METHANE EMISSION REDUCTION: AN APPLICATION OF *FUND*

RICHARD S. J. TOL[1, 2, 3], ROEBYEM J. HEINTZ[1, 4] and
PETRONELLA E. M. LAMMERS[1, 5]

[1]*Centre for Marine and Climate Studies, Hamburg University, Troplowitzstrasse 7, 22529 Hamburg, Germany*
E-mail: tol@dkrz.de
[2]*Institute for Environmental Studies, Vrije Universiteit Amsterdam, The Netherlands*
[3]*Center for Integrated Study of the Human Dimensions of Global Change, Carnegie Mellon University, Pittsburgh, PA, U.S.A.*
[4]*Currently at International Energy Agency*
[5]*Currently at NOVEM*

Abstract. Methane is, after carbon dioxide, the most important anthropogenic greenhouse gas. Governments plan to abate methane emissions. A crude set of estimates of reduction costs is included in *FUND*, an integrated assessment model of climate change. In a cost-benefit analysis, methane emission reduction is found to be instrumental in controlling the optimal rate of climate change. In a cost-effectiveness analysis, methane emission reduction largely replaces carbon dioxide emission reduction. Methane emission reduction reinforces the case for international cooperation in climate policy, but complicates the efficient allocation of emission reduction efforts. Methane emission reduction at the short run does not help to achieve the ultimate objective of the Framework Convention on Climate Change.

1. Introduction

Methane is a potent greenhouse gas, in its contribution to anthropogenic climate change second only to carbon dioxide. Methane emission reduction should therefore be part of a climate policy portfolio, and this is indeed recognised in the international negotiations, notably the Kyoto Protocol (United Nations, 1997). However, the academic community has not yet progressed that far. The trade-offs between methane and carbon dioxide are approximately known in terms of climate change (Albritton et al., 1994; Schimel et al., 1996) and climate change impacts (Fankhauser, 1995; Hammitt et al., 1996; Kandlikar, 1995, 1996; Reilly and Richards, 1993; Schmalensee, 1993; Tol, 1999e; Tol et al., 2001), but knowledge on the costs of methane emission reduction is scant (Hogan, 1993a,b; Hourcade et al., 1996a,b; Kruger et al., 1998; Van Amstel, 1993; Van Ham et al., 1994, 2000; Watson et al., 1996). As a result, the appropriate mix of reductions in gases' emissions has hardly been analysed, even though the Kyoto Protocol calls for such advice.* This paper analyses the trade-off between methane and carbon dioxide

* Michealis (1992) is an early exemption, but the empirical basis for his paper is even weaker than here. Also, the model used here is more extensive.

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emissions, and estimates the optimal amount of methane emission reduction. This is done for various assumptions about desirability, the international regime, and the costs of methane emission reduction. All analyses are done with *FUND*, an integrated assessment model of climate change.

Reilly et al. (1999) look at the trade-offs between carbon dioxide emission reduction and other greenhouse gases. Their analysis is broader than ours, which is restricted to carbon dioxide and methane, but our paper is deeper in its assessment of the economic issues, particularly on the longer term. We discuss the global warming potential as well. Manne and Richels (2001) have goals similar to ours, but their model, *MERGE*, is very different from ours, *FUND*. Besides, Manne and Richels (2001) restrict themselves to cost-effectiveness issues. Hayhoe et al. (1999) look at the trade-offs between methane and carbon dioxide emission reduction for the U.S. until 2010 only. Godal and Fuglestvedt (2002) focus on the effect of different 'global warming potentials' (in the broadest sense of the word) on cost-effective emission reduction policy, with an empirical application to Norway only. Jensen and Thelle (2001) analyse emission reduction costs and the distribution of abatement efforts using a multi-regional computable general equilibrium model with all Kyoto gases as well as carbon sinks.

Although the data are weak, this paper shows that, in the short term, methane emission reductions may well provide an opportunity to limit the costs of climate change control, and hence should have a prominent place in the policy mix. However, independently of the data used here, methane emission reduction is no panacea for a long term solution to the stabilisation of atmospheric greenhouse gas concentrations.

Section 2 briefly discusses the model. Section 3 reviews the costs of methane emission reduction. Section 4 treats the effects of methane emission reduction on cost-benefits analyses of climate control, controlling emissions so as to balance the costs of emission reduction against the impacts of climate change. Section 5 presents results of selected policy scenarios aiming at atmospheric stabilisation while minimising economic costs (cost-effectiveness analyses). Section 6 discusses the global warming potential of methane. Section 7 concludes.

2. The Model

The *Climate Framework for Uncertainty, Negotiation and Distribution* (*FUND*) serves various purposes. It was primarily developed to analyse efficient emission reduction strategies for various groups of countries (Tol et al., 1995; Tol, 1997, 1999a,b,c, 2001a). Following the political agenda, *FUND* is now regularly used for cost-effectiveness analysis as well (Tol, 1999b,c). Uncertainty (Tol, 1999d), equity (Tol, 2001b, 2002c; Kemfert and Tol, 2003) and impacts (Tol, 1995, 1996, 1998a, 2002a,b) have also been important considerations. This paper extends *FUND* to the analysis of the trade-off between methane and carbon dioxide emission reduction.

Essentially, *FUND* consists of a set of exogenous scenarios and endogenous perturbations, specified for nine major world-regions, namely OECD-America, OECD-Europe, OECD-Pacific, Central and Eastern Europe and the former Soviet Union, Middle East, Latin America, South and South-East Asia, Centrally Planned Asia, and Africa.

The model runs from 1950 to 2200, in time steps of a year. The prime reason for extending the simulation period into the past is the necessity to initialise the climate change impact module. In *FUND*, some climate change impacts are assumed to depend on the impact of the year before, so as to reflect the process of adaptation to climate change. Without a proper initialisation, climate change impacts are thus misrepresented in the first decades. Scenarios for the period 1950–1990 are based on historical observation, viz. the *IMAGE* 100-year database (Batjes and Goldewijk, 1994). The period 1990–2100 is based on the IS92a scenario, with IS92d and IS92f as alternatives (Leggett et al., 1992). Note that the original IPCC scenarios had to be adjusted to fit *FUND*'s nine regions and yearly time-step. The period 2100–2200 is based on extrapolation of the population, economic and technological trends in 2050–2100, that is, a gradual shift to a steady state of population, economy and technology. The model and scenarios are so far extrapolated that the results for the period 2100–2200 are not to be relied upon. This period is only used to provide the forward-looking agents in *FUND* with a proper perspective.

The exogenous scenarios concern economic growth, population growth, urban population, autonomous energy efficiency improvements, decarbonisation of the energy use, and nitrous oxide emissions. Methane emissions, however, are given by a fixed scenario (essentially IS92a), related to the scenarios about the size and the structure of the population and the economy. However, model-driven perturbations of population and economy do not affect methane emissions, as this would require a far more detailed model than *FUND*. Similarly, climate change may well affect methane emissions (Prinn et al., 1999). Instead of explicitly modelling this, we rely on sensitivity analyses. Policy interventions do influence methane emissions. Other factors (e.g., sulphur dioxide emissions) are assumed to be unaffected by methane emission reduction.

Incomes and population are perturbed by the impact of climate change. Population falls with climate change deaths, resulting from changes in heat stress, cold stress, malaria, and tropical cyclones. Heat and cold stress are assumed to affect only the elderly, non-reproductive population; heat stress only affects urban population. Population also changes with climate-induced migration between the regions. Economic impacts of climate change are modelled as deadweight losses to disposable income. Scenarios are only slightly perturbed by climate change impacts, however, so that income and population are largely exogenous.

TABLE I
Parameters of Equation (1)

Gas	α [a]	β [b]	Pre-industrial concentration
Methane (CH_4)	0.3597	1/8.6	790 ppb
Nitrous oxide (N_2O)	0.2079	1/120	285 ppb

[a] The parameter α translates emissions (in million metric tonnes 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 assumedly equilibrium) concentrations; $1/\beta$ is the atmospheric life-time (in years) of the gases; source: Titus and Narayanan (1995).

The endogenous parts of *FUND* consist of carbon dioxide emissions, the atmospheric concentrations of carbon dioxide, methane and nitrous oxide, the global mean temperature, and the impact of climate change on coastal zones, agriculture, extreme weather, natural ecosystems and malaria.

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

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

where C denotes concentration, E emissions, t year, and *pre* pre-industrial. Table I displays the parameters for both gases. Equation (1) is an extremely simplified representation of the relevant atmospheric chemistry. Particularly, the atmospheric life-time is not constant, but depends on the concentrations and emissions of other chemical species. We do not model this explicitly, but rather rely on sensitivity analysis about methane's life-time.

The carbon cycle is a five-box model:

$$Box_{i,t} = \rho_i Box_{i,t-1} + 0.000471\alpha_i E_t \tag{2a}$$

with

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

where α_i denotes the fraction of emissions E (in million metric tonnes of carbon) that is allocated to box i (0.13, 0.20, 0.32, 0.25 and 0.10, respectively) and ρ the decay-rate of the boxes (ρ = exp(–1/lifetime), with life-times infinity, 363, 74, 17 and 2 years, respectively). Thus, 13% of total emissions remains forever in the atmospheric, while 10% is – on average – removed in two years. The model is due to Maier-Reimer and Hasselmann (1987), its parameters to Hammitt et al. (1992).

It assumes, incorrectly, that the carbon cycle is independent of climate change. Carbon dioxide concentrations are measured in parts per million by volume.

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

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

Global mean sea level is also geometric, with its equilibrium determined by the temperature and a life-time of 50 years. These life-times result from a calibration to the best guess temperature and sea level for the IS92a scenario of Kattenberg et al. (1996).*

The climate impact module is fully described in Tol (1996). The impact module has two units of measurement: people and money. People can die prematurely and migrate. These effects, like all impacts, are monetized. Damage can be due to either the rate of change (benchmarked at 0.04 °C/yr) or the level of change (benchmarked at 2.5 °C). Benchmark estimates can be found in Table II. Damage in the rate of temperature change slowly fades at a speed indicated in Table III. Damage is calculated through a second-order polynomial in climatic change. Damage is distinguished between tangible (market) and intangible (non-market) effects. Tangible damages affect investment and consumption; through investment, economic growth is affected; through consumption, welfare is affected. Intangible damages affect welfare. Relative vulnerability to climate change changes with economic development in many ways. The importance of agriculture falls with per capita income growth, and so do malaria incidence and the inclination to migrate. Heat stress increases with urbanisation. The valuation of impacts on non-marketed goods and services increases with per capita income.

The costs of emission reduction are calibrated to the survey results of Hourcade et al. (1996b) supplemented with results of Rose and Stevens (1993) for developing countries. Regional relative costs are shrunk to the global average. This particularly influences the developing regions, for which much less information on emission abatement costs is available. Costs are represented by a power function, with the power of two. Table IV displays the parameters. Roughly, a 1% cut in emissions (from baseline) in one year costs 0.02% of GDP; a 10% cut costs 2%.

FUND distinguishes generations of decision makers. Each decision maker has control over a ten-year period only, but does care about the entire future, by optimising the net present welfare of her region from the start of the control period up to 2200. Each decision maker exactly knows the emission reduction efforts of all

* *FUND* also calculates hurricane activity, winter precipitation, and winter storm activity because these feed into the damage module. These factors are assumed to depend linearly on the global mean temperature. This is merely accounting, awaiting a better representation.

TABLE II

Monetized estimates of the impact of global warming (in 10^9 U.S.$)

Region	Species	Life	Agric.	Sea	Extreme	Total
Level	(Global mean temperature: +2.5 °C; sea level: +50 cm; hurricane activity: +25%; winter precipitation: +10%; extratropical storm intensity: +10%)					
OECD-A	0.0	–1.0	–5.3	0.9	2.5	–2.9
OECD-E	0.0	–1.1	–6.0	0.3	0.3	–6.5
OECD-P	0.0	–0.5	–6.1	1.5	5.5	0.3
CEE&fSU	0.0	3.7	–23.2	0.1	0.2	–19.1
ME	0.0	3.5	3.1	0.1	0.0	6.6
LA	0.0	67.0	7.3	0.2	0.0	74.5
S&SEA	0.0	81.4	15.8	0.2	0.6	98.8
CPA	0.0	58.4	–22.2	0.0	0.1	36.3
AFR	0.0	22.5	5.4	0.1	0.0	28.0
Rate	(Global mean temperature: 0.04 °C year; other variables follow)					
OECD-A	0.3	0.2	0.3	0.2	0.2	1.2
OECD-E	0.3	0.2	0.0	0.2	0.0	0.7
OECD-P	0.2	0.1	0.0	0.3	0.4	1.0
CEE&fSU	0.1	0.1	0.0	0.0	0.0	0.2
ME	0.0	0.0	0.1	0.0	0.0	0.2
LA	0.0	0.4	0.1	0.1	0.0	0.6
S&SEA	0.0	0.3	0.1	0.1	0.0	0.6
CPA	0.0	0.2	0.3	0.0	0.0	0.5
AFR	0.0	0.0	0.1	0.0	0.0	0.2

Source: After Tol (1995, 1996).

TABLE III

Duration of damage memory per category [a]

Category	Years	Category	Years
Species loss	100	Immigration	5
Agriculture	10	Emigration	5
Coastal protection	50	Wetland (tangible)	10
Life loss	15	Wetland (intangible)	50
Tropical cyclones	5	Dryland	50

[a] Damage is assumed to decline geometrically at a rate of 1-1/life-time.
Source: After Tol (1996).

TABLE IV
Parameters of the emission reduction cost function [a]

OECD-A	2.08	CEE&fSU	2.05	S&SEA	2.13
OECD-E	2.32	ME	2.10	CPA	1.95
OECD-P	2.22	LA	2.13	AFR	2.09

[a] The loss of GDP C of emission reduction R follows from $C_t = \alpha R_t^2$, where t denotes the year. The parameter α is displayed in the table. Costs and reduction are relative to the situation of uncontrolled emissions in year t (note that abatement in earlier years shifts this baseline). The costs to GDP are modelled as a deadweight loss to the economy. Emission reduction is brought about by a permanent shift in energy- and carbon intensity.
Source: After Hourcade et al. (1996) and Rose and Stevens (1993).

decision makers in all regions at all times. Below (except in Section 4), net present welfare per region is maximised under a (joint) constraint on carbon dioxide (and methane) emissions for each decade.* In the cooperative cases, or 'trade cases', the sum of the net present welfare per region is maximised, knowing the emission reductions in other time periods. If there are no emission constraints (Section 4), net present welfare is maximised so as to balance the costs of emission reduction and the costs of climate change, either per region (non-cooperation) or the sum over the regions (cooperation).

3. The Costs of Methane Emission Reduction

Little knowledge is available on the costs of methane emission reduction. An extensive literature and internet search delivered scattered information, mostly rough estimates of the direct costs of selected emission reduction options (cf. Hourcade et al., 1996b). For the time being, the knowledge base is necessarily small and the assumptions heroic.

De Jager and Blok (1993; cf. Blok and De Jager, 1994) is the first comprehensive study of the costs of methane emission reduction. It is the basis for the work here. It is a bottom-up study for the Netherlands. Bottom-up studies tend to underestimate the true costs of emission reduction (Hourcade et al., 1996a). With regard to methane emissions, the Netherlands is hardly comparable to other countries, because of its dense population, intensive agriculture (including pig-farming), and dense grid for distribution of natural gas. Because the data are so weak, the numerical findings given below should be interpreted with great caution. We do, however, develop a number of insights that are largely independent of the exact numbers.

* Note that the emission constraint typically forces emissions below what would be considered optimal. Under such a constraint, the welfare programme essentially changes to finding the cheapest mix of carbon dioxide and methane emission control to meet the decade's aggregate emissions target.

TABLE V

Costs of methane emission reduction in the Netherlands

Measure	Reduction (Kton CH_4/yr)	Costs (Dfl/ton CH_4)
Gas-production		
Increased gas utilization	11 (1%)	–160
Further increased gas utilization	22 (2%)	–18
Offshore flaring	6 (1%)	1,000
Gas-distribution		
Replace grey cast-iron network	52 (5%)	4,500
Double leak control frequency	9 (1%)	3,000
Animal manure		
Adjustment of stable/storage	18 (2%)	0
Large-scale digestion	4 (0%)	–120
Farmscale digestion (mesophilic)	6 (1%)	960
Farmscale digestion (psychophilic)	12 (1%)	1,100
Landfills; waste gas recovery		
Electricity generation	72 (7%)	–95
Upgrading	31 (3%)	–70
Flaring	51 (5%)	16
Landfills; reduced landfilling		
Composting	5 (1%)	600
Fermentation	1 (0%)	1,300
Incineration	6 (1%)	15,700
Total	307 (31%)	

Source: De Jager and Blok (1993).

Table V reproduces the technological options, their emission reduction potential, and their average cost according to De Jager and Blok (1993). Figure 1 presents the findings as a cost-effectiveness curve, starting with the cheapest options. An exponential curve was calibrated to the results of De Jager and Blok (1993). De Jager (personal communication, 1997) admits that there may be missing costs. We therefore add an arbitrary DGl. 165 per kilotonne of methane to all costs of all options, so that the cheapest reduction costs DGL 5 per kilotonne of methane (instead of a negative DGl. 160). We thus exclude a free lunch in methane emission reduction. The slope of the emission reduction cost curve is varied in the sensitivity analysis below.

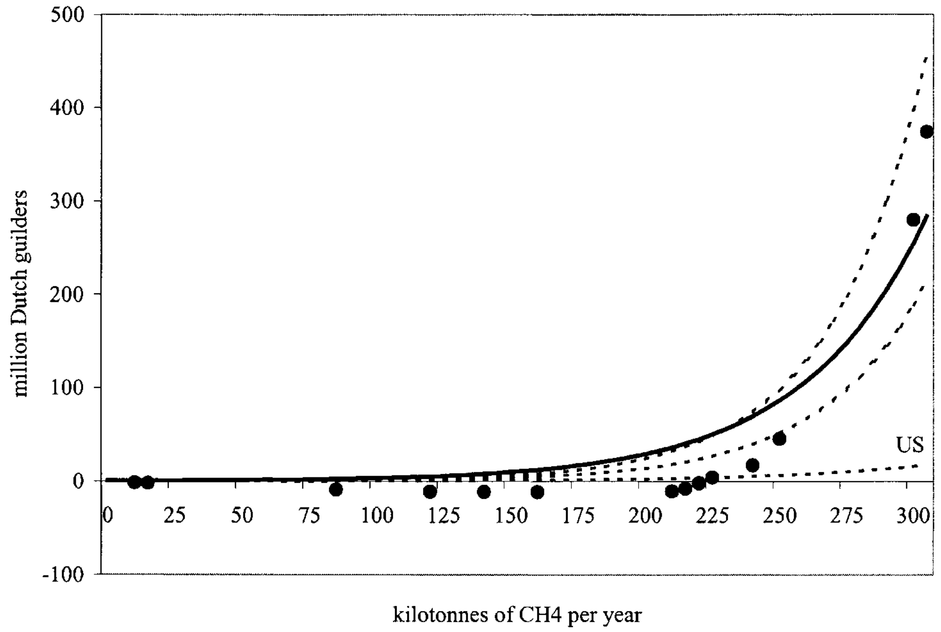


Figure 1. Cumulative costs of methane emission reduction in the Netherlands as estimated by De Jager and Blok (dots) and as fitted by Equation (5) (line); the intermittent lines indicate the high and low cost cases used in the sensitivity analysis; results from the USEPA are shown for comparison.

Next, the natural logarithm of cumulative reduction costs was regressed on cumulative reduction. Expressing costs as a fraction of GDP, and reduction as a fraction of emissions, the result is

$$C = 6.5 \cdot 10^{-7} e^{21.6R} \tag{4}$$

with C costs and R reduction. This methane emission reduction cost curve is assumed to apply to all regions in all time periods. That is, the relative costs of relative reductions are equal across time and space. This implies that the *absolute* costs of methane emission reduction are smaller in regions that are poorer, and in regions that have a high emissions of methane per GDP. Absolute carbon dioxide emission reduction costs have the same pattern. Relative costs of methane emission reduction are likely to change over time, but it is at the moment hard to foresee how fast and even in what direction; technological progress would push costs down, but higher gas or meat consumption would push costs up. In this study, relative costs are assumed to be constant.

The analysis of the USEPA (Kruger et al., 1998) suggests that, for the U.S.A., the costs would be higher initially but increase slower. A preliminary USEPA study for the whole world indicates a similar pattern (Dastin, personal communication, 1998). This study came available only after most of the analyses for this paper had been completed. Hayhoe et al. (1999), Manne and Richels (2001) and Reilly et al.

TABLE VI

Global damage potential, impact per tonne of CH_4 relative to impact per tonne of CO_2

	FUND [a]	Kandlikar [b]	Fankhauser [c]	Hammitt [d]	GWP [e]
CH_4	14	12	20	11	25

[a] Emissions between 1995 and 2004; time horizon: 2100; discount rate: 3%; model: *FUND*1.6; scenario: IS92a; no higher order effects. The marginal costs of carbon dioxide emissions are about \$6/tCO_2, the marginal costs of methane about \$89/tCH_4.
[b] Time horizon: 100 years; discount rate: 2%; scenario: IS92a; quadratic damages.
[c] Emissions between 1991 and 2000; time horizon: 2100; GDP is calculated as ratio of mean marginal damages.
[d] Emissions in 1995; time horizon: 2100; discount rate: 3%; scenario: IS92a; middle case.
[e] Time horizon: 100 years.
Sources: Own calculations, Kandlikar (1995, 1996), Fankhauser (1995), Hammitt et al. (1996), Schimel et al. (1996).

(1999) do base their work on the EPA studies. The slope of the emission reduction cost curve is varied in the sensitivity analysis below.

4. Methane Emission Reduction and Optimal Climate Control

Table VI displays the marginal costs of carbon dioxide and methane emissions, according to *FUND*, and their ratio according to other models used in the literature. For comparison, the latest estimate of the Global Warming Potential by the IPCC is also displayed. Methane is more important if one is interested in its effect on warming rather than in its effect on impacts. Two effects are at play. Methane warming is concentrated in the first couple of decades after emission. Firstly, methane emissions are *more* important looking at damages rather than at warming because of discounting. Secondly, methane emissions are less important because they occur at a time that climate changed relatively little. The second effect dominates the first one in all published models. This also explains the rising marginal costs of carbon dioxide emissions (cf. Pearce et al., 1996).

Figures 2 and 3 display the atmospheric concentrations of carbon dioxide and methane, respectively, under five scenarios: no control, non-cooperative control of carbon dioxide, non-cooperative control of carbon dioxide and methane, co-operative control of carbon dioxide, and cooperative control of carbon dioxide and methane. As far as we know, this is the first analysis of efficient methane emission reduction. In the absence of international cooperation, welfare optimisation does not lead to substantial cuts in greenhouse gas emissions, and the option to reduce methane emissions does little to change this. Methane emission reductions does not noticeably influence carbon dioxide emission reductions. Carbon emissions are

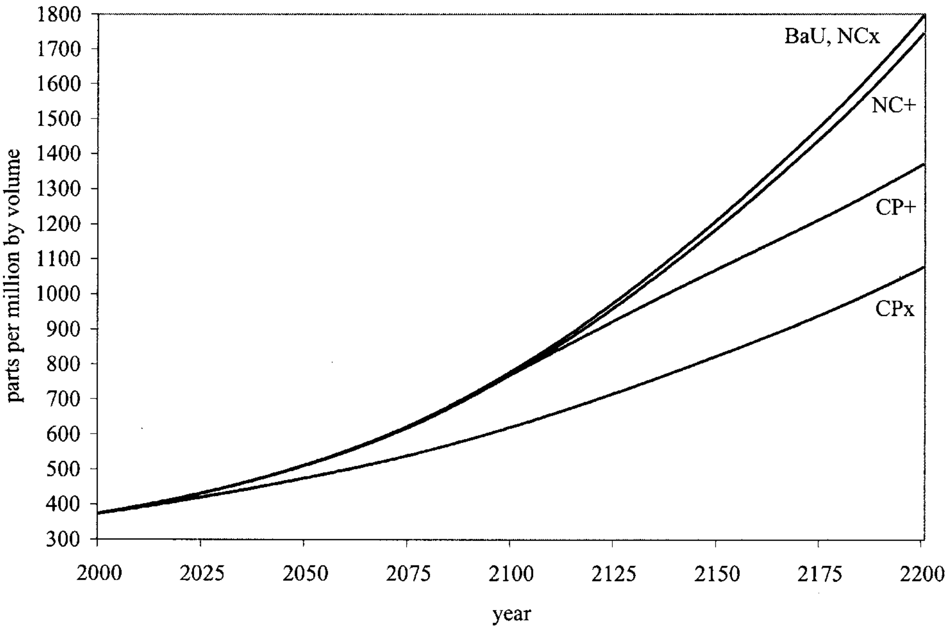


Figure 2. The atmospheric concentration of carbon dioxide, from top to bottom, the business as usual scenario (BaU), the non-cooperative optimal control scenario without methane emission reduction (NCx), the non-cooperative optimal control scenario with methane emission reduction (NC+), the cooperative optimal control scenario with methane emission reduction (CP+), and the cooperative optimal control scenario without methane emission reduction (CPx). The two non-cooperative optimal control scenarios are indistinguishable.

slightly lower, however, due to the slightly reduced economic growth if methane emissions are cut.

The case with international cooperation is more interesting. In the first century or so, methane emission reduction replaces carbon dioxide emission reduction. Methane concentrations start falling in the second half of the 21st century. In the 22nd century, however, carbon dioxide emissions are reduced, and methane emission reductions are relaxed. This pattern is explained by the structure of the climate change impact module. First, in the model, the rate of warming is more important for the impacts of climate change (Tol, 1995, 1996, 1998a, 1999e). Methane emission reduction is a good option to keep this rate in check, because modest methane emission reductions are relatively cheap. Later, the level of climate change is more important. Carbon dioxide emission abatement controls this more effectively, because carbon dioxide emission abatement has a structural impact on both the atmosphere and the economy, in contrast to methane emission abatement which transient impacts on both (see below for further discussion). A sustained reduction of methane emissions would require a sustained effect, the costs of which add up (cf. Section 6).

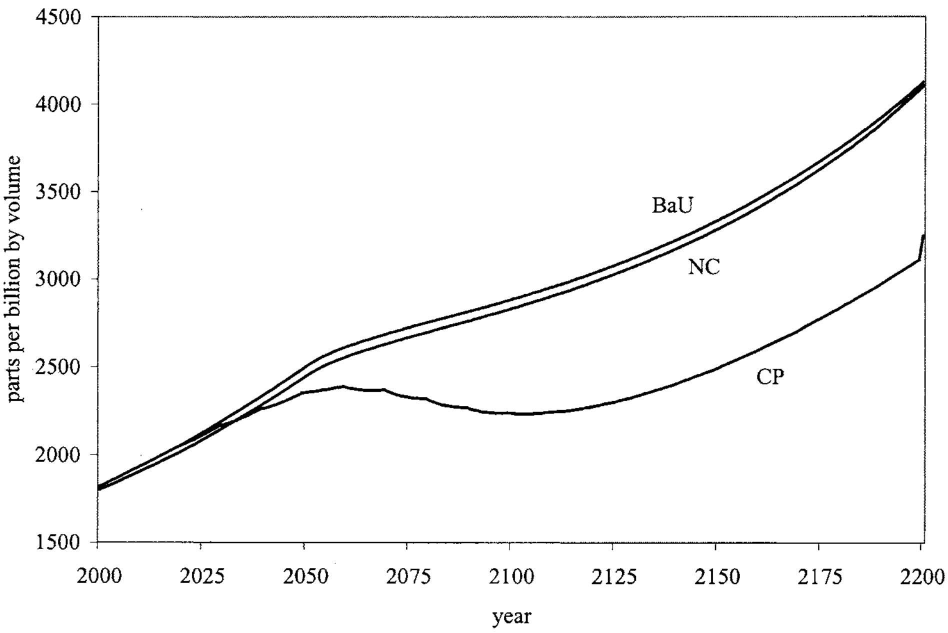


Figure 3. The atmospheric concentration of methane, from top to bottom, the business as usual scenario (BaU), the non-cooperative optimal control scenario (NC), and the cooperative optimal control scenario (CP).

5. Methane Emission Reduction and Atmospheric Stabilisation

The previous section discusses optimal emission reduction. This is at odds with the current political agenda, which seeks to stabilise atmospheric concentrations at a 'safe' level. That level is here assumed to be a carbon dioxide concentration of 550 ppm, about twice the pre-industrial concentration. The emission reduction path towards that concentration is due to Wigley et al. (1996). This path adheres to the basic principles of cost-effectiveness, although it is not derived from a full-fledged cost minimisation (for that, see Manne and Richels, 1998), let alone economic rationality (cf. Tol, 1998b,c).

The regional allocation of emissions is as follows. Until 2030, only Annex I regions reduce emissions. Initial emission allocations assume equal percent-wise reduction in the four regions. After 2050, emission allocations are equal per capita across the world. The period 2030–2050 is a linear transition between the two systems. In the non-cooperative case, each region is to reduce its emissions to its allocation. In the cooperative case, international emission permit trading is allowed within Annex I until 2030, and globally after 2030. These assumptions are somewhat arbitrary. However, the prime aim of this paper is to demonstrate the effect of taking up methane emission reduction. In addition, a 'Kyoto550' scenario is analysed. This scenario meets the targets of the Kyoto Protocol by 2010 and

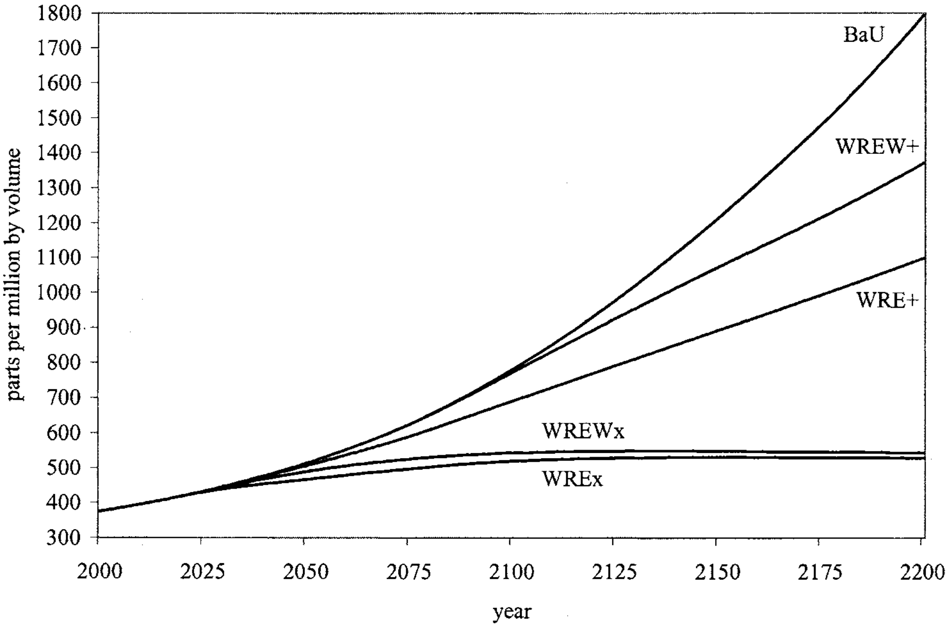


Figure 4. The atmospheric concentration of carbon dioxide according to, from top to bottom, the business as usual scenario (BaU), the WRE550 scenario with international cooperation and with methane emission reduction (WREW+), the WRE550 scenario without international cooperation and with methane emission reduction (WRE+), the WRE550 scenario with international cooperation and without methane emission reduction (WREWx), and the WRE550 scenario without international cooperation and without methane emission reduction (WREx).

follows the WRE550 scenario from 2030 onwards; emission targets in the period 2010–2030 follow a linear transition between the two.

Figure 4 displays the atmospheric concentration of carbon dioxide according to the no-control scenario, and the cooperative and non-cooperative emission reduction scenarios with and without methane control. Methane emission *reductions* are added to carbon emission *allocations* using a global warming potential of 25 (see below). The model finds, per decade, the cheapest mix of methane and carbon dioxide emission reduction while meeting the emission constraints as described above. Allowing methane emission reduction has a profound effect on carbon dioxide emissions and concentrations. Methane emission reduction is substituted for carbon dioxide emission reduction. Particularly in the case without international cooperation, the substitution is substantial.

Figure 5 displays the atmospheric concentration of methane according to the no-control (of methane emissions) scenario, and the cooperative and non-cooperative emission reduction scenarios. Methane emission reductions are substantial. Deeper cuts in methane emissions are made in the case of international cooperation, as the relative advantages of methane emission reduction outside the OECD are opened.

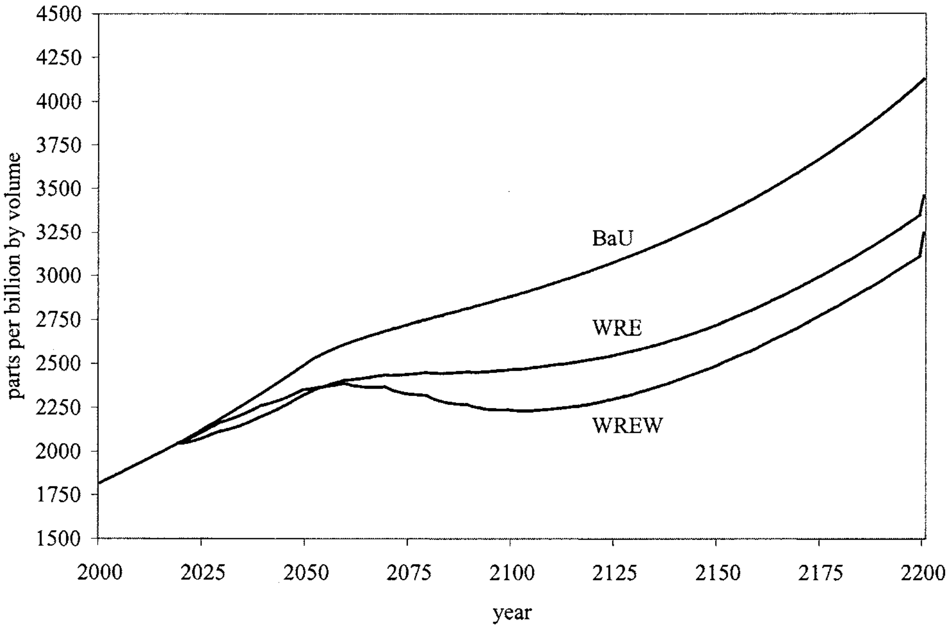


Figure 5. The atmospheric concentration of methane according to, from top to bottom, the business as usual scenario (BaU), the WRE550 scenario without international cooperation (WRE), and the WRE550 scenario with international cooperation (WREW).

Figure 6 displays the costs of the reduction scenarios with and without cooperation, and with and without methane emission reduction. Costs are expressed as the loss of consumption over the period 1990–2200, discounted to 1990 at a 5% discount rate. Allowing methane emission reduction cuts costs to about 35% (WRE) and 38% (Kyoto)* in the cases without international cooperation,** and to about 19% in the case with international cooperation. Cooperation cuts costs to about 25% without methane emission reduction, and to about 13% in the case with methane emission reduction. Methane emission reduction thus has a significant effect on total costs, in the same order of magnitude as has international cooperation. For comparison, Jensen and Thelle (2001) find that a multi-gas strategy cuts emission reduction costs to 65–80%; Reilly et al. (1999) report cost reductions of up to 50% until 2010 (Kyoto); Hayhoe et al. (1999) find costs savings of 25–30% until 2010 in the U.S.A. only (Kyoto).

Methane emission reduction also reinforces the case for international cooperation for emission reduction. With more policy instruments, the relative gains of

* In the first decade (the Kyoto commitment period), methane emission reduction almost completely offsets carbon dioxide emission reduction, cutting costs by more than 95%.

** Kyoto550 is a little cheaper than WRE550; WRE550 is far from the cost-effective scenario in *FUND* (cf. Tol, 1999a,b).

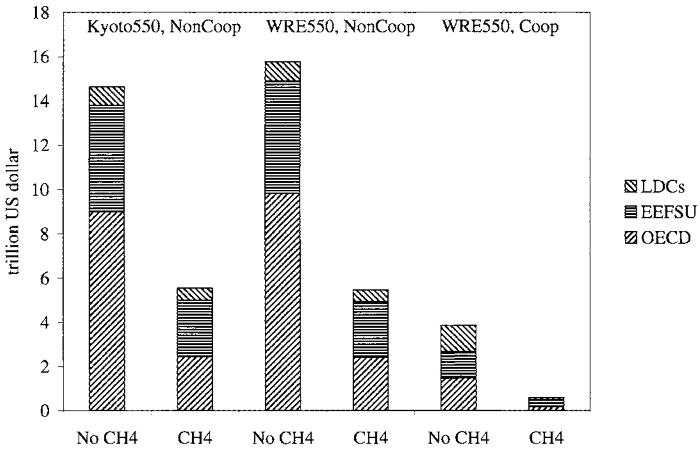
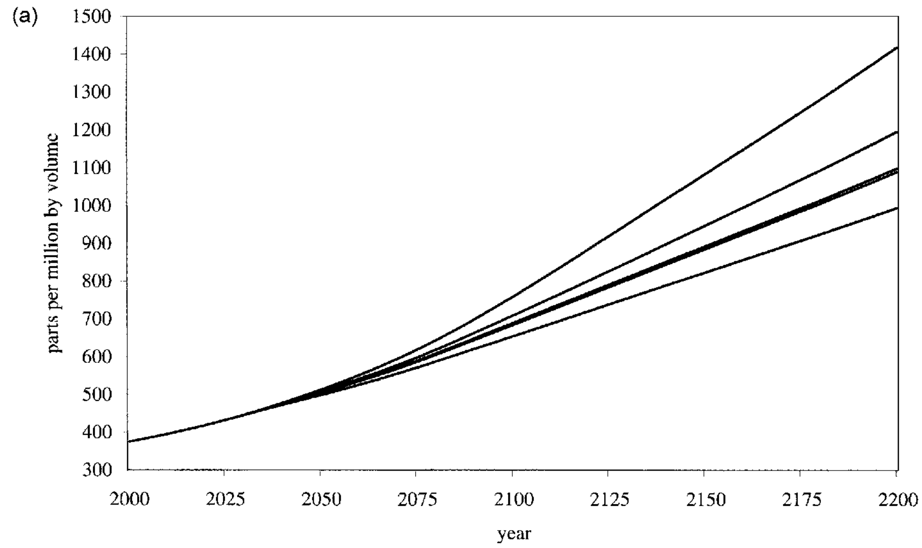


Figure 6. The net present consumption losses of the Kyoto550 and WRE550 scenario (relative to the business as usual scenario) with and without methane emission reduction. WRE550 is given with and without international cooperation. The discount rate is 5%.

international coordination always increase (at least not decrease), because there are more potentially cost-saving transactions.

Figure 7 displays a sensitivity analysis around the costs of methane emission reduction. Costs are halved or doubled, and the parameter in the exponent of Equation (5) – 21.6 – is increased and decreased with 10 (see also Figure 8). Total emission reductions increase and decrease predictably. The effect is asymmetric in the parameter changes. This asymmetry is clearer in case of the atmospheric concentrations of carbon dioxide. The asymmetry is caused by the assumption that the marginal costs of carbon dioxide emission reduction are linear, while the marginal costs of methane emission reduction are exponential. The slope of the emission reduction cost curve has a greater influence than doubling or halving the costs. Figure 8 presents the effect of the alternative parameters on the total costs. Costs are very sensitive, particularly to the slope of the cost curve. If costs are halved (doubled), methane emission abatement reduces costs to 29% (41%) of the cost with only carbon dioxide emission reduction; if the exponent is decreased (increased) by 10, methane reduces costs to 10% (52%).

Figure 7 also displays the sensitivity to alternative methane emissions scenarios. In the low emission scenario, methane emissions are 50% of base emissions in 2050, 25% in 2100 and 0% in 2200. In the high emission scenario, emissions are 150% of base emissions in 2050, 200% in 2100 and 400% in 2200. The IS92 methane emission scenarios in the year 2100 range from 63% to 130% of the base scenario used here; the SRES scenarios range from 34% to 128%. The sensitivity analysis thus adequately spans the lower half of the range in the literature; these scenarios ignore the potentially positive feedbacks of climate change on methane emissions, justifying the high emissions scenario used here. The total costs of emission reduction are very sensitive to the amount of methane emitted



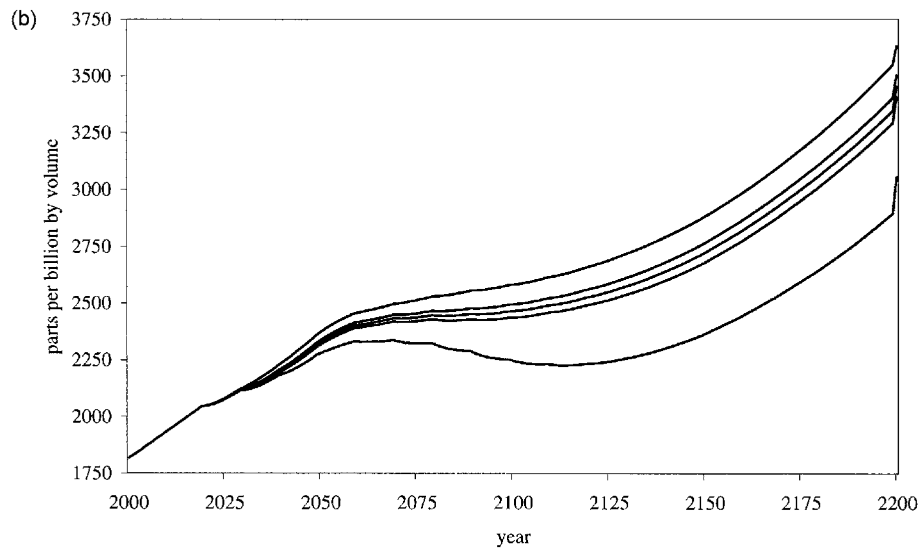


Figure 7. The atmospheric concentration of carbon dioxide (a) and methane (b) under five alternative assumptions about the costs of emission reduction. The middle line is for the base assumptions. In the narrower interval, costs are doubled or halved. In the wider interval, the steepness of the cost curve is varied. In all cases, methane and carbon dioxide emission reduction jointly meet the WRE550 scenario without international cooperation.

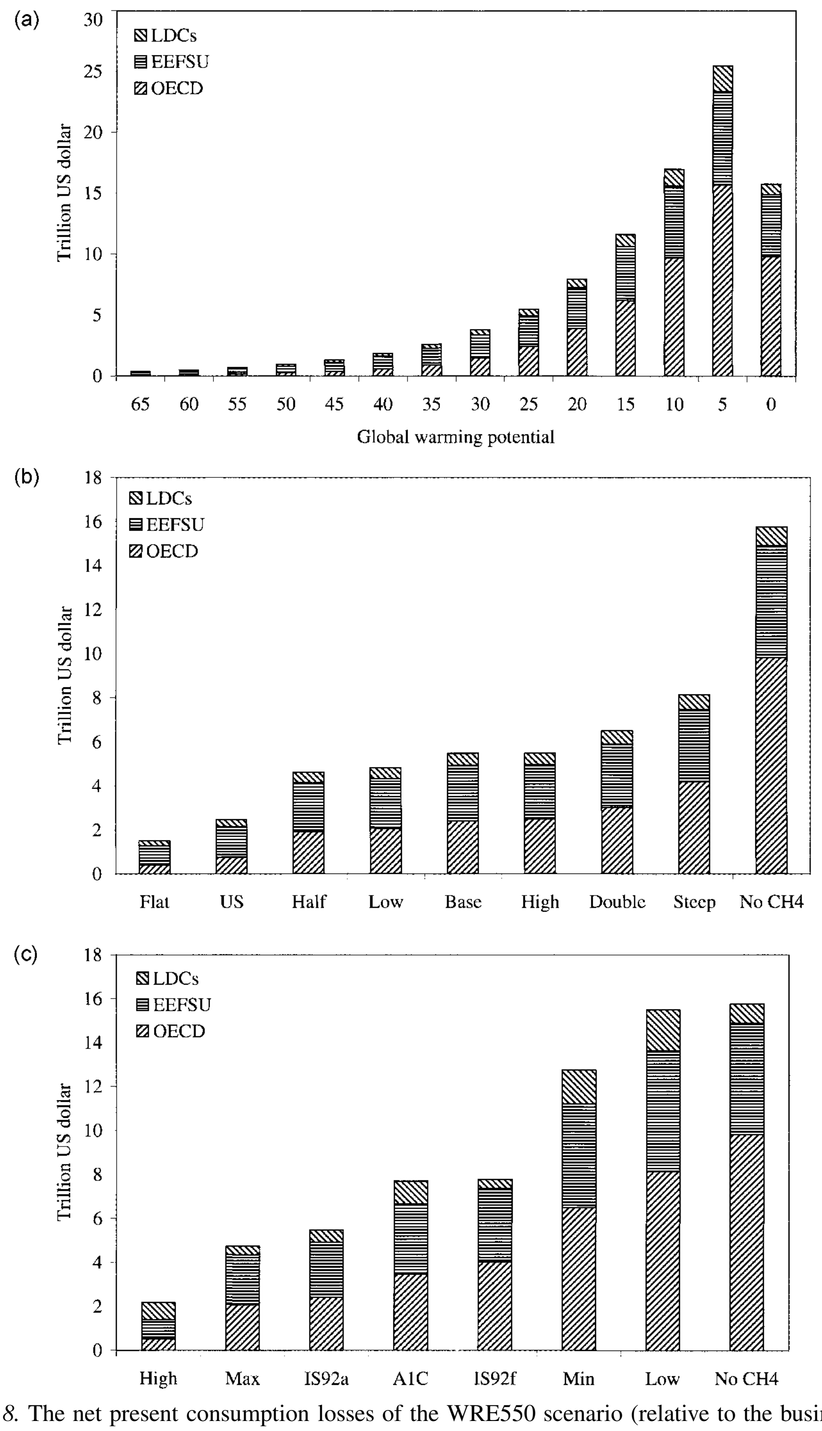


Figure 8. The net present consumption losses of the WRE550 scenario (relative to the business as usual scenario) without international cooperation and with methane emission reduction, for various assumptions about the global warming potential of methane (a), the costs of methane emission reduction (b) and the emissions of methane (c). The discount rate is 5%.

(Figure 8). If emissions are low, there is little potential for reduction, and costs are high (recall Equation (5) which is specified in *relative* methane emission abatement). Conversely, if emissions are high, the potential is high and costs are low. With low emissions, costs increase to 98% of the costs without methane emission abatement; with high emissions, costs are cut to 14%. Figure 8 also shows the effect on total costs of intermediate methane scenarios. Besides the high and low methane emissions scenarios, we add scenarios that follow the maximum and minimum of the range of IPCC IS92 and SRES scenarios. The base scenario (derived from IS92a) is towards the high end of the IPCC scenario range. Therefore, the costs are only slightly lower in the maximum scenario, but a lot higher in the minimum scenario. In all five scenarios, methane emissions rise steadily. In the IS92f scenario, methane emissions rise slowly to 2050, and then accelerate. In the SRES A1C scenario, emissions rise till 2050 and then start falling. Figure 8 also shows the results for these scenarios. Costs are higher than for IS92a, as total methane emissions are lower. Total costs are almost the same for the two scenarios, but not the distribution. The less developed countries reduce their costs under IS92f, because this has higher emissions in the furthers future, when these regions bear the bulk of emission reductions.

Above, the global warming potential of methane equals 25. This number is subject to scientific refinements and international agreements, while the concept is debatable (cf. Section 6). In Figure 8, the global warming potential is changed from 65 to 0* – the range reported in Hayhoe et al. (2000)** – in steps of 5. Increasing the GWP lowers the cost, as the same emission reduction counts for more. This is not always the case, though. This is explained by the fact that the overall concentration target is translated into decadal emission targets. There are three components to this:

1. Carbon dioxide emission reduction is assumed to lead to semi-permanent changes in technology and capital stock (Schneider and Goulder, 1997; Manne and Richels, 1998). By and large, carbon dioxide emission reductions are structural rather than incidental in nature. Therefore, emission reductions in one decade reduce emissions in following decades as well, without any additional cost.
2. Methane emission reduction is assumed not to have such an effect. The methane reduction options in Table V are mostly incidental 'end of pipe' solutions,

* A global warming potential of zero of course corresponds to the case of carbon dioxide emission reduction only.

** The range of GWP potentials for methane reflects first and foremost the time horizon considered but also uncertainties in the projections of future emissions and in the physics and chemistry of atmosphere and climate. The atmospheric life-time is one of these uncertainties. Given decadal targets for emissions, abatement policies are, obviously, independent of the atmospheric life-time.

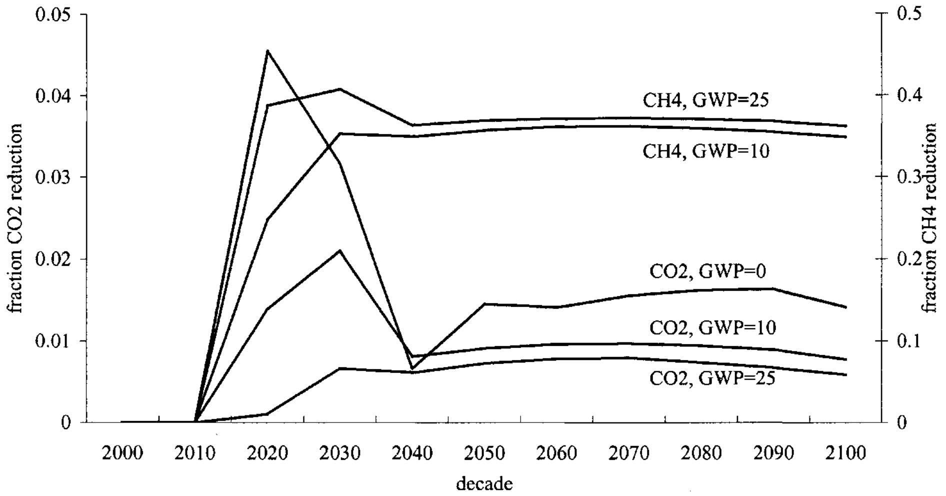


Figure 9. The emission reduction effort of OECD-Europe for carbon dioxide and methane to meet the WRE550 scenario without international cooperation, for methane global warming potentials of 0, 10 and 25.

quick to install and quick to remove again, and so likely to disappear if the reduction policy ceases.*

3. Decision makers are assumed to be constrained only by their decadal emission targets, optimising the trade-off between methane and carbon dioxide emission abatement, but ignoring the spill-over of their actions on the next decade. This is a reflection of the Kyoto Protocol, with its targets for 2012, ignoring the longer term.

Lowering the attractiveness of methane emission reduction by lowering its GWP, increases carbon dioxide emission reductions. This lowers the costs of meeting the emission target in the next decades, because carbon dioxide emissions are lower. This is illustrated for OECD-Europe in Figure 9. It may happen that, unexpectedly, a lower GWP for methane reduces overall emission reduction costs.

This would, of course, not happen in a full, intertemporal cost-minimization.** The practical implication of this finding is that in case methane emission reductions are taken into consideration, an *ad hoc* intertemporal allocation of emission targets – the current political situation – is even more dangerous than in case of

* Note that, if methane emission reductions were semi-permanent, methane emission reduction would be even more attractive relative to carbon dioxide. If half of the emission reductions are still active a decade after they were induced by policy, total emission reduction costs would be cut in half.

** See Manne and Richels (2000) for a cost-effectiveness analysis of emission reduction including methane. Tol (1998b,c) discusses some of the conceptual difficulties associated with cost-effectiveness analysis in an intergenerational setting, particularly with regard to the difficulty of capital transfers needed to make an *actual* Pareto improvement from a *potential* one.

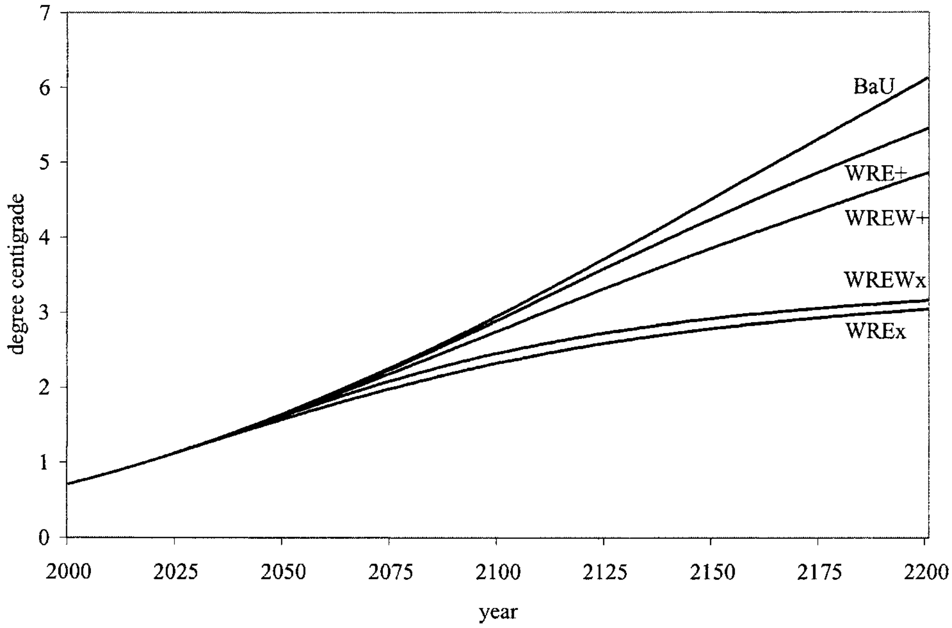


Figure 10. The global mean temperature (change from pre-industrial times) according to, from top to bottom, the business as usual scenario (BaU), the WRE550 scenario without international co-operation and with methane emission reduction (WRE+), the WRE550 scenario with international cooperation and with methane emission reduction (WREW+), the WRE550 scenario with international cooperation and without methane emission reduction (WREWx), and the WRE550 scenario without international cooperation and without methane emission reduction (WREx).

carbon dioxide alone. The next section discusses a second practical complication that arises in the context of methane emission reduction.

6. Global Warming Potentials

Figure 10 displays the global mean temperature resulting from the reduction scenarios of the previous section. Although emission reduction aims at stabilisation of the temperature, it obviously fails to achieve this in the case both carbon dioxide and methane emissions are reduced. Methane emission reductions may be a great help in reducing the costs of meeting, say, the targets of the Kyoto Protocol. Methane emission reduction does not help to meet the ultimate objective (Article 2) of the Framework Convention on Climate Change.

The problem lies in the definition of the global warming potential, an issue also noted by Wigley (1998) and Smith and Wigley (2000a,b). The global warming potential of methane is defined as the ratio of two time integrals. One integral measures the change in radiative forcing over a period of 100 years (say) of a small change in methane emissions in 2000 (say). The other integral measures the same for carbon dioxide. The problem with this definition is that no distinction is made between changes in radiative forcing in the short run and the long run. Methane changes radiative forcing particularly in the first 15 years after emission. For climate stabilisation, one is rather interested in the change in radiative forcing in the long run. Methane emission reduction in the near future has little to contribute to this, at least much less so than does carbon dioxide emission reduction. Global warming potentials do not reflect this, and are thus inappropriate to use in this context.

Global warming potentials consider the relative influence of greenhouse gases averaged over a long period of time. If properly reinterpreted in economic terms (Reilly and Richards, 1993, and Schmalensee, 1993, were the first to note this point; Fankhauser, 1995, Hammitt et al., 1996, Kandlikar, 1995, 1996, Tol, 1999e and Tol et al. 2001, fill in the numbers), global warming potentials, or rather global damage potentials are useful in a cost-benefit analysis. For, the global damage potential of methane is the ratio of the marginal damages of methane and carbon dioxide emissions. In a cost-effectiveness analysis, the proper measure for the trade-off at time t would be the relative, marginal costs with which the maximum radiative forcing can be reduced to its constraint.

Figure 11 illustrates the point. It depicts the relative influence on radiative forcing of a small change in methane and carbon dioxide emissions in the decade 2000–2009. The integral under the curve is the global warming potential. However, the proper measure in a cost-effectiveness analysis is the value at the time the constraint starts to bite, that is, the ratio of the shadow prices of carbon dioxide and methane. If that time is nigh, the value may be over 50. If that time is over 50 years in the future, the value is close to zero. As atmospheric stabilisation is presently a long way into the future, the global warming potential of methane should be substantially lower than the currently recommended value. Indeed, with an atmospheric life-time of 8.6 years (cf. Table I), the effect of changes in methane emissions in 2000–2009 falls to almost zero by 2060. Even with an atmospheric life-time of 17.2 years, the effect of methane emission reduction in the coming decade falls to almost zero by 2100. Manne and Richels (2001) provide a full-blown analysis of the trade-off between methane and carbon dioxide in the context of a cost-effectiveness analysis.

Figure 11 also depicts the relative influence on the global mean temperature. Although the integrals under the curve are very similar (Hammitt et al., 1996, come to the same conclusion) the annual values obviously are not. So although the handy short-cut of using radiative forcing rather than the more controversial temperature or impact may work fine in a cost-benefit context, it does not in a cost-effectiveness context. However, it should be noted that the effect of methane emission reduction in the short run on temperature fades much slower than its effect on radiative forcing.

The weight to be placed on methane emission reduction is, obviously, sensitive to the atmospheric life-time of this gas. Table VII contains estimates of the

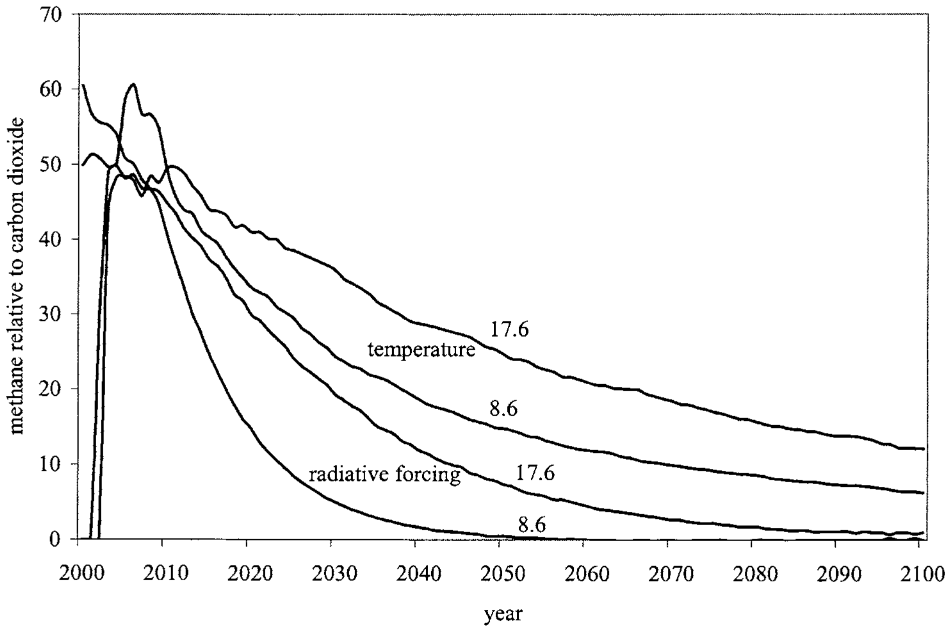


Figure 11. The influence of a small change in methane emissions in the period 1995–2004 on radiative forcing and temperature, relative to a small change in carbon dioxide emissions, for atmospheric life-times of methane of 8.6 year (bottom lines) and 17.6 year (top lines).

marginal costs of methane emissions. We vary the life-time in the range reported by Prinn et al. (1999). The marginal cost estimates are not very sensitive to this, varying between 97% and 109% of the initial estimate at most. We also include cases with increasing and decreasing life-times, as suggested by Lelieveld et al. (1998). Here, life time changes linearly with time. The effect on marginal costs is even smaller, between 99% and 102%; this does not justify extending the *FUND* model with complex atmospheric chemistry. Only if we double and half the life-time,* the marginal costs vary considerably, in this between 54% and 178% of the original estimate; however, this range is narrowed to 68%–128% for a reasonable discount rate of 5%. The uncertainty about the atmospheric life-time of methane is small compared to other uncertainties.

7. Conclusions

This paper analyses the trade-off between carbon dioxide and methane emission reduction using ‘real numbers’. Estimates of the costs of methane emission reduction are still scarce, however, and the quality of the estimates is substantially lower

* Various referees objected to this wide a range.

TABLE VII

The sensitivity of the marginal costs of methane emissions (in \$/tCH4) to the atmospheric life-time of methane

Life-time [a]\disount rate	0%	1%	3%	5%	10%
4.3	243	215	149	101	44
8.3	432	356	227	146	57
8.6 decreasing [b]	439	361	230	147	57
8.6	446	366	232	148	58
8.6 increasing [b]	452	370	234	150	58
8.9	459	375	236	151	58
9.5	486	393	245	155	59
17.2	792	582	323	191	66

[a] Life-time measures in years; cf. Table I.
[b] Initial life time is 8.6 years, decreasing resp. increasing at 0.01 year per year.

than that of carbon dioxide. However, a number of conclusions can be drawn which are largely independent of the exact numbers.

If the cost estimates used here are indicative for the real costs, then methane emission reduction should have a substantial effect on the way climate policy is designed. Obviously, since there is an additional instrument, joint reduction of carbon dioxide and methane emissions leads to a higher welfare than does reduction of carbon dioxide emissions alone – the same conclusion is reached by Hayhoe et al. (1999), Reilly et al. (1999), Manne and Richels (2001), Jensen and Thelle (2001) and Godal and Fuglestvedt (2002).

Besides lowering the carbon dioxide emission abatement effort, the different atmospheric properties of the two greenhouse gases, and their different reduction cost structures lead to different spatial and temporal patterns of carbon dioxide emission reduction as well. This implies that extra care needs to be taken when designing a greenhouse gas emission reduction policy. This is worrisome, since politicians apparently have already great difficulty in designing a carbon dioxide emission reduction policy that makes economic sense. The joint case of carbon dioxide and methane is more complicated. By extrapolation, considering other greenhouse gases – such as nitrous oxide, sulphur hexafloride, and halocarbons – would substantially further complicate the matter.

Methane emission reduction does not help to justify a stringent climate policy in a cost-benefit type of analysis. It is cheaper to control the rate of climate change in the short run with methane emissions than it is with carbon dioxide emissions. *Vice versa*, it is cheaper to control the level of climate change in the long run with carbon dioxide emissions than it is with methane emissions. In this regard, methane emissions could be used, for example, to control undesired medium-term climate variability. The reason for preferring methane emission control for the shorter run, and carbon dioxide emission control for the longer run is not so much their difference in marginal abatement costs, although that plays a role as well. The main reason is that the methane emission reduction options considered in the literature are more or less end-of-pipe measures, which are easy to apply, but require an effort to maintain. Carbon dioxide emission reduction options, in contrast, are generally more structural, and thus harder to initiate but with a bonus in the long run.

In the case of a cost-effectiveness analysis, methane emission reduction may well be a good alternative to carbon dioxide emission reduction – the same conclusion is reached by Hayhoe et al. (1999), Reilly et al. (1999), Manne and Richels (2001), Jensen and Thelle (2001) and Godal and Fuglestvedt (2002). This is particularly the case in the short run, when total emission cuts are not so drastic as in the longer run. Methane emission reduction also implies that, if given the chance, OECD countries shift more of total emission reduction effort to other countries. Because methane and carbon dioxide emission abatement have different structural effects on both economy and climate, it is more complicated to design a good emission control policy.

The most serious drawback of methane emission reduction is that it does not help to solve the problem. Policies are formulated in short-term emission reductions. The problem, however, is long term accumulation of greenhouse gases in the atmosphere. Sure, methane can help to meet policy goals but, because it is short-lived, methane cannot help to reduce concentrations in the long run – see also Manne and Richels (2001). Lowering the global warming potential of methane is the appropriate response. This problem is amplified if one considers that it probably takes less time to reduce methane emissions than it does to abate carbon dioxide emissions. Also for this reason, a cost-effective emission reduction strategy would, at the start, put more emphasis on carbon dioxide than on methane.

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Discussions with Michelle Dastin-van Rijn, Jean-Charles Hourcade, David de Jager and Rich Richels as well as comments by five anonymous reviewers helped substantially improve this paper. The European Commission DG Research's Environment and Climate Programme (ENV4-CT96-0197), the U.S. National Science Foundation through the Center for Integrated Study of the Human Dimensions of Global Change (SBR-9521914) and the Michael Otto Foundation for Environmental Protection provided welcome financial support. All errors and opinions are ours.

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