions would fall with carbon dioxide emissions, which may imply additional warming in the short run. Sulphur dioxide thus partly offsets carbon dioxide emission reduction, and would make radiative forcing targets harder to achieve.

Figure 6 shows the atmospheric concentrations of carbon dioxide for a policy aiming at a stabilisation at 4.5 Wm^{-2}, with and without CH_4 and N_2O, and with and without SO_2. In all four cases, emissions are drastically cut because the target is stringent. With CO_2 only, the extra emission reduction due to SO_2 is smaller than with all three greenhouse gases. This is because, without CH_4 and N_2O, CO_2 and hence SO_2 emissions are lower. Without SO_2, the gap between CO_2 only and 3G is larger than with SO_2. This is because, as the target gets stricter (and it does so, albeit implicitly, by considering SO_2), CH_4 and N_2O emission reduction reach their technical potential earlier and more of the burden is shifted to CO_2. Figure 7 shows the net present value of the consumption losses. Without SO_2, costs would be \$28.2 (23.1) trillion less with all three gases (CO_2 only).

3.3. Alternative cost functions

In Section 2, the reasons for preferring a quadratic cost function over an exponential one are presented. Here, I show the result for an exponential cost curve. Tables 2 and 3 show the parameters. The main differences are that, with an exponential cost curve, the marginal costs of emission reduction are greater than nought at zero emission reduction, and that drastic emission reduction is more expensive. As a result, greenhouse gas emission reduction is more expensive in the early decades as well as in the later decades, but may be cheaper in between.

Figure 2 (methane) and Figure 3 (nitrous oxide) indeed show that the other gases are less reduced with an exponential cost function. As a result, emission reduction costs, as measured by the net present value of consumption loss, go up. As shown in Figure 7, costs increase by $4.8 trillion.

3.4. Trade-offs between gases

Above, all trade-offs between the three greenhouse gases is based on the 100-year global warming potentials (GWPs) published by the IPCC; see Table 1. This is the set of equivalences accepted by the UNFCCC, but it is now widely acknowledged that GWPs have limited validity in the natural sciences (Smith and Wigley, 2000a,b), and no validity in economics or policy (Reilly and Richards, 1993; Schmalensee, 1993; Kandlikar, 1995, 1996; Hammitt *et al.*, 1996; Lashof, 2000; O'Neill, 2000; Manne and Richels, 2001; Godal and Fuglestvedt, 2002; Sygna *et al.*, 2002). In a cost-benefit analysis, the proper equivalence between CO_2 and, say, CH_4 is the ratio of the marginal damage costs. In a cost-effectiveness analysis (as is done here), the proper equivalence is the ratio of the shadow prices. With a radiative forcing target, alternative greenhouse gas share the same shadow price of the constraint, and the ratio is determined by the relative contribution to radiative forcing in the binding period. This particularly affects methane, which has a life-time that is much shorter than that of nitrous oxide and carbon dioxide. If the target is relatively far into the future, current methane emission reduction contributes much less than does carbon dioxide and nitrous oxide emission reduction.

With a target of 4.5 Wm^{-2}, the turning point lies around 2070. The dynamics of the baseline scenario and emission abatement are such that, if radiative forcing is below 4.5 Wm^{-2} in 2070, it is below that target for the entire period. Therefore, emissions of the three gases are compared as to their contribution to radiative forcing in 2070 following the gas dynamics and radiative forcing as specified in *FUND*. Emissions after 2070 are treated as emissions in the period 2060-2070.

Figures 2 (methane) and 3 (nitrous oxide) show the results. As expected, methane emission reduction is less in the first decades but more in the later years. This allows for a slight reduction in abatement of carbon dioxide (results not shown) and nitrous oxide (see Figure 3). As a consequence, emission reduction costs fall. See Figure 7. However, the reduction in costs is only $0.1 trillion. This is again due to the stringent target, which necessitates deep cuts in carbon dioxide (and nitrous oxide) emissions regardless of the cuts in methane emissions.

3.5. The choice of target

In the scenarios above, the radiative forcing target is 4.5 Wm^{-2}. This is a fairly ambitious target, as can be seen from the low CO_2 concentrations and the high costs. It roughly corresponds to the EU target of letting the global mean temperature not rise more than 2°C above today's temperatures. The justification for this target is very weak. It is based on the argument that this is the maximum temperature that the human species has experienced in its existence. However, subsidies to agriculture are also at its historical peak, as are democracy and communication technology, and the EU does not seem to object to that. I therefore vary the target.

Figure 8 shows the atmospheric concentration of carbon dioxide for radiative forcing targets of 4.0, 4.5, 5.5, 6.5 and 7.5 Wm^{-2}. The 4.0 Wm^{-2} target is used rather than a 3.5 Wm^{-2} target because the latter cannot be achieved. This is another indication that the 4.5 Wm^{-2} is very ambitious. Figure 8 also depicts the business as usual scenario, and an optimal control scenario. In the optimal control scenario, the target is not a random number but based on considerations of welfare maximisation. Based on a meta-analysis of 28 studies, Tol (forthcoming) estimates that the current Pigou tax on carbon dioxide emissions should be $7/tC. This is the carbon tax used in 2010; the carbon tax increase by 5% per year after that. Under this scenario, radiative forcing reaches 7.5 Wm^{-2} in 2200, but peaks at 8.8 Wm^{-2} in 2130.

Figure 9 shows the net present value of the consumption losses. For the 4.5 Wm^{-2} target, costs are a hefty $33 trillion; for the 4.0 Wm^{-2} target, this goes up to a staggering $75 trillion. For 7.5 Wm^{-2}, costs fall to $5 trillion, while the optimal policy costs only $2 trillion. If the EU policy target is adopted, $31 trillion would be overspent.

Figure 9 also shows the net present value of the consumption losses for the same targets with carbon dioxide emission reduction only. Costs increase substantially in all cases.[4] The cost savings due to methane and nitrous oxide emission abatement change with the stringency of the target, but not monotonously so. If the target is very strict, meeting it with CO_2 only is almost impossible. If the target is somewhat less strict, the role of CH_4 and N_2O falls. However, if the target gets looser still, CH_4 and N_2O emission abatement options get saturated less quickly, and these gases increase in importance again. Finally, if the target gets even looser, CH_4 and N_2O become less important, because the need to drive CO_2 emissions to zero in the long term becomes the dominant effect. It can be expected that the relative importance of CH_4 and N_2O depends strongly on model and baseline scenario as well.

5. Discussion and conclusion

The following results emerge from the analyses above. First, how flexibility matters. It can help reducing the costs of greenhouse gas emission reduction by between 26 and 43% depending on the long-term abatement target. However, if the abatement target is stringent, methane and nitrous oxide emission reduction can only offset carbon dioxide emissions by so much. In fact, if the aim is to stabilise atmospheric stabilisation, then net emissions of carbon dioxide need to be reduced to (almost) zero, regardless of methane and nitrous oxide.

Second, nitrous oxide is more important than is methane. As a corollary, the discussion about the appropriate exchange rate between greenhouse gases is a fairly academic one, as alternative global warming potentials differ substantially for methane but much less for nitrous oxide.

Third, sulphate aerosols matter. Sulphate aerosols make climate policy substantially harder. Sulphate aerosols also make that radiative forcing, rather than concentrations, is the appropriate aim for climate policy.

The results in this paper should be interpreted with the usual caution. *FUND* is a fairly aggregate model, so that emissions from methane and nitrous oxide are not really tied to economic activity. This also hampers CH_4 and N_2O emission reduction. Emission reduction costs are static, reflecting neither technological change nor changes in economic structure. The current analysis neglects that carbon dioxide emission reduction is represented in the model as a mix of end-of-pipe and structural measures (so that, should policy stop, emissions

[4] except the for “optimal” carbon tax; in this case, the costs of carbon dioxide emission reduction are the same, but the costs for methane and nitrous oxide emission reduction are zero in one case and positive in the other

would not bounce back to the business as usual scenario) while methane and nitrous oxide measures are end-of-pipe only (so that emissions would bounce back). The climate module of *FUND* is fairly simple, perhaps distorting the trade-offs between the greenhouse gases.

Although a lot of research remains to be done, two conclusions are likely to be robust. First, methane and particularly nitrous oxide emission reduction are options to limit the total costs of greenhouse gas emission reduction and so increase the political feasibility of climate policy. Second, methane and nitrous oxide emission reductions offset only a part of carbon dioxide emission reduction.

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References

Aaheim, A., Fuglestvedt, J. S., & Godal, O. 2004, *Costs Savings of a Flexible Multi-Gas Climate Policy*, CICERO, Oslo, Norway, Working Paper 2004:03.

AEAT (1998a), *Options to Reduce Methane Emissions,* Commission of the European Communities Directorate-General Environment, Brussels (http://europa.eu.int/comm/environment/enveco/climate_change/methane_emissions.pfd)

AEAT (1998b), *Options to Reduce Nitrous Oxide Emissions,* Commission of the European Communities Directorate-General Environment, Brussels, http://europa.eu.int/comm/environment/enveco/climate_change/nitrous_oxide_emissions.pfd

Bates, J. & Haworth, A. 2000, *Economic Evaluation of Emission Reductions of Methane in the Waste Sector in the EU*, AEA Technology Environment, Abingdon, U.K..

Batjes, J. J. & Goldewijk, C. G. M. 1994, *The IMAGE 2 Hundred Year (1890-1990) Database of the Global Environment (HYDE)*, RIVM, Bilthoven, 410100082.

Cline, W. R. (1992), *The Economics of Global Warming* Institute for International Economics, Washington, D.C.

de Jager, D. & Blok, K. 1993, *Cost-Effectiveness of Emission Reducing Measures for Methane in the Netherlands*, Ecofys Research and Consultancy, Utrecht.

de Jager, D., Blok, K., & van Brummelen, M. 1996, *Cost-effectiveness of emission-reducing measures for nitrous oxide in the Netherlands*, ECOFYS, Utrecht, M704.

de Jager, D., Oonk, J., van Brummelen, M., & Blok, K. 1996, *Emissions of methane by the oil and gas system*, ECOFYS, Utrecht, M 707.

Fankhauser, S. (1994), 'Protection vs. Retreat -- The Economic Costs of Sea Level Rise', *Environment and Planning A*, **27**, 299-319.

Godal, O. and Fuglestvedt, J. (2002), 'Testing 100-year global warming potentials: Impacts on compliance costs and abatement profile', *Climatic Change*, **52**, 93-127.

Goulder, L. H. and Schneider, S. H. (1999), 'Induced technological change and the attractiveness of CO_2 abatement policies', *Resource and Energy Economics*, **21**, 211-253.

Goulder, L. H. and Mathai, K. (2000), 'Optimal CO_2 Abatement in the Presence of Induced Technological Change', *Journal of Environmental Economics and Management*, **39**, 1-38.

Grubb, M. J., Ha-Duong, M., and Chapuis, T. (1995), 'The Economics of Changing Course', *Energy Policy*, **23** (4/5), 417-432.

Ha-Duong, M., Grubb, M. J., and Hourcade, J.-C. (1997), 'Influence of Socioeconomic Inertia and Uncertainty on Optimal CO_2 -Emission Abatement', *Nature*, **389**, 270-273.

Hammitt, J. K., Lempert, R. J., and Schlesinger, M. E. (1992), 'A Sequential-Decision Strategy for Abating Climate Change', *Nature*, **357**, 315-318.

Hammitt, J. K., Jain, A. K., Adams, J. L., and Wuebbles, D. J. (1996), 'A Welfare-Based Index for Assessing Environmental Effects of Greenhouse-Gas Emissions', *Nature*, **381**, 301-303.

Hasselmann, K., Hasselmann, S., Giering, R., Ocana, V., and von Stoch, H. (1997), 'Sensitivity Study of Optimal CO_2 Emission Paths Using a Simplified Structural Integrated Assessment Model (SIAM)', *Climatic Change*, **37**, 345-386.

Hogan, K. B. (eds.) 1993, *Opportunities to Reduce Anthropogenic Methane Emissions in the United States*, U.S. Environmental Protection Agency, Washington, D.C., EPA 430-R-93-012.

Hogan, K. B. (eds.) 1993, *Options for Reducing Methane Emissions Internationally -- Volume I: Technological Options for Reducing Methane Emissions*, U.S. Environmental Protection Agency, Washington, D.C., EPA 430-R-93-006.

Hogan, K. B. (eds.) 1993, *Options for Reducing Methane Emissions Internationally -- Volume II: International Opportunities for Reducing Methane Emissions*, U.S. Environmental Protection Agency, Washington, D.C., EPA 430-R-93-006 B.

Hourcade, J.-C., Halsneas, K., Jaccard, M., Montgomery, W. D., Richels, R. G., Robinson, J., Shukla, P. R., & Sturm, P. (1996), "A Review of Mitigation Cost Studies," in *Climate Change 1995: Economic and Social Dimensions -- Contribution of Working Group III to the Second Assessment Report of the Intergovernmental Panel on Climate Change*, J. P. Bruce, H. Lee, & E. F. Haites, eds. (eds.), Cambridge University Press, Cambridge, pp. 297-366.

Hourcade, J.-C., Richels, R. G., Robinson, J., Chandler, W., Davidson, O., Finon, D., Grubb, M. J., Halsneas, K., Hogan, K., Jaccard, M., Krause, F., la Rovere, E., Montgomery, W. D., Nastari, P., Pegov, A., Richards, K., Schrattenholzer, L., Siniscalco, D., Shukla, P. R., Sokona, Y., Sturm, P., & Tudini, A. (1996), "Estimating the Costs of Mitigating Greenhouse Gases," in *Climate Change 1995: Economic and Social Dimensions -- Contribution of Working Group III to the Second Assessment Report of the Intergovernmental Panel on*

Climate Change, J. P. Bruce, H. Lee, & E. F. Haites, eds. (eds.), Cambridge University Press, Cambridge, pp. 263-296.

IEA GHG (1998), *Abatement of Methane Emissions*, International Energy Agency Greenhouse Gas R&D Programme, Cheltenham http://www.ieagreen.org.uk

IMAGE Team (2001), *The IMAGE 2.2 Implementation of the SRES Scenarios*, CD-ROM Publication 48108018, RIVM, Bilthoven.

Jensen, J. & Thelle, M. H. 2001, *What are the Gains from a Multi-Gas Strategy?*, Fondazione Eni Enrico Mattei, Milano, Italy, 84.2001.

Kandlikar, M. (1996), 'Indices for Comparing Greenhouse Gas Emissions: Integrating Science and Economics', *Energy Economics*, **18**, 265-281.

Kandlikar, M. (1995), 'The Relative Role of Trace Gas Emissions in Greenhouse Abatement Policies', *Energy Policy*, **23** (10), 879-883.

Kattenberg, A., Giorgi, F., Grassl, H., Meehl, G. A., Mitchell, J. F. B., Stouffer, R. J., Tokioka, T., Weaver, A. J., & Wigley, T. M. L. (1996), "Climate Models - Projections of Future Climate," in *Climate Change 1995: The Science of Climate Change -- Contribution of Working Group I to the Second Assessment Report of the Intergovernmental Panel on Climate Change*, 1 edn, J. T. Houghton et al., eds. (eds.), Cambridge University Press, Cambridge, pp. 285-357.

Kroeze, C. 1994, *Nitrous Oxide (N_2O) - emission inventory and options for control in the Netherlands*, National Institute of Public Health and Environmental Protection, Bilthoven, NL, 773001004.

Kruger, D., Dastin-Van Rijn, M., & Harvey, R.Gibbs, M. J. (eds.) 1998, *Costs of Reducing Methane Emissions in the United States*, Environmental Policy Agency, Washington, D.C..

Lashof, D. A. (2000), 'The use of global warming potentials in the Kyoto Protocol', *Climatic Change*, **44**, 423-425.

Leggett, J., Pepper, W. J., & Swart, R. J. (1992), "Emissions Scenarios for the IPCC: An Update," in *Climate Change 1992 - The Supplementary Report to the IPCC Scientific Assessment*, 1 edn, vol. 1 J. T. Houghton, B. A. Callander, & S. K. Varney, eds. (eds.), Cambridge University Press, Cambridge, pp. 71-95.

Maier-Reimer, E. and Hasselmann, K. (1987), 'Transport and Storage of Carbon Dioxide in the Ocean: An Inorganic Ocean Circulation Carbon Cycle Model', *Climate Dynamics*, **2**, 63-90.

Manne, A. S. and Richels, R. G. (2001), 'An alternative approach to establishing trade-offs among greenhouse gases', *Nature*, **410**, 675-677.

Manne, A.S. and R.G. Richels (2000), *A Multi-Gas Approach to Climate Policy – With and Without GWPs*, unpublished, http://www.stanford.edu/group/MERGE/multigas.pdf

O'Neill, B. C. (2000), 'The jury is still out on global warming potentials', *Climatic Change*, **44**, 427-443.

Reilly, J., Prinn, R., Harnisch, J., itzmaurice, J., Jacoby, H., Kicklighter, D. W., Melillo, J. M., Stone, P., Sokolov, A., and ng, C. (1999), 'Multi-gas assessment of the Kyoto Protocol', *Nature*, **401**, 549-555.

Reilly, J. M. and Richards, K. R. (1993), 'Climate Change Damage and the Trace Gas Index Issue', *Environmental and Resource Economics*, **3**, 41-61.

Schmalensee, R. (1993), 'Comparing Greenhouse Gases for Policy Purposes', *Energy Journal*, **14**, 245-255.

Shine, K. P., Derwent, R. G., Wuebbles, D. J., & Morcrette, J.-J. (1990), "Radiative Forcing of Climate," in *Climate Change - The IPCC Scientific Assessment*, 1 edn, vol. 1 J. T. Houghton, G. J. Jenkins, & J. J. Ephraums, eds. (eds.), Cambridge University Press, Cambridge, pp. 41-68.

Smith, S. J. and Wigley, T. M. L. (2000), 'Global Warming Potentials: 2. Accuracy', *Climatic Change*, **44**, 459-469.

Smith, S. J. and Wigley, T. M. L. (2000), 'Global Warming Potentials: 1. Climatic Implications of Emissions Reductions', *Climatic Change*, **44**, 445-457.

Sygna, L., Fuglestvedt, J. S., and Aaheim, H. A. (2002), 'The adequacy of GWPS as indicators of damage costs incurred by global warming', *Mitigation and Adaptation Strategies for Global Change*, **7**, 45-62.

Tol, R. S. J. (2001), 'Equitable Cost-Benefit Analysis of Climate Change', *Ecological Economics*, **36** (1), 71-85.

Tol, R. S. J. (2002), 'Estimates of the Damage Costs of Climate Change - Part 1: Benchmark Estimates', *Environmental and Resource Economics*, **21**, 47-73.

Tol, R. S. J. (2002), 'Estimates of the Damage Costs of Climate Change - Part II: Dynamic Estimates', *Environmental and Resource Economics*, **21**, 135-160.

Tol, R. S. J. (2003), 'Is the uncertainty about climate change too large for expected cost-benefit analysis?', *Climatic Change*, **56**, 265-289.

Tol, R. S. J. (1999), 'Kyoto, Efficiency, and Cost-Effectiveness: Applications of FUND', *Energy Journal Special Issue on the Costs of the Kyoto Protocol: A Multi-Model Evaluation*, 130-156.

Tol, R. S. J., Heintz, R. J., and Lammers, P. E. M. (2003), 'Methane emission reduction: An application of FUND', *Climatic Change*, **57**, 71-98.

Tol, R. S. J. and Fankhauser, S. (1998), 'On the Representation of Impact in Integrated Assessment Models of Climate Change', *Environmental Modeling and Assessment*, **3**, 63-74.

Tol, R. S. J. (1999), 'Safe Policies in an Uncertain Climate: An Application of FUND', *Global Environmental Change*, **9**, 221-232.

Tol, R. S. J. (1999), 'Spatial and Temporal Efficiency in Climate Change: Applications of FUND', *Environmental and Resource Economics*, **14** (1), 33-49.

Tol, R. S. J. and Verheyen, R. (2004), 'State responsibility and compensation for climate change damages - a legal and economic assessment', *Energy Policy*, **32**, 1109-1130.

Tol, R. S. J. (1995), 'The Damage Costs of Climate Change Toward More Comprehensive Calculations', *Environmental and Resource Economics*, **5**, 353-374.

Tol, R. S. J. (1996), 'The Damage Costs of Climate Change Towards a Dynamic Representation', *Ecological Economics*, **19**, 67-90.

Tol, R. S. J. (1999), 'The Marginal Costs of Greenhouse Gas Emissions', *Energy Journal*, **20** (1), 61-81.

Tol, R. S. J. (1999), 'Time Discounting and Optimal Control of Climate Change -- An Application of *FUND*', *Climatic Change*, **41** (3-4), 351-362.

Tol, R. S. J. and Dowlatabadi, H. (2001), 'Vector-borne diseases, development & climate change', *Integrated Assessment*, **2**, 173-181.

Tol, R. S. J. (2002), 'Welfare specifications and optimal control of climate change: an application of fund', *Energy Economics*, **24**, 367-376.

US EPA (1999), *U.S. Methane Emissions 1990-2020: Inventories, Projections, and Opportunities for Reductions*, U.S. Environmental Protection Agency, Washington, D.C., EPA 430-R-99-013.

US EPA (2003), *International Analysis of Methane and Nitrous Oxide Abatement Opportunities: Report to Energy Modeling Forum, Working Group 21*, United States Environment Protection Agency, Washington, D.C. http://www.epa.gov/ghginfo/reports/methodologych4.pdf

van Amstel, A. R. (eds.) 1993, *Methane and Nitrous Oxide -- Methods in National Emissions Inventories and Options for Control*, RIVM, Bilthoven.

van Amstel, A. R., Swart, R. J., Krol, M. S., Beck, J. P., Bouwman, A. F., & van der Hoek, K. W. 1993, *Methane, The other greenhouse gas - research and policy in the Netherlands*, National Institute of Public Health and Environmental Protection, Bilthoven, NL, 481507001.

van Ham, J., Baede, A. P. M., Meyer, L. A., and Ybema, R. (eds.)(2002), *Non-*CO^2 *Greenhouse Gases: Scientific Understanding, Control and Implementation* Kluwer Academic Publishers, Dordrecht.

van Ham, J., Janssen, L. H. J. M., and Swart, R. J. (eds.)(1994), *Non-*CO_2 *Greenhouse Gases: Why and How to Control? -- Proceedings of an International Symposium, Maastricht, The Netherlands, 13-15 December 1993* Kluwer Academic Publishers, Dordrecht.

Table 1. Parameters of equation (1) (based on Schimel *et al*., 1996)

gas	α[a]	β[b]	pre-industrial concentration	GWP
methane (CH_4)	0.3597	1/8.6	790 ppbv	21
Nitrous oxide (N_2O)	0.2079	1/120	285 ppbv	310

[a] The parameter α translates emissions in millions of metric tons of CH_4 or N_2O into concentrations in parts per billion by volume.

[b] The parameter β determines how fast concentrations return to their pre-industrial (and assumed equilibrium) concentrations; the reciprocal of β is the atmospheric life time of the gases in years.

Table 2. Parameters of the methane emission reduction cost curve.

	Quadratic			Exponential - constant			Exponential - exponent		
USA	5.74E-04	(4.15E-04	7.90E-04)	5.43E-06	(4.44E-06	6.64E-06)	10.28	(9.66	10.90)
CAN	1.20E-03	(8.70E-04	1.64E-03)	7.69E-06	(6.30E-06	9.37E-06)	12.49	(11.75	13.23)
WEU	3.71E-04	(2.34E-04	5.80E-04)	1.82E-06	(1.37E-06	2.43E-06)	14.27	(13.10	15.45)
JPK	1.27E-04	(8.75E-05	1.84E-04)	4.19E-07	(3.32E-07	5.29E-07)	17.43	(16.23	18.63)
ANZ	4.12E-03	(3.03E-03	5.57E-03)	1.25E-05	(1.03E-05	1.51E-05)	18.18	(17.14	19.21)
EEU	3.90E-03	(2.81E-03	5.38E-03)	3.13E-05	(2.56E-05	3.83E-05)	11.17	(10.49	11.85)
FSU	8.87E-03	(7.49E-03	1.05E-02)	8.51E-05	(7.65E-05	9.46E-05)	10.21	(9.89	10.52)
MDE	6.32E-03	(4.86E-03	8.19E-03)	1.26E-05	(1.07E-05	1.49E-05)	22.38	(21.29	23.47)
CAM	3.65E-03	(2.87E-03	4.62E-03)	1.30E-05	(1.12E-05	1.51E-05)	16.77	(16.03	17.52)
SAM	2.75E-02	(1.81E-02	4.14E-02)	4.07E-06	(3.14E-06	5.27E-06)	82.24	(75.89	88.58)
SAS	3.16E-02	(2.43E-02	4.08E-02)	2.51E-05	(2.13E-05	2.95E-05)	35.45	(33.74	37.16)
SEA	1.43E-02	(1.06E-02	1.91E-02)	1.94E-05	(1.62E-05	2.33E-05)	27.15	(25.66	28.65)
CHI	1.26E-02	(9.50E-03	1.67E-02)	3.18E-05	(2.67E-05	3.80E-05)	19.93	(18.88	20.97)
MAF	1.43E-02	(1.06E-02	1.91E-02)	1.94E-05	(1.62E-05	2.33E-05)	27.15	(25.66	28.65)
SSA	1.43E-02	(1.06E-02	1.91E-02)	1.94E-05	(1.62E-05	2.33E-05)	27.15	(25.66	28.65)
SIS	1.43E-02	(1.06E-02	1.91E-02)	1.94E-05	(1.62E-05	2.33E-05)	27.15	(25.66	28.65)

Table 3. Parameters of the nitrous oxide emission reduction cost curve.

	Quadratic	Exponential - constant	Exponential - exponent
USA	2.14E-05 (1.91E-05 2.39E-05)	1.36E-08 (1.29E-08 1.45E-08)	39.61 (38.56 40.65)
CAN	6.92E-05 (6.29E-05 7.60E-05)	1.62E-08 (1.54E-08 1.70E-08)	65.33 (63.88 66.78)
WEU	7.26E-06 (6.60E-06 7.98E-06)	1.97E-08 (1.88E-08 2.08E-08)	19.18 (18.75 19.60)
JPK	5.32E-07 (3.21E-07 8.57E-07)	9.54E-09 (7.38E-09 1.23E-08)	7.46 (6.60 8.33)
ANZ	2.08E-04 (1.89E-04 2.29E-04)	4.62E-09 (4.39E-09 4.86E-09)	212.40 (207.68 217.11)
EEU	9.39E-05 (8.89E-05 9.93E-05)	8.35E-08 (7.91E-08 8.83E-08)	33.53 (33.53 33.53)
FSU	1.05E-05 (1.00E-05 1.10E-05)	1.94E-08 (1.91E-08 1.98E-08)	23.25 (22.91 23.60)
MDE	1.05E-05 (1.00E-05 1.10E-05)	1.94E-08 (1.91E-08 1.98E-08)	23.25 (22.91 23.60)
CAM	2.35E-04 (2.19E-04 2.53E-04)	2.00E-08 (1.89E-08 2.13E-08)	108.39 (107.83 108.95)
SAM	1.05E-05 (1.00E-05 1.10E-05)	1.94E-08 (1.91E-08 1.98E-08)	23.25 (22.91 23.60)
SAS	5.64E-04 (5.29E-04 6.01E-04)	1.71E-07 (1.62E-07 1.80E-07)	57.44 (57.14 57.74)
SEA	2.55E-15 (2.16E-15 3.01E-15)	4.72E-18 (4.12E-18 5.40E-18)	23.25 (22.91 23.60)
CHI	2.16E-05 (2.02E-05 2.30E-05)	1.42E-07 (1.35E-07 1.50E-07)	12.32 (12.26 12.39)
MAF	1.05E-05 (1.00E-05 1.10E-05)	1.94E-08 (1.91E-08 1.98E-08)	23.25 (22.91 23.60)
SSA	1.05E-05 (1.00E-05 1.10E-05)	1.94E-08 (1.91E-08 1.98E-08)	23.25 (22.91 23.60)
SIS	1.05E-05 (1.00E-05 1.10E-05)	1.94E-08 (1.91E-08 1.98E-08)	23.25 (22.91 23.60)

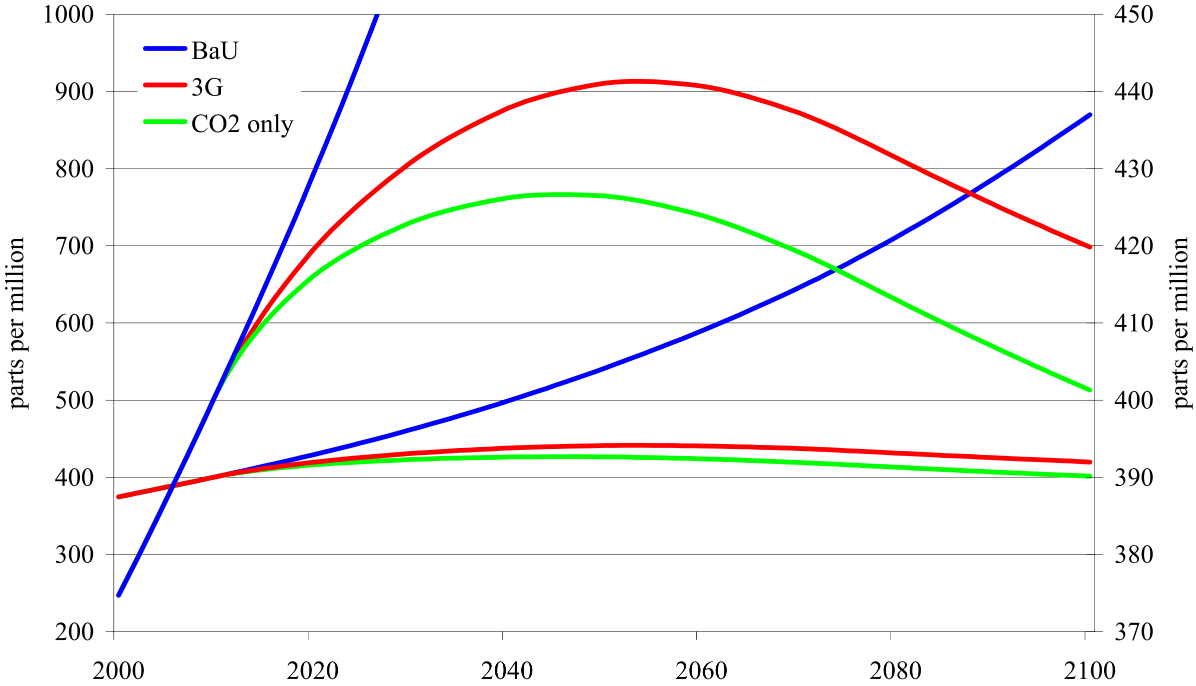

Figure 1. The atmospheric concentration of carbon dioxide for the business as usual scenario and two scenarios keeping anthropogenic radiative forcing below 4.5 Wm^{-2}, one with only CO_2 emission reduction, and one with CO_2, CH_4 and N_2O emission reduction (3G). The scenario on the left and right axis are identical, but displayed at a different scale.

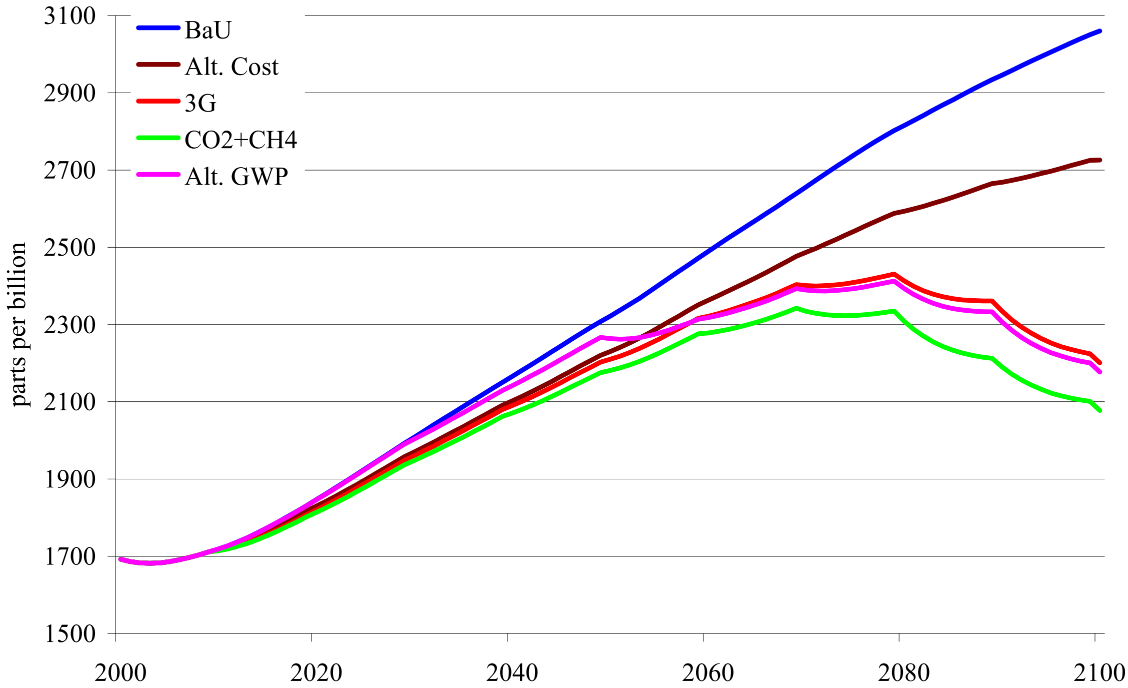

Figure 2. The atmospheric concentration of methane for the business as usual scenario and four scenarios keeping anthropogenic radiative forcing below 4.5 Wm^{-2}; one with only CO_2 and CH_4 emission reduction, and three with CO_2, CH_4 and N_2O emission reduction (3G, Alt. Cost, Alt. GWP). The “Alt. Cost” scenario uses exponential cost curves for methane and nitrous oxide rather than quadratic ones; the “Alt. GWP” scenario uses the actual contribution to radiative forcing in 2070 rather than the IPCC 100-year GWPs.

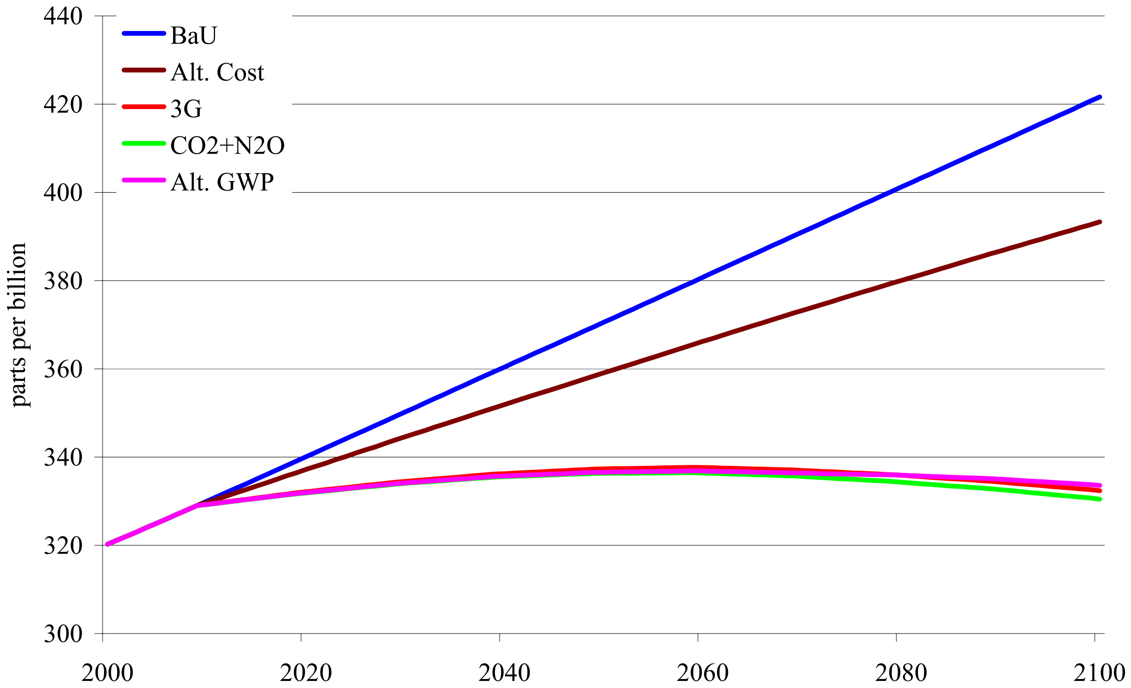

Figure 3. The atmospheric concentration of nitrous oxide for the business as usual scenario and four scenarios keeping anthropogenic radiative forcing below 4.5 Wm^{-2}; one with only CO_2 and N_2O emission reduction, and three with CO_2, CH_4 and N_2O emission reduction (3G, Alt. Cost, Alt. GWP). The "Alt. Cost" scenario uses exponential cost curves for methane and nitrous oxide rather than quadratic ones; the "Alt. GWP" scenario uses the actual contribution to radiative forcing in 2070 rather than the IPCC 100-year GWPs.

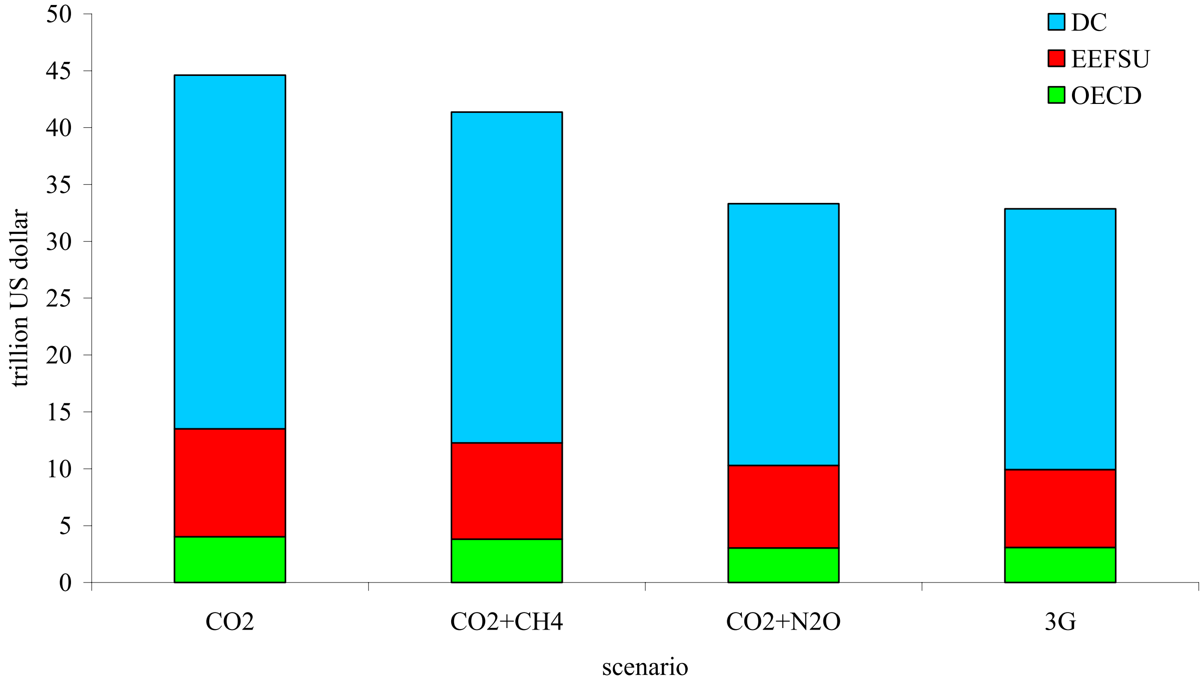

Figure 4. The net present value of consumption losses due to alternative policies to keep anthropogenic radiative forcing below 4.5 Wm^{-2}, viz. only CO_2 emission reduction, CO_2 and CH_4 emission reduction, CO_2 and N_2O emission reduction, and emission reduction with all three gases (3G).

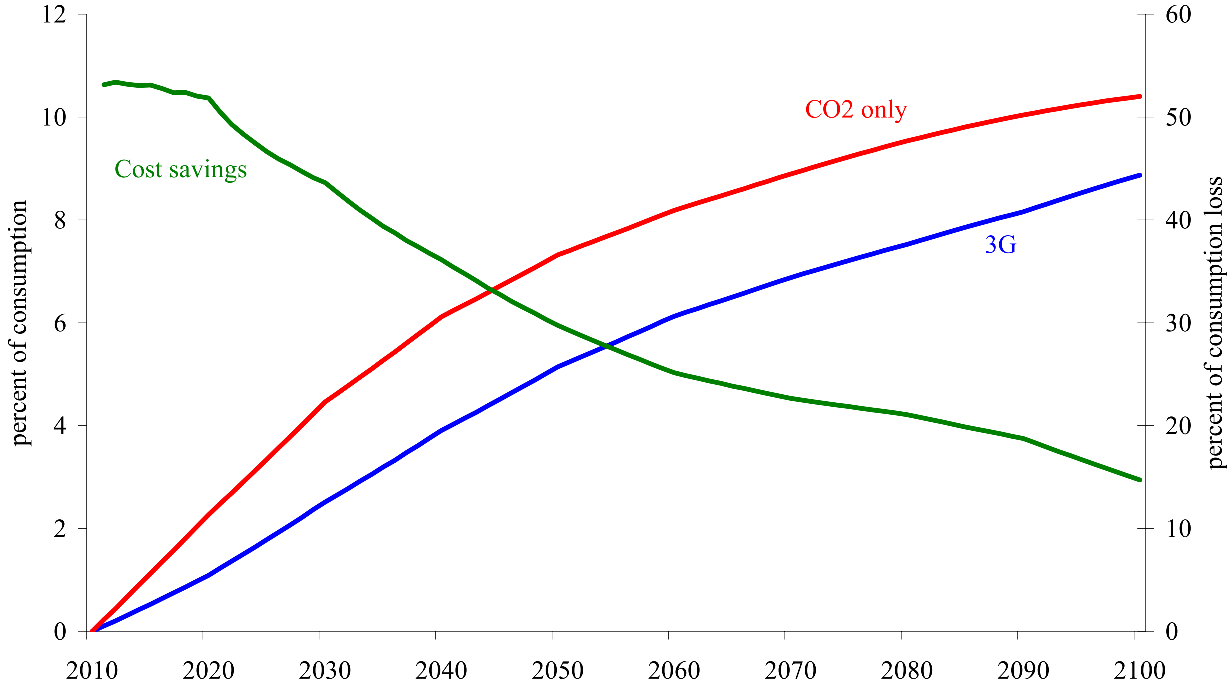

Figure 5. Annual world consumption losses (left axis) due to alternative policies (3G: three gases; CO_2 only) to keep anthropogenic radiative forcing below 4.5 Wm^{-2}; the cost savings due to the other gases is shown on the right axis.

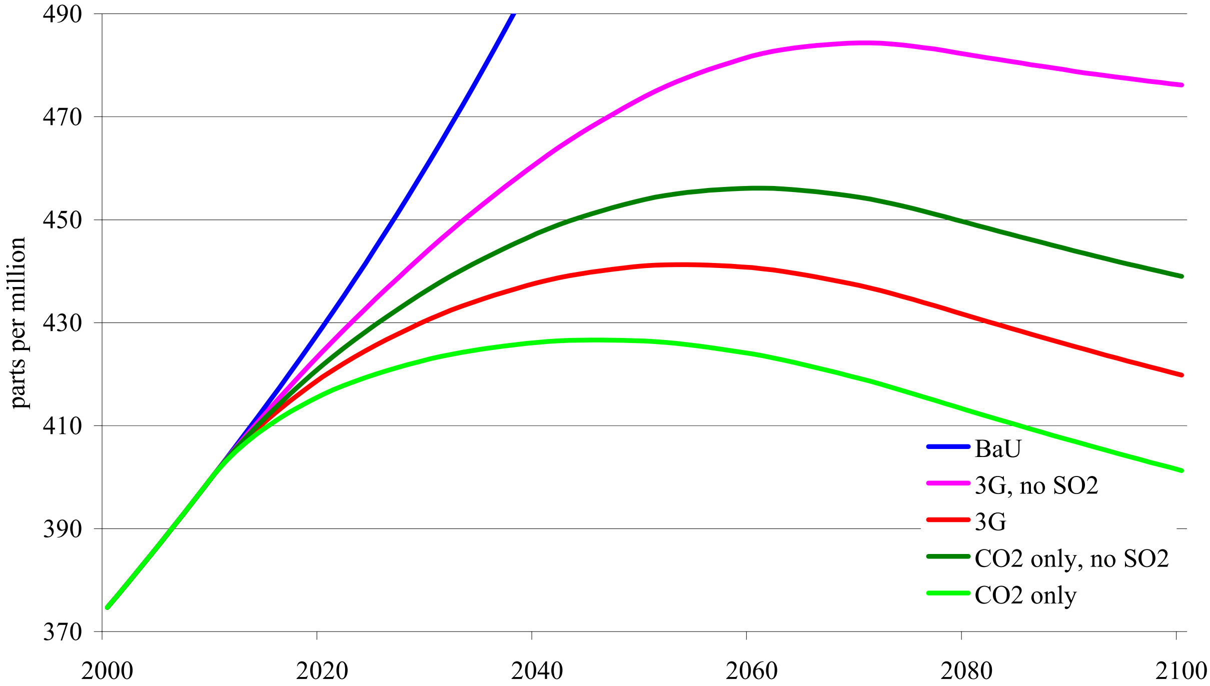

Figure 6. The atmospheric concentration of carbon dioxide for the business as usual scenario and four scenarios keeping anthropogenic radiative forcing below 4.5 Wm^{-2}, two with only CO_2 emission reduction, and two with CO_2, CH_4 and N_2O emission reduction (3G). A further distinction between the scenarios is whether or not SO_2 is included.

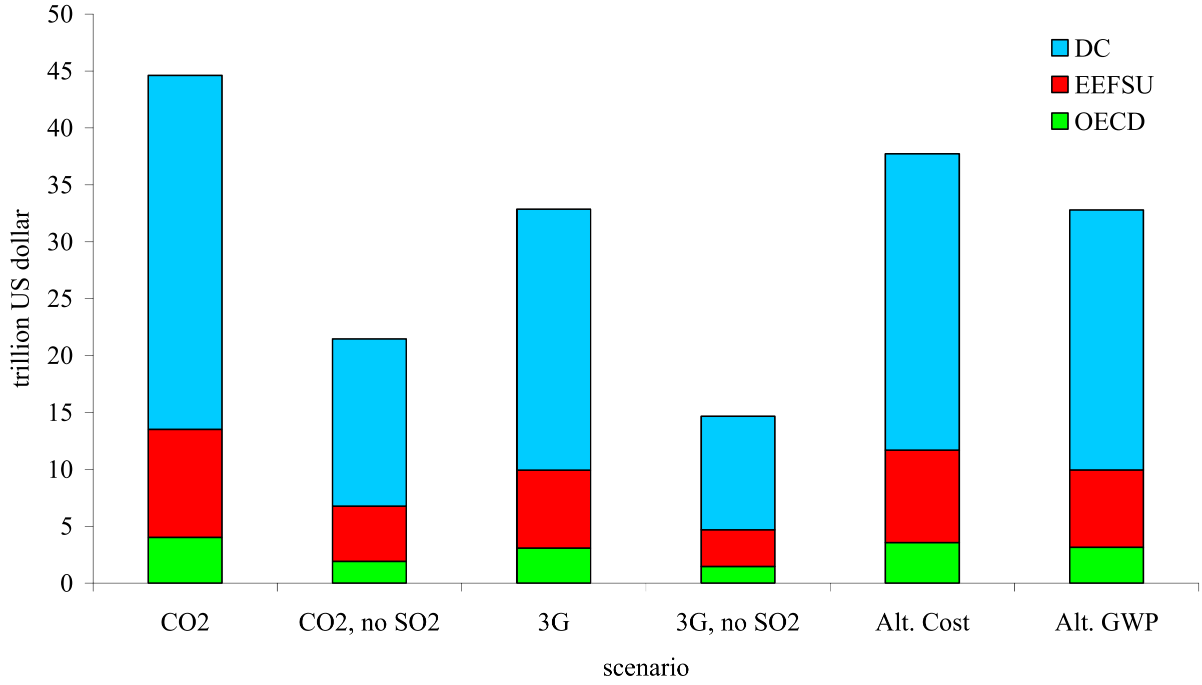

Figure 7. The net present value of consumption losses due to alternative policies to keep anthropogenic radiative forcing below 4.5 Wm^{-2}, viz. only CO_2 emission reduction (with and without SO_2), emission reduction with all three gases(3G, with and without SO_2), emission reduction with all three gases with exponential rather than quadratic cost function (Alt. Cost), and emission reduction with all three gases with contributions to 2070 radiative forcing rather than IPCC GWP (Alt. GWP).

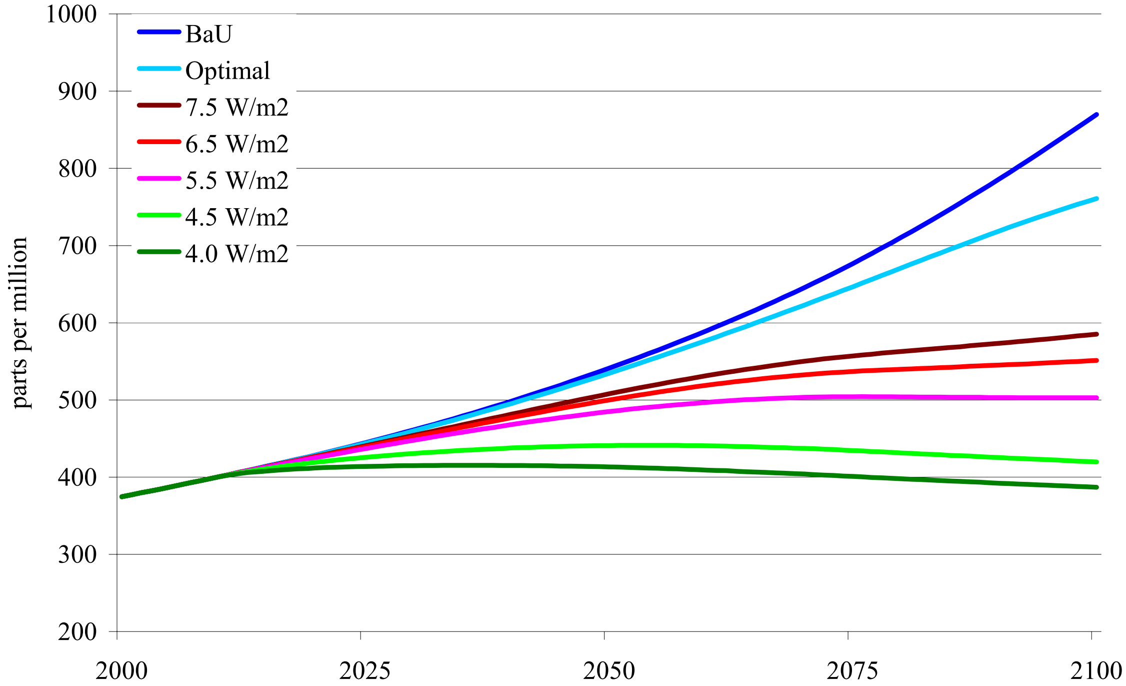

Figure 8. The atmospheric concentration of carbon dioxide for the business as usual scenario and five scenarios keeping anthropogenic radiative forcing below 4.0, 4.5, 5.5, 6.5 and 7.5 Wm^{-2}, respectively. Also shown is the scenario in which marginal emission reduction costs are set equal to the marginal damage costs in 2005 ($7/tC), rising with the discount rate (Optimal).

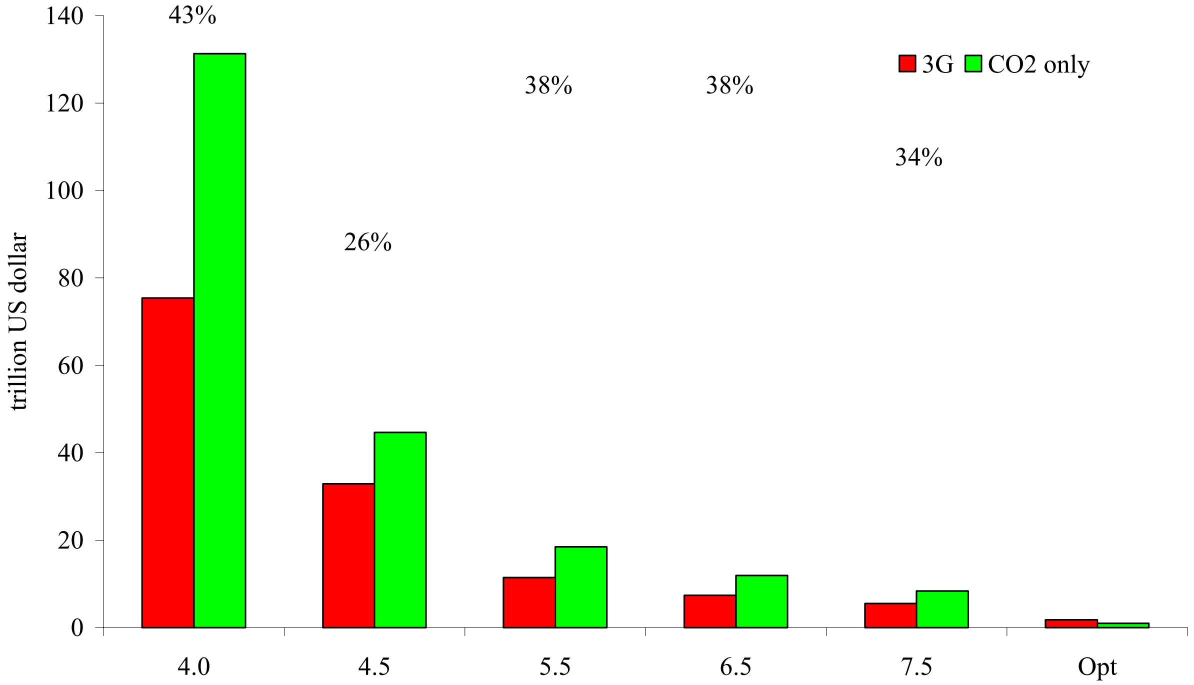

Figure 9. The net present value of consumption losses due to alternative policies to keep anthropogenic radiative forcing below 4.0, 4.5, 5.5, 6.5 and 7.5 Wm^{-2}, respectively, with carbon dioxide, methane and nitrous oxide emission reduction (3G) and with only carbon dioxide. Also shown are the costs of the scenario in which marginal emission reduction costs are set equal to the marginal damage costs in 2005 ($7/tC), rising with the discount rate (Opt). The percentages are the costs savings due to include methane and nitrous oxide emission abatement.

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Tol, R.S.J. (2000), *How Large is the Uncertainty about Climate Change?*, **FNU-3** (*Climatic Change*, **56** (3), 265-289).

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