6. MULTI-GAS SCENARIOS TO STABILIZE RADIATIVE FORCING

Abstract. Using the results of a recent model comparison study performed by the Energy Modeling Forum, we have shown in this chapter that including non-CO_2 gases in mitigation analysis is crucial to formulating a cost-effective response. In the absence of climate policies, the emissions of non-CO_2 greenhouse increase from 2.7 GtC-eq per year in 2000 to 5.1 GtC-eq per year in 2100 (averaged across all the models). A multi-gas reduction strategy stabilizing radiative forcing at 4.5 W/m^2 (compared to pre-industrial) reduces the emissions (on average) to 2.5 GtC-eq. Such an approach leads to a cost reduction of 30–40% compared to a CO_2-only reduction strategy for the same target. The choices of a target and how the gases are valued form an essential part of developing multi-gas strategies. Model results show that the use of IPCC global warming potentials (GWPs) as a basis for substitution has large consequences for the timing of methane reductions. In this context, an assessment on multi-gas metrics, going beyond the mere physical aspects, is important for both research and policy-making.

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6.1 Introduction

Of the set of gases that contribute to the enhanced greenhouse effect, carbon dioxide provides the largest contribution. Nevertheless, taken collectively, the non-CO_2 greenhouse gases contribute about 25% of current greenhouse gas emissions. In terms of equivalent emissions and using IPCC 100-year global warming potentials (GWPs), non-CO_2 greenhouse gases (NCGGs) comprise CH4, N_2O, PFCs, HFCs and SF_6. Despite this still appreciable contribution from NCGGs, most of the literature on mitigation scenarios has concentrated on CO_2. One reason for the limited number of so-called multi-gas studies is that consistent information on emission reduction costs for the NCGG gases has been lacking. Over the last few years, the number of studies that consider NCGGs as well as CO_2 abatement potential have been increasing. Such studies generally find that major cost reductions can be obtained through: (1) relatively cheap abatement options for some of the NCGGs (USEPA, 1999; Blok et al., 2001) and (2) an increase in flexibility in abatement options (Gielen and Kram, 1998; Hayhoe et al., 1999; Reilly et al., 1999; Tol, 1999; Jensen and Thelle, 2001; Manne and Richels, 2001; Van Vuuren et al., 2003b). Other studies report additional advantages of multi-gas strategies, such as in avoiding climate impacts by focusing on short-lived gases (Hansen et al., 2000). Interestingly, policy makers already acknowledged the potential benefits of a multi-gas approach in 1997 by formulating the Kyoto Protocol targets as strategy in terms of a basket or aggregation of greenhouse gases, thereby allowing substitution among these gases. At the time, this was mostly based on the theoretical understanding that increased flexibility leads to a reduction of costs. More recently, the U.S. Administration also choose a multi-gas approach for its climate policy aiming to meet a GHG intensity target.

Considering CO_2-only stabilization, a reasonable understanding of mitigation potential and the associated costs has been gained through a large range of studies covering a wide spectrum of climate targets, and based on a wide range of assumptions and modeling approaches (see Hourcade and Shukla, 2001). A similar situation for multi-gas stabilization did not exists, as the number of individual studies is still rather limited. Furthermore, methodologies have not been compared and studies have generally not assessed multiple stabilization targets. A large model comparison study and the data that has recently been collected on marginal abatement costs for NCGGs provide an opportunity to improve that situation. The study was conducted under Stanford University's Energy Modeling Forum (EMF-21; (Weyant et al., 2006))[i].

Here we will use the results of the EMF-21 scenarios to develop insights into the question of how multi-gas climate change mitigation strategies differ from CO_2-only mitigation strategies. We also compare these new multi-gas scenarios to the baseline scenarios employed earlier by IPCC in the Third Assessment Report (the SRES scenarios) (Nakicenovic and Swart, 2000) and compare the results of the different modeling groups. Finally, we use the results to discuss some crucial methodological issues with regard to multi-gas reduction strategies. In order to evaluate the trade-offs of reducing one gas instead of another, we need to make the climate impacts of each of the various gases and their associated reduction costs comparable. As shown in this chapter, the choice of such metrics is far from straightforward and can crucially change the resulting optimal reduction strategy.

Section 6.2 provides an introduction to the methodological questions that are addressed in this chapter, while Section 6.3 discusses the results for the scenarios without climate policy. Section 6.4 discusses the results for the mitigation scenarios. These results form the basis of a broader discussion in Section 6.5 on the metrics of multi-gas mitigation scenarios. Finally, conclusions are drawn in Section 6.6.

6.2 Methodological questions in multi-gas analysis

The main source of information used in this chapter comes from the EMF-21 study on multi-gas scenarios. In EMF-21, 18 modeling groups and 8 expert organizations on mitigation options collaborated in improving the current state of multi-gas modeling. The purpose of the exercise was twofold. The first was to perform a comprehensive assessment of modeling work to improve the understanding of including NCGGs and terrestrial carbon sequestration (sinks) into short- and long-term mitigation policies;

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[i] The authors acknowledge the contribution of the modeling teams, who provided input for the EMF-21 study. This input has served as the basis for analysis in this chapter.

second, the assessment would strengthen the collaboration between experts on NCGG, and sinks abatement options and modeling groups. The second purpose was felt necessary, as many groups had no representation of NCGG emissions or abatement at the beginning of the exercise. Table 6.1 provides a summary listing of the models and characteristics. Three main model categories can be identified for those participating in the EMF-21 study; we classify them as MultiSector Computable General Equilibrium models (MS-CGE), Aggregate Computable General Equilibrium models (A-CGE) and Integrated Structural Models (ISM). The first group consists of macro-economic models, with considerable sectoral detail. The second group consists of models that focus more on integrated assessment of the economy and climate change, include inter-temporal optimization, and in this context tend to reduce the amount of sectoral detail. The last group consists of models that focus more the structural (physical) processes underlying emissions. Obviously, these groups overlap, but as Table 6.1 shows, within these categories similar techniques are often used to include the non-CO_2 gases (see Table 6.1; and text further in this section).

Given the body of knowledge on CO_2 abatement, a crucial question is how our insights will have to change if multi-gas strategies are to be adopted. Models that are able to address such questions need to be able to deal with a set of rather obvious questions directly related to modeling NCGGs:

a. What activities cause emissions of NCGGs and how are these activities represented in the models?
b. What is the abatement potential of different sources of NCGGs and how can this information be included in the models?
c. How do implementation barriers influence the abatement potential that can be implemented at any point of time?
d. How will the abatement potential for NCGGs evolve over time; and be influenced by technological change and/or reductions of implementation barriers?

In the EMF-21 study, the first question was addressed by developing a dataset of current NCGG emissions in different regions and indicating their main economic driving forces. The way models include this information depends highly on the type of model being considered (see Table 6.1). Detailed integrated structural models generally couple emissions of NCGGs to activities explicitly included in the models (e.g. the number of farm animals). General equilibrium models, in contrast, usually include these gases by incorporating them in the production function of the model. To help answer the second question, this NCGG dataset was extended by including a set of abatement options that could be identified for 2000–2020.

Information on these abatement options has been made available in terms of the characteristics of individual measures, but also in the form of so-called marginal abatement cost curves (MACs). Again, the way models adopted this information differs, depending mostly on the type of model (including a description of individual reduction measures, use of MACs, or incorporating the information into the production functions). The last two questions (c and d) were left mainly to the individual modeling groups to address.

Table 6.1 Key characteristics of EMF 21 models

Model	Model type (a)	Representation of NCGG emission reduction options (b)	NCGG contribution method (c)	Solution concept (d)	Time horizon (e)	Group in this chapter (f)
AMIGA	MS-CGE	RFPF	GWPs	RD	2100	1
GTEM	MS-CGE	RFPF	GWPs	RD	2030	1
GEMINI-E3	MS-CGE	RFPF	GWPs	RD	2050	1
EU-PACE	MS-CGE	RFPF	GWPs	RD		1
EDGE	MS-CGE	RFPF	GWPs	RD	2030	1
EPPA	MS-CGE	RFPF	GWPs	RD	2100	1
IPAC	MS-CGE	RFPF	GWPs	RD	2100	1
SGM	MS-CGE	RFPF	GWPs	RD	2050	1
WIAGEM	MS-CGE	RFPF	GWPs	RD	2100	1
Combat	A-CGE	MAC	RF	INTOP	2100	2
FUND	A-CGE	MAC	RF	INTOP	2100	2
MERGE	A-CGE	MAC	RF	INTOP	2100	2
GRAPE	A-CGE	MAC	RF	INTOP	2100	2
IMAGE	ISM	MAC	GWPs	RD	2100	3
MESSAGE	ISM	SM	GWPs	RD	2100	3
AIM	ISM	SM	GWPs	RD	2100	3
MiniCAM	ISM	SM	GWPs	RD	2100	3
POLES/AgriPol	ISM	MAC	GWPs	RD	2030	3

NCGG: non-CO_2 GHG gases.
(a) MS-CGE: Multi-Sector Computable General Equilibrium; A-CGE: Aggregate Computable General Equilibrium; ISM: Integrated Structural Model, used here to indicate the group of models that include relatively detailed structural models of the sectors that emit non-CO_2 greenhouse gases; most of the models in this group can also be classified as Integrated Assessment Models.
(b) RFPF: Reduced Form Adjustment to Production Functions; MAC: (Reduced Form) Marginal Abatement Costs curves; SM2 indicates models that have included individual reduction measures.
(c) RF:Radiative Forcing; GWPs: Global Warming Potentials.
(d) RD: Recursive Dynamic; INTOP: Inter-temporal Optimization.
(e) Time horizon
(f) Groups used in this chapter, color coded to correspond to in the figures.

For recent work on the question of how potential can evolve over time (see Graus et al., 2004; Delhotal and Gallaher, 2005; Lucas et al., 2007).

In addition to the set of questions raised above, a second set of questions is needed to address multi-gas abatement strategies, which originate from the need to combine the contributions of the different gases, with their different lifetimes and different radiative properties. This second set of questions, as set out below, is also directly relevant to policy-making:

1. How to define a mitigation target for a multi-gas stabilization scenario?
2. How to allow for substitution among the different greenhouse gases and which metric is used to determine the value of each gas?

In response to the first question, the modeling teams in EMF-21 decided, as a group, that the appropriate target for a multi-gas, mitigation exercise would be radiative forcing as: (1) it was the most comparable to the concentration targets used earlier in CO_2-only studies, while (2) it allowed for substitution among different gases. In quantitative terms, the group decided to compare model runs that focused on stabilizing radiative forcing at 4.5 W/m^2 above pre-industrial levels. A radiative forcing target of 4.5 W/m^2 is more or less equal to a CO_2 concentration at 550 ppmv (the standard case in most earlier work), assuming 1 W/m^2 additional forcing for the NCGGs (a value based on the IPCC-SRES scenarios) (Wigley and Raper, 2001). For reference purposes, a 4.5 W/m^2 target also roughly corresponds to a 3 ^{8}C equilibrium temperature increase relative to pre-industrial times using a medium climate sensitivity. With respect to the second question (how to define substitution among gases over time) this was again left to the individual modeling groups to address. As Table 6.1 shows, two main methods were used: substitution based on the 100-year GWPs of the different gases and substitution based on inter-temporal optimization under the radiative forcing target[ii]. In both cases, the time horizon plays an important role. In the former case, alternatives for 30 or 500-year GWPs produce varied results; in the latter, results critically depend on the optimization year chosen (here 2100–2150). The common practice is to compare and aggregate emissions by using GWPs. Emissions of NCGGs are converted to a carbon dioxide equivalent basis using GWPs. GWPs used here are calculated over a 100-year period, and vary according to both the ability of the gases to trap heat and their atmospheric lifetime compared to an equivalent mass of CO_2.[iii] We return to the question of stabilization and substitution metrics (GWPs) in Section 6.5 with reference to the modeling results.

On the basis of all the considerations above, three main scenarios were run in each model:

1. a reference scenario without climate policy, based on the preferences of individual modeling teams;
2. a scenario that aims to stabilize radiative forcing at 4.5 W/m^2 (above pre-industrial) using a CO_2-only strategy and,
3. a scenario that aims to stabilize radiative forcing at 4.5 W/m^2 (above pre-industrial) using a full multi-gas strategy.

The first scenario aimed to give insight into NCGG emissions in the absence of climate policies. The second and third scenarios, taken collectively, aimed to give insight into the potential role of non-CO_2 gases in mitigation under a long-term stabilization target (and the methodological questions raised above). It should be noted that in both stabilization scenarios (2 and 3), no weight is given to short-term benefits of mitigation,

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[ii] For clarity, to determine the climate impact of emissions of different gases in any point of time, obviously a climate model is needed that is able to account for the properties of each gas. In this context, the two alternative approaches with regard to substitution can also be characterized as taking full account of the complex dynamics of the climate responses which can only be done through inter-temporal optimization, or instead using a more simple proxy (GWPs).

[iii] Although the GWPs have been updated by the IPCC in subsequent Assessment Reports, estimates of emissions in EMF21 use the GWPs from the Second Assessment Report, in order to be consistent with international reporting standards under the United Nations Framework Convention on Climate Change. The consequences of using this are small.

which critically influences results (see the discussion section). Formally, the EMF21 exercise also included a scenario in which a maximum rate of temperature change target was selected. However, too few models were run with this scenario to allow comparison of results. Finally, the stabilization scenarios did not allow for an overshoot of the radiative forcing target at any point of time.

6.3 Development of emissions without climate policies

All modeling groups provided a reference scenario that included projections of the emissions of the major greenhouse gases in the absence of climate policy. Figure 6.1 shows the pathways for GDP included in the baseline, while Table 6.2 and Figure 6.2 show the results for these reference cases for the emissions of four main categories of gases.

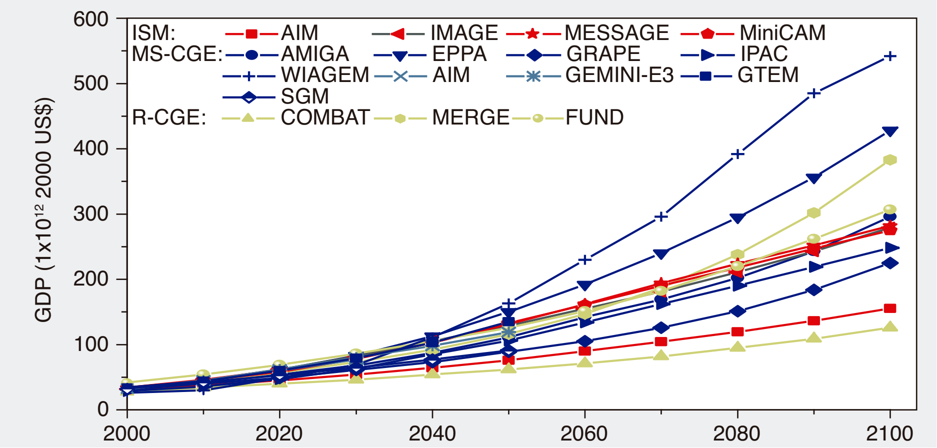

Figure 6.1 GDP trajectories in the EMF-21 scenarios.

Table 6.2 Results (in GtC-eq.) for reference scenarios averaged across the long-term models

	2000				2100				Growth rate		
	Mean	˜SD	+SD	Contribution (Mean) (%)	Mean	˜SD	+SD	Contribution (Mean) (%)	Avg. (%)	˜SD (%)	+SD (%)
CO_2	6.61	6.33	6.89	71.2	19.47	14.68	24.26	79.1	1.1	0.8	1.3
CH_4	1.73	1.57	1.89	18.6	3.07	2.10	4.79	12.5	0.6	0.2	1.0
N_2O	0.83	0.68	0.97	8.9	1.23	0.87	1.86	5.0	0.4	0.0	0.8
F-gases	0.13	0.11	0.14	1.4	0.83	0.49	1.17	3.4	1.9	1.4	2.3
Total	*9.29*	*8.69*	*9.89*		*24.62*	*18.93*	*30.32*		*1.0*	*0.7*	*1.2*

GtCeq: Gigaton Carbon equivalent; SD: Standard deviation. NCGGs are converted using GWPs from the IPCC Second Assessment Report.

The numbers include most of the long-term models with EMF-21 that have reported results. Two models, however, were not included in the average results reported here and elsewhere in this chapter, as their results were too different from the other models (particularly unlikely to comply to the 4.5 W/m^2 target). The results of these models are included in the graphs showing the individual results of the models.

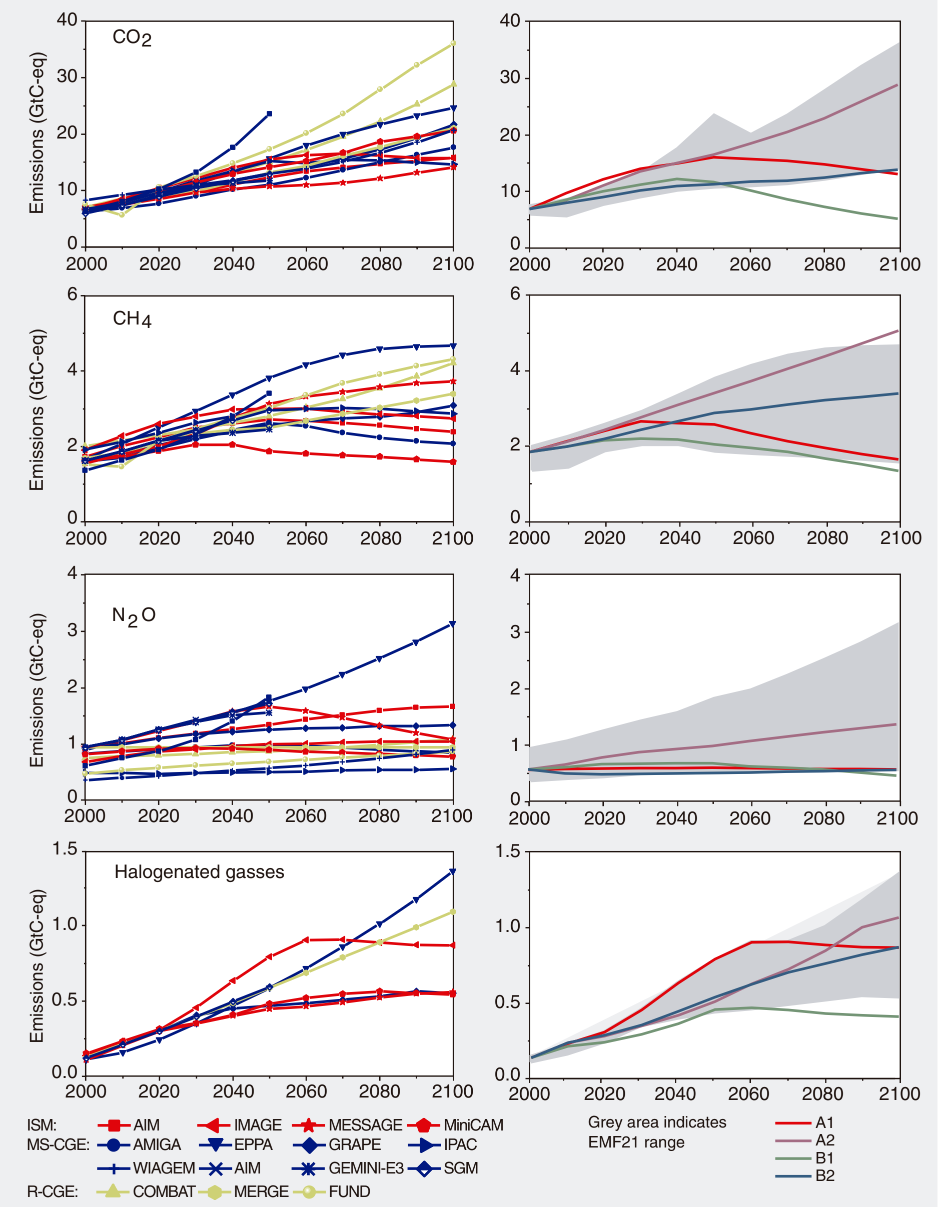

Figure 6.2 Baseline emission development in the EMF-21 scenarios (left) and comparison to the SRES marker scenarios (right).

On average, GDP (Figure 6.1) is expected to grow (across all models) by a factor 3.6 in the 2000–2050 period (2.6% annually) and 9.4 in the 2000–2100 period (2.2% annually). The spread across the models is considerable—with one model indicating a fivefold increase of GDP up to 2100 and another model a 20-fold increase. The MS-CGE as a group seems to show a somewhat higher GDP growth rate than the ISM and A-CGE group (but the difference is not statistically significant).

CO_2 emissions (Figure 6.2) are projected to increase in all models compared to 2000; however, the spread in model results is considerable, ranging from 14 to 36 GtC per year in 2100. CO_2 emissions (across the long-term models) increase on average by 1.1% per year during the 21st century (where results range (standard deviation) from 0.8% to 1.3% growth annually). A considerable part of the spread originates in the second part of the century – where some models show sustained emissions growth, while others show emission growth slowing down or even going negative (mostly due to assumptions on a stabilizing or declining global population). The substantially slower (or even negative) emission growth rate in the second half of the century occurs in most of the models included in the ISM and MS-CGE group. The A-CGE group, on average, seems to have higher CO_2 emission growth rates than the other models in this period. Comparison with Figure 6.1 shows that this difference does not originate from economic growth assumptions. Differences are likely to be related to assumptions on saturation of energy consumption in certain sectors or assumptions on fossil fuel depletion.

The projected increase in CH_4 emissions is considerably less than that for CO_2 for most models. Averaged across the different models, the annual emission increase amounts to 0.6% per year, leading to a decline in the CH_4 share in total emissions from 19% to 13%. The main reason for the slower growth of CH_4 compared to the CO_2 growth is that emissions mostly originate from the agriculture sector. Activities in this sector are expected to grow slower than the main driver of CO_2 emissions, energy consumption. Almost all models show signs of stabilizing and declining emissions in the second half of the century, except for those in the A-CGE group. One reason could be that this modeling group does not capture the saturation dynamics of the driving forces of methane emissions. The range of results for CH_4 is somewhat broader than for CO_2.

Averaged across all models, emissions of N_2O are projected to grow 0.4% annually in the 21st century (one standard deviation range from 0.0 to 0.8%). This is the slowest growth rate of the four groups of gases discussed here, and as a result, the share of N_2O in total emissions drops from 9% to 5%. Note that for N_2O, base year emissions of the different models differ substantially. Two factors may contribute to this. First of all, there are different definitions of what should be regarded as human-induced and natural emissions in the case of N_2O emissions from soils. Secondly, some models may not have included all emission sources.

In the last group, the fluorinated gases (F-gases: PFCs, HFCs and SF_6), emissions grow on average faster than CO_2 emissions (1.9% per year). As a result, the contribution of these gases in equivalent emissions increases from 1.4% to 3.4%, in some models even surpassing N_2O. It should be noted that only a limited subset of models included these gases into the simulations. Most, but not all, of the models project the most rapid increase to occur in the first half of the century.

In conclusion, without climate policies, the baseline scenarios project that emissions of NCGGs will grow significantly. At the same time, their share in total emissions will drop as CO_2 emissions are expected to grow faster than the most important NCGG emissions[iv].

Figure 6.2 also compares the EMF-21 results with the IPCC SRES scenarios (Nakicenovic and Swart, 2000). In general, the range of the EMF-21 emission projections coincides with those from SRES. Some difference is noted for CO_2, where, in the short term, two SRES scenarios are above the EMF-21 range; in the longer term, the B1 is clearly below the EMF-21 range. The latter is due to the deliberate assumption of radical energy efficiency improvement and penetration of renewable energy in B1. For N_2O, the comparison is slightly complicated by the spread of base year emissions in the EMF-21 set (see discussion above); however, in general, growth rates seem to be similar. The coincidence between the SRES and EMF-21 ranges bears further evaluation. First of all, it should be noted that the ranges in the EMF-21 and SRES study originate from very different causes. In the SRES study, deliberate assumptions to map out possible pathways (storylines) cause emissions to diverge across the different scenarios. In EMF-21, a very similar range results from the use of a multitude of models that were free to choose their own modeler's preference baseline scenario. In that sense, the correspondence between the EMF-21 and SRES sets is interesting as the ranges have different causes.

There is some overlap in the models included in the two studies, but the models that were also included in SRES do not represent a majority within the whole EMF-21 set (4 out of the 14 models that reported results: AIM, IMAGE, MESSAGE, MiniCAM). They do, in fact, very seldom form the EMF-21 range. With respect to the other modeling groups included, it is unlikely that simply reproducing SRES results has led to this result, given the independent status of the models, and the methodological differences between these models and most of the SRES models.

The total emission growth under these baseline scenarios implies a sharp increase in radiative forcing as indicated in Figure 6.3. Reported increases in radiative forcing projected by the model groups increase from (on average) 1.7 W/m^2 above pre-industrial today to 6–8 W/m^2 in 2100. This implies that none of the reference scenarios will comply with the 4.5 W/m^2 stabilization target without additional policies in place. The higher radiative forcing of FUND in 2000 is due to FUND not including the (negative) radiative forcing of aerosols (the reason for other differences is unknown).

[iv] For reporting purposes, overall emissions here are post-calculated on the basis of 100 year GWPs. As indicated in the main text, some of the models do not use GWPs as a basis for substitution, while other models do.

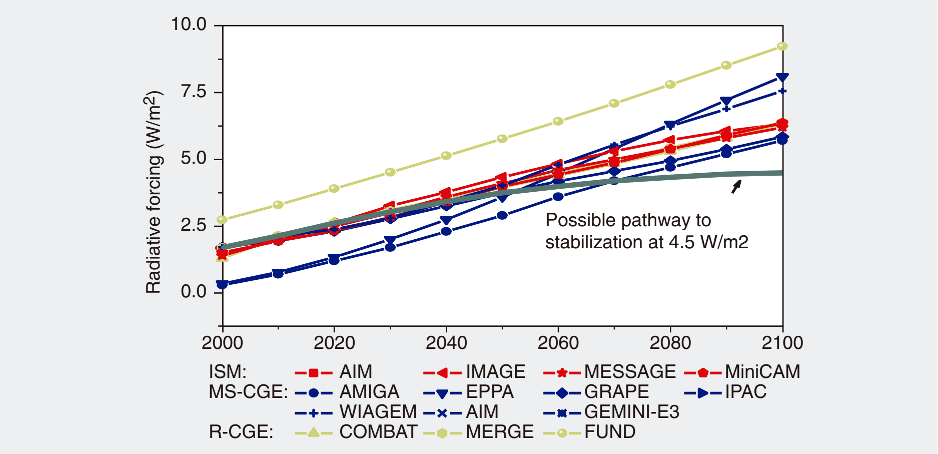

Figure 6.3 Increased radiative forcing under the reference scenarios (without climate policies). The thick black line indicates a possible pathway to the stabilization target of 4.5 W/m^2.

6.4 Stabilizing radiative forcing at 4.5 W/m^2: multi-gas versus CO2-only

6.4.1 Emission reductions (total greenhouse gas reductions)

In order to stabilize greenhouse gas radiative forcing at 4.5 W/m^2, compared to pre-industrial levels, greenhouse gas emissions need to be reduced substantially in comparison to the baseline emissions. The exact numbers obviously differ depending on the baseline. The emission pathways, averaged across all models and including the standard deviation range, are shown in Figure 6.4. The emission reductions compared to baseline amount on average to about 10% in 2020 and to 35% in 2050 and 65% in

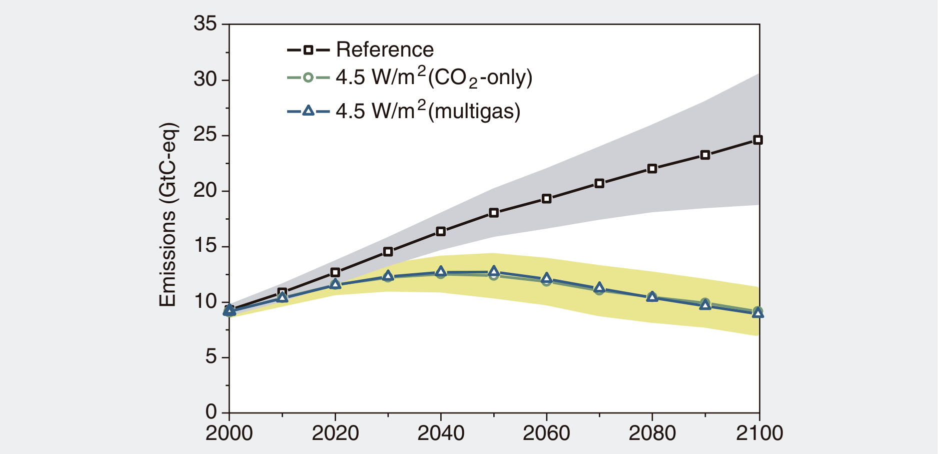

Figure 6.4 Total equivalent CO$_2$ emissions under the reference scenarios, and the stabilization scenarios (area indicates the standard deviation) averaged across all models).

2100. There is no significant difference between the total equivalent emission numbers of the multi-gas and CO_2-only strategy. As to be expected, the range across the models is reduced somewhat in going from the reference scenario to stabilization scenarios—caused by the (equal) additional constraint set on all models to stabilize radiative forcing.

6.4.2. Emission reductions (reductions by gas)

If we start untangling the contribution of the different gases, we can see that in the CO_2-only strategy the largest contribution in mitigation originates from reducing CO_2 emissions (by construction). CO_2 emissions are reduced by about 75% in 2100 compared to baseline. Nevertheless, as shown in Figure 6.5 and Table 6.3, a small number of the emission reductions, are, in fact, achieved through reductions in CH_4 and N_2O as systemic changes in the energy system; this is induced by putting a price on carbon, which also reduces these emissions. For instance, the reduction in fossil fuels use also reduces CH_4 emissions during production and transport of coal, oil and natural gas. On average, emissions of CH_4 are reduced by about 20% and N_2O by about 10%.

Compared to the CO_2-only strategy, a much larger share of the emission reductions occurs in the multi-gas strategy through reductions of non-CO_2 gases, and as a result smaller reductions of CO_2 are required. The emission reduction for CO_2 in 2100 drops (on average) as a result from 75% to 67%. This is still a fairly high percentage caused by the large share of CO_2 in total emissions (on average, 60% in 2100) and partly by the exhaustion of reduction options for the NCGGs. The reductions of CH_4 across the different models average around 50%, with remaining emissions coming from sources that are currently are considered to be difficult to abate, such as CH_4 emissions from enteric fermentation. For N_2O, the increased reduction in the multi-gas strategy is not as large as for CH_4 (almost 40%). The main reason is that the identified potential for emission reductions for the main sources of N_2O emissions, fertilizer use and animal manure, is still limited. Finally, for the F-gases, high reduction rates (about 75%) are found across the different models.

Several factors play a role in the differences among the different models. These include the total reduction burden (which depends strongly on projected baseline emissions), the distribution among different sources, the different methodologies used to represent technological change, and also the method chosen to determine substitution among the different gases.

It should be noted that although the contributions of different gases change sharply over time, there is considerable spread among the different models. This can be seen in Figure 6.5. Many models project relatively early reductions of both CH_4 and F-gases under the multi-gas case. However, the subset of models that does not use GWPs as substitution metric for the relative contributions of the different gases to the overall target – but that does assume inter-temporal optimization in minimizing abatement costs – does not start to reduce CH_4 emissions substantially until the end of the period.

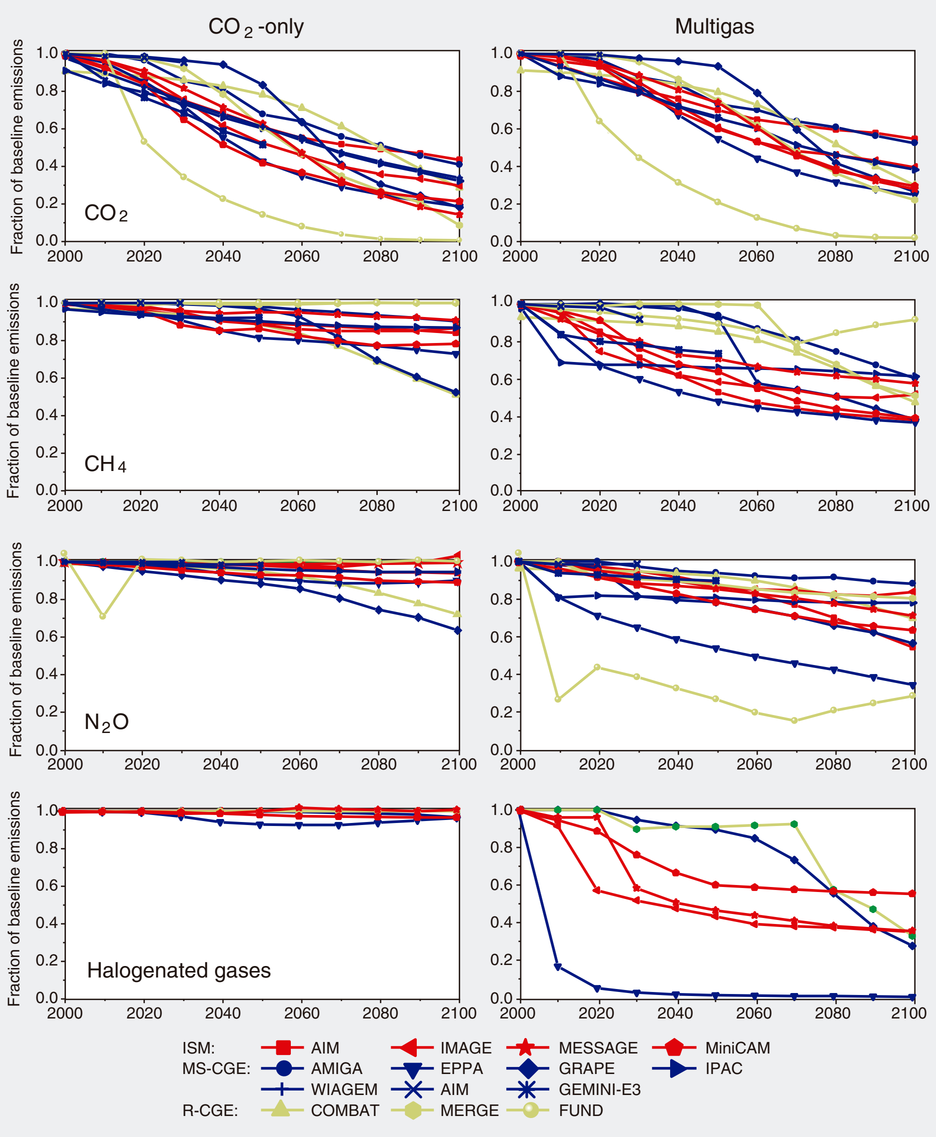

Figure 6.5 Reduction of emissions in the CO_2-only versus multi-gas strategies.

Table 6.3 Percentage reductions in greenhouse gases in CO_2-only and Multi-Gas strategies

	Reference	CO2-only				Multi-gas			
	2100	Avg.	-Std-Dev	+Std-Dev	Red.	Avg.	-Std-Dev	+Std-Dev	Red.
CO2	19.47	4.85	2.75	6.95	**75%**	6.49	4.71	8.27	**67%**
CH4	3.07	2.39	1.61	3.17	**22%**	1.48	0.99	1.97	**52%**
N2O	1.23	1.11	0.54	1.68	**10%**	0.77	0.60	0.93	**38%**
F-gases	0.83	0.82	0.49	1.17	**2%**	0.22	0.09	0.35	**73%**
Total	24.62	9.18	7.13	11.23	**63%**	8.95	7.22	10.68	**64%**

Emissions are reported in CO_2 equivalence using 100-year GWPs.

The reason for this result is that in aiming at the long-term target, it does not pay to engage in early CH4 emission reductions because CH_4 has a short atmospheric lifetime (about 10 years). In other words, since the benefits in reducing radiative forcing in the atmosphere are more immediately felt with CH4 mitigation, these models wait to reduce these emissions as the target approaches. In their calculations, there is not much benefit in reducing CH4 early in the simulation.

In the models that use GWPs as the basis for their substitution, however, CH_4 emission reductions are relatively attractive early-on (compared to CO_2 emission reductions) based on the availability of low-cost emission reduction options. It should be noted that for N_2O, reductions in the first few decades also seem to be substantial—and here the results do not differ among the different categories of models. Here, inter-temporal optimization and use of GWPs give the same results because N_2O and CO_2 have similar (medium-length) lifetimes in the atmosphere.

6.4.3 Costs of mitigation

In the EMF-21 study, two costs concepts were considered: the marginal costs of emission reduction and the reduction of GDP from a baseline scenario. The first concept can be calculated by all models, while the second concept can only be calculated if it somehow includes a description of the macro-economy. Figure 6.6 shows the ratio of marginal costs (i.e. the carbon tax used to induce the required emission reductions) in the multi-gas case to the CO_2-only case. While there are clear differences among the models and in time, the reduction in the marginal costs amounts, on average, to 30–60%. Almost all models show a much greater reduction in the first few decades; in this period a considerable part of the more expensive emission reductions are now being replaced by cheaper reductions in NCGG emissions. The average reduction in the carbon tax in the first few decades amounts to 50–60% across all models. In the second part of the century, the carbon tax is reduced by about 35–40% on average. Some models, however, again show an increasing cost benefit from the multi-gas strategy by the end of the scenario period since the higher flexibility avoids the steep cost increases involved in the deepest CO_2 emission reductions.

More or less the same results can be seen for the second cost indicator, GDP losses. The cost reduction here is about 30–40%, with again the largest benefits occurring in the first few decades of the scenario period. The slightly lower impact on GDP losses than on marginal reduction costs (carbon tax) is to be expected given the nature of the cost measures (the first measure deals with marginal costs, while the second measure integrates across the whole range of measures taken). The differences in results across the different models are larger in the case of GDP losses, which can be understood as these are influenced by a much wider range of uncertainties. In both cases, however, the impacts on costs of multi-gas strategies vis-à-vis CO_2-only strategies are very substantial—certainly in comparison to the smaller contribution of NCGGs to overall emissions.

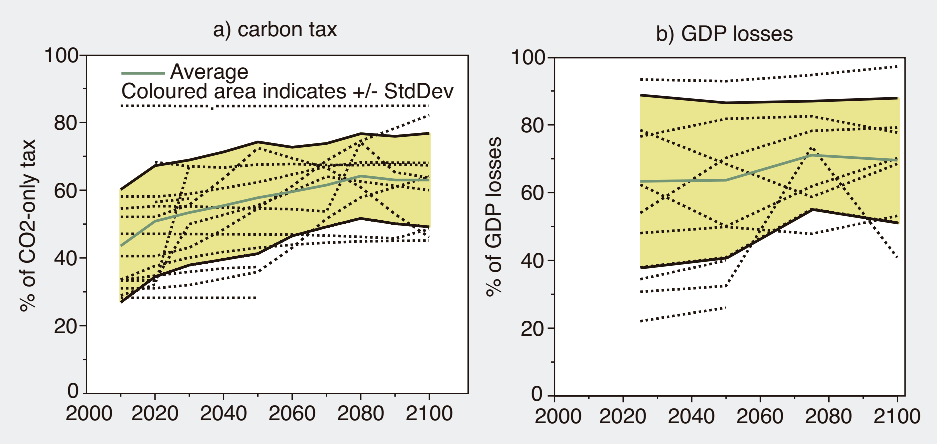

Figure 6.6 Costs of stabilizing radiative forcing at 4.5 W/m^2, ratio of costs in the multi-gas case to the CO_2-only case (grey area indicates standard deviation).

6.5 Discussion on the metrics of multi-gas scenarios

The previous sections have indicated the importance of considering multi-gas strategies as part of stabilization scenarios. In the introduction, however, we indicated that multi-gas strategies are more complicated than CO2-only strategies as they need metrics to compare the contribution of a set of gases with different lifetimes and different radiative properties. Such metrics are needed for two important issues (which some approaches combine into a single issue):

a. how to define the stabilization target for a multi-gas stabilization scenario and,
b. how to allow for substitution among the different greenhouse gases in a way that reflects their relative contributions to climate change.

In this section we will discuss some of the advantages and disadvantages of different targets and, where possible, use EMF-21 results to analyze them.

6.5.1 Definition of stabilization target

As the UNFCCC calls for a stabilization of greenhouse gas concentrations at a level that prevents dangerous anthropogenic interference, most mitigation studies have focused on stabilization scenarios. In models and studies that consider only CO_2 this meant stabilizing CO_2 concentration (the CO_2-only strategy as defined in this study is slightly different, as any increase in NCGG concentrations needs to be compensated by further CO_2 emission reductions). For multi-gas studies, one would need a similar long-term climate target but now integrating all of the NCGGs with CO_2.

In general, a target for climate policy can be chosen anywhere in the causal change of climate change, as indicated in Figure 6.7. Choosing a target early in the chain increases the certainty of required reduction measures (and thus costs), but decreases the certainty on climate impacts (see Figure 6.7 and Table 6.4). Selecting a climate target further down the cause–effect chain (e.g. temperature change, or even climate impacts avoided) increases certainty on impact reductions, but decreases certainty on required reduction measures (UNFCCC, 2002). Uncertainties increase most (either way) in the step from radiative forcing to temperature change due to the large uncertainty range for climate sensitivity (Matthews and van Ypersele, 2003). Analogy with the CO_2 concentration suggests formulating targets in terms of radiative forcing, which is equivalent to the concentrations of the different gases weighted by their radiative properties. The additional advantage of choosing radiative forcing targets over temperature targets is that in determining required emission reductions the uncertainty caused by the unknown climate sensitivity does not play a role. The downside is, of course, that a wide range of temperature impacts is possible for the same radiative

Table 6.4 Assessment of the main advantages of using different targets in modeling exercises, model comparison studies and assessment of available literature

Target	Advantages	Disadvantages
Impacts	Direct link to aspects climate policies aim to avoid (direct link to Article 2, UNFCCC)	Very large uncertainties in required emission reductions and costs
Global mean temperature	Metric is also used to organize impact literature, and has proven to be a reasonable proxy for impacts	Large uncertainty on required emission reduction (as result of the uncertainty in climate sensitivity) and thus costs
Radiative forcing	Relatively easy to translate to emission targets (thus does not include climate sensitivity in cost calculations) Allows for full flexibility in substitution among gases Connects up well to earlier work on CO_2 stabilization Allows for easy connection to work with GCMs/Climate models	Not as familiar as emissions or concentrations (but can be expressed in terms of CO_2-equivalent concentration) Cannot be directly observed or measured
Concentrations of separate greenhouse gases	Can be translated relatively easily into emission profiles (reducing uncertainty on costs)	Does not allow for substitution among gases (thus loses the opportunities of cost reduction of 'What' flexibility)
Emissions	Lower uncertainty on costs	Very large uncertainty on global mean temperature increase and impacts Either needs a different metric to allow for aggregating different gases (e.g. GWPs) or forfeits opportunity of substitution
Costs/activities	Low uncertainty on direct abatement costs; relatively low uncertainty on macro-economic costs	Very large uncertainty on global mean temperature increase and impacts
Rate of temperature increase	Related to some forms of ecological impacts	Very high uncertainty on costs and probably unrealistic in the first few decades

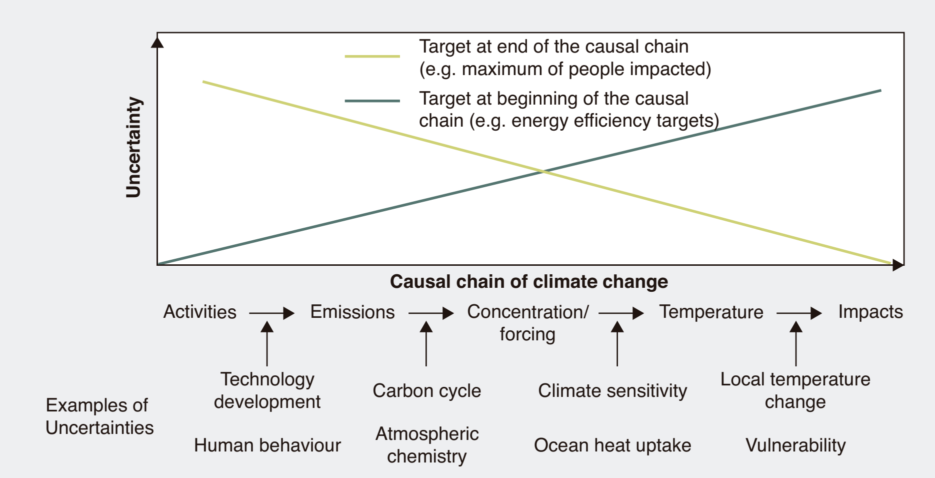

Figure 6.7 Simple representation of the cause-effect chain of climate change, illustrating the consequences for uncertainty from the choice of policy target within the chain.

forcing level. Temperature targets have an important advantage of being more easily associated with impacts (which can be related to global temperature increase – as argued in the Third Assessment Report (IPCC, 2001).

In addition to long-term targets, short-term targets may be also be chosen for climate policy (e.g. the maximum rate of temperature increase). The rationale for such targets is that climate impacts are also related to the rate of climate change if this rate is too fast for ecosystems or human systems to adapt to. However, the little modeling done in EMF-21 on these targets suggest that in the first few decades, stringent temperature rate targets can be difficult to comply with. In particular, MERGE calculations found that stringent temperature rate targets of 0.2°C per decade can lead to high abatement costs (Manne and Richels, 2006). Other models suggested similar results, by showing the high rate of temperature increase in their mitigation scenarios in the first few decades, partly due to reduction of sulfate cooling in this period (van Vuuren et al., 2006b). The implication is that if temperature rate targets are used, they need to be set carefully in the early decades.

The choice of different targets is not only relevant because it leads to a different interpretation of (the same) uncertainty ranges. It is also relevant because it can lead to different strategies and outcomes. The clearest is that for targets such as concentration and emission targets by gas, the opportunity of substitution among gases is forfeited (the advantage of allowing this substitution was shown in Section 6.4). But also the timing of emission reduction may depend on the stabilization target chosen. If the aim is to stabilize temperature, it often seems economically more attractive to peak radiative forcing in a certain year, and next, to further reduce emissions to decrease radiative forcing levels instead of stabilizing radiative forcing directly. The former strategy can avoid the (delayed) further warming associated with the radiative forcing peak level, while still delaying some of the emission reductions in time and thus reducing discounted costs (den Elzen and Meinshausen, 2005).

The discussion in Table 6.4 concentrates on the selection of one particular target (e.g. for model comparison). In policy-making, however, a set of related targets will generally be chosen (instead of one single target) and this set will be updated in due time. For instance, the EU and several European countries have, as an ultimate target, decided on a maximum increase in global mean temperature of 2°C compared to pre-industrial levels. This target is translated into related greenhouse gas concentration levels and then into emission reduction targets. In the course of time, new insights into costs, climate sensitivity and/or impacts are likely to lead to re-evaluation of these targets. In this way, some of the disadvantages of certain targets, as indicated in Table 6.4, can be avoided.

6.5.2 How to define substitution among gases

For the second methodological question, a measure is needed by which the emissions of different greenhouse gases with different atmospheric lifetimes and different radiative properties can be compared. Ideally, such a measure would allow for substitution among different gases (in order to achieve cost reductions) but ensures equivalence in climate impact. Fuglesvedt et al. (2003) provide a comprehensive overview of the different methods proposed, and the advantages and disadvantages of using them. In the modeling described in this chapter, two methods were used: 1) substitution based on GWPs and 2) inter-temporal optimization under a radiative forcing target.

The first method has been adopted in most current climate policies, such as the Kyoto Protocol and US climate policy (White-House, 2002). There has also been a continuous debate on their use for this purpose, based on both natural science and economic arguments (Wigley, 1998; Manne and Richels, 2001; Godal, 2003; O'Neill, 2003; Person et al., 2004). These arguments include the argument that GWPs do not account for the economic dimension of the problem and are based on rather arbitrary time horizons. Inter-temporal optimization models that include radiative forcing and climate change equations can, in fact, totally avoid the use of substitution metrics such as GWPs by simply optimizing across the different gases under the long-term target, as shown within EMF-21.

The question of how to substitute among different gases over time is not independent of the policy target discussed in the previous section. If only long-term targets are selected, the cost optimal strategies from the inter-temporal optimization models will early-on not focus on reducing short-lived gases. This is shown, for instance, by Manne and Richels (2001). The debate can be well illustrated by the comparison study performed in EMF-21. Figures 6.8 and 6.9 show the reduction rates over time again for methane, aiming at stabilization of radiative forcing at 4.5 W/m^2 using a multi-gas approach.

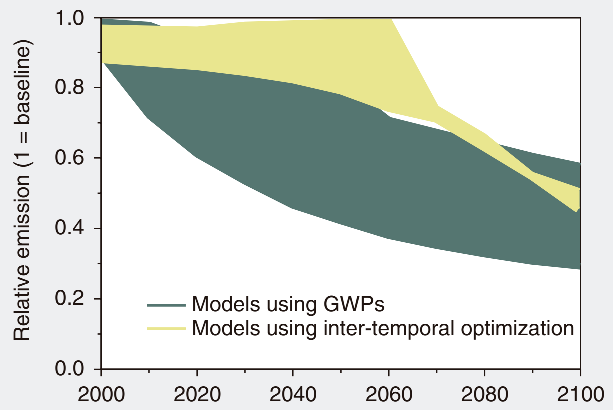

Figure 6.8 Reduction of methane for models that use year-by-year fixed (GWPs) or that base substitution on inter-temporal optimization.

While most models based substitution on using GWPs, four models based substitution on direct contributions to radiative forcing within a full inter-temporal economic optimization framework. The last four are indicated in Figure 6.8. While there are no clear differences among the two groups for most gases, there is a very clear difference for methane. For those models that base substitution on GWPs, the reduction of CH_4 emissions in the first three decades is already substantial. In contrast, models that do not use GWPs only start to reduce CH_4 substantially by the end of the period. The logic in the latter case is that aiming specifically on the long-term target set in the analysis, early CH_4 reduction does not pay off given its short lifetime. In the first group of models, however, CH_4 emissions are attractive on the basis of the available low-cost reduction options. This is illustrated too in Figure 6.9, where a direct comparison is seen between IMAGE (based on GWPs) and MERGE (based on contributions to radiative forcing within an inter-temporal cost optimization framework) results. In IMAGE, a very substantial share of reductions is obtained from CH_4 and the F-gases in the early periods. Their share declines over time (as cheap reduction options are exhausted). MERGE, in contrast, shows almost no reduction in methane emissions until 2070. N_2O, however, shows a major share of early reductions. Finally, by 2100 there is not much difference between the two approaches.

What do these results imply for policy-making? For policy-making purposes, a substitution metric should not only be operational in a modeling context, but also in the real world. The cost reductions from a multi-strategy shown in Section 6.4 can only be achieved if substitution metrics are available that are acceptable to a large group of actors involved in climate policy. As alternative to the GWPs that are now used as substitution metric, it is, in principle, possible to derive the exchange rates of different gases from model results of the cost-optimizing models, as shown by Manne and Richels (2001).

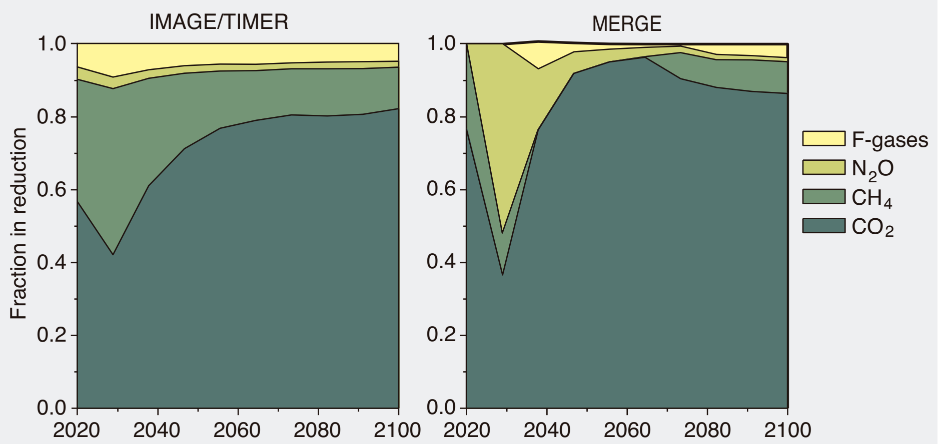

Figure 6.9 Contribution of different gases in overall reductions. Comparison of a model using GWPs as a basis for substitution (IMAGE) versus a model that uses inter-temporal optimization (MERGE)

However, there are two complications. First, these alternative metrics are model-dependent (for example, on the current insights into present and future mitigation costs) and (by definition) dependent on the target that is chosen in the analysis. As uncertainties on costs add to those on radiative forcing, these alternative exchange rates are more uncertain and require a debate on the correct economic model and mitigation potentials. The second complication is that for multi-gas emission reduction strategies and multi-gas trading markets to function correctly, the changes in the value of the exchange rate over time (if any) need to be predictable and smooth. Otherwise, the additional risk of changes in the exchange rate could prevent investors from making otherwise cost-optimal investments. Given the dependency on models and mitigation costs, fully cost-optimal metrics might not be able to pass this test. Relevant questions are therefore: (1) what are the additional costs of using GWPs versus not using them (are the costs with use of GWPs as metric close enough to the lowest costs achievable); and (2) can other real world metrics (that do comply with the considerations above) be developed that have a better performance. Several studies, (O'Neill, 2003; Person et al., 2004; Aaheim et al., 2006), have argued that the disadvantages of GWPs are likely to be outweighed by their advantages by showing that the cost difference between a multi-gas and CO2-only strategy is much larger than between a GWP-based multi-gas strategy and a cost-optimal strategy (thus suggesting that GWPs can achieve most of the cost savings).

One should also note that the cost-optimal results as discussed here are fully optimized under a long-term target, with no benefits assigned to short-term benefits, such as a lower rate of temperature change. This assumption leads to much more extreme differences between the cost optimization and GWP-based strategies than alternative analyses that would have valued short-term gains as well. As GWPs are calculated on the basis of the integral of radiative forcing throughout the century, they automatically lend some value to short-term benefits. Strategies with GWP-based substitution (or cost-optimal results based on temperature rate targets) lead to significantly less warming throughout the scenario period achieved by considerable reductions of CH4 early in the scenario period. Postponing this abatement (as suggested by flexible optimization) leads to higher rates of temperature in the first few decades. Thus, a relevant question on metric within the debate is whether climate policy should focus on long-term targets only, or also on short-term targets such as the rate of temperature change.

The discussion above indicates a debate on useful substitution metrics that is still open. It would seem very appropriate to reconsider the use of GWPs as a substitution metric in the light of the debate on costs and benefits (and not only in the light of their physical properties, which has been the focus of the debate on GWPs up to now). The results of such evaluation are not yet clear. They would focus on the costs of using GWPs versus ideal metrics, but also on their capacity to make a multi-gas strategy feasible in the real world.

6.6 Conclusions and the way forward

EMF-21 performed a multi-model comparison project on scenarios that not only include CO2, but also other major greenhouse gases. The analysis has shown the following results:

- **Under baseline conditions, emissions of non-CO2 gases are expected to grow considerably from around 2.7 GtC-eq. per year in 2000 to 5.1 GtC-eq. per year in 2100 (average across all models; standard deviation range of 3.2–7.1 GtC-eq.year).** Despite this emission increase, the share of non-CO2 gases is expected to be reduced from 29% to 21%. Both CH4 and N2O are expected to grow slower than CO2, as their emissions originate mainly from agricultural activities (growing less rapidly than the main driver of CO2 emissions, energy use). Emissions of the group of F-gases are expected to grow considerably faster than CO2.

- **A multi-gas strategy can achieve the same climate goal at considerably lower costs than a CO2-only strategy.** The cost reduction may amount to about 30–40% for GDP losses and 35– 60% for the marginal abatement costs. The largest cost reductions are expected to occur early on in the mitigation policy.

- **The use of different metrics to aggregate and compare different greenhouse gases (either for the stabilization target or for substitution) plays a crucial role in the final results of a multi-gas strategy.** More analysis and assessment (for instance, by IPCC) could help to further develop insights into the consequences of selecting certain metrics. This is very important for both research and policy-making. The crucial impact of substitution metrics for multi-gas strategies can be directly seen in the EMF-21 results. Under a multi-gas strategy using the 100-year GWPs, the contribution of the non-CO2 gases in total reductions is very large early in the scenario period (50–60% in the first two decades). Later in this period, the contribution of most gases becomes more proportional to their share in baseline emissions. Not using GWPs, but determining substitution on the basis of cost-effectiveness instead of realizing a long-term target within models, implies that reductions in CH4 are delayed to later in the century. Regarding the stabilization target (the second metric), EMF-21 analysis has focused on stabilizing radiative forcing. However, some publications have indicated that stabilization of global temperature can be achieved more cost-effectively through profiles that result in radiative forcing levels that peak and then decline. Further research could focus on such overshoot scenarios.

- **Identified reduction potentials for non-CO2 gases become exhausted if substantial emission reductions are required, for instance, reductions to 40% for N2O compared to baseline across all models and to 50% for CH4 (compared to almost 70% for CO2).** Further research into identifying means to reduce agricultural CH4 and N2O emissions and expected technological change is therefore an important research topic.